New Century, New Light

The role of design in the transition to LED technology

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Certificate Of Original Authorship

I certify that the work in this thesis has not previously been submitted for a degree nor has it been submitted as part of requirements for a degree except as part of the collaborative doctoral degree and/or fully acknowledged within the text.

I also certify that the thesis has been written by me. Any help that I have received in my research work and the preparation of the thesis itself has been acknowledged. In addition, I certify that all information sources and literature used are indicated in the thesis.

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Light is like no other physical medium – it can reach out and influence our mood and emotions. My passion and enthusiasm for working with light continues – now with greater knowledge.

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Abstract

This thesis is concerned with a particular moment of technological change – the emergence of LED technology in the early part of the 21st century as a viable architectural light source. The advent of this technology into the provision of artificial light has not been straightforward, since LEDs have created many design challenges not seen in the lighting technologies of the 20th century.

This thesis therefore examines both the challenges and potential of LED technology. Additionally, it explores both the ways LED lighting can be used to take advantage of the benefits this technology offers and new design processes that may be required for that purpose.

A series of practice-led experiments were undertaken to gain a greater understanding of the nature of LED light. An approach based on 'frames for practice' was adopted to guide these experiments, which themselves were supported by the technical and scientific literature that discusses the way light is generated, measured and experienced.

LEDs are part of a wider technological change from industrial to digital technologies. Actor- network theory (ANT) has provided the lens through which moments of technological change in lighting in the past and the current transformation are examined.

Research outcomes include a suggested method of working with LEDs and possible new uses of LED light in different lighting scenarios. Above all, a fuller understanding of the move from industrial to digital lighting and its implications was gained.

Introduction

This thesis explores the challenges of designing everyday lit environments and lighting experiences using Light Emitting Diode (LED) technology as an energy efficient replacement for 20th century lighting technologies. Despite the benefits offered by LED technology and considerable government support (Archenhold, 2008), LEDs have not easily found a place in interior lighting design. For the purpose of this study, the research has a focus on the domestic environment while recognising that the same challenges exist in other sectors.

The first area of study addresses the challenge of *designin*g with LEDs, a lighting technology that stubbornly refuses to conform to the norms of previous lighting technologies. In every way – aesthetically, technically, the way the technology is made, sold and where it came from – LEDs are different to any other light source that I as a designer have used.

The second area of study examines how the transition to LED technology is unfolding. Before commencing the research, I had a tacit assumption (which I found was shared by the lighting industry) that LEDs were another light source to be incorporated into an existing infrastructure, much as previous light sources such as fluorescent or halogen lamps were used throughout the 20th century. However, LEDs defied these expectations and were, in fact, a new paradigm of light source that did not transfer easily into existing networks for the delivery of artificial light.

LEDs are from the digital rather than the industrial age. Just as the arrival of industrialisation in the early 19th century created whole new networks for the delivery of particular services, digital technologies are similarly reconfiguring different service sectors today. Within this larger digital transformation, LEDs are transforming the provision of artificial light in the 21st century.

The significance of LEDs

In the first decade of the 21st century, LED technologies were recognised as a potential solution to the issue of energy consumption in the lighting sector and therefore aroused government interest. Governments invested in LED development and enacted a series of regulations to drive the transition to LED technology (Archenhold, 2008). So significant was the development of LED technology seen to be that the 2014 Nobel Prize for Physics was awarded to the three scientists - Isamu Akasaki, Hiroshi Amano and Shuji Nakamura – who were responsible for the breakthroughs that allowed LED technology to develop into a light usable for interior lighting.

LED technology was considered particularly important because it is the only artificial lighting source with the potential to convert 100 per cent of energy input into light (Shur & Zukauskas, 2005). However, there are barriers to realising this potential, many of which are connected to the way the technology is configured as a light emitting device.

Arriving at the question

Informed opinion in professional lighting circles in 2008 was that light emitting diodes (LEDs) represented the future in lighting. An article in the respected German design magazine *md* on new LED applications said, ‘Experts are convinced about the worth of LED technology and consider it to be a kind of all-purpose light of the future’ (Anonymous, 2007 p. 66). Monica Pietrasanta in *Interni* magazine said that LEDs were ‘justifiably considered the light of the future for interior and outdoor use’ (Pietrasanta, 2008 p. 94). Kevin Dowling, chairman of the Illuminating Engineering Society of North America subcommittee on solid state lighting (LEDs), noted that among illumination engineers there was excitement and even a degree of hype around LEDs. This interest was due to the ability of this technology to address a conjunction of concerns around sustainability and energy savings, as well as engineering enthusiasm for a 'genuinely new source and new concepts' (Dowling, 2008 p. 18).

Government support for LEDs, most notably from the US Department of Energy (DOE), accelerated the rapid development of the technology. In 2005 the DOE formed an alliance with the lighting industry called the 'Next Generation Lighting Initiative' with the explicit aim of accelerating the development of white-light LEDs (*Energy Policy Act,* 2005). Funding of $350 million was allocated between 2007 and 2013 for this work (Department of Energy, 2006). The DOE recognised that there were significant technical challenges that restricted the application of LEDs. The 'Core Development of LEDs Program' funded by the DOE focused on resolving technical challenges that restricted the application of LEDs. The research focused on technical issues such as quantum efficiency, phosphors and packaging materials. The DOE also funded product development to advance application of LEDs in commercially viable devices or systems (MacShane, 2008). The DOE recognised that lighting designers had a role to play in overcoming the challenges connected with the application of LEDs. They met regularly with industry representatives to gain a better understanding of industry needs and to share latest developments (Brodrick, 2008b)

The proceedings of the 2008 *Euroled* conference in Brussels noted the *importance* of government regulations in driving LEDs as an efficient light source (Archenhold 2008). The announcement in 2008 that the European Union (EU) would phase out inefficient general lighting service (GLS) incandescent lighting by 2012 (Whitaker, 2009) and the duplication of this phase-out in many other countries (Azevedo et al., 2009) seemed to confirm the claim that LEDs were indeed the future of lighting.

However, further research revealed a more complex picture, as the lighting industry seemed very wary of engaging with LEDs. In some informal interviews conducted with lighting professionals around 2008, 'LEDs are not ready' was often given as a reason for not working with the technology. In his history of the LED, Johnstone observed that the lighting industry initially reacted to LED technology by saying 'it shows promise' or 'let's wait until it reaches the crossover point' (Johnstone, 2007 p.13). In my discussions with lighting suppliers and during my visits to showrooms, I was surprised by the lack of forward planning as to how this technology would be used in lighting fixture design. The large lighting shows where new products and directions were launched indicated very little real engagement with LED technology. Lighting designer Hamish Little [on LEDs] noted that 'Frankfurt *Light and Build* [the largest lighting event in the world] had surprisingly little considering the hype' (Hamish Little, 2008, pers. comm., 14 October). Rather than being excited by LEDs, designers in the lighting sector appeared to evince a level of scepticism. Some lighting professionals thought that LEDs would be useful for automotive, signage and street lighting applications but doubted whether LEDS could offer effective interior light sources (Davis, 2010; Shaw 2009). Existing or competing light sources were championed over LEDs (Casey, 2007; Davis 2010).

An editorial in *SSL Magazine* reporting a 2008 'round table' between the US Department of Energy and professional lighting designers expressed a sense of disappointment at the risk-averse attitude of the lighting community in relation to LED technology. The editorial expressed a sense that even experimental adoption of the technology would be slow. The president of the International Association of Lighting Designers in the US argued that LEDS would always be a complementary addition to existing light sources (Crockett, 2008). Italian lighting designer Francesco Murano, while appreciating the particular innovations possible using LEDs, noted that they 'will not replace all other sources' (F. Murano 2009, pers.comm., 18 September). There appeared to be little belief that LEDs would be anything but a supplementary light source, limited to a few applications. This attitude was at odds with the aims of government programs and legislative moves towards an energy-efficient future in lighting.

From a personal point of view, I was surprised that a genuinely new light source was not being embraced for the possibilities it offered. The degree of support in the media and from governments was not reflected in on-the-ground innovations. My focus at this stage of the project was on lighting and the lighting industry. I was to find later in my research that there *was* a great deal of innovative activity around LEDs but it was in sectors outside the traditional lighting industry. This disjuncture between the lighting industry and other sectors became more apparent as the research progressed.

The heart of the difficulty experienced by the lighting industry, including designers, is identified in a brief statement on the website of US Government supported Next Generation Lighting Industry Alliance (NGLIA) noting that, 'The physical behaviours exhibited by solid state materials [LEDs] are substantially different from traditional lighting technologies.' The NGLIA added that there was a need for 'the creation of new practices to fully exploit the technology's potential' (NGLIA, 2005). The NGLIA's view is that LEDs are a lighting technology so different from previous light sources that new approaches to design are required. Hamish Little concurred with this view, noting that designing with LEDs needs a different design philosophy. He suggested that LEDs will 'redefine how we do lighting' (Hamish Little 2009, pers. comm., 14 October). Developing an understanding of how to design with LEDs has been complicated by the lighting industry's attempts to simply replace existing light sources with LEDs rather than develop alternative and more appropriate designs. James Brodrick, lighting program manager for the US Department of Energy's Building Technologies Program, noted a tendency to look for LED products that can simply be placed into existing fixtures (Brodrick, 2008a). Frustration has been expressed at the slow rate of design progress around LEDs. Judges in the DOE's Next Generation Luminaires competition in 2008 asked, 'Why is there no effort being put into creative fixtures that could really address some needs that aren't already being met by traditional lighting?' These thoughts were echoed by lighting consultant Kevin Wilmorth at the 2008 *ArchLED* conference in Chicago when he questioned the continuing influence of older light sources and asked where the approaches were that 'showcase what LEDs can do?' (Koerth-Baker, 2008 p. 56). Willmorth's views were supported by lighting consultant Kevin Dowling when, writing in *Architectural Lighting* magazine, he argued that LEDs had an opportunity to 'redefine how lighting and architecture interact' but would not be able to do that if constrained by the thinking around the 'legacy of traditional light sources' (Dowling, 2008 p.20).

The questions addressed in this study

This study became focused on the role of design in the ongoing development of LED technology. The slow uptake of LED technology by the lighting design industry suggested that new skills would be required but the exact nature of those skills was unclear. It seemed possible that the adoption of LEDs could lead to different approaches to lighting. This research project set out to explore these possibilities.

New lighting technologies, which had been enfolded into the existing lighting industry, had appeared over the 20th century. Would the transition to LEDs be similar to these processes or would it be different? How would LEDs influence the future of lighting? Given the changing landscape in lighting, would the role of design in lighting be similar or different to that of the 20th century or not, and if so how? Preliminary research indicated that the adoption of LEDs could lead to different approaches to lighting. This research project set out to explore these possibilities.

My research study focused on the three following areas:

1. What new design approaches are required to work effectively with LEDs? What is the potential for new lighting applications using LED technology which make the best use of their attributes?
2. What are the implications of the transition to LEDs for the lighting sector? What is the nature of the transition to LED technology?
3. What role will product design have in the future of LED lighting?

In this research, the term 'light' refers to the phenomenon of visible light, or illumination, rather than the designed artefact that houses the source of artificial light. The latter category will be referred to, throughout the thesis, as 'light fittings' or 'luminaires'.
Light is an experiential phenomenon. To understand the experience of light created by LEDs and the most effective design approaches in mediating the light, it was important to create the lighting effect itself. It was planned that a major part of the investigation would involve practice, which would allow me to acquire knowledge in three areas:

1. the intrinsic qualities of LED light; its strengths and weaknesses and how it could be mediated to create visual effects
2. the design skills needed to work with this technology
3. the creative possibilities offered by LEDs in terms of illuminating spaces.

Towards a practice-led approach

While design practice is increasingly accepted as a part of research, there is ongoing uncertainty as to its role. A variety of terminologies exist for the use of practice in a research context and this multiplicity of terms is adding to the confusion. These terms include practice-*based* research and practice-*led* research (Niedderer and Roworth-Stokes, 2007).

Practice-*based* research and practice-*led* research are frequently used interchangeably. However, Candy (2011) argues that these terms are *not* synonymous and that differentiating between them can be useful, particularly in relation to the creation of artefacts. Candy suggests that in practice-*base*d research the emphasis is on the artefact and that 'the insights from making, reflecting and evaluating may be fed back directly into the artefact itself' (Candy, 2011 p. 3). The research findings are embodied in the final artefact, as developed through the practice-based research process; referring to text on its own is not enough. The most common approach to practice-*based* postgraduate research degrees in an art or design context involves the creation of a series of artefacts (often presented as an exhibition) accompanied by a written text called an *exegesis*. The exegesis locates the work in a context, examines theoretical approaches and provides a documentation of the development of the work (de Freitas, 2002).

In practice-*led* research, the emphasis is on creating new understandings to inform the practice. The creation of artefacts during the research process is for experimentation and testing, in order to arrive at understandings that can inform ongoing practice. The outcomes can be used by the practitioner/researcher and can be handed on to other practitioners in the form of guidelines or reports (Candy, 2011).

Candy's distinction between practice-based and practice-led design research was foreshadowed in Pedgley and

Wormald's articulation of three models for design research where practice is adopted as the primary mode of enquiry. These three models are described in relation to three different aims of the research:

A. to find out about current design practices (e.g., pursuing a design project to help uncover decision-making processes)

B. to devise improvements in design methods (e.g., pursuing a design project to help conceive and develop new design procedures, information, priorities and tools)

C. to make improvements to designed artefacts (e.g., pursuing a design project to contribute to what is known about how a type of product can or ought to be designed, how it can be improved and to demonstrate the benefits to be gained).

Model B aligns with *practice-led* research while Model C can be identified as *practice-based* research.

My early experiments with LEDs had made it evident that this technology required a very different approach to that informed by my expertise in designing with incandescent and other legacy lighting technologies. The research project became an opportunity to understand LED technology and how best to work with it, rather than an opportunity to create exemplary artefacts. A practice-*led* approach that enabled new understandings to be developed through the creation of artefacts was therefore adopted as the methodology for this study.
To clarify the particular value of design practice within a doctoral research project, Pedgley and Wormald recommend that the researcher ask:

> What would be lost without the designing? What is the essential research function of the design project(s)? The inclusion of own design activity in

> a PhD must essentially be to advance an identified body of knowledge. (Pedgley and Wormald 2007 p. 84)

Without the design practice component of this research, it would have been impossible to develop an answer to the central research question: 'What approaches should lighting designers take if they are to realise the potential of LED technology for lighting in domestic settings?' Such a question cannot be answered without actual experimentation and making.

The practice-led experiments created in this study used a range of LED formats in conjunction with different materials and light mediation techniques to create a series of lighting effects. Each project sought to generate a useable or exhibitable lighting artifact that would create pleasing experiences of LED light; however, the value of the designing was realised not in the final artefact itself, so much as in the process of getting to know the technology, its behaviour and its potential interactions with different materials and surfaces; and the ongoing process of trial and error, questioning and adjustment that informed the design process.

Through the design experiments I became familiar with the type of light created by LEDs, and developed an understanding of the ways the light could be manipulated by working with a variety of optical principles. The challenge of designing for specific contexts or functions brought into focus the potential applications of LEDs and gave insight into the future potential of the technology for lighting. Understandings reached through the practice-based experiments have been translated into advice for designers new to working with this technology, strategies that can be adopted in getting a feel for LED light, and a list of technical skills required to work with it. An approach to designing LED lighting fittings that utilises this knowledge was developed and included in the findings of this study.

Designer to practitioner-researcher

I came to this study with a background in industrial design and more recent experience in lighting design. I had manufactured and sold many light fittings; I had won awards and grants, and had exhibited in museums, galleries and commercial expositions such as the *Salone del Mobile* in Milan. My experience was not grounded in design research but in design practice. Cross (2000) argues that design practice does have its own strong intellectual culture and that there are forms of knowledge that come from practice which he calls 'designerly ways of knowing'. Buchanan (1998) notes that the search for answers to 'difficult questions' has always been present in design practice. Design competencies in practice are highly valued. However, while design competency would be needed for this research project, the goal was not the realisation of designed artefacts, but the development of new understanding concerning how to work with this technology. The success of the project would be measured by the worth of the understanding arrived at and communicated, in answer to the research questions (Biggs and Buchler, 2007).

An examination of previous practice-led theses in design encouraged me further to pursue a practice-led direction for the study (Pedgley, 1999; Rissanen, 2013). Pedgley's thesis was consulted early in this study and from this I gained an appreciation of the level of documentation needed in practice-led research. Rissanen, an experienced fashion designer, needed to make the journey from practitioner to researcher. His 'frames-for-practice' approach, developed to provide some distance from personal practice whilst still using professional competencies, was incorporated into the structure of my own practice-led inquiry. It was helpful to see previous successful outcomes in the area of practice-led research.

Practice-led experiments: external support, collaboration and venues

Practice-led research has its own set of practical concerns. The funding, technical support and logistics of making can be challenging. Creating a body of work based around LED technology needed financial resources. I was fortunate that some of the practice-led experiments could be conducted in tandem with the development of light art installations, and so be eligible for funding by bodies associated with the *Vivid Sydney* Light Festival. Projects associated with *Vivid* (except for the *Isis* installation) and the *Nimbus* project were undertaken in collaboration with Ben Baxter. LEDs are not standardised and are available with a bewildering array of options for different lenses and outputs. All LEDs have drivers and, in some cases, control systems that need to be integrated into a whole design. Important technical support and advice was offered by Rick Cale from Xenian Light, who became a sponsor from early days.

The practice-led experiments conducted for this research were focused not only on the technical skills necessary to working with this light source, but on the experience of the light created. For this reason, the lighting effects had to be seen or experienced in some way. The *Vivid Sydney* light festival provided a venue. *Vivid Sydney* also provided a degree of freedom, as the aim of the festival is to create interesting light experiences, not to solve problems connected with specific illumination requirements. As a venue for experimenting with a new light source, it therefore offered advantages. Working in a festival context required the production of effective lighting installations for the viewer and the festival organisers. However, as practice-led experiments, they were also learning projects and the installations were intended neither as prototypes for immediate production nor as solutions to a particular need.

In addition to the projects developed for *Vivid Sydney*, a parallel set of practice-led experiments was developed specifically for domestic interiors. This set of luminaires underwent a more formal evaluation process, as documented in Chapter 5. Ethics approval was granted for this evaluation (HREC 2009000213). Detailed records of the development process were kept for each set of practice-led experiments, including photography, videos, diagrams, product information, card models, mock-ups, 3D modelling and technical drawings. These have been archived, and are referenced in this thesis. A number of experts and technical advisors assisted at various stages.

Literature supporting the research process

It was important for me as a researcher to interrogate my tacit assumptions concerning light. I needed to locate my lighting design practice in historical, cultural and other contexts. I needed to develop an understanding of the nature of technological change and how that might impact on the transition to LEDS. I also needed to increase my technical understanding of light, and of LEDs in particular. The following sections review the literature I consulted in the course of this study.

1. Actor-Network Theory

Actor- network theory (ANT) was developed by sociologists working in science and technology studies in the 1980s, as an approach to describing ecologies of scientific work and processes of technological innovation. The three thinkers most responsible for developing this approach were Bruno Latour, Michel Callon and John Law. ANT views technology transitions as changes in the assemblage of actors (human and non-human) associated with the performance of particular functions, such as the delivery of artificial light. This theoretical lens is useful in design research as it understands agency as arising from the performance of networks of human and non-human actors, rather than from individual humans with intentions. Viewed through this lens, designed things are seen as participants in the production of particular practices and modes of inhabiting the world. Technology change involves shifts in these practice world and habitual modes.

Although I make no claims to be an actor-network theorist, I drew upon the concepts developed within ANT to understand *how* technological change happens and to illuminate the difficulties inherent in such changes. I found some ANT histories of technological innovation useful precedents for looking at the difficulties encountered in the transition to LEDs (Bijker, 1992; Latour 1991; Law & Callon, 1992). The ANT concept of 'recruitment' – the gathering of support for a new technology - provided an insight into the roles of particular human and non-human actors in the incremental shifts toward the adoption of LEDs (Law, 1991). An engagement with ANT helped me understand how some technological changes can happen reasonably smoothly while others encounter difficulties, as occurred with the emergence of LEDs.

2. Historical study

The history of lighting revealed a complex story of individual lighting technologies, from ancient torches to current electric lighting, both shaping and being shaped by customs, practices, expectations, infrastructures and design approaches. Transitions were often accompanied by periods of upheaval and uncertainty, as is the current situation with LEDs. In the course of this research, a variety of books, paper and exhibition catalogues were consulted. I visited the Powerhouse Museum in Sydney where the librarians assisted with obtaining material. The collection of the Victoria and Albert Museum in London, which I consulted via the internet, had relevant examples of light fittings and implements, supported by detailed discussion. Broader discussions on how new lighting technologies can influence the social landscape were found in Christopher Otter's *The Victorian eye : a political history of light and vision in Britain, 1800-1910* (2008) and Wolfgang Schivelbusch's *Disenchanted Light* (1988). Brian Bower's *Lengthening the Day* (1998) gave an historical overview from oil lamps to electricity, with an emphasis on the implements, technology and infrastructure of lighting. Maureen Dillon's *Artificial Sunshine* (2002) provided detailed information on the design of light fittings. Jane Brox in *Brilliant: the Evolution of Artificial Light* (2010) provided detailed insight into the history of lighting in America. A history of the creation of the gaslight network was gleaned from a series of papers by Leslie Tomory, (2011; 2012; 2014), and Sarah Milan (1998). William O'Dea's *Social History of Lighting* (1958) is a widely cited general discussion, covering public and private lighting applications. Exhibition catalogues of lighting implements were a useful source of information on implements, fittings and techniques for creating and enhancing light. Particularly useful texts were those by Bluhm & Lippincott (2000), Smith (1992), Wlock (1979), O'Dea (1951) and Daw (1973). Further insight was drawn from literature on the preservation of houses, including Thwing (1939), Crowe-Leviner (2000), O'Dea (1948).

3. Technical and industry

A variety of technical and scientific texts were consulted in order to develop an understanding of the technical issues concerning lighting in general and LEDs in particular. For general information on lighting I consulted Rea (2000), Tregenza & Loe (1998) and Julian (2011), all of whom are well known in the field. The *Illuminating Engineering Society of North America Handbook* by Rea (2000) was a particularly formidable but informative source. More specific information on technical aspects of LEDs was sought from scientific papers by Azevedo et al. (2009), Shur & Zukauskas (2005), Protzman & Houser (2006) and Freysinnier (2009). A variety of supporting scientific papers from journals published by bodies such as the Illuminating Engineering Societies (which have been cited throughout the study) and books such as Zukauskas et al., (2002) and Kitsinelis (2011) were also consulted. Johnstone (2007) included not only technical information but an account of the early days of the LED industry. Johnstone (2017) continued discussion of the development of LEDs.

During the course of my research, LEDs gradually moved from the periphery to the centre of attention of the lighting industry. It was important to track these developments which, once they gained momentum, were surprisingly rapid. Lighting magazines (*mondo arc, SSL, LEDS Magazine, Lux Review*) and reputable online discussion forums, often associated with particular magazines such as *Lux Review* and *Architectural SSL,* were monitored throughout. I followed lighting conferences, as the topics of published papers, as well as the choice of keynote speakers, were instructive in relation to industry focus. This required constant monitoring and cross checking, with discussions evolving as fast as the LEDs themselves.

I attended the 2010 *Lightfair* in the United States, where I made a presentation on my research (McDermott, 2010), *Light and Build* in Frankfurt in 2014 and the *Salone Del Mobile* in Milan in 2015. At the 2010 *Connected* Conference in Sydney, I presented a paper written with my then supervisor, Dr Sally McLaughlin, and Dr Timo Rissanen (McDermott, McLaughlin & Rissanen, 2010). I presented a paper at the IASDR 2011 (International Association of Societies of Design Research) *Diversity and Unity* in Delft on the evaluation process discussed in Chapter 5 (McDermott, 2011). At the 2015 Association of Architectural Science Conference in Melbourne, I presented a paper written with my supervisor Dr Susan Stewart (McDermott

& Stewart, 2015). These conferences all connected me with other researchers working in the field of lighting and associated areas. I contacted numerous writers and industry experts and found them to be very helpful, expressing a genuine interest in the transition to LEDs. They were able to give me information that I could not find in other resources; Rene Geerts, for example, gave me a frank and honest evaluation of the current stage of the transition to LEDS.

4. Light quality

Early experiments alerted me to the propensity of LEDs to create conditions of glare unacceptable for interior applications, so a body of research associated with lighting design, light quality and glare was consulted.
The earliest formal research into lighting effects was undertaken by engineers in the late 19th and early 20th centuries. These researchers assumed that the goal of lighting design was the provision of functional, well-lit environments that enabled efficient work practices. This engineering approach can be seen in the work of the Illuminating Engineering Societies formed in 1906 (USA) and 1910 (United Kingdom) to develop guidelines for lighting design to achieve better visibility for tasks, and efficiency and economy of illumination through the application of rigorous scientific principles (Cuttle, 2012). Early research into light quality was chiefly concerned with eliminating the problem of glare arising from the intensity of light from, associated, in the first place, with the newly-developed GLS, and later with fluorescent lighting technologies (Luckiesh & Holladay, 1925, Guth 1949). A human-factor approach to research on light quality was introduced by R.G. Hopkinson in the 1960s and 1970s. This approach focused on how people behave under different lighting conditions (Hopkinson & Longmore, 1959; Hopkinson, 1963; Hopkinson & Collins, 1970). John Flynn

and his colleagues were also important contributors to lighting research, focusing on the psychology of lighting. They developed a set of tools to translate the qualitative experience of lit environments into quantitative data (Flynn, 1973; Flynn et al.1979).
Recent developments in the field of illumination engineering, exemplified in the work of Jennifer Veitch and Guy Newsham, focus on the relationship between lighting quality and social behaviour (Veitch & Newsham, 1996; Veitch, 2006). These texts plus various papers and book chapters (Canter, 1974; Loe, 1998, Marsden, 1972, Shepherd et al, 1992, Taylor et al., 1974) were consulted to gain a greater understanding of the issues around light quality and to formulate the evaluation process presented in Chapter 5.

5. Architectural lighting design

An alternative to the engineering approach to lighting design gained momentum in the 1930s, when designers with a background in scenography such as Richard Kelly and Stanley McCandless became involved in the emerging field of interior spatial design. These designers had the ability to bring the 'magic of theatrical experiences to their creations' (Cuttle, 2012 p. 126). Their concern was the atmosphere created by light facilitation of the efficient performance of tasks. Richard Kelly developed a particularly influential approach to lighting design. (Neumann, 2010). Kelly sought to address general audiences, not just professionals. To this end, he wrote in journals such as the *College Art Journal* (Kelly, 1952) and contributed to domestic design magazines. His highly influential method helped shape my understanding of the range of possible approaches to illuminating interiors.

6. Cultural influences

Different cultures have different attitudes to light.

These attitudes may be influenced by the material and technological conditions of the culture, but they also reflect broader cultural attitudes. The degree of brightness preferred in lit spaces varies both historically and according to culture. Equally, sensitivity to different lighting effects, such as glow or gleam, can be nurtured or neglected in different in particular cultural settings.
The 'atmosphere' and 'feel' created by architecture belonging to different cultures is, in part, due to the way it is lit (Plummer, 1995). An influential text that illustrates the differences between Japanese and Western attitudes to lighting is Junichiro Tanizaki's widely-cited book *In Praise Of Shadows* (1933), which combines a refined aesthetic appreciation with powerfully evocative writing. This was one of the first books I read in connection with this thesis; it alerted me to the power of light and shadow in interiors and provided a window onto a different way of looking at light.
Scandinavia also has a distinct culture around lighting and Hayden Willey (1998) makes a connection between the Scandinavian tradition and Tanizaki's work. The Scandinavians were concerned with collecting as much scarce light as possible over a long, dark winter and an architectural language of high vertical skylights with angled planes for reflection, funnels and other devices to gather horizontal light has evolved as a result (Norberg-Schulz, 1996). Finishes are a diffuse white or blonde wood to better gather every last photon of light and reflect it towards the viewer. These practices point to a closer connection to light and a better understanding of its value in cultures where light is in short supply.
An anthropological approach to lighting practices provided by Bille & Sorenson (2007) was one of the most helpful resources texts. It discusses the relationship between light, material culture and social experiences. Of particular interest was their discussion of the concept of 'living

light' in Danish homes. Many cultural practices around lighting in the Nordic areas are disappearing, as noted by Garnet (1994); however, this idea of 'living light' or *hygge* in Denmark is remarkably persistent.
Looking at different cultural and historical practices in relation to light provided me with an awareness of the cultural specificity of my own assumptions concerning light, and a recognition that different cultures of light are not only possible, but offer different pleasures to those prioritised by the western culture that had shaped assumptions and experiences.

Thesis structure

Chapter 1 provides a brief history of LED technology, its development as a viable source of white light and its entry into the lighting market. It discusses how LEDs work and the nature of the light they produce, while noting the various challenges created by LED light. A comparison is made between the practice of light art, a sector where LEDs have been rapidly adopted and transformative, and design for light in domestic settings, where the transition to LED based lighting is proving more challenging.

Chapter 2 discusses the nature of technological change using examples from the lighting sector. Four innovation scenarios are discussed and Actor-network theory is used to analyse how different scenarios for innovation create different amounts of disruption. The transition to LEDs is identified with the fourth scenario discussed.

Chapter 3 discusses the development of a framework for the practice-led experiments. It describes the difference between professional design practice and practice-led research. The 'frames-for-practice' approach is introduced and appropriate 'frames' for this study are identified. A template for reporting the results of the practice-led experiments is introduced.

Chapter 4 discusses the first set of practice-led experiments with their focus on 'getting to know the technology'. The optical principle of refraction provided the 'frame' for these experiments. Understandings arising from these experiments are reported, and suggestions for further work using this 'frame of practice' are made.

Chapter 5 discusses the second set of practice-led experiments. The focus of these experiments was the mediation of LED light for use in domestic settings through the creation of lighting artefacts. The 'frames of practice' adopted for these experiments were the optical principles of 'reflection', 'diffusion'. An evaluation methodology was developed to gather feedback from both design professionals and lay people on the performance of the artefacts. How the artefacts could be taken forward into more resolved products and what was learned from this set of practice-led experiments is discussed.

Chapter 6 explores the digital nature of LED, using the 'reflection' and 'obstruction' frames of practice. Digital control of an array of LED lights was formatted into a three-dimensional form with an 'egg crate' configuration of surfaces. The 'frames for practice' adopted for these experiments were reflection and obstruction and, later, diffusion. This experiment was conducted in the context of developing a large-format piece of light art. This piece was later resized into a set of artefacts more suitable for interior applications and three different materials were explored in these later artefacts.

Chapter 7 discusses unexpected but positive aspects of LED technology that were not immediately obvious when the technology was launched. These include new scenarios for illuminated interior spaces, the possible integration of LED technology into architecture and LEDs acting as a 'smart' material in the built environment. The opportunities for control through the Internet of Things and the implications for new ways of delivering building services are discussed. The relationship between LEDs and renewable energy sources such as solar power is explored.

Chapter 8 outlines findings, including new design approaches and skills required by designers to work effectively with LEDs. The influence of LEDs as a digital light source in the landscape of the lighting industry and the role of design and designers in a future world of LED lighting is discussed.

Chapter 1.
The LED

Chapter 1.
The LED

This chapter discusses how LEDs create light, the nature of LED light and the specific challenges created by this light for interior applications. Part 1 charts the development of LEDs from being relatively unknown in the early 20th century to their final realisation as an important energy efficient light source in the early 21st century. Part 2 discusses how the technology works as a light source and some of the technical challenges around the technology. Part 3 discusses the particular type of light that is created by LEDs and notes a series of challenges that need to be addressed when designing with the technology. The easy transition of LEDs into areas of spectacular light (such as light art) is discussed and contrasted with the challenges that LEDs face in creating acceptable lighting conditions for interiors.

Part 1.

A brief history of the development of LED technology

There is a particular kind of experience of light that belongs to 20th century industrialised nations that is shaped by the incandescent lamps and associated technologies, such as fluorescent lamps. Our experience of abundant and instantly available light generated by these technologies, although completely normalised in industrial nations, is historically very recent. Cultures that live with scarce light have prevailed for many thousands of years.

The technologies that established cultural expectations of abundant light belonged within an historical moment when energy supplied by fossil fuels flowed readily, and with little apparent consequence. Energy was relatively inexpensive and inefficient technologies such as GLS incandescent lamps were in common use.

From the 1970s onwards, there were growing concerns about the consumption of fossil fuels, from both a geo-political and an environmental point of view. This reassessment of the costs of fossil fuel based energy encouraged a quest to identify more energy efficient technologies for lighting (Brown, 1993; International Energy Agency, 2006; Rosenfeld et al, 1993). A promising, but limited technology at the time for producing light efficiently was available in the form of light emitting diodes (LEDs). The newly perceived urgency to develop efficient forms of lighting focused additional research to address the limitations of LED technology. It was hoped that LEDs could create white light and hence be established as a viable replacement for the predominant but inefficient incandescent lighting technologies (Department of Energy, 2006, Archenhold, 2008).

A new light source

LEDs have an older provenance than is widely recognised. In the mid-1920s, an obscure Russian scientist, Oleg Vladimirovich Losev, had observed the emission of light when a current was passed through the zinc oxide and silicon carbide crystal rectifier diodes used in radio receivers. Between 1924 and 1930, Losev published 16 papers in journals where he provided a thorough study of the LED and outlined its applications (Zheludev, 2007). Losev, who was self-educated, supported himself and his research by working as a technician at various Soviet institutions such as the Nizhniy Novgorod Radio Laboratory and Leningrad Medical Institute. His work was interrupted by the onset of World War II and then cut off by his premature death in 1942; since he had no colleagues or co-researchers, his work into LEDs as a viable light source developed no further (Zheludev, 2007).

The dominance of GLS incandescent and fluorescent light sources was well established by the mid-20th century and semiconductor lighting was largely ignored. This situation changed in 1962, when four US research groups simultaneously reported that they had developed a functioning LED semiconductor laser based on gallium arsenide crystals, emitting light in the amber to red range. Phosphorous was used in the technology, allowing the bandwidths to be manipulated into colours that were visible to the human eye (Johnstone, 2007 p. 54). Three of these four groups published in the same issue of *Applied Physics Letters*. The lead authors included Robert Hall and Nick Holonyak from two separate General Electric Company laboratories, Marshall Nathan of IBM and Robert Rediker of MIT (Zheludev, 2007).

The chemical company Monsanto, which was looking for new uses for its phosphorous products, was among the first of many companies from a non-lighting background to become involved with the development and manufacture of LED technology. It developed commercial LED products from 1967, primarily for use in car dashboard indicator lights and in signage (Johnstone, 2007). LEDs have been very successful in applications which require direct viewing and high brightness. However, the characteristics which make them successful in this sector have created challenges when they move into other sectors which require more nuanced and varied lighting conditions There was ongoing research around the development of a blue LED which would give a wider range of applications to the technology. More importantly, blue LED light could produce white light. Blue light is important, as the photons at that end of the spectrum have more energy than those at the red end, and this extra energy can activate phosphor to create white light (Savage, 2000). With white light, LEDs would offer an alternative light source to the older, inefficient, technologies used to illuminate interior spaces, buildings and outdoor areas.

The development of a bright blue LED proved elusive until 1993, when a Japanese engineer, Shuji Nakamura, announced the creation of a bright blue LED using indium gallium nitrate (InGaN) in the substrate of the chip. Nakamura worked for a Japanese chemical company called Nichia that manufactured phosphors for fluorescent lighting and televisions but, like Monsanto, was not directly involved in lighting. The significance of Nakamura's breakthrough was the blue colour combined with the relative brightness of the light source. While other blue LEDs had been manufactured (for example, by Cree Research in the US), these LEDs were not particularly bright and their use was limited to indicator lights on consoles. While the announcement of Nakamura's innovation caught many LED companies by surprise, the development of this light source was rapid. Within 18 months, Cree had a competing bright blue LED on the market, with other companies following suit (Johnstone, 2007).

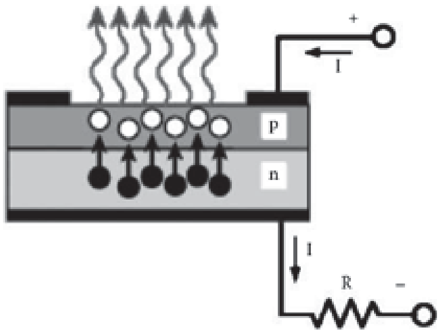

Figure 1.1
Radiation emission from the junction of a semiconductor during flow of electricity (Kitsinelis 2011, p.128)

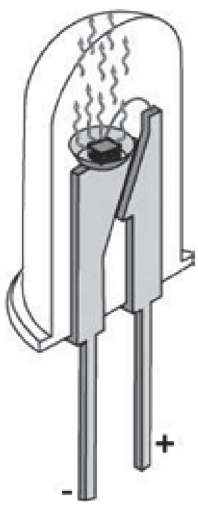

Figure 1.2
Light-emitting diode (LED) diagram (Kitsinelis 2011, p.130)

The early days of LEDs entering the lighting sector were characterised by the involvement of companies from outside traditional lighting industry, such as Cree Research (founded by mechanical engineers) and Color Kinetics (founded by robotics engineers). Ray Letasi, Marketing Manager in the early days at Color Kinetics, noted that his company was the only one to present LED technology at the 2000 Light & Build (the largest lighting exposition in the world) in Frankfurt (R.Letasi 2009, pers. comm. , 25 September,). Investment was difficult to find in the early days as most investors did not understand the nature of LEDs or how the technology could develop into a viable industry (Johnstone, 2007). However, as noted in the Introduction to this thesis, significant government support accelerated the research trajectory and helped to improve the performance and cost effectiveness of LEDs.

Increasing efficiencies of LEDs

In 2004, commercially available LEDs had a power-to-light conversion of around 30 lumens per watt (lm/w) (Craford, 2008). This performance was more efficient than that of incandescent lamps (at 18 lm/w) but not as efficient as fluorescent lighting, which produced around 100 lm/w (Azevdo et al, 2009). In 2006, LED manufacturer Cree claimed to have created an LED under laboratory conditions with a 131 lm/w performance. Performance of the commercially available product briefly lagged behind that achieved under laboratory conditions (Protzmann & Houser, 2006). However, conversion of laboratory performance to commercial product was rapid and by 2007, various manufacturers (Philips, Nichia) were claiming efficiencies for LEDs at well over 100 lm/watt (Craford 2008). By 2014, Sun et al. (2014) were able to report a performance of 175 lm/w for LEDs suitable for interior applications. In the same year, Cree announced the demonstration of a 200 lm/w concept luminaire

(Kelly-Detwiler, 2014). This research was realised as a commercially available LED in April, 2016, when Cree announced the launch of the XLamp XPG Platform which offered efficiencies of over 200 lm/W (Cree, 2016). The rapid development predicted in the early days of the technology by Shur & Zukauskas (2005) has been realised.

Figure 1.3
Components in LED light source showing heat sink and optics
(Cree 2013, p.6)

Longevity has also improved. Predictions of LED longevity made in 2009 were 30,000 to 50,000 hours (Azevedo et al., 2009, p. 485). More recently, Philips Lumleds are still achieving 70% of their optimum output after 67,000 hours (Lumileds, 2017). Life spans of LEDs are increasing as a result of ongoing research in the sector.

Other electroluminescent light sources

LEDs are part of a family of light sources that use electroluminescence to create light. Other examples are OLED (organic light emitting diodes) and EL lamps (high field electroluminescent lamps), both of which are in a flat planar format (Rea, 2000). EL lamps are used in the display sector and are particularly useful in outdoor situations with a challenging climate. They are not suitable for illuminating large areas as EL technology has low lumen per watt output. OLEDs were initially thought to be a light source that would complement or even rival LEDs. However, their costs have remained high and they cannot compete because LEDs have become less costly and more efficient over time. OLEDS are used in niche applications in cars and smartphones (Maloney, 2016).

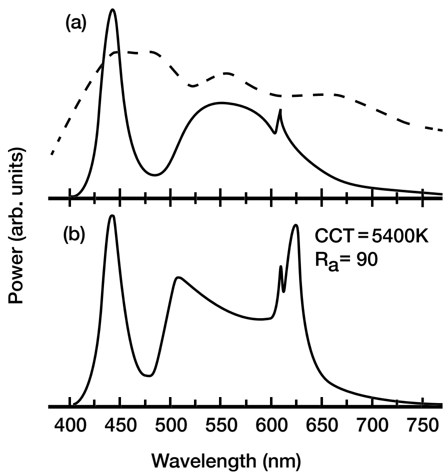

Figure 1.4
Spectral distribution of a) phosphor LED and b) mixed RGB LED.
The broken line is the spectral distribution of overcast daylight
(Shur Zuskauskus 2005, p.1695)

Part 2. How LEDs work

The light emitting diode is a semiconductor device made up of a layer of electron-rich material (p) separated from a layer of electron deficient material (n). This layered construction is referred to by a variety of terms, including wafer, substrate or crystal. The wafer is cut into smaller

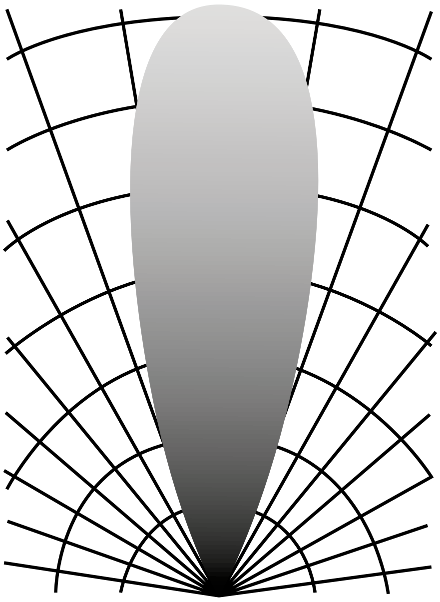

Figure 1.5
Narrow angles of LED light
(Kitsinelis 2011, p.132)

pieces, called dies, which are mounted on a microchip. When voltage is applied to the microchip, electrons flow from the (p) area to the (n) area and combine with the positive charges. Each time this happens, a photon of light is emitted (Johnstone, 2007; Rea, 2000).

Converting the light emitting diode into a useable light source involves mounting the chip into a package, adding phosphor (depending on the chip and colour desired) and a lens (known as the primary optic). The lens directs the light, provides protection to the LED chip and acts as a conductive path to carry generated heat away (Shur and Zukauskas, 2005).

In the LED technology currently available, the emission of each photon generates heat at the junction of the (p) and (n) areas. Reducing the amount of heat produced is an important focus of ongoing research, as this will increase the efficiency with which an LED converts energy into light, and thereby improve its performance. Managing the temperature at the junction of the (p) and (n) layers (called junction temperature) is an important consideration. Cooling techniques used in previous light sources, such as leaving an air gap for ventilation, are insufficient to provide proper thermal management for optimal LED performance. More active approaches, such as the use of heatsinks, therefore need to be considered in any LED design application (Kitsinelis, 2011; Shailesh, 2015).

LEDs emit light in a very narrow band of spectra, which means that the light is coloured, such as red or, in more recent times, blue. The particular band of spectra, and hence the colour of light emitted, is determined by the chemical make-up of the die (Kitsinelis, 2011).

White light from LEDs can be created in two ways. The first method involves grouping red, green and blue LEDs together and ‘mixing’ the light to create white. The second method uses a blue LED with phosphor, a material that emits white light when struck with blue or ultraviolet light.

The second method involving phosphor is a more cost-effective way of creating white light and is more widely used. This chemical method creates white light that is different from that produced by incandescent light sources, such as electric GLS, gas light or candles.
High quality white light is dependent on good colour rendering and appropriate colour temperature. The white light produced by incandescence contains a continuous spectrum (similar to that of the sun), thus creating excellent colour rendering properties. The colour temperature of GLS is 2800K; this is a warm light considered suitable for domestic contexts particularly in the evening (Hopkinson and Collins, 1970) and hence it is easy to attain quality light from a GLS source.
By contrast, the chemical processes that create white LED light do not contain an even spectrum; hence colour rendering is uneven. Additionally, colour temperature is initially high (which makes the light bluish) and difficult to manipulate. Manufacturers of LEDs in the early days focused on efficiency (high lumens per watt) rather than creating good quality light. As the addition of phosphor (which improves the quality of the light) compromises efficiency, the first LEDs on the market had a distinctly bluish tinge (Kellog, 2009, Kugler, 2008). Additionally, variations within the chemical make-up of the phosphor could compromise light quality. Thus there are challenges in creating quality white light with LEDs (Shur and Zukauskas, 2005 Julian, 2011, Kitsinelis, 2011). The process involves a delicate balance between the competing needs of lumen-per-watt efficiencies, an acceptable colour temperature and colour rendering. Research and development into the management of light colour produced by LEDs is ongoing, with improvements appearing on a yearly basis (Houser, 2015).

Part 3.

The experience of LED-generated light

Light has a particular feel and behaviour, depending on its source. The carefully husbanded, scarce light generated by the lamps and candles of pre-industrial times was able to illuminate only specific areas. Outside a small area of light, deep shadows could be observed. The light sources introduced during the Industrial Revolution (advanced oil lamps, gas lighting and electric lighting) produced light that was progressively more abundant in volume and quality. The light flowed out from a single source to illuminate larger areas, even whole rooms. LEDs create a new experience of light that differs significantly from that associated with either scarce or abundant light, although continuing to share certain characteristics with each of those conditions.

Like pre-industrial light sources, LEDs illuminate only limited areas within a darkened space. By contrast, GLS and fluorescent technologies provide general illumination, allowing whole spaces to be evenly lit. LEDs generate a high volume of light, as do the technologies of abundant light; however, the trajectory of the light is narrow rather than dispersed, and the effect is of concentrated brightness rather than luminosity.

The characteristics of LED light are bound up with the physical structure of the light source. LED light is created on a microchip, so the light is planar rather than the three-dimensional character of incandescent light sources. Additionally, the concentrated light from an LED source flows in a narrow, directional stream from the diode.

These characteristics create a new set of challenges for the lighting designer. Three of these challenges are outlined below:

> 1. The intensity and concentration of light produces glare, which is a source of discomfort for the user.
>
> 2. The narrowly concentrated light flow has little sideways spill, meaning that the light does not disperse and the demarcation between lit and unlit areas is crisp; the contrast between lit and shadowed areas is absolute, rather than soft.
>
> 3. A single linear flow, emitted from one diode, cannot be mediated sufficiently to illuminate a space, hence an array of diodes must be created. The challenge of creating an array that can give form to the light is particular to this technology, and is often discounted by those who have worked with GLS, where no such challenge existed.

I will discuss the technical aspects of each of these challenges, and the responses of designers, under the following headings: glare, crispness and formlessness.

a. Glare.

Glare is the effect experienced when intense light is viewed against contrasting darkness. Broadly, glare occurs when there is excessive contrast in lighting levels in the field of view (Julian, 2011). The relative size of the light source is important; researchers found that small, bright light sources can cause discomfort (Hopkinson and Longmore, 1959).

The term ‘glare’ was introduced by early illumination engineers researching light quality, following the development of the tungsten filament for GLS lamps in 1913. The tungsten filament burned far more brightly than previous GLS technologies, and the discomfort produced by the contrast between the brightness of the lamp and surrounding darkness, had emerged as an issue (Luckiesh and Holladay, 1925). However as general levels of interior illumination increased following the widespread adoption of these lights, the problem of contrast diminished.

The introduction of fluorescent technology in the 1930s saw another flurry of research into light quality and the problem of glare.

Ultimately, however, neither of these 20th century lighting technologies represented an intractable source of glare; the light generated by GLS lamps is distributed across a filament and radiates in three dimensions, while that generated by a fluorescent lamp is distributed along a tube, creating a more diffuse effect. The wider the area in which the light is distributed, the less average brightness is perceived at any particular point and glare is experienced correspondingly less (Flynn & Mills, 1962 p. 61). By contrast, LED light is created by a chemical reaction on a very small flat microchip; the light produced is therefore planar and one-directional and, with all the lumens pouring out of a very small point, it is perceived by the viewer as a small intense pinpoint of light. As Berman has noted, the move to small and high luminance lighting systems, such as LEDs, means that understanding glare is becoming much more important (Berman et al., 1994).

Lighting researchers distinguish between two types of glare, disability glare and discomfort glare (Rea, 2000). Veitch and Newsham (1996) suggest that the distinction between these two types should be understood in terms of their behavioural effects. They categorise disability glare as a visual performance effect, and discomfort glare as a comfort and health effect. An example of disability glare would be the experience of a drop in vision due to approaching headlights when driving (Tregenza and Loe, 1998). Because of its association with performance failure, disability glare has been quantified within a significant body of scientific research and is well understood. Performance contexts such as the workplace and road safety have been the main focus of this research. Discomfort glare, by contrast, is considered an inconvenience rather than a safety or productivity issue. It arises when excessive brightness within a visual environment causes discomfort but no measurable reduction in visibility. While there have been qualitative studies on responses to discomfort glare, no objective correlate has been identified (Berman et al.,1994). However, Julian (2011) notes that while there is difficulty in measuring discomfort glare, the results of a range of studies using subjective assessment of glare have been consistent. Twentieth-century domestic environments were lit largely by GLS. The ease with which light from GLS lamps could be mediated meant that there was little perceived need for research into glare in domestic settings. However LEDs, if widely incorporated into 21st century homes, are a much more likely source of glare. Julian (2011) observes that when glare is experienced in interior environments, fatigue and distraction can result. He suggests that these effects are particularly incompatible with task performance, which is often the context of activity in interior settings. Glare created by LEDs is thus a significant issue for future domestic lighting design. Indeed, Fredrik Nyberg of Louis Poulsen Lighting has commented that, when designing domestic fittings with LEDs, glare 'is probably the biggest sinner' (F. Nyberg 2009, pers. comm., 8 August). The relationship between high brightness LEDs and sensations of discomfort glare identified by practitioners such as Nyberg, has also been confirmed by lighting research (Tashiro et al., 2015).

Figure 1.6
Bling light (McDermott 2008)
Left: Light source 6W LED MR-16 equivalent
Right: 40W reflector lamp using an incandescent light source with silvered reflector shape

b. Crispness

Understanding the lighting effects of LEDs means an awareness of the type of shadowing created by this light source. One of my early experiments (Figure 1.6) illustrates the difference between incandescent and LED light. The same light fitting was photographed with an incandescent spot light (right) and an MR-16 type LED (left). The crisp, cool light of the LED, with a localised illuminated area on the wall behind and pronounced definition between light and dark, contrasts with the more generous spread and softer light of the incandescent light source.
The even three-dimensional distribution of light from GLS lamps means that transitions between illuminated areas and darker areas are relatively gradual, with soft edges. On the other hand, light from LEDs creates shadowing with a more defined contrast and there is no gradual transition from light to dark (Schanda & Vidovsky-Nemeth, 2010). Without soft edges, the shadows appear more pronounced. LED delivers no generosity or soft transition of light.
The lighting effect created by LEDs was described by lighting consultant and interior designer, Kori Martin, as 'crisp' (K. Martin 2009, pers. comm., 21 August). This crisp light and pronounced shadowing of LEDs also creates noticeably concentrated highlights on objects.

c. Formlessness

A luminaire (or light fitting) is an object containing a light source that provides artificial illumination. The luminaire gives the light source physical support and protection, encloses any fuel or electrical gear and provides optical control.
Historically, designers have always had to consider the shape of the actual light source in the design of luminaires. The invention of the incandescent lamp freed designers from the consideration of oil sumps, gas pipes and

candleholders. Instead they needed to consider the shape of the GLS lamp when designing light fittings. Designers do not need to consider any three-dimensional form of the light source itself in the design of LED luminaires
To create a useful amount and spread of light, LEDs are usually used in groups or matrices. As a result, decisions need to be made as to the size, spacing and shape of these matrices in relation to the purpose of the light fitting. Without a considered design approach, LEDs are perceived by the viewer as a group of individual 'light spots', which may not create a pleasing visual effect. Researchers have noted that the tendency of LEDs to be grouped in matrices or lines, as against earlier single sources lights, can create visual discomfort for the viewer (Kasahara et al. 2006).
LED light sources have created a different challenge for designers, because designers need to 'design the light source too' (F. Nyberg 2009 pers. comm., 8 August).
Kori Martin, interior designer and lighting consultant at Artemide, Sydney, concurred, saying LEDs were unique in that they have 'no fixed form' (K. Martin 2009, pers. comm., 21 August). Distinguished Italian lighting designer Michele De Lucchi commented that LEDs were like a 'light spot' and he 'can't draw a light spot' (Artemide, 2014).
While the option of designing the light source creates more freedom for the designer, it also creates a challenge in terms of controlling the final lighting effect. This process is more complex than designing for a three-dimensional light source with an easily understood form and lighting output.

Figure 1.7
A View of the Fire-workes and Illuminations at his Grace the Duke of Richmond's at Whitehall on the River Thames on Monday 15 May 1749. Performed by Charles Frederick Esq. (Anonymous 1749)

Figure 1.8
Lunar Nets
(McDermott & Baxter 2014)

'Fantasy, wonderment and intrigue'

The challenges of introducing LEDs into interior applications contrast with the rapidity with which they have transformed urban night-life, re-energising the role of artists in city-branding, and leading to the proliferation of light festivals. Edensor (2013) argues that these contemporary expressions of spectacular light have

Figure 1.9
iColorFlexMX
(Philips 2014, p.2)

their antecedents in historic festivals and celebrations when royalty used a variety of technologies to show their power and impress their subjects. In an age of relatively scarce light, the spectacular effects were a demonstration of wealth and prestige. Wolfgang Schivelsbusch notes that the night itself lent an aura of unreality to the celebrations and 'blurred the relationship between reality and fantasy' (Schivelsbusch, 1988 p. 138).

The contemporary version of these older forms of spectacular light, light festivals, create opportunities for light to produce 'fantasy, wonderment and intrigue' (Edensor 2014 p. 56). In a globalised world, cities need to stand out and promote themselves as desirable places to visit, live in or invest in. Lighting and the spectacular imagery that emerges from the festivals can brand a city in the collective consciousness. They also offer a joint experience with many others, thus offering a sense of community and accessible public entertainment. Light festivals create spectacle, scale, intense colour and a reimagining of a familiar urban infrastructure, be it space, building, bridge or street. Expectations of festival atmosphere and display include a play of intense, spectacular and constantly changing colour against the contrasting blackness of the night. There is a relationship between the effects created by LEDs and public expectations of spectacular light shows.

The widespread use of LEDs in light festivals, media facades on buildings and urban light art is bound up with the characteristics of the technology. This technology is particularly suitable for spectacular light for a number of reasons.

a. Intensity and precision

LED light comes from a small microchip and radiates out in a tight angle compared to the omnidirectional radiation of older light sources such as GLS and fluorescent. Both these older technologies require specific reflectors to create directional light and, in this process, some of the light intensity can be lost, particularly if the reflecting surface is matt (Rea 2000, p. 1-17). Because the light from LEDs does not disperse, the light can be aimed very precisely and can be perceived from a great distance. Therefore a great deal of control of what is lit and what is left in shadow is possible.

Colour and addressability

LEDs emit light in a narrow spectrum and are intrinsically coloured either red, amber, green or – in the past 20 years – blue (Shur and Zukauskas, 2005p.1694). The colour depends on the chemical composition on the microchip itself and appears to be bright and saturated. A colour-changing LED node can be created by combining three LEDs, red, green and blue (or RGB). Digital technology mixes the RGB and allows control of all aspects of colour, namely, hue, saturation and brightness. The range of colours is wide and the control is precise and instantaneous (Johnstone, 2007 p. 155). The LEDs are controlled through commercially available digital programs which require specific programming skills and hardware. Each LED node has an individual 'address' which is controlled by software and can be turned on and off, dimmed or coloured according to the overall requirements. Large matrices of LED nodes create the changing patterns and colours seen on media facades. They can also illuminate objects to powerful effect.

b. Size and robustness

The small size of LEDs means they can be incorporated into architecture or objects in a way that was not possible with previous light sources. LEDs can be embedded in sculptures, natural objects such as trees, textiles and built environment detail. Robust and lightweight, they are flexible in application, which has liberated approaches to light art and created new relationships between light and materials.

For these reasons, the realm of the spectacular – previously dominated by the older technologies of fireworks and neon – is now a sector in which the LED is very much at home.

Interior applications

The impetus towards energy efficient lighting (outlined in the Introduction p.3) means that LEDs are now taking the place of other, older technologies (GLS incandescent and fluorescent) in interior applications. However, architectural lighting of interiors is subject to a different set of expectations of visual pleasure and task facilitation to those of spectacular light where LEDs have been so successfully applied (McDermott and Stewart, 2015). The nature of LED light, with its long thin 'throw' and tendency to create defined highlights, can work well in situations where a particular object or material needs to be highlighted. These characteristics, however, create challenges when LEDs are required for interior lighting.
Prominent mid-century architectural lighting designer Richard Kelly has argued that lighting effects for interiors fall into three categories: 'focal glow', 'ambient luminescence' and the 'play of brilliants'. Kelly notes that all good interior lighting environments should combine these three conditions. Using analogies, Kelly describes 'play of brilliants' as being like 'Times Square at night; it is the 18th century ballroom of crystal chandeliers'. 'Focal glow' he likens to a 'follow spot on the modern stage' or 'the shaft of sunshine that warms the end of the valley'. Ambient luminescence he defines as 'shadowless illumination' which creates a sense of calm through an even distribution of light (Kelly, 1952). Kelly's approach alerts us to the wide range of lighting conditions in interiors. The success of LEDs in light festivals indicates the ability of the technology to achieve a 'play of brilliants'. The other, more subtle and nuanced lighting effects are a

challenge for this intense, directional light source.

Summary

- LED is a chemically generated light source with behaviour and characteristics that are very different to the lighting technologies that dominated the 20th century; namely GLS incandescent and fluorescent.

- The impetus to create usable light using LED technology originally sprang from the efficiency it offered, with potential to convert 100% of energy input into light output.

- The particular qualities of LED light, including intense, narrowly defined flows of light with little spill, high levels of colour control, and compatibility with digital control systems, have led to rapid adoption in the field of Light Art, in which these qualities are highly desirable.

- There is a mismatch between expectations of more subtle and varied light conditions in interior environments, particularly domestic interiors, and many of the characteristics of unmediated light from LEDs, including glare and crispness.

- The light from LEDs is not easy to mediate because of its intensity, directionality, and formlessness. Mediating the light from LEDs to create applications suitable for interior environments presents challenges for the designer.

Chapter 2.

Technology Transitions

Chapter 2.

Technology Transitions

While the arguments for a shift to LEDs as a light source are compelling, the shift itself has not been straightforward. This chapter argues that the current technology transition from industrialised light (delivered by light sources which emerged in the 19th century) to digital lighting has been a complex process that has involved uncertainty and difficulties. One of the reasons is that LED technology did not slot easily into the existing infrastructure of light delivery that had grown up around industrialised lighting technologies such as incandescent (GLS and halogen) and discharge technologies (fluorescent and sodium). Nor has the transition played out as the simple substitution of an efficient light source to replace other, less efficient, light sources.

This chapter discusses technological change as a process. It discusses why some technological change happens reasonably easily while other changes take longer and involve major disruption to the sector. This discussion will assist in explaining the particular challenges around the transition to LED technology.

Part 1 of the chapter introduces concepts from Actor-network theory (ANT) that can help to provide an understanding of how technological change happens and to illuminate the difficulties inherent in such changes. Part 2 presents four different scenarios of technological change, each with different experiences and outcomes and illustrated by examples and commentary from the lighting sector. Part 3 locates the emergence of LEDs in a particular scenario and uses concepts drawn from Actor-network theory to describe some of the difficulties encountered in the transition.

Part 1.

Concepts drawn from Actor-network theory

According to ANT, an actor is a human or non-human actant that plays a role in the performance of an action (Callon, 1991). An actor-network is a heterogeneous assemblage of actors that work together to enable particular kinds of action (Latour, 1987). For example, the creation of a lit space after sundown is an action currently enabled by the performance of an assemblage of human and non-human actors including power stations, distribution networks, switching technologies, lighting fixtures and so on. The act of flipping a light switch, performed by a human, is insufficient to light a space without the participation of other actors in the network. Actor-networks include both human and non-human actors, and actors that are material and non-material. Designed objects and infrastructure are material actors. Non-material actors include preconceptions concerning the experience of light and the embodied habits and practices associated with the generation and use of light. Design approaches, tacit knowledge and expectations are often-overlooked but influential actors. Because these networks contain a combination of human, non-human, material and non-material actors, they are referred to as heterogeneous networks.

How does Actor-network theory help in understanding technology change?

Heterogeneous networks are not fixed or static, and reconfigure themselves in response to changing contexts, demands and technologies (Law, 1992). New technologies require different actors and different assemblages, and often allow different kinds of performance from those carried out by previous assemblages. By focusing on the relations between actors in a network, and the different effects achieved through the reconfiguration of a network, ANT allows us to see technological change in terms of its impact on networks, and on actors in those networks. Using ANT as a theoretical lens for research on the introduction of a new lighting technology allows us to see how the design task changes according to the stability of the actor-network for which it is being designed.

Stability and change

Heterogeneous networks can remain stable for many years, as can be seen in the pre-industrial technologies supporting the provision of light from lamps and candles (Dillon, 2002, Wlock, 1979). These networks included actors involved in growing or harvesting sources of energy; those involved in extracting, transporting and retailing the energy source, and those responsible for producing the material resources for lighting implements, as well as the design and manufacture of those implements and luminaires (see Appendix 2).
While there were ongoing subtle shifts in these networks

of production, supply and delivery, relations between the networks and the configuration of actors were durable, lasting for many centuries (Law, 1992, Callon, 1991). Disruptive technologies are those whose introduction destabilises existing network configurations. In periods of radical change, not only are actors replaced by other actors but whole networks can be replaced by new networks (Latour, 1991). This can be seen in the transition from artisanal to industrialised light in the 19th century. Gas, generated in centralised plants and piped to the point of consumption, eventually overcame the established supply and distribution networks that serviced the older technology of oil lamps and candles. The new network, and the gas technology it supported, worked at first in parallel with, then increasingly to replace, the previous technology network. Some actors in the previous assemblage resisted this transition fiercely – particularly the larger actors that were well established and employed many people (such as the whaling industry, which supplied oil for lamps). History is full of examples of how actors in an established network often employ strategies to prevent the introduction and stabilisation of an alternative network; the appearance of a new network providing the same service initiates controversy and conflict between the old and the new.

Reconfiguration and stability

The reconfiguration of an actor-network following the introduction of a new technology is not always straightforward and the outcome remains unpredictable until the network stabilises once more (Latour, 1991). This has been shown in numerous historical studies by actor-network theorists. Examples are Bijker (1992) on the introduction of the fluorescent lamp, Latour (1991) on the development of the Kodak camera and Law and Callon (1992) on the development of defence aircraft.

A new network does not become stable until sufficient support has been *recruited* (Law, 1991). This is particularly evident with industrialised technologies, which require large numbers of consumers to make the technology viable. Once a new network has gained a foothold, it will compete with the established network in a variety of ways; sometimes by offering better experiences, sometimes by offering more efficient performances, sometimes by generating fewer costs or more profit. These advantages recruit even more actors to the network and at some point the new network will overcome the older network, which will become redundant.
An example of successful competition from a new network is seen in the introduction of electric light. Early promoters of electricity and electric light bulbs were aware that large numbers of consumers were needed to offset the costs of centralised generation and distribution, particularly in more remote areas. Bowers (1998) noted the publication of a book called *The electric light in our homes* in 1884 by Robert Hammond, an early advocate of electric light. The book included instructions on how to create the perfect light for the home, using an electric light source. Such a book was necessary because the only experience of electric light available at that time was of arc lighting in the streets or in large public places such as railways stations. The more familiar light of gas and kerosene lamps was still offering competition to electric light in the domestic area. In order was to recruit more householders to choose electric light and the Hammond travelled widely, distributing his book, giving lectures and demonstrating electric lighting. Overcoming the public's prejudices against the new and alien technology was critical to its establishment.
Actors capable of recruiting new participants to a network play a crucial role in giving the new technology sufficient weight to compete a established network. The shape of the new network is the result of a 'politics of adjustment

and negotiation' (Silverstone & Haddon, 1996) between the various actors. The new technology will stabilise only if the *relationships* between all actors in the heterogeneous network are stabilised (Callon & Latour, 1981; Pantzar, 1997).

Part 2.

Scenarios of change

Every design realises a new possibility, whether in terms of aesthetics, product usability, production procedures, material configuration or a more radical shift in human, material and technology relations. In some new design, there is little disruption of existing configurations of actors. In other cases, for example in contexts of technology transition, there may be considerable disruption, uncertainty and even conflict. Different change scenarios produce different kinds of design response. The degree of disruption that follows the introduction of a new technology varies. The following discussion draws on the terminology of actor-network theory to discuss different scenarios for design, and the role of design and innovation in each.

Scenario 1: Incremental progress

Within an established and stable set of human-thing relations there is always a striving to produce additional value in the context of those relations. The kind of design development that happens in this scenario involves refining the formal and functional qualities of designed things. For example, in the enduringly stable human-thing relations established around the provision of light in the pre-industrial period, lighting implements largely followed established formal precedent; however, these designs were not completely standardised. There was ongoing adaptation and refinement of form in relation to contexts of particular use or material economies. An example can be seen in the series of improvements made to tallow candles during the 19th century. Tallow candles, an odorous light source made of animal fat, produced inferior light and needed constant trimming of the wicks. In the 1820s, French chemist Michel Chevreul analysed tallow and found that better tallow candles could be made from just one of its components, stearine. Once stearine could be manufactured economically, cheaper and better candlelight was available for all. Wicks were also improved so that constant trimming and snuffing were no longer necessary (Hardyment, 1997 p. 173, Laing, 1982)

The adjustments to tallow candles added new actors to the tallow manufacturing network, enabling stearine to play a more prominent role in the performance of those candles. These adjustments to the network, however, did not significantly disrupt relations either in or beyond the existing light production network.

The driver for new design in contexts where network relations are stable is a desire from within the network for some type of improvement in effect or performance. In the context of 20th century industrialised cultures, elements that added beauty, functionality, efficiency and embodied pleasures to everyday contexts of production and consumption were considered to represent good design. Such designs created incremental progress toward the goal of ‘a better life’ in 20th century terms. Often progress would occur through the simple substitution of a better-performing version of the same actor in the existing assemblage.

In this design context, the kind of incremental improvement offered by new designs fits with the existing cultural conception of what is desirable. Participants in that culture have already been recruited to an appreciation of the value the new design offers. The assemblage is further consolidated and stabilised by design that works in harmony with the existing relations in the network. The outcome of a new design is a network offering better performances while still keeping relations between the wider assemblage of actors intact and in the same set of relationships.

In scenarios of incremental progress, what constitutes good design is easily recognised and adopted by an already-recruited market. For example, the Anglepoise lamp, originally designed in 1932 by automotive engineer George Carwardine for use in contexts requiring focused illumination of a work surface, was quickly adapted for the domestic market. The stabilising set of relations around focused work that the Anglepoise played into was recognised as being as relevant to the home as to the workplace. Since that time the Anglepoise has had the input of various designers (Sir Kenneth Grange, Sir Paul Smith) to create different versions – larger, smaller and with different colours and finishes - but still retaining the original combination of springs and pivot arms to provide control over the angle and positioning of the light. Anglepoise continues to market and sell the lamp successfully to the extent that it has attained design classic status, as confirmed by its appearance in a series of 2009 British stamps celebrating design icons (Anglepoise, 2012). In Scenario 1, the role of design is to maximise the value created in existing, stable networks. Better design enhances the value generated in a particular network, and in doing so consolidates the place of that network in the wider cultural contexts in which it plays a role.

Figure 2.1
***Anglepoise* 1227 (Carwardine 1935)**
Originally in black, this version was designed for a domestic setting.

Figure 2.2
***Anglepoise* 1228 (Grange 2004)**
This version has a rotating shade to focus light on specific areas

Scenario 1 is important to understand because it is the normal context for design. My own training as a designer, which shaped my understanding about what constitutes good design, was largely set in Scenario 1. The assumptions that I carried into my professional work, and the assumptions that initially framed this project, were largely drawn from this scenario, and from Scenarios 2 and 3 described below. Scenario 4, which I argue is the context for designing with LED, represented a new situation that I did not immediately recognise or know how to deal with.

Scenario 2: Substitutions in the cast of supporting actors.

In Scenario 2, major reconfigurations of production or supply networks are effected in order to satisfy drivers in those networks. These changes are most easily accomplished when there is little impact on the stabilised networks that shape consumption of the product. In this scenario, technology change that benefits the performance of a production or supply network is facilitated by having an already recruited and stabilised market. Market allegiance to the new production or supply network can be secured if the network of practices around consumption are left largely undisturbed, and any change in the experience of consumers is perceived by them as positive. When the change in production or supply aligns with drivers already operating in the consumption context, such as a cost advantage or greater embodied pleasure, then the beneficial changes to production and supply networks are facilitated.
In Scenario 2, the incremental shifts in user experience hide larger shifts in supply chains. This is a change that is straightforward because of the pre-existing desire in the network for a particular tangible benefit (such as lower cost) that the improvement then offers. Making it easy and desirable for consumers to access new benefits can enable

change that displaces other players, such as the vested interests of an older supply chain network.

An example of a Scenario 2 transition can be seen in the shift around 1860 from oil (from organic sources such as whale or colza) to kerosene (from petrochemicals) as lamp fuel. The main driver for this shift was the desire to find a cheaper lighting fuel. Kerosene was immediately successful and for the first time in history, poor people could afford abundant light (Dillon, 2002). Brox (2010) commented that there was an almost immediate replacement of whale oil by kerosene. As well as being cheaper, kerosene was lighter and less viscous than oil, so lamps could be simpler in design with no need for gravity feeds or mechanisms to pump oil to the site of the flame. It was possible to adapt existing oil lamps to kerosene and this assisted the rapid and widespread adoption of kerosene in favour of whale oil. As far as consumers were concerned, very few actors in their lighting network had changed. The change was far more disruptive to production networks, as whaling lost business and fossil fuel interests moved into the energy supply chain.

Figure 2.3
Kerosene lamp
(Anonymous 1857-1865)

Kerosene lamps did need meticulous cleaning on a daily basis for both a better light and general safety (Brox, 2011). However, the disadvantage of having to clean the lamp was clearly outweighed by the advantages of lower cost and simpler design. Kerosene lamps were very popular and continued to be used domestically until made redundant by the electricity network.

The role of design in this context may have been to achieve good performance in the new production or supply networks, or to ensure that relations between the new network, and networks that it depended on, were smoothed. Kerosene lamps retained a visual resemblance to earlier oil lamps, but they were slimmer, lighter and simpler to operate. Design in this situation smoothed the transition by referencing the familiar while incorporating

Figure 2.4
MR-16 Tungsten halogen lamp (Illuminating Engineering Society 2015)

new advantages.

A more contemporary example of Scenario 2 can be seen in the incorporation of tungsten halogen technology into the Actor-network that delivered artificial lighting in the second half of the 20^{th} century. Tungsten halogen technology is a variation of GLS incandescent technology. It was first used for airport runway lighting applications. Tungsten halogen technology became useful in applications where directionality was important, such as in flood and spot lighting, and it became common in retail situations (Wallace, 2001).

While tungsten halogen did supplant some older, reflector-style light fittings, it did not destabilise the assemblage; it could plug into existing sets of relations without disrupting them. The actor-network simply expanded to include tungsten halogen technology which provided specialised advantages for particular situations.

Technology transitions are accomplished far more quickly and easily in Scenario 2 conditions than if the surrounding consumption networks are impacted. Occasionally major network transformations that will ultimately impact consumer practices are achievable in a Scenario 2 by disguising and delaying those impacts. Design can enable the immediate consumer experience to remain largely unchanged or changed in pleasurable ways, with the larger consequences playing out over an extended time frame to allow consumer expectations and desires to adjust gradually.

Scenario 3: New products or processes that enable realisation of latent cultural possibilities

This scenario occurs when new materials, technologies or production processes enable the realisation of already desired, but previously suppressed or unrealisable, formal possibilities, functionality or experiences in relation to designed things. A 20th century example can be seen in the widespread adoption of thermoplastics in the decades immediately after World War II. Thermoplastics were developed for military applications during the war. In the period of relative prosperity and accelerating consumption that followed, this new material possibility mapped onto the desire for stylistic experimentation and rapid turnover of consumer items. The rise in the use of thermoplastics was as much about the period as it was about the availability of new materials and the capacity to manufacture them. Led by experimental fashion designers such as Courrèges and Paco Rabanne, plastic dropped its more utilitarian garb and became not only 'cool' but representative of a new approach to design which looked clearly to the future (Fenichell, 1996).

Figure 2.5
Acrylic 'window' for bombers in WWII (Fenichell 1996, p.54)

With the arrival of thermoplastics into the post-World War II era, the actor-network servicing product design was enlarged to include new suppliers of materials, such as the petrochemical companies that made plastics. Supply chains developed and mass production techniques were refined further to reduce costs. Novelty was considered important, as the cultures of the 1950s and 60s sought to put the past behind them. Designers were employed to keep a flow of new and fashionable products streaming onto the consumer market. Thermoplastics met the needs of a wider shift to a confident consumer culture that was focused on novelty and accelerated obsolescence. This embrace of consumer culture contrasted dramatically with, and was in large part a reaction to, the enforced frugality of the 1930s and the war years.

The driver for change in Scenario 3 is a match between a newly-emerged material or practical possibility, and a desire that has been latent but previously unrealisable, in the context of consumption networks.

In Scenario 3, the transition is accompanied by a major reconfiguration of consumer priorities and cultures, but

Figure 2.6
Nelson, G. 1950, *Bubble Lamps 1*
(Abercrombie & Nasatir 1996, p.120)

Figure 2.7
Panton, V. 1960, *Spiral lamps*
(Fiell & Fiell 2005, p.190)

this transformation is relatively easily accomplished as consumers are ready (often eager) to be recruited to the emergent networks.

Designers can find a role in recognising and designing for latent desires, in defining how the new technologies can be realised into forms and making sure that the new forms create pleasurable experiences for users.

The post-World War II availability of plastics made possible a wider range of sculptural shapes and brilliant colours for use with GLS lamps. Designers developed an experimental approach that 'challenged the boundaries of lighting and art' (Fiell & Fiell, 2005 p. 43). Like plastic, the accommodating nature of GLS illumination lends itself to playful experimentation. Consequently, luminaire designers moved rapidly beyond a concern with utility and comfort; a light fitting now could be almost anything: a sculpture, an artwork, a symbol of style, fashion or status (McDermott & Stewart, 2015). A design focus on the mediation or control of light was unnecessary, as incandescent light sources produced pleasing light effects themselves. As well-known lighting designer, Michele de Lucchi, said in an interview, designers of this period saw their role as being to 'dress' the light source, rather than to focus on optical principles or performance (*Artemide*, 2014). Looking back with some nostalgia, lighting designer and editor Kevin Willmorth (2014 p. 80) described the world of lighting design in the second half of the 20th century as 'a mix of pure instinct, artistic flare and just a dash of verification'. Willmorth candidly admitted to enjoying the freedom of designing 'like kids playing in the park'.

The actor-network supporting the marketing and consumption of light fittings expanded over the same period. Annual lighting events such as Euroluce in Milan and Light and Build in Frankfurt launched ranges of new and novel light fittings for an international audience.

Styling became an important actor in the assemblage delivering artificial light. Lighting brands such as Flos and Artemide launched new lighting products designed by high-profile designers every year. There was a confluence of cultural moment, new materials and the latent desire for consumer goods, which combined to make easy the transition from a frugal to a profligate culture of consumption based on playful experimentation and a craving for novelty.

Figure 2.8
Nummi, Y. 1960 *Skyflier Hanging Light* (Fiell & Fiell 2005, p.62)

Scenario 4: External pressures

In Scenario 4, the entire actor-network associated with a service is impacted. Most of the actors connected with supply and distribution are either altered or replaced by new actors. There are changes in consumption patterns that reflect the wider reshaping of the actor-network. Unlike previous scenarios, the expectations and practices of the consumer in Scenario 4 are not easily fulfilled and are frequently challenged by the new technology that emerges.

In this scenario, drivers for change come from outside the existing network; in fact, the impetus for change is often in conflict with its interests.

An example of Scenario 4 is the ‘industrialisation of light’ over the 19^{th} century (Schivelbusch, 1988 p.5). Drivers for this innovation came from outside the traditional network of lighting. The first driver was the Industrial Revolution and the economies of industrial production. Industrialists wanted to increase productivity by extending working hours into the night, which was difficult and expensive using candles. William Murdoch (who was working for the Boulton & Watt company in Birmingham) undertook early experiments to see if usable light could be produced from the flammable gas that was a by-product of distilling coal in 1794. Murdoch developed the process into a factory-wide system fed with lighting installations fuelled by gas,

Figure 2.9
Map of gas lines in London 1814
(Tomory 2011, p.90)

conveyed by pipe. Boulton & Watt sold this lighting system to various manufacturing companies (Tomory, 2012; Dillon, 2002).

The development of gas lighting technology into large-scale lighting systems for cities was propelled by a second driver - entrepreneurs - who saw the manufacturing and supply of gas light as a commercial possibility to be exploited. The earliest of these entrepreneurs was a German immigrant called Frederick Winsor who developed the world's first gas network in London (Tomory, 2011).

The creation of a centralised system for gas distribution, with its network of underground pipes connecting every dwelling to the source of gas production, represented a radical break from the fuel economies that supported artisanal lighting.

Unlike the previous scenarios, Scenario 4 can impact all parts of the previous actor-network, including consumers, in negative ways. This can complicate the transition. Milan notes the contrast between the lower acceptance of gaslight into the domestic sphere with the easy and 'enthusiastic acceptance' of gaslight into public areas (Milan, 1998 p. 122). Some people did not like the lighting effect gas created. Edgar Allen Poe complained 'it is inadmissible indoors. Its hard and unsteady light offends' (Moss, 1988 p. 100). Gaslight blackened rooms, bringing an aesthetic of dark colours into interiors to hide the grime. Householders were prejudiced against gaslight and found its abstract nature unsettling (Brox, 2010). There was flame but no wick, no candle, no oil reservoir - just a switch connecting the light to a distant and mysterious source. Schivelbusch (1988) argued that there was a perception that gas was an industrial product which made its journey into the home a difficult one.

Gas had been promoted as a liberator from 'filthy tallow candles and stinking oil lamps' (O'Dea 1952) but in reality the transition created new work for the consumer. Sets of practices had to evolve around maintaining 'wet metres', managing stopcock valves and airing rooms. These new responsibilities were alien to the familiar maintenance practices around oils lamps which had been embedded into the daily routine (Clark Ratcliffe, 1990). The householder's allegiance still belonged to the established stable network that delivered candle and lamp light and initially there was little enthusiasm for change.

Prejudices against gas created problems for the early gas companies. Householders had to be recruited to provide sufficient consumers for profitability (Tomory, 2011). This recruitment was made difficult by the increased competition offered by newly-improved candles and then, in the 1860s, cheaper kerosene light sources. As outlined above, kerosene lamps were adopted with enthusiasm, even though gaslight was, by that time, a viable alternative. In Scenario 4, existing actors resist displacement by a variety of strategies. In the early days of gaslight, the whaling industry argued that the service traditionally provided by whalers, in training recruits for the Royal Navy, was a reason for the government to protect the industry (Lacey & Chandler, 1949). In another strategy around 1814, the whaling industry sent a series of anonymous letters to *The Times* questioning the safety of gas lighting and in this campaign they were supported by tallow candle manufacturers (Tomory, 2014). In Scenario 4, conflict will occur not only in the transition between the new and the established actor-networks but also between competing actors wanting a place in the new networks. The early days of gaslight were marked by fierce competition between companies promoting their different forms of gas technology (Tomory, 2014; Dillon 2002). Milan (1998) argues that though there were advantages to this unregulated market in that consumers could shop around for the best prices, it was a period of confusion, with sometimes up to eight different main pipes being laid in

Figure 2.10
Gasolier
(Anonymous c. 1870)

a single street. Pipes were badly laid and caused pollution in soil and drinking water. To save costs, workmanship in installation was often very poor. The experience of using gaslight was compromised by these early uncertainties. Actor-network theory notes the existence of performative actors such as expectations and habits. These actors are embedded in tacit ways of in the world that are difficult to shift. Assumptions that come from habituated experience of a previous technology will shape the reactions of consumers to an emerging technology that demands different embodied habits. Silverstone and Haddon (1996) argue that a new technology may need to mediate its aesthetic presentation to a form that is familiar to the user. This creates a degree of tension, as these familiar forms may be at odds with the nature of the new technology and may limit possibilities for formal and material explorations by designers.

The introduction of gas lighting and industrialised infrastructure represented a shift in society. However, the design of light fittings for gas exhibited similarities to kerosene and oil lamps (Rybczynski, 1986). Ornate lampshades (frequently spherical in shape) made of decorated glass were used to diffuse this new bright light source and this type of lampshade became a typology closely associated with gas lighting. In this situation, design was used to disguise the radical effects of Scenario 4 by making the artefacts resemble those associated with the easier transitions described in Scenarios 1, 2 and 3.

Once accomplished, the technology transition associated with Scenario 4 established such a different world that it could not have been conceived from the previous network. At the time of the first experiments with gas lighting, a centralised light supply network would have been difficult to conceive. And yet within 25 years there were active gas networks supplying parts of London and the world had moved into the industrial age.

Part 3.
The transition to digital lighting – the Light Emitting Diode

Part 2 outlined four different scenarios of innovation, from the relatively easy transitions to those involving disruption and a degree of conflict. The emergence of LED technology in the early 21st century is a transition belonging to Scenario 4. Early indications that this is a contested transition have been noted in the Introduction. The driver behind the transition to LED technology has been the move to reduce energy consumption out of concern that emerged in the late 20th century about the use of fossil fuels. It was recognised that energy consumed for lighting represented a significant proportion of all energy consumed. For example, based on statistics from the early 21st century, Azevedo et al. (2009) note that lighting was responsible for 20 per cent of total electricity energy consumption in the United States. They note that the EU has a similar proportion of energy consumed by lighting. As discussed in Chapter 1, there was a search for energy efficient lighting technologies (Brown, 1993; International Energy Agency, 2006; Rosenfeld et al, 1993). LED technology was identified by governments as a light source offering potential energy-saving benefits> Governmentsconsequently offered funding for research and enacted legislation to encourage the transition to LED technology in the United States and Europe (Department of Energy, 2006; Archenhold, 2008). A second, less well-recognised, driver for the transition to LEDs is the digital nature of the technology. LEDs are technically transistors, like computer components, and are a *digital* light source. This contrasts with previous lighting technologies, which use either incandescent or discharge processes. This characteristic means LEDs

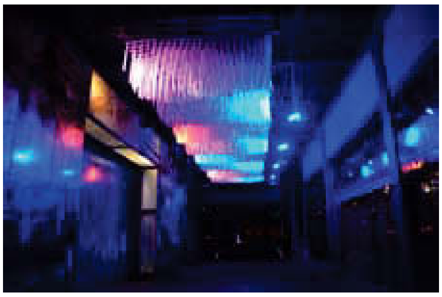

Figure 2.11
Luminous Canopy
(McDermott & Baxter 2015)

are compatible with other digital technologies. As the digital technology sector expands rapidly into new areas of practice, different digital technologies, such as computers and LEDs, are increasingly networked to provide additional functionality and control.

In the Introduction to this thesis I described the slow response to LED technology on the part of the traditional lighting industry which has supplied artificial lighting fixtures throughout the 20th and into the 21st centuries. This slow response from the lighting industry contrasts with the reactions of entrepreneurs in the electronics sector who saw the potential of LED technology from its early days. An example of entrepreneurial expansion into LED technology is given in the rapid growth and ongoing influence of the LED company Color Kinetics. This technology start-up, founded by two robotic engineers, George Mueller and Ihor Lys, in 1997, brought the 'playful, poke-it-and-see-what-happens mentality of the computer hacker' to experimentation with LEDs (Johnstone, 2007 p.150). The products made by Color Kinetics combined the processors, modulation techniques and digital control software common to the robotics industry, with red, green and blue (RGB) LEDs to create what could be called 'robotic' lighting (Koerner, 2012). Digital control of LEDs gives control over the hue (colour), saturation (how much white is present) and brightness of the light. The brilliant effects seen in 21st century light art and media facades are due to these early breakthroughs.

The entry into the field of entrepreneurs with a background in electronics and digital technology, brought a completely different culture to the delivery of artificial light. Entrepreneurs are interested in technological breakthroughs and opportunities for expansion. This attitude is unlike that of the more sedate lighting sector that has operated comfortably in the stabilised networks of pre-digital lighting context with lower growth and slower technological change. George Mueller has called the traditional lighting industry 'old hat, describing it as being about 'glass, brass and gas', with little technological innovation (Johnstone, 2007, Savage, 2000). The disjuncture in attitudes and approaches between the old and new lighting industries has become more apparent as LEDs have grown in significance.

Recruitment of actors comfortable in the actor-networks of 20th century lighting to the new actor-networks growing around digital lighting has been a challenge for LED technology. Governments were recruited easily due to the geopolitics of energy efficiency, and the high technology sector was drawn to the digital nature of the technology, however, other sectors remained uncertain and aloof. Consumers had heard about the technology and were interested in the possibility of lower power bills, but the technology did not find a place in their lives immediately. Chapter 1 discussed the physical attributes of LED technology and how LEDs neither look nor behave like previous, legacy, light sources. While consumers could appreciate LEDs in playful, experimental situations such as light art or solar powered Christmas lights, living with LED technology on a daily basis in the home was hard to imagine. Consumer expectations of lit domestic space, and practices (such as being able to buy a replacement bulb for an existing fitting at a hardware shop) were not immediately met by LED technology.

The other major actor-network that did not embrace LED technology was the lighting industry, and for good reason. LEDs as a light source are technically demanding and difficult to deal with. LEDs do not conform to existing expectations of lighting interiors and were not immediately compatible with existing lighting typologies. The manufacture of LEDs (which is about growing crystals) was foreign to industries that had worked with glass bulbs and tubes with electrodes. Even the energy-efficient aspects

Figure 2.12
CFL Lamp with E27 base
(Philips 2015)

Figure 2.13
Type-A halogen lamp with E27 base
(Philips 2015)

Figure 2.14
LED bulb
(Compact 2017)

of LED technology were a challenge to industries that had built entire businesses on selling replacement bulbs.

Industry resistance to the introduction of LEDs

The pattern of resistance to technology displacement, seen in the introduction of gas in the 19^{th} century, recurred with the arrival of LED technology in the early 21st century. The first reaction of the lighting industry was to stall the adoption of LEDs in the market place for as long as possible by promoting alternative high-efficiency products that replicated the format of GLS lamps. One such was the compact fluorescent light (CFL), a smaller version of the fluorescent tube used to light work environments, but redesigned to plug into a GLS socket and fit within the space of a typical GLS luminaire. CFLs are more efficient than GLS and halogen technologies, the parameters for their performance being between 70 and 87 lm/watt (Rea, 2000, Julian, 2011, Karlen et al., 2012). However, the conversion efficacy of fluorescent technology is unlikely to grow much above 100 lm/W (Azevedo et al., 2009 p. 483) and, unlike LEDs, this technology cannot attain 100% efficiency. Furthermore, there are concerns over the use of mercury (a persistent, bio-accumulative toxin) in fluorescent lamps. Aucott et al (2003) estimate that between 17 and 40% of the mercury in broken low-mercury fluorescent bulbs is released into the air during the two-week period immediately following a breakage. This mercury content creates challenges in the safe disposal of fluorescent lamps and has led to some governments considering phasing out their use altogether (Leslie 2015). The 2016 decision of General Electric (GE) to cease production of CFLs to concentrate on LED technology (Spector, 2016) anticipates a future without CFL technology.

An older light source from the 1980s, halogen technology, has been made available in GLS type lamps (called A-type halogen by the lighting industry). These lamps have been promoted as an alternative to the banned GLS. The A type halogen lamp has a performance of between 15 lm/w and 30 lm/w (Rea, 2000, Karlen et al., 2012) which is only a small improvement on the GLS lamp though it does offer greater longevity than GLS. European governments planned to phase out the A-type Halogen in 2016 however, resistance from the lighting industry and persistent lobbying of governments led to a postponement of the ban until 2018. This postponement has caused division within the industry; some are calling for an immediate ban, others want the ban to start in 2020 (Halper, 2015, Ala–Kurikka, 2015). The phase-out of halogen products is still in the planning stages in Australia but scheduled to commence in 2018 (Douglas, 2016). Eventually, the A-type halogen will become a 'legacy' light source, as is the GLS incandescent.

A second strategy of resistance used by the lighting industry was to accept the LED light source, but to reshape it into a form that could fit into existing light fittings, be sold through existing retail networks, and be replaced using the same embodied know-how as the GLS incandescent lamp. The bulb that was developed to translate LED into a form that would work with these GLS networks was named the E27 LED bulb, to reference the E27 screw-based bulb originally invented by Thomas Edison. Rene Geerts, a long-standing industry professional, has criticisms of this LED format. He cites poor optical distribution and inadequate thermal management of the LEDs as reasons for dissatisfaction with the E27 LED bulb (R. Geerts 2014, pers. comm., 12 August). Poor thermal management leads to excessive heat in the centre of the bulb where the power supply is placed. As the efficiency and longevity of the LED are negatively impacted if the power supply is not kept cool, the design of the E27 LED can be seen to be sacrificing the advantages of LED technology in order to enable it to conform with existing networks.

This reliance on short term and improvised approaches can have long term negative effects. In discussing the changes in socio-technical systems required for sustainable development, Kemp et al. (2007 p. 81) argue that the impact of short-term solutions on the longer term outcome is unclear. They also note the danger of being locked into forms or solutions that are not optimal from a long-term perspective, adding that 'by choosing the best available option at the beginning of a transition process while other options are still in development, the chances are that the future will be dominated by that specific option'. Several leading practitioners in the lighting sector have recognised that developing LED products using the 'retrofit' approach (either in the choice of bulb or older design approaches) is a short-term strategy and works to the detriment of the long-term realisation of the full benefits of LED technology (Willmorth, 2014, Hansen, 2011).

In Scenario 3, the 'cultural moment' aligns with a new possibility it is the 'right time' for the new material, technology, or approach to production, and this facilitates the transition. In the case of LEDs, while this new technology did align with the need for energy-efficient light sources, it did not align with expectations of how interiors should look and feel that had been established over the 20th century.

There is evidence that the 'cultural moment' may be changing. The shift to a digital economy is now well under way, and consumers are beginning to expect that the different functions in their world can be managed from networked digital devices. The digital nature of the LED may prove a more profound motivator for consumers than energy efficiency has been. However the need to mediate the light from LEDs in ways that conform to expectations of domestic light, remains.

During the 20th century, GLS lighting had come to represent freedom. GLS created even, bright light that filled rooms rather than just illuminating the immediate surroundings. The transformation of spatial experience following the introduction of electric light included the development of an aesthetic that eliminated deep shadow. While GLS technologies made it possible to banish shadows, it was the hygiene movement that made such banishment culturally desirable (Rybczynski, 1986). Reform movements such as the domestic science movement influenced by the writings of Frederick Taylor focused on efficiency and hygiene (Taylor, 1913). A new desire to flood interior spaces with abundant light was extended, through GLS technologies, beyond the hours of daylight and into the evening.

This new lighting environment in the 20th century stood in stark contrast to the 19th century layout and aesthetic of interiors. Influenced by gaslight, 19th century interior colours were dark and the rooms were small (for airing). Homes were private, a haven from the demands of a rapidly changing world. With the advent of new lighting conditions in the 20th century, homes were no longer the cosy retreats of the 19th century; rather, they were the place of reason, fitness and efficiency (Nye, 1991).

The shift to bright, even lighting in the home paralleled the introduction of abundant light into the workplace. Illuminating Engineering Societies, established at the beginning of the 20th century, were instrumental in developing lighting standards for the workplace. These standards were based on the need for visibility in relation to certain tasks in places such as factories (Cuttle, 2013). An important aspect of these standards was the concept of general illumination (or general lighting), which is described as uniform illumination throughout an (interior) area exclusive of any provision for special local requirement (Rea, 2000). Levels of illumination in all buildings grew. The International Energy Agency (IEA) (2006) suggested that installed illumination levels in OECD countries in the 20^{th} century commonly exceeded recommended levels. The uniformly high levels of illumination that became a default in 20^{th}-century buildings were not always supported by architects. Distinguished architect Sir Nicholas Grimshaw expressed dismay at the uniform engineering of high illumination in built interiors, commenting that 'lighting levels could easily come down by 50 per cent,' (Birch, 2016 p.22). Conditions of general illumination, easily generated by the omni-directional and generous spread of incandescent and fluorescent light, cannot be created easily with LEDs. The narrow stream of light is generated from an intense, pinpoint source that has no fixed form. Glare and defined darker shadows also influence the illuminated landscape. LEDs are a relatively new light source and we have, as yet, no innate understanding of how they behave. We have no history or tradition of light fittings for this source from which we can learn; there are no iconic shapes or traditional forms for LED technology. The typologies of light fitting that we *are* familiar with, and instinctively draw upon, were developed for abundant light and have limited application for LEDs.

The role of design

> …the appreciation of specific material qualities of light, the *ecstasies* of the bulb's colour reproduction and temperature, the patina and multi-sensuality of orchestrating lightscapes through the shadows …is at the heart of understanding the contestation against adopting a new technology (Bille and Sorenson, 2007)

The phase out of the beloved but inefficient incandescent lamp caused a degree of consternation amongst many, including the designers of light fittings. One designer said 'when the old [incandescent] bulbs are phased out, I'll have to run and hide' (Lacey, 2008). Incandescent light with its attendant excellent colour rendering properties, warm colour temperatures and omni-directional spread of light was always a pleasurable and straightforward light source with which to work. Incandescent light has been described as having 'incandescent coziness' (Kellog, 2009) and a 'warm restfulness' (Comrie-Smith, 1954). The ease of designing with GLS light, in particular, was noted, rather colourfully, by Chris James from LED company Cree Research when he said, 'Before [LEDs] all the lighting fixture guys had to do was bend some metal, plug it into a wall because the Edison bulb took care of the rest' (Johnstone, 2007 p263). In my own experience, working with incandescent light meant not having to think about the light source at all – it took care of itself and always looked acceptable.

For designers, there was uncertainty as to how to engage with the emerging LED technology. Sandro Tothill from LZF, an international lighting company based in Spain, commented on his attempts to use LEDs in light fittings 'I have no idea of how I'm going to do it at the moment but I think it's all a question of refraction and reflection of the LED light off other surfaces' (Lacey, 2008). When discussing the range of LED fixtures on display at the 2008 *Light & Build* exhibition in Frankfurt, Vrinda Bhandarkar commented, 'Designers are familiar with incandescent light as it shines through a luminaire. LEDs as new directional point sources are a new alphabet in the vocabulary of decorative lighting design' (Bhandarkar, 2008).

Lack of design innovation or a strategy to keep the network intact

There have been concerns raised by various writers and researchers about the continuing use of older light fitting typologies, rather than the development of new LED-specific typologies (Dowling, 2008, Hansen, 2011, Shaw, 2009). The lack of innovation in light fitting design continues to be noted in the second decade of the 21st century, even as LED technology has developed. Dr Geoff Archenhold, technical editor at international lighting magazine *MondoArc*, noted the absence of design development in his yearly round up of 2012, calling it a year of 'solid growth for LED lighting, exceptionally unimaginative fixture design' (Archenhold 2012 p.32). Kevan Houser (2015), in an editorial for *Leukos*, praised the development of LEDs as a technology but expressed concern over the persistence of older typologies of light fitting in their application. In a presentation at the 2015 Strategies in Light Europe conference, industry consultant Dr Thomas Knoop commented on the lack of progress around LED application:

> When LEDs were established as the future of lighting it was expected that they would stimulate a new approach to both products and design applications, enabling a rush of creative new solutions. However, so far the newest LED luminaires often look like their conventional predecessors, and most building applications remain similarly consistent, with new technologies simply replacing the lamps of before (Knoop,2015 p.20).

There is an echo of the old approaches even in products where the LED is directly integrated into the fitting. This integrated method is considered preferable as it incorporates properly-designed heat management and optics into the fitting. While integrated LEDs should free up design approaches, this is not always the case. As one lighting designer remarked:

> I'd also like to see innovative responses to new technologies – why manufacturers continue to force the old reflector concepts upon lambertian sources and/or bolt pre-manufactured LED modules into old product families that then require bulky heat management never ceases to confound me (Steel, 2014 p.18).

Award-winning lighting designer Dean Skira, in an interview in January 2017 (Bullock, 2017), noted that 'most of the product designers in light fixture design are thinking in the traditional way of old[er] sources'. Skira suggested that designers need to perform a 'Control-Alt-Delete' on their thinking and change their mindset. Dr Monica Hansen (2011), research scientist and Contracts Head at LED company Cree Research, has argued the need for specifically-designed LED luminaires capable of balancing the competing requirements of optics, mechanics, electronics, thermal management and the light engine which transfers power to the LED itself. This indicates the need for a new approach that understands LEDs and their technical requirements to ensure that the benefits of this new light source are realised.

The benefits offered by LEDs have not led to an easy integration into the lighting sector, any more than access to instantaneous, bright light meant a quick transition from candles to gas. LEDs do not conform to expectations of how interiors are illuminated and how light fittings should appear. These expectations are influenced by the particular characteristics of GLS and similar legacy light sources. In terms of design, the technology that underpinned the older light sources was relatively simple and the light quality intrinsically pleasant. Designing was, in most cases, straightforward. LED light does not fit into these expectations and will not create illuminated landscapes in the same way as older light sources. LEDs create challenges in design and need new approaches and a better understanding of what is a technically complex light source.

The digital nature of LED technology should have alerted those concerned with lighting that the transition to LEDs would be as significant as the move from artisanal to industrialised light in the early 19th century. LED technology is not simply a new efficient light source; it is part of a wider transition from industrial to digital technologies. While digital technologies have been present in society for several decades, digital lighting remains a challenge. The established lighting industry has been slow to recognise the full implications of lighting in a digital landscape and this transition is ongoing.

Summary

- Actor-network theory is a useful lens for understanding technology transitions.

- Four different scenarios for technology transition can be identified, each with different implications for the designer. The four scenarios are:

  - Scenario 1: incremental progress, or refinement within an established actor-network

  - Scenario 2: changes within actor-networks of production or supply, that leave consumption networks and experiences largely unchanged

  - Scenario 3: changes in actor-networks that impact everyday consumer experience, driven by new possibilities for realising pre-existing desires

- Scenario 4: changes to established actor-networks in response to pressure from external forces

• The transition from GLS incandescent and fluorescent to LED lighting technologies belongs to Scenario 4, in which change is driven by pressures external to established actor-networks associated with delivery of a particular set of performances – in this case the actor-networks of the established lighting industry, that are responsible for the generation of artificial light.

• External drivers for a shift to LED lighting, that place it within Scenario 4, are:

1. the need for energy efficiency and

2. the digital transformation.

• Existing actor-networks concerned with the supply of artificial light have resisted the transition to LED technologies, while players external to 20th century lighting industries and more closely associated with the development of digital technologies, have embraced it.

• The growing uptake of networked digital technology among consumers may provide the impetus that tips the transition to LEDs from Scenario 4 into Scenario 3. However, techniques for mediating LED light to conform with expectations of light for interior contexts, particularly domestic interiors, is needed, if the full advantages of LED technology are to be realised.

Chapter 3.

Introducing the practice-led experiments

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Introducing the practice-led experiments

Designing involves material, technological and formal explorations, in order to see what effects can be achieved, what is possible. In all this, there is a final aim to develop an artefact that meets a particular need or creates a better solution to a problem (Buchanan, 1998). In professional design practice, if the design process is successful, the artefact will function as an appropriate, designed response to a client requirement without need for further analysis or theorising (Rust et al., 2000).

Part 1.

Developing a practice-led approach

Design practice in a research context follows a different direction to that of professional design practice. Practice-led research investigates issues that have been identified as worthy of exploring with a view to making a contribution to the field (Cross, 2000). Practice-led design research takes the material and technological experimentation of the designer particularly seriously. The process of exploration becomes more disciplined and formalised than in most professional practice, where tacit knowledge guides design (Pedgley & Wormald, 2007). Methods employed must be transparent and the researcher must be able to make the creative process public (Biggs & Buchler, 2007). However, the artefacts produced within the research process do not necessarily represent final design solutions ready for production in order to meet market demand. Rather, the research-driven experimentation is conceived as a series of learning projects requiring ongoing analysis of, and reflection on, the artefacts produced and the design processes that produced them (Cross, 1998; Frayling, 1997).

Create effect versus mitigate effect

When I reflect upon the assumptions that I brought to the first stages of this research, I realise that the research question I assumed I would be working to was ‘how do I achieve X effect?’ where X was a particular designed lighting effect familiar to me from the history of excellent lighting design. However, once I began working with LEDs the research question almost immediately switched to ‘how do I mitigate Y effect?’ where Y was an undesirable aspect of LED lighting. My initial investigations alerted me to the difficulty, if not impossibility, of creating effects similar to those achieved with incandescent light sources. It became apparent that LED light would need more careful control and mediation and, possibly, different design approaches to previous light sources. I became aware that there was a need for design approaches that were not limited by previous assumptions of what an appropriate design outcome might be. Practice-led experiment methods were sought that would take advantage of my experience and skills whilst safeguarding against an over-reliance on habitual ways of working. This was particularly important in this research project, where the discovery of new *processes* of designing with light was part of the overall aim of the research.

Frames for practice

'Frames for practice' is a term developed by Timo Rissanen as part of his doctoral studies on achieving zero-waste fashion design. Rissanen's study had a significant practice-based element and the 'frames' were developed specifically to counter the tendency of practitioners to rely on 'habits of practice' (Rissanen, 2013).
Rissanen (2009) identified five methods fashion designers used in developing new designs and then developed each of these approaches into design briefs to guide his practice-based experimentation. Having identified that design methods varied with each practitioner, he developed these design briefs to reflect the diversity of practice in the fashion industry. In Rissanen's case, three of the five approaches were different to his. I could see from this that the 'frames-for-practice' approach could be adapted to form a structure for my own practice-led experiments. Buchanan (1998) describes design as 'particular knowledge - tacit, personal and private'. The 'frames for practice' allows design practitioners to step outside their tacit knowledge while continuing to work within the broader practices of their own industry. I focused my attention on finding a set of 'frames for practice' for lighting.

Optical control of light 'frames for practice'

It has been identified that the light from LEDs needs careful management and precise optical control (Reo, 2008) and prior research has noted that glare is a particular challenge with LED light. I focused my efforts on consulting the literature on how light could be controlled and glare mediated. Four methods of mediating and exercising control over light were identified through scientific and historical sources: refraction, reflection, diffusion and obstruction.

The role of the light fitting

In most cases, artificial light is experienced through the agency of a light fitting or luminaire. Tregenza and Loe (1998) list a number of functions performed by a light fitting. The light source itself, be it flame, bulb, tube or chip, needs to be supported, protected and connected to the source of power. Unwanted heat needs to be managed for safety and performance reasons. All light fittings that control and distribute light employ one or more of the four forms of optical control in order to manage lighting effects. Refraction, reflection, diffusion and obstruction are used not only in light fitting design, but also in architectural approaches to lighting. I decided to use these four light mediation principles as a way of structuring the practice component of the research.

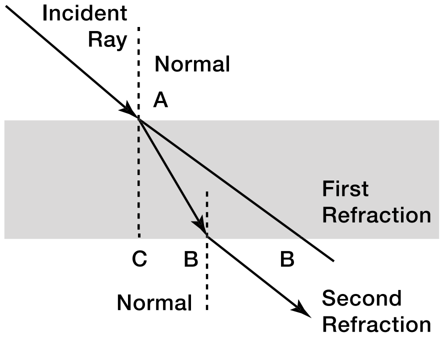


Figure 3.1
Refraction at the boundary of two optically different materials (Julian 2011, p.40)

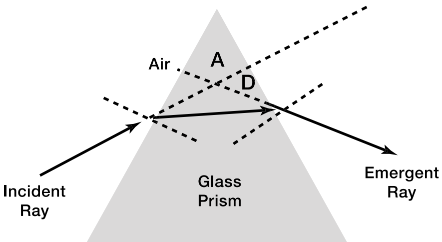


Figure 3.2
Prism with non-parallel faces (Julian 2011, p.44)

Part 2.

Principles of light mediation

The following section discusses the four methods of controlling light in terms of each principle, and the lighting effect created by the principle.

Refraction

In his seminal treatise of 1730, *Opticks*, Isaac Newton discussed how the direction of light is changed (refracted) at the junction of two transparent materials such as air and glass (Newton, 1730). As a ray of light travels from a less dense medium, such as air, into a denser medium such as glass, the light will bend towards the normal (i.e., a line that is perpendicular to the surface). The ray of light as it enters is called the incident ray. If the two sides of the refracting medium are parallel, the refracted ray will emerge at the same angle as the incident ray (Figure 3.1).
Newton also observed the behaviour of light as it passed through a prism (basically a four-sided pyramid made of glass), as illustrated in Figure 3.2. When the light enters the refractive medium at an oblique angle (not at 90°), the light appears to bend towards the normal (as illustrated above). When the light exits the prism, however, it bends away from the normal. The angle at which the ray of light bends depends on the refractive index of the material. The refractive index is a measure of the propagation velocity of light in the material and is a characteristic of all light transmitting materials (Julian, 2011). The use of non-parallel faces such as those in Figure 3.2 allows the angle of the light to be controlled, the final angle depending on the refractive index of the material.

Lighting effects created by refraction

In terms of visual effect, refraction creates a glowing surface at the interface of the two media where the light changes speed, e.g., between acrylic and air. The number of glowing surfaces can be increased by introducing new cuts at different angles. Multiple cut surfaces refract the light over a wider area, making it seem more voluminous, the effect of which mitigates any glare (Flynn and Mills, 1962).

Figure 3. 3
Candelabrum 1750
(Bluhm Lippincott 2000, p.58)

The case of the chandelier

> Chandeliers, especially ones of crystal and glass, were from the beginning, and just as much so today, a crowning feature in room decoration, and, like a coronet set with diamonds, radiated light, lustre, brilliance and sparkle all around them (Smith, 1974 p. 17)

While many transparent materials refract light, lead crystal is particularly known for its bright sparkle and rainbow-coloured effects. Lead crystal was developed in Britain around 1674 when it was found that by adding lead to glass a particularly lustrous effect could be created (Macleod, 1987). When lapidary cutters used jewellery techniques to create individual gem shapes from lead glass and these shapes were then placed adjacent to candles, the light was refracted in a multitude of directions with a brilliant sparkle effect (Figure 3.3). While chandeliers appear to enhance the light, that is, create a greater lighting effect, in reality, they are acting as a *distributor* of light, giving volume to the amount of light present.

Reflection

Reflection occurs when light falls on an opaque (non-light conducting) surface and is then redirected. The law of reflection states that the angle of incidence (created by the incoming ray of light) is equal to the angle of reflection about the normal (which is 90° to the reflecting surface) (Rea, 2000).

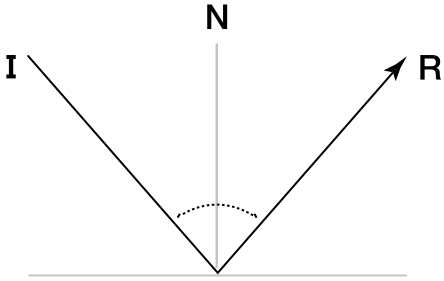


Figure 3.4
Law of Reflection
(Rea 2000, p.31)

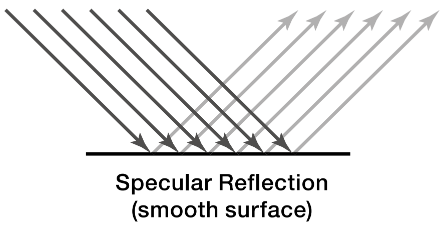


Figure 3.5
Specular reflection
(Rea 2000, p.31)

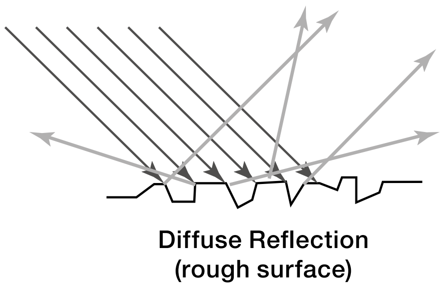


Figure 3.6
Diffuse reflection
(Rea 2000, p.31)

Lighting effects created by reflection

When light is reflected, the lighting effect is influenced by the shape and material of the surface. *Specular* reflection is observed when the reflective material is smooth and mirror-like (or at least very shiny) (Rea, 2000). This creates a defined reflection of the light, which can be perceived as sparkle, but in certain situations it can also create glare (Figure 3.5). Reflecting material that is uneven or has a matt surface composed of many small angled surfaces that scatter the light in many directions creates an effect called *diffuse* reflection (Figure 3.6). The law that the angle of incidence equals the angle of reflection still holds. The light is scattered and made more voluminous, mitigating glare. The overall effect is a softer visual light more akin to glow. On a larger scale, it is possible to create an ambient luminescent effect using large matt surfaces such as walls and ceilings.

Gleam – the evolution of light fittings

Historically, splint holders, terra cotta and bronze oil lamps and wooden candleholders were employed to manage and support light sources. The humble, non-reflective materials employed to support everyday lighting needs were not able to enhance, direct or mediate the light itself. By contrast, lighting implements associated with religious ceremonies, or high status persons, were made of precious, highly reflective materials. These evolved into light fittings that could distribute the light. The optical principles of reflection and, later on, refraction have long been central to the design of light fittings and are still used in light fittings today (Tregenza & Loe, 1998). Around the 17th and 18th centuries, furniture and interior fittings were specifically developed to enhance the lighting effects of candles with such devices as wall sconces and *girandoles*. These fittings developed from the practice of fixing a reflecting plate of brass or copper behind a candle, the intention being to enhance and distribute the light from a very small light source. An

approach such as this would meet the need to give volume to the pinpoint of candle light.
Although described as a mirror, this piece (Figure 3.7) doubles as a *girandole*, with three arms to support candles. This *girandole* works as a light fitting by using two types of reflection. An exact image of the candle would be reflected in the mirror (*specular* reflection), thus doubling the number of light sources. The frame would act as a softer, more *diffuse,* reflector, working particularly well with qualities of gold. The multiple, intricate surfaces of the decorations would distribute the light further. As well as being a beautiful object, this girandole was a piece of technology and an early light fitting.

Figure 3.7
Girandole
(Chippendale 1762-1765)

Diffusion

Diffusion (sometimes called transmission) scatters light as it passes through a translucent medium. This light mediation technique is a variation of refraction (Tregenza & Loe, 1998) Translucence is created by the presence of a multitude of tiny opaque particles in a transparent medium. These particles act as reflectors within the medium, reflecting light in a multitude of directions (Julian, 2011). The intensity of light is reduced according to how much the material absorbs the light, the ratio between absorption and transmission of light varying from one material to another (Rea, 2000 p. 38).

Lighting effect

Light mediation by diffusion softens the lighting effect and makes the light source appear larger, which in turn helps to mitigate glare. However, this method calls for the exercise of judgment in balancing the need for usable light and the desire for a softer effect.
In pre-industrial times, the principles of refraction and reflection were both employed to give greater volume to the scarce light generated by candles. By contrast, the

Figure 3. 8
Noguchi, I. 1951 *Akari* Light
(Kida 2003, p.32)

Figure 3.9
Moshabak
(Babaei et al. 2013, p.157)

mediation of industrialised light sources such as GLS and fluorescent tubes aimed to soften, rather than increase, the lighting effect (Figure 3.8). For this reason, diffusion as a mediation technique is largely associated with industrial lighting technologies. A further advantage of diffusion is that translucent surfaces can hide potentially unattractive components from direct view. This ability to soften and disguise, accounts for the frequent use of diffusing materials in a domestic environment.

Obstruction

The principle of obstruction masks direct viewing of the light source, sometimes through patterned screening to control the brightness of the light. A familiar example of the obstruction principle can be found in cove or pelmet lighting in interiors. A screen with perforated patterns can be used to mediate the light source by breaking it up into smaller modules of light interspersed with an opaque surface, thus lessening the intensity of the light.
Many cultures in hot and arid climates use perforated screens (often in windows) to mediate bright exterior light (Figure 3.9). These screens have a variety of names: *moshabak* in Iran and *mashrabiya* in Saudi Arabia, to name just two. In addition to mediating harsh external light without banishing it altogether from the interior, these screens provide a degree of privacy, enclosure and intimacy (Babaei et al, 2013).

Lighting effect

When large areas of bright light are broken up by a perforated screen into smaller areas of light interspaced with an opaque material, the intensity of the light is mediated. However, obstruction does not redirect light or give it volume. The challenge associated with mediating light through an obstructing screen is that the light source itself can still often be observed, as in Figure 3.9. This is acceptable when the light source is large, as with natural light, a GLS lamp or natural light. However, when using small but bright light sources such as LEDs, there is a need for careful orientation and consideration of the number and type of masking patterns.

Practice-led experiments using different forms of optical control.

The four principles outlined above were used to frame the series of practice-led experiments using LED technology. In each experiment, either one optical principle formed a focus, or several were worked with in tandem.

Reporting practice

Reporting the results of practice-led research needs a different approach from the reporting of design practice in a professional context. In design practice, reporting (often seen in design magazines or books) often takes the form of a 'grand narrative' leading to a triumphant outcome. Kees Dorst (2006) notes how 'dead ends', or inconvenient difficulties, are often omitted when designers report on their practice. Other designers will read this narrative for inspiration, to enrich their own understanding of the design process or out of enthusiasm for a project. For researchers, on the other hand, the practice is really a series of practice-led experiments that are learning projects. The focus of the documentation/communication needs to be on *what* was learned and *how* it was learned, rather than on the outcome. In this research, the effects achieved were important insofar as they provided feedback on the success, or otherwise, of the approaches to light mediation taken in each experiment. I have reported each set of practice-led experiments using the following structure:

1. Images of the final artefacts produced by

the practice-led experiments. Some of these were light art pieces that were exhibited as part of a wider festival; others were created specifically for this study.

2. Chart, with descriptors of the artefact, lighting sources, the lighting effects and what was learned.

3. A discussion of the practice-led experimentation, including manipulation of the mediating surfaces of the artefact, the technical details of the light sources used and a description of the effects created.

4. Discussion of how the practice could be taken forward and what possibilities for using LEDs were uncovered.

5. Reflection on process and what was learned from the practice-led experiments.

The arrangement of points 4 and 5 above varied for the different experiments. The early experiments focused on developing an understanding of the light source, while later experiments focused more on how to take the practice forward.

Summary

‘Frames of practice’ was adopted as an approach for the practice-led experiments.

- The frames adopted were based on four optical principles for light mediation: refraction, reflection, diffusion and obstruction.

- Each optical principle offers a different approach to managing the specific challenges of LED light, namely the intensity and directionality of the light source, and the need to mitigate glare.

- Each optical principle has a specific history of use in light mediation.

- Refraction and reflection have been important techniques in managing scarce light as they add volume to the light.

- Reflection, diffusion and obstruction have been important techniques in managing intense light, as they variously break up, disperse, redirect or absorb light.

- Reporting on the practice experiments includes:

    - Images of the final artefacts

    - A chart setting out details of the light source used, lighting effects created, and what was learned

    - A discussion of the procedure of the experiment and the outcomes

    - Ideas on how the practice can be taken further

    - A reflection on the process and what was learned

Timeline

Research Activities

January 2008
Enrolled Masters of Design by Research.

May 2008
Australian Technology Network (ATN) Online educational module on Practice-Led Research in Arts, Media and Design.

May 2008
Moved to practice-led model.

May 2008
Practice around the principle of refraction *Isis* installation at *Artlight*.

Literature

January 2008
Literature around future of lighting.

January 2008
Historical literature on lighting.

January 2008
Scientific literature around principles of light mediation.

April 2008
Technical literature around the development of LEDs. This engagement continued throughout study.

June 2008
Literature around practice-led research.

June 2008
Literature associated with architectural lighting.

June 2008
Literature associated with cultural approaches to lighting.

January 2010
Literature connected with computer human interface (CHI).

Outputs

December 2009
Confirmation of Candidature 1 UTS Masters examination.

Research Activities

March 2010
Practice around principle of *reflection* and *diffusion Lightlouvres*

June 2010
Commence evaluations of *Lightlouvres* with lay and professional people.

May/June 2011
Practice around the principle of refraction Web of Light at *VIVID Sydney*.

May/June 2012
Practice around principle of reflection and obstruction Cumulus at *VIVID Sydney*.

2014
Leave of Absence.

April 2015
Practice around principles of reflection, diffusion and obstruction *Nimbus* at *Salone De Mobile, Milan*.

2016

March 2017
Submission of thesis for examination.

Literature

2013
Literature around Actor-network theory and consumer practices.

Outputs

February 2010
Presentation at IDEA Conference Brisbane.

March 2010
Presentation at Doing DAB internal symposium at UTS.

May 2010
Presentation at Lightfair, Las Vegas, NV.

June 2010
Refereed conference paper *ConnectED* 2012. Co-authored with Dr Sally McLaughlin and Timo Rissanen.

October 2010
Upgraded to Doctor of Philosophy in Design.

May 2011
UTS Doctoral examination.

October 2011
Refereed conference paper *IASDR 2011 Diversity and Unity Delft*.

December 2012
Presentation at *Interstices 2012 Immaterial materialities*.

December 2015
Refereed conference paper *49th International Conference of the Architectural Science Association* co-authored with Dr Susan Stewart.

Chapter 4.
Getting to know the technology

Chapter 4. Getting to know the technology

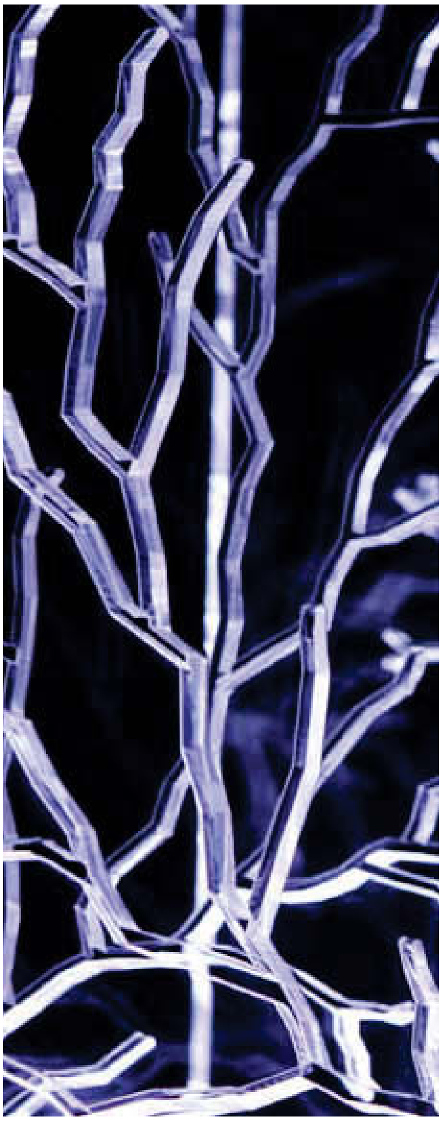
The first set of practice-led experiments was an exercise in getting to know LED technology. This included gaining a better understanding of the light produced by LEDs, the methods that could be used in working with the technology and the technical demands of LEDS. The experiments outlined in this chapter took the form of light art contributions to the first and second *VIVID Sydney* light festivals in Sydney in 2009 and 2011. These contributions were funded by bodies associated with the festival. The first practice-led experiment (*Isis* installation) was undertaken by myself. The second (*Web of Light*) was a collaboration with Ben Baxter.

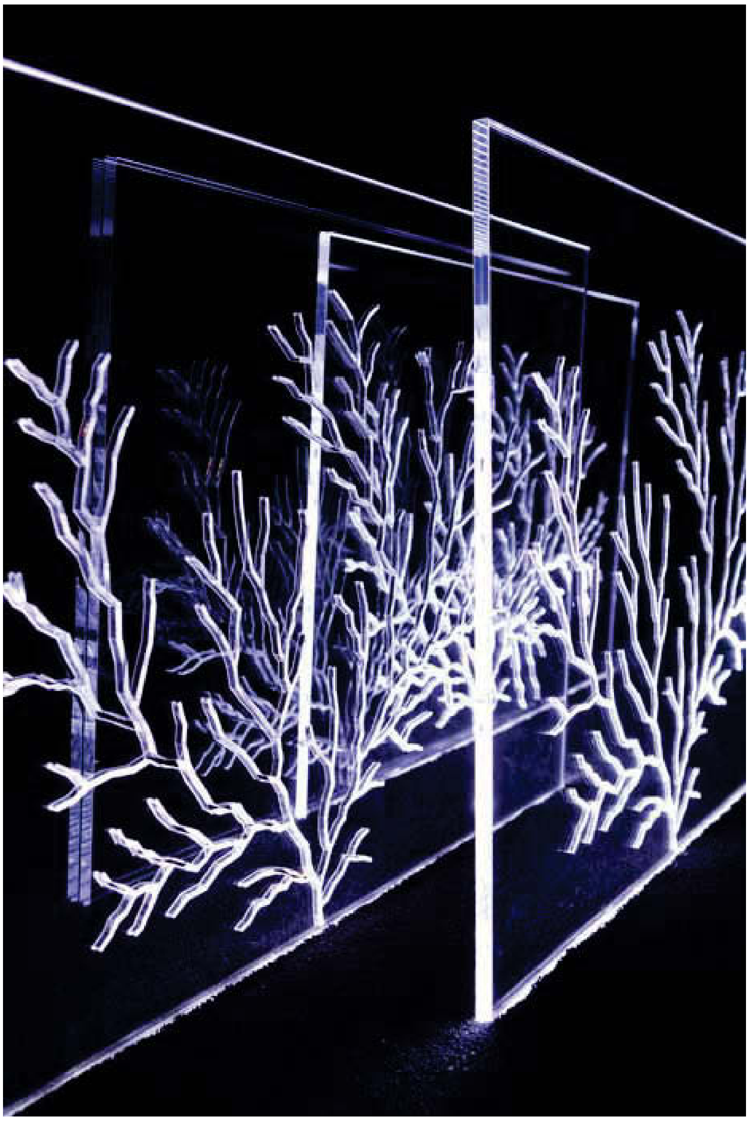
Refraction as an optical principle was chosen as the 'frame for practice' for these practice-led experiments for two reasons. The first reason was the festival environment, where the sparkle effect generated by refraction was considered appropriate to the context. The second reason was that I had not used refraction in any light fitting or light art installation in my previous practice. This latter reason was influenced by Timo Rissanen's approach in his development of 'frames for practice'. Rissanen ensured the 'frames' were design approaches used in the industry but not necessarily part of his existing practice (Rissanen, 2013). I had not used refraction in any light fitting or light art installation before this time. Following Rissanen, the selection, in the first instance, of a 'frame' that I had not previously worked with would ensure that I would not unreflectively reproduce my usual design strategies, but would actively reflect on each design decision.

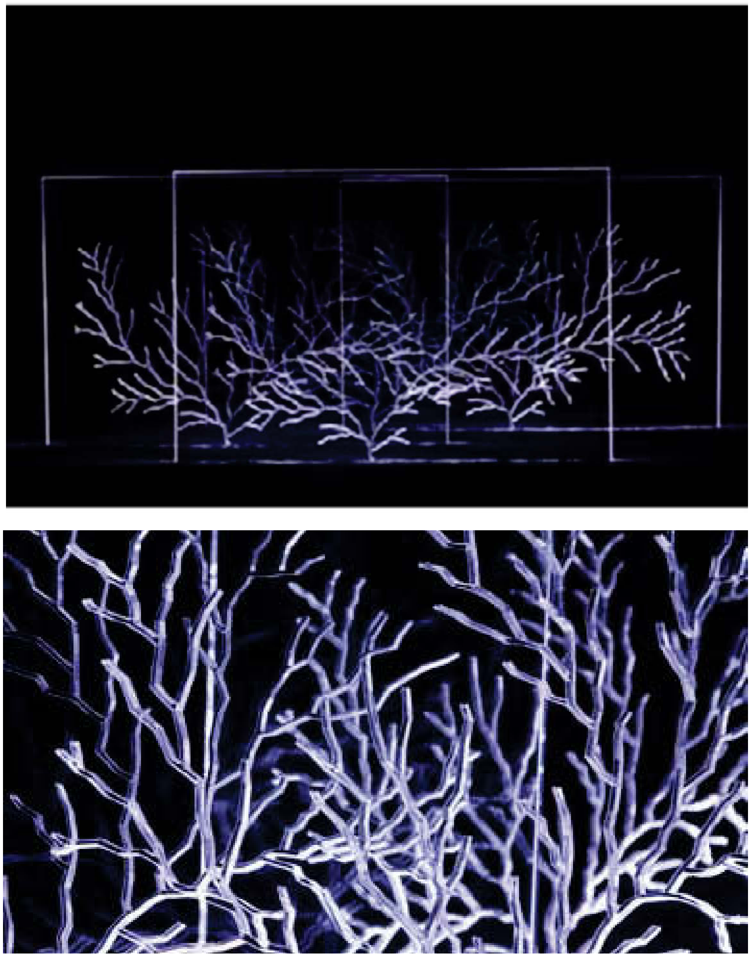
Part 1 of this chapter discusses the first practice-led experiment, the *Isis* installation. This was created for the *Artlight* exhibition in the main building foyer of the University of Technology Sydney, with funding provided by the University.

Part 2 discusses a second practice-led experiment based on refraction, the *Web of Light*. This was a light art project to be displayed in an external environment as part of the 2011 Vivid Sydney. It was funded by the festival, created in collaboration with Ben Baxter and was inspired by the beauty of water droplets on a spider web. Whilst the *Isis* installation explored refraction with LEDs using a thermoplastic, acrylic, the *Web of Light* used lead crystals as in traditional chandeliers.

Part 3 presents reflection on, and feedback from, the refraction-based LED experiments. Possible applications of the refraction technique for LED-based interior lighting are discussed. Part 4 reflects on what was learned about working with LEDs from these two experiments.







Figures 4.1-4.4
Isis installation
(McDermott 2009)

Isis installation	Mediation of light	LEDs
	Mediation technique Refraction at the interface between acrylic and air **Medium** 12mm thick clear acrylic sheet **Surface for generating lighting effects** The laser-cut edge of the acrylic **Technique for modifying medium or surface** Acrylic modified by laser cutting to create refracting surface along line of cut **Configuration of mediating surfaces** Parallel, cut-acrylic edges, 4mm apart, in a pattern of short, straight sections at different angles.	**Lumen output:** 534 lumen **Beam angle:** Can be adjusted **Colour temperature:** 3000K **Configuration:** linear array **Spacing of LEDs:** 25mm centres

Table 4.1 *Isis* summary

Management of LED	Effects	What was learned
Mounting: supplied within eW Cove MX Powercore housing **Housing: standard eW Cove MX Powercore** **Thermal management: integrated within module** **Cabling: supplied within eCove housing module** **Location of driver: within module** **Data enabler: not used**	• Light was refracted off the cut edges of the acrylic, providing brilliantly glowing lines following the pattern of cuts. • The effect created was crisp and without discomfort glare. • The sparkle effect generated by refraction was distributed along the cut edge, and therefore was subdued rather than concentrated. • The intensity of the lighting effect diminished with distance from the light source. • A small amount of unintended light spill was reflected off surfaces at a distance from the installation • The light source within the plinth was effectively screened.	1. The intensity of the lighting effect along a refractive surface contrasts with the very small amount of general illumination achieved. 2. LED is an unforgiving technology to work with – small inaccuracies of placement and surface treatment result in complete failure to achieve the desired effect. • Accurate mock-ups and models at all stages are necessary. • Due to the small size of the LEDs and their inherent directionality, their placement, angle and relationship with the refractive surface needs to be worked out in detail. • Even small changes in the placement of the LEDS could result in a very different lighting effect. 3. Undesirable effects are more easily achieved than desirable effects. • The light source must be effectively screened. • A balance between the intensity of the lighting effect and the potential to create discomfort glare needs to be managed.

Figure 4.5
Experiment A

Figure 4.6
Experiment B

Figure 4.7
Experiment C

Part 1.

The *Isis* installation Summary

Experimental process for the *Isis* installation Format of mediating surfaces

Preliminary experiments with formats for mediating surfaces were undertaken with small pieces of acrylic approximately 150mm square and a single LED to illuminate each square. The design in Figure 4.5 Experiment A had many small straight facets that dispersed the light effectively. This design also created the smooth surfaces needed for refracting light. The curved surfaces in Figure 4.6 Experiment B had a 'tooth' that did not refract light cleanly, while Figure 4.7 Experiment C refracted light cleanly but created 'spots' of light that were not appealing. Experiment A was considered the most successful.
In response to the size of the exhibition venue, the experimental approaches were developed into free-standing screens. These allowed modules of LEDs to be used in groups to obtain the greatest intensity of light.
An advisor from the Department of Physics at UTS, Jim Franklin, suggested that a thick acrylic (e.g., 12mm), when cut, would result in larger bright surfaces. He also suggested that the air gap between the surfaces should be no more than a third of the thickness of the sheet. This would ensure that at least some of the light would continue travelling to the other side of the cut and not be 'refracted out' (J. Franklin, 2009, pers. comm., 3 March).
Based on Jim Franklin's advice, it was decided that the cuts could be no more than 4mm and would work best with a consistent width. The screen edges would be diamond polished, particularly the lower edge, to create the cleanest

surface possible and thereby allow maximum light from the LED modules to flow into the screen.
Experiment A in Figure 4.5 demonstrated the need to develop a pattern with many small straight surfaces and a consistent cut. Additionally, any pattern that involved a 'crisscrossed' design would fail, as pieces of acrylic cut on all sides would detach from the surrounding material. This would result in an inconsistent refractive effect. Following some previous work with corals for another exhibition, I chose the sea fern shape (Figure 4. 8) as being effective in an exhibition context, with a high aesthetic appeal and able to meet the technical requirements above. I developed a final pattern adapted digitally from material on sea ferns sent to me by Dr Katherine Fabricius from the Australian Institute of Marine Science, a marine biologist and expert on these plants. Since their scientific names are *Zignisis* from the *Family Isididae*, I shortened the name to *Isis*.
A decision was made to overlap three 900mm x 500mm screens in a staggered arrangement, as in Figure 4.9. The width created made the installation more impressive and allowed the viewer to see all of the sea fern patterns at once. The decision to stagger the screens was also influenced by the 'layering' seen on traditional chandeliers where crystals behind other crystals enhance their effect. For refraction to produce enough light to function as a light fitting, the medium needs as many refractive surfaces as possible. While this could be achieved by cutting refractive surfaces into a single large panel, the alternative of using a number of smaller panels allowed for a grouping and overlapping of the refractive effects.

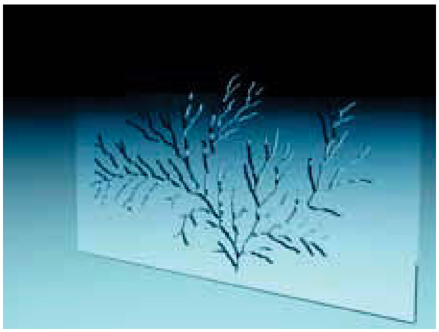


Figure 4.8
Visual of screen with *Isis* pattern

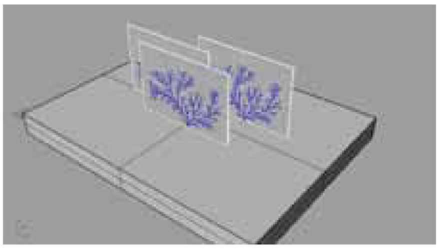


Figure 4.9
Image of 3D modelling of final installation

Figure 4.10
eW Cove MX Powercore
(Philips 2009, p.5)

Light source

The lighting company that assisted me in the process of selecting lights, Xenian Light, suggested the Philips Color Kinetics eCove product, a linear module of LEDs that could be plugged together easily to form a long light source and

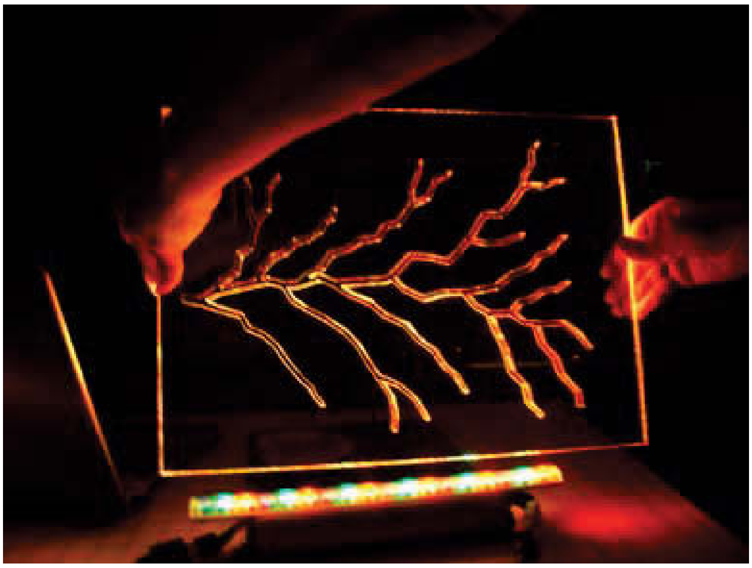


Figure 4.11
Laser cut acrylic with eW Cove MX
Powercore Red

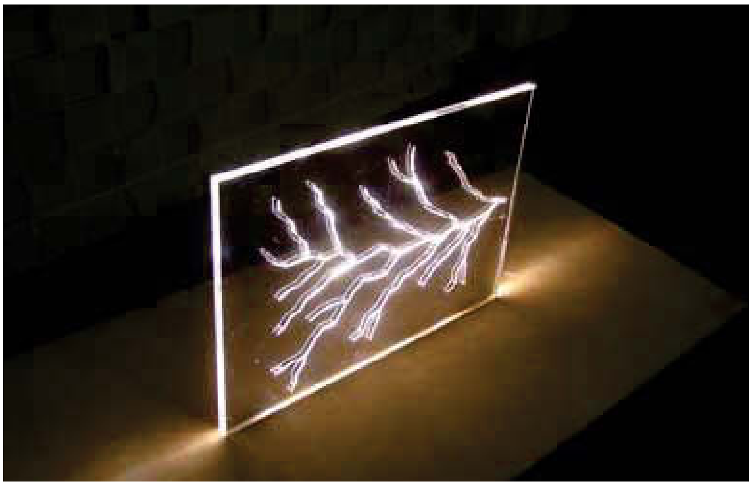


Figure 4.12
Experimental mock-up

be placed under the acrylic screens, so that light would shine up through the material.
It was possible to use a coloured linear module (Figure 4.11); however, the use of colour would reduce the light intensity. For this experiment I needed as much light as possible; thus it was decided to use cool white for this context. White would also provide a better contrast to the dark interior of the exhibition and was closer to the original idea of lead crystal chandeliers.

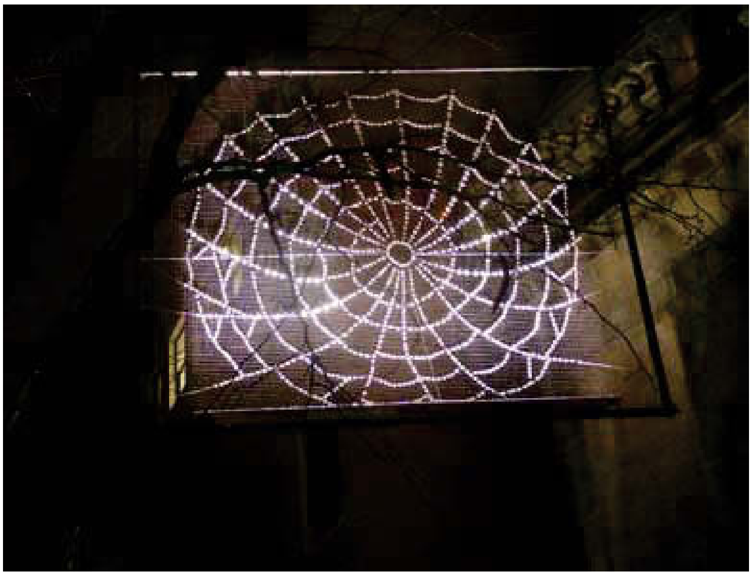
Figure 4. 13
View of mock-up with eW Cove MX Powercore module

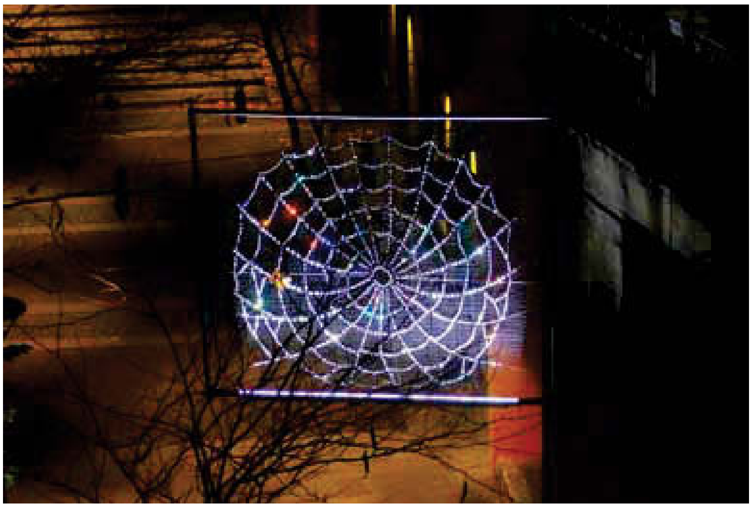
Creation of effects

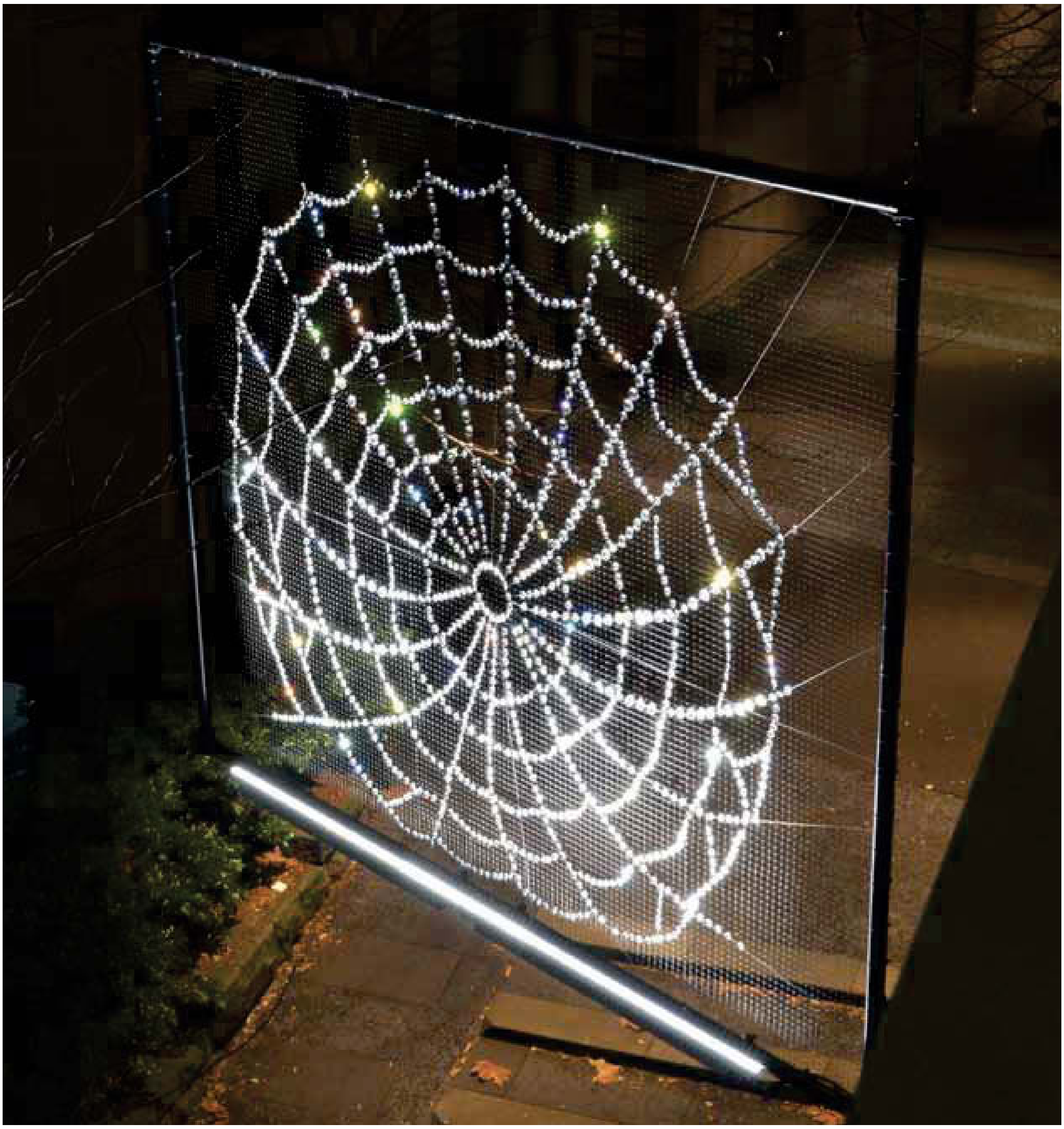
There was a need to find an optimum mounting height of light below the surface of the plinth to get maximum light output while limiting glare. A small experimental rig was made with a sample of 12mm acrylic (400mm x 300mm) laser cut with the Isis pattern and illuminated by the white eW Cove modules (Figure 4.12)
The rig was viewed from a variety of distances and angles. From this mock-up it was found that the modules needed to be about 30mm below the surface to avoid glare. It was also observed that the light could be ‘refracted out’ and lose intensity before reaching the top of the screen. A ‘long and low’ format for the screens was therefore developed, to create many refractive surfaces while still keeping the material near the light source.
In the final installation, the LED modules were mounted directly below each screen (on a shelf under the plinth) so that they shone directly up through the acrylic. The modules needed to be mounted within the plinth to prevent exposure to glare but sufficiently close to the surface to ensure maximum light output (Figure 4.14). Again on the recommendation of Jim Franklin, all internal surfaces were white to maximise all light.

Figure 4. 14
Plinth upside down showing ‘shelves’ for mounting LEDs

Part 2. *Web of Light*







Figures 4.15–4.18
Web of Light
(McDermott & Baxter 2009).

Web of Light	Mediation of light	LEDs
	Mediation technique Refraction at the interface of lead crystal glass and air **Medium** Transparent sheet acrylic 12m thick with polished edges **Surface for generating lighting effects** Cut surfaces of the glass **Technique for modifying medium or surface** Cutting lead crystal glass into individual 'beads' using lapidary techniques **Configuration of mediating surfaces** Crystal beads suspended in planar web mounted within a 2.5m x 3m frame	**Lumen output:** 2600 lumen **Mediating lens:** Narrow light spread 18 degrees. **Colour temperature:** 4000K **Configuration:** linear array **Spacing of LEDs:** 25mm centres

Table 4.2 *Web of Light* summary

Management of LED	Effects	What was learned
Mounting: supplied within eW_ Graze housing module Housing: standard eW_Graze module by Philips Thermal management: ribbed surface of eGraze housing module Cabling: supplied within eW_ Graze housing module Location of driver: external mounted near power outlet Data enabler: not used as white only.	• Light refracting from multiple faceted surfaces of the bead crystals created sparkling effect without discomfort glare. • The bead crystals glowed intensely. • The lens enabled distribution of intense light across approx. 600mm spread of beads, with a wider angle of light spill illuminating the remainder of the 2,000mm expanse of beads with diminishing intensity with distance from the direct flow of lumens from the LED. • Adjacent surfaces and some details on the support structure such as the upper frame and a cross piece were highlighted. This was an unintended effect.	1. The LEDs illuminated the crystals very effectively and created an intense lighting effect · LEDs show a strength in their ability to illuminate other things – be it surfaces or objects. · There was a downside in that LEDs can also be effective in illuminating objects that you don’t want to be highlighted. LEDs have a long thin shape to their illumination. Light spill can be created easily. 2. The need for accurate placement of LEDs in terms and angling of the light itself was even more important when mediating medium is in large format. • For larger formats, technical drawings, accurate models and mock-ups necessary. • Need to work full size not at a smaller scale with mock-ups. 3. Understanding the format of the technology itself · There is a need to build up knowledge on the different aspects of LED technology and how it is encapsulated into products. · Need to understand and manage the variables such as lens format and colour temperature. • Need to manage the placement of external components such as LED driver.

Figure 4.19
Making the *Web of Light*

Figure 4.20
Web of Light in frame

Figure 4.21
Mock-up of *Web* detail interior

Figure 4.22
Mock-up of *Web* detail exterior

Experimental process for *Web of Light*

Format of the mediating surfaces

To create the greatest visual impact and to generate as much refractive light as possible, the *Web of Light* needed to be as large as logistics and the budget would permit.
It was therefore decided that it would be 2.5 metres by 3 metres and be mounted in a frame for support. This frame would in turn be suspended high above the ground at the site that had been allocated to us by the organisers of *Vivid Sydney*. This height would allow viewers to get the best viewing angle. This decision was made by myself and my collaborator, Ben Baxter, in conjunction with engineers, riggers and the final makers of the *Web*.

Web of Light light source

Experience with the *Isis* installation had revealed the need to consider very carefully the relationship between the LEDs and the mediating materials. A series of experiments were undertaken to uncover the best approach to illuminating the *Web of Light*.
A mock-up was made of a web section, which was suspended above LED modules (they were the modules from the *Isis* experiments). The modules were placed in a box lined with foil to reflect as much light as possible onto the web while masking distracting glare (Figure 4.20). The mock-up was a full-size detail from the final drawing and used the same size crystals as would be used in the final installation. We experimented having the light source placed above the mock-up but it was found that the lighting from below gave the best effect. These experiments made us aware that the light spill needed to be contained, i.e., that excess light needed to be prevented from shining on the surrounding surfaces.
To gain a more accurate idea of the final, the experimental mock-up was placed outside (Figure 4.22). The exterior

experiments gave a more accurate sense of the lighting effect that would be created. However, the need for a more accurate set-up to work out the best LED module for this application and the optimum distance of the module from the mock-up became apparent.

A series of experiments were undertaken on the premises of our lighting sponsor, Xenian Lighting. The overall height of the crystal pattern was intended to be around 2 metres. Using a linear Philips eGraze LED array as the light source, and a strip of card to hide the glare it emitted, we tested the mock-up first mounted immediately above the light source (Figure 4.23), and then two metres above the light source (Figure 4.23 and 4.24). While we could have used RGB (coloured) LEDS, we chose to stay with white, because it had a higher lumen output and was more in keeping with the spider web concept.

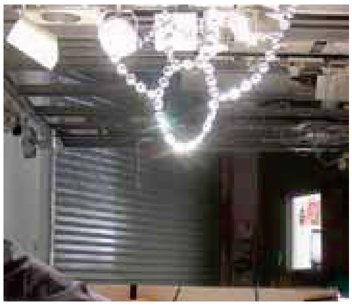


Figure 4.23
Mock-up on adjustable rig

Figure 4.24
Mock-up on rig raised

Creation of lighting effects

Xenian Lighting suggested an important variation from these first experiments, namely, that the light source be mounted out from the array and angled up to 'skim' the crystals rather than light them from below. With this experimentation we worked out that the module needed to be mounted 100mm out from the bottom of the web, facing upwards and angled at about 5 to 10 degrees. This was a shift from the approach used in the *Isis* installation, where, the light source was directly below the screens.

Figure 4.25
eW Graze Powercore
(Philips 2011, p.6)

During the installation of the Web, with the riggers on the scaffolding, we were able to turn the light on to adjust the LED array. In this way we were able to ensure that the strongest light was slightly less than halfway up the web. The riggers had already installed the LED module at the correct distance from the frame; the main issue was making sure the angle was correct. We had been concerned as to how these modules would impact on the final appearance however it worked well. The slim line of the LED modules were visually integrated into the frame around the Web.

Figure 4.26
Installing the *Web of Light*

Part 3. Taking practice forward

Isis installation

Although both sets of these practice-led experiments had a focus on ‘getting to know the technology’, rather than on developing specific applications, there were some interesting possibilities for the future raised by *Isis*.

The following comments are based on feedback on the *Isis* installation from interior designers Rachel Luchetti, Bettina Easton and Mike Day, who was the curator of the exhibition (M. Day 2009, pers. comm., 10 July; B. Easton 2009, pers. comm., 8 July; R. Luchetti 2009, pers. comm., 21 July). Their feedback included a number of suggestions as to how this approach could be used to create to create new lighting typologies to provide interior illumination. The following incorporates their suggestions and my own ideas into a list of future applications for an *Isis* -style screen:

1. Refractive screens could form light emitting dividing screens and wall treatments. These screens could be available in standard sizes, as are existing translucent glass walls. The addition of some translucent treatment (sandblasting or frosting) could add to the sense of privacy without claustrophobia. Customisation, or at least a range of patterns, could be offered to add to the interior design interest. The combination of pattern and light emitted from an *Isis*-style screen could work together to provide some degree of privacy or separation without creating a sense of claustrophobia.

2. The screens could also be suspended ‘blades’, which could be placed together to form a light fitting or ceiling treatment.

3. *Isis* screens could also be laid flat across a space to

form an illuminated ceiling surface while still giving a sense of height.

Design approaches which could create brighter lighting effects with *Isis* were suggested by my optics advisor from the UTS Department of Physics, Jim Franklin (J .Franklin 2009, pers. comm., 5 July).

1. The Isis pattern itself could be changed. The existing *Isis* pattern reflects light to the side. A different *Isis* pattern using two sea ferns where the 'branches' faced each other would direct light towards each other and create a brighter and more luminous effect.

2. Other patterns could be used to enhance lighting effects.

3. Foil or reflective material could be placed around the edges to reflect light back into the screen rather than allowing it to escape.

4. The refractive effect could be enhanced by layering screens together.

Looking backwards to go forwards

Historically the building fabric played an important role in managing the balance between admission of daylight and provision of thermal mass to protect occupants from extremes of temperature. These roles played by the building fabric gradually became less crucial as industrial technologies introduced more powerful sources of heat and light into the home. However, the introduction of gas and electric lighting and central heating, resulted in greater energy consumption (Burns, 1982 p. 2). Since the late 20th century, a desire to reduce energy consumption has renewed interest in the performance of the building fabric With the renewed interest in energy conservation, older techniques used in building construction may have a role.

Figure 4.27
Example of transom windows and side lights in an historic building (Stacey 1968, p.27)

Figure 4.28
Contemporary example of borrowed light
(Tilse 2016, p.24)

In relation to this study, traditional building features such as transom windows, fan lights, side lights and borrowed windows could work in tandem with LED technology to provide illumination day and night. Traditionally, these specialist windows were placed around an exterior door to allow illumination into a dark entry area. Examples of this building feature can be seen in Georgian architecture, where such windows formed a distinctive architectural feature in their own right as well as drawing attention to the door itself (Figure 4.27).

Internal windows were often incorporated to allow illumination to flow through into other interiors. Called 'borrowed windows' (because they borrowed light), they were often used to illuminate interior hallways that had no other light source. If these building features – particularly internal borrowed lights – could be used with LED technology in an *Isis*-type screen, then illumination could be provided both night and day. Sensors could be used to monitor light levels and turn on the LEDs when needed. Further integration of the *Isis* concept into the building fabric could be achieved by using refractive screens to form a 'splash-back' in a kitchen, allowing light for some simple tasks, such as unloading the dishwasher, or creating room-wide softer illumination. In this scenario, if higher levels of illumination are required for a specific task, such as cutting food, it could be provided by a specific task light which could be angled off the wall. Kitchens are frequently poorly served by the general illumination approach, where the work is often done in the shadow of a centrally mounted fixture or ceiling downlights. The 'splashback' idea could be taken into bathrooms with dividing screens and sink surrounds.

Certain types of public area in homes, such as vestibules, living and dining rooms, could also use these types of screens, for example to divide living and dining areas while still allowing a flow of daylight and creating illumination at night. The incorporation of control and sensor technology into refractive screens would allow a connection to a wider control system. If higher light intensity is required, it could be created by layering several *Isis*-like screens or by the use of a reflective surface (looking at historic precedent). Using *Isis* screens could also provide the interior designer with both a decorative and functional element.

Web of Light - taking the practice forward

Lead crystal is a relatively old optical material which carries with it connotations of ceremony, splendour and romance. Despite what would seem an unusual combination of the old and new, the LED experiments with this material did point to some interesting possibilities. LEDs can highlight individual crystals so that each one looks like a glowing light source on its own; it was noted, however, that this would need to be done with great accuracy. Light fittings could also be created, although they would have some limitations in terms of the position of the material in relation to the LED light source. Additionally, the power of refraction to ‘bend’ light could be used to control the direction of the light emanating from LEDs. It is theoretically possible to create a specifically shaped crystal that could direct light back to the viewer or in any direction desired.

Part 4.

What was learned from *Isis* and *Web of Light*

Lighting effects

There was an interesting difference in the effect created by the two installations. With the *Isis,* an intense line of light was created along the refracting surface of the pattern of the design (the Isis sea fern) distributing the light over a large area, which offers possibilities for entire walls or

Figure 4.29
GIO LED downlight with heatsink
(ACDC 2009, p.10)

ceilings.The crystals in the *Web of Light* ‘gathered’ the LED light. Each became an intensely glowing, sparkling orb. The refractive ‘rainbow’ effect, a characteristic of lead crystal (see Appendix 2) was evident particularly when the *Web of Light* was viewed from above. It was difficult to judge how much illumination of the environment the *Web of Light* provided in this exterior placement. However, the lighting on the adjacent surface did indicate that the bright crystals offered some degree of illumination.

In both these practice-led experiments, LEDs demonstrated a real strength in their ability to illuminate objects, surfaces and materials.

In Chapter 1, glare was identified as an important issue to be controlled when using LEDs. It is a challenge to place LEDs so that the glare they produce is minimised but the light output is fully exploited. The question posed by the practice was how to design the lighting effect so that the light source itself cannot be seen.

In terms of light fittings, downward-pointing LEDs are the most easily masked. From a distance, the viewer cannot see the light source itself and would be aware of it only when standing directly underneath it looking up; this happens only infrequently.

This has been noted by manufacturers such as lighting company ACDC. Their technical literature about the Gio LED downlight (Figure 4.29) states that the LED light source is recessed deep within the luminaire in order to minimise glare. Note the large heatsink for thermal management on the Gio LED downlight.

Upward-facing LEDs can be used at ground level; however, since people are more likely to look down than up, the issue of masking the light source can be difficult and may reduce the effectiveness of the light from the LED.

In the *Isis*, the light source was placed 30mm below the surface of the plinth and a viewer would have needed to be almost directly above the screens to see it. In the case of the *Web of Light,* the light source was suspended high above the viewer and angled towards the suspended crystals, and no glare was visible (Figure 4.30).

LED is an unforgiving technology to work with; small inaccuracies in placement and surface treatment result in failure to achieve the desired effect. Unlike omni-directional light sources where the light flows out more generally from the source, LEDs can illuminate only specific areas. The challenge with LEDs is that it is easier to achieve undesirable effects than desirable effects. Strategies around LED placement and angle to minimise glare and create the desired effect must be considered in the development process of any application of LED technology. Even small changes in the placement of the LEDS could result in a very different lighting effect from that desired or even in no lighting effect at all.

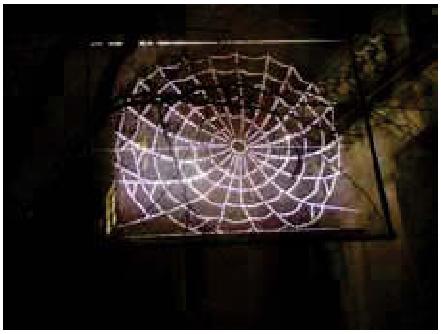


Figure 4.30
Web of Light illuminating adjacent surfaces

Figure 4.31
Isis installation in exhibition context with light spill on ceiling

Awareness of light spill

A downside of the power that LEDs have to illuminate items is the possibility that objects that should not be highlighted will be inadvertently illuminated. As high-intensity LEDs have a long, slim throw, there is a need to consider light spill. This was most evident with the *Web of Light* when, in the early experimental mock-ups in an interior, the walls and ceiling were so illuminated that they detracted from the visual impact of the refractive piece, as seen in Figure 4.21.

With the final *Web of Light*, there was still light spill on the adjacent wall, even with the narrow beam. In context, this was acceptable, as the dark colours and textures of the surrounds added to the effect and gave the *Web* a sense of scale.

However, if this method of illuminating crystals was to be used in an interior situation, light spill would be an important design concern. Light spill was noticeable with the *Isis* as it illuminated the ceiling above the installation. Although an unintended by-product, it was not an issue in this context. However, in other contexts, unintended illumination of ceilings, floors and walls may detract from the overall design effect. To compensate for this, the light sources would either need to point down (so the ground may be lit, which could be advantageous) or any light spill on the ceiling or walls would need to be part of the overall design intention.

The nature of LED light

The crisp light of LEDs can be rather unforgiving in the way it highlights every detail; this can sometimes work well but sometimes be a drawback. As seen in Figure 4.30, the crisp, hard light of the LED highlighted the cross bar at the top of the *Web of Light* and the horizontal support wire. This highlighting cannot be avoided when using LEDs and the designer needs to develop form and detailing to compensate for it. The directional and tightly focused nature of this LED array was advantageous in that the *Web of Light* crystals and the *Isis* screens were highlighted accurately.

Limitations of form

Both the practice-led experiments reported in this chapter ended up having a 'screen' typology. While this was quite acceptable in these contexts, it was interesting how tightly the forms needed to match the shape array of LEDs. This was particularly the case with the *Web of Light* where there was a need to create a certain angle between the crystals and the LED modules so that the array was 'skimmed' by the light. While variations on the form of the *Web* could be achieved by investigating cylindrical or square options using modules of LEDs, they would still be variations on a screen. A traditional form (such as a chandelier) would be difficult to use with LED modules and new forms of light fitting that exactly match the characteristics of LEDs need to be developed. The *Isis* and *Web of Light* were designed around the capabilities of LEDs and, conversely, would not have been as effective with any other light source.

Knowledge of LEDs

In the case of both the *Isis* and the *Web of Light*, the input of experts was necessary to source the best option from the large array of LED products that would be appropriate for this application.

In the case of *Isis*, the Philips eW Cove was recommended. This light source was easily mounted and was 'plug and go', which was very convenient for a temporary exhibition. However, if the idea was to be developed further into a permanent installation or product, a different type of LED module with lower cost and possibly more lighting output could be used.

With the *Web of Light,* we were concerned that the light fitting at the lower edge of the frame would look oversized and detract from the appearance of the installation. However, the eGraze light fitting itself was very slim in relation to the size of the installation and had no impact on the overall aesthetic. The compactness (even with the accompanying thermal management issues) of LEDs is a distinct advantage for certain applications.

LEDs are powered by electricity through what are known in the industry as 'drivers'. These devices will convert AC voltage to low-voltage DC according to the LED requirements. LED drivers are not merely transformers (as used with other low voltage lights such as tungsten halogen). They need to regulate the flow of current through the LED (DiLouie, 2004). They are a specialist item and need to be tailored to the particular LED. When working with LEDs, designers need to consider how the driver is incorporated in the application.

In both practice-led experiments, the light sources were more than satisfactory but there was a reliance on the advice of the supplier/manufacture of the LED units for the most appropriate model.

Figure 4.32
MR-16 halogen downlight
(Illuminating Engineering Society 2015)

Figure 4.33
T8 fluorescent tube
(Osram 2017)

Figure 4.34
60W incandescent lamp
(Philips 2017)

The LED industry is still young and product ranges are still developing. Because of the modular nature of LEDs, they can be put together in a large range of combinations such that the product ranges can appear confusingly extensive. This developing industry also has many manufacturers from different countries producing LEDs of varying quality. As yet, LEDs have not yet developed into 'standard' light fittings such as the MR 16 halogen downlight (Figure 4.32) , the T8 fluorescent tube (Figure 4.33) or the 60W incandescent lamp (Figure 4.34), all of which are well understood, easily procured and have been commonly used up to this point.

When using LEDs, designers need to understand the challenges and opportunities of this new light source. There is a real necessity for designers to increase their own understanding of this light source by engaging with suppliers and technical support to source the most appropriate LEDs.

Methodology

The process involved in both practices highlighted the need for very accurate mock-ups when using LEDs, even from the very first experiments. Time and resources need to be invested in coming to an understanding of *how* the light source would react with the material, which may be outside existing expectations. With LEDs there is a need for greater accuracy - they are a tiny light source so any change in heights or angles can alter the overall effect quite markedly. Working out the most effective and accurate placement of LEDs in relation to the refracting medium was very important. With the *Isis*, this involved construction of a small version of the final plinth with the correct LED module and an example of the laser cutting to the correct scale fairly early in the process. Similarly, a correctly scaled sample of the *Web* was necessary for our own testing and then for more formalised testing with the industry experts.

This was in contrast to previous light installations I have designed, where initial mock-ups could be of a more informal nature.

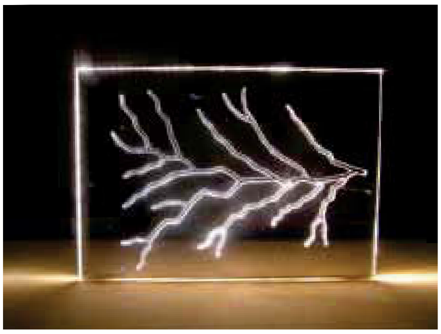


Figure 4.35
Mock-up of *Isis* detail

Summary

The aim of this set of practice-led experiments around refraction was to familiarise myself with LED technology. While some of the findings discussed related specifically to refraction and pointed to some interesting directions for these artefacts, there were also important items of information to take forward to the next practice:

- LEDs do not give the design freedom associated with omnidirectional light sources; they impose limitations on the final form.
- There is a need to consider the relationship between mediating material and LEDs to obtain the maximum lighting output while addressing issues around glare and directionality.
- There is a need to understand the inherent characteristics of the light source. For example, directionality and 'crispness' can highlight all details and can be unforgiving.
- Design methodology needs to include accurate mock-ups at all stages, a good knowledge of both intrinsic LED characteristic and the various supplier options to obtain the most suitable light sources.
- The materials used with LEDs should give a sense of warmth, quality and personality, bearing in mind that LED light can cheapen the look of some materials.
- Some variation in the light level can be an advantage.
- The long, thin 'throw' of LED light can create unwanted 'light spill' on adjacent surfaces.
- Working with LEDs often involves creating lighting effects while hiding the light source itself.

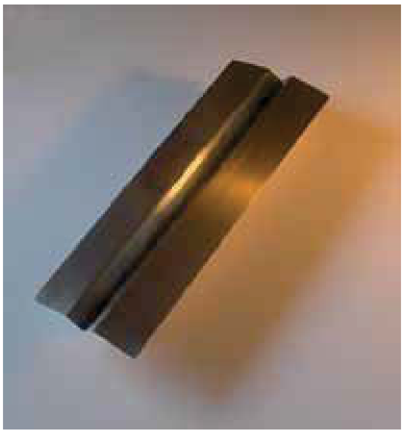
CHAPTER 5. Bringing technology and context together

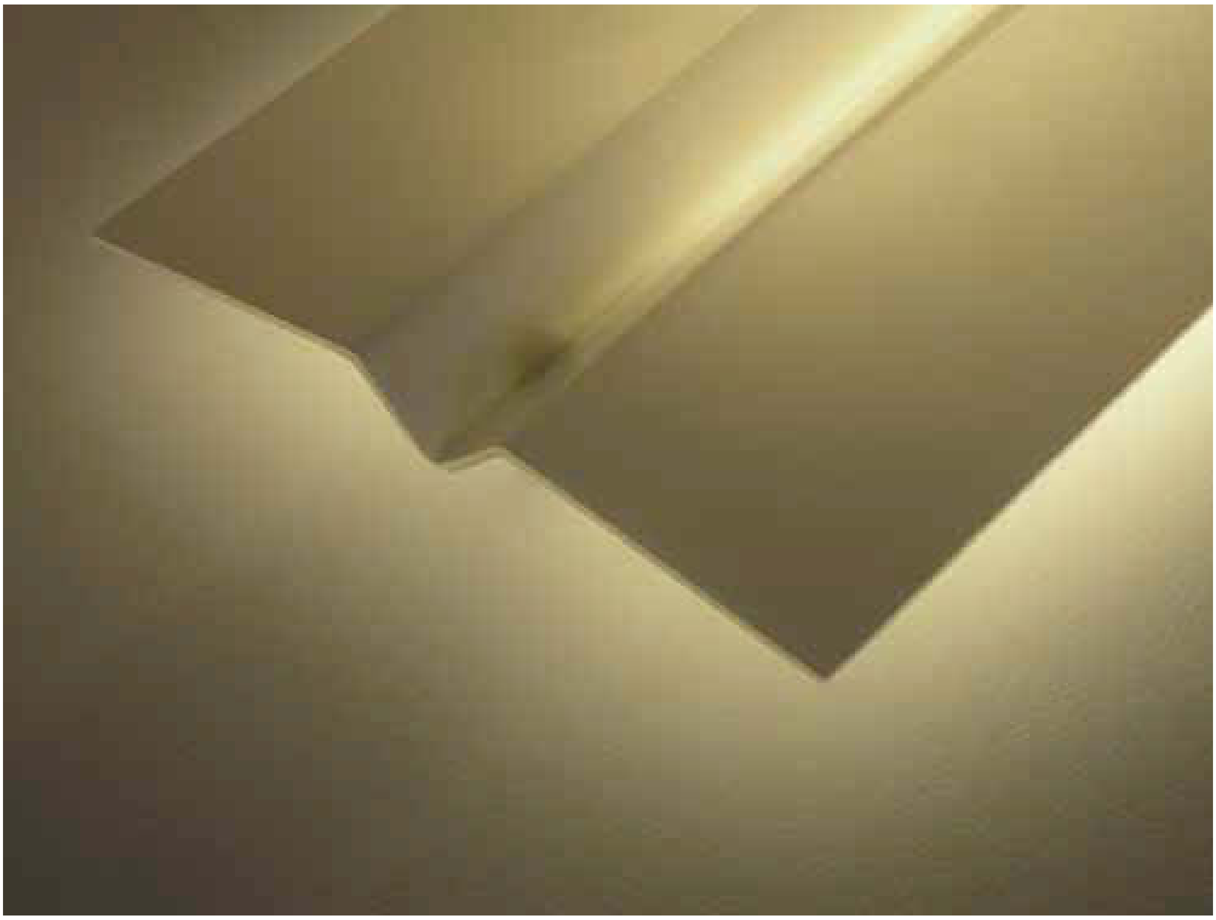
Figure 5.1
Diffusion Lightlouvre
(McDermott 2011)

Figure 5.2
Diffusion Lightlouvre
(McDermott 2011)

Figure 5.3
Reflection Lightlouvre
(McDermott 2011)

Figure 5.4
Reflection Lightlouvre
(McDermott 2011)





Lightlouvre reflection

Mediation of light	LEDS
Mediation technique: Reflection with some obstruction **Medium:** 2mm stainless steel sheet - brushed finish on one side, mirror on the other **Surface for generating lighting effects:** Surface under the louvre **Technique for modifying medium or surface:** Mirror finish **Configuration of mediating surfaces:** Folded into louvre shape	**Name:** Nichia ribbon **Lumen output:** Not known **Mediating lens:** None **Colour temperature:** 3200k **Configuration:** LED chips in a line **Spacing of LEDs:** 10mm

Table 5.1 *Reflection Lightlouvre summary*

Management of LED	Effects	What was learned
Mounting: Mounted on aluminium strip then placed into support board. LEDs visibile through cutout **Housing:** No extra housing **Thermal management:** Aluminium strip **Cabling:** internally mounted within support board **Data enabler:** not used	The overall lighting effect was long and slim with different intensities of light in bands. There was a defined edge to the reflected light which was not hard. There was some residual light outside the defined band. There was no sensation of discomfort glare from the light sources.	1. Reflection as an optical principle can give a great deal of volume to LEDs. 2. The creation of this volume needs to be balanced with how the lighting effect is perceived and whether it is suitable for interior applications where the viewer is in close proximity to the effect. 3. As in the diffusion version, the pattern of reflection was quite altered by a small change in the reflecting surface, requiring the designer to pay close attention to the different surface characteristics. 4. Any faults in the reflecting surface will be amplified in the final lighting effect.

Lightlouvre diffusion	Mediation of light	LEDS
	Mediation technique: Diffusion with some reflection	**Name:** Nichia ribbon
	Medium: Clear 2mm acrylic sheet	**Lumen output:** Not known
	Surface for generating lighting effects: Matte texture on lower surface	**Mediating lens:** None
	Technique for modifying medium or surface: Upper surface painted white to create a translucent material rather than transparent material	**Colour temperature:** 3200k
	Configuration of mediating surfaces: Folded into louvre shape	**Configuration:** LED chips in a line
		Spacing of LEDs: 10mm

Table 5.2 *Diffusion Lightlouvre summary*

Management of LED	Effects	What was learned
Mounting: Mounted on aluminium strip then placed into support board. LEDs visibile through cutout **Housing:** No extra housing **Thermal management:** Aluminium strip **Cabling:** internally mounted within support board **Data enabler:** not used	The overall lighting effect was soft and diffuse. There were three levels of light – the halo effect around the edge, the strong strip of light in the centre and the intermediate light along the surface of the louvre. The halo effect reflected across the support surface with a graduations from light to shadow. There was no sensation of discomfort glare.	1. LEDs offer the possibility of 'designing the light source' with their greater flexibility and their small size. They can be reformatted into non-standard formats to work with different light mediating forms. 2. Creating non-standard LED light sources requires a high degree of knowledge and demands new types of understandings which are not based on previous experience. 3. Unlike incandescent light, there is no intrinsic beauty in the light from LEDs. The designer needs to 'help' the LEDs – understanding their strengths and weaknesses. 4. Materials need to give the light source a feeling of quality. 5. Even fairly subtle changes can result in a different effect.

CHAPTER 5. Bringing technology and context together

For LEDs to create a significant amount of energy saving, they need to operate effectively in *all* sectors, including the residential area. However, lighting within a residential context presents challenges that are different to those in areas where LEDs have been successful, such as light art. The practice-led experiments discussed in this chapter took LEDs into a specific context of the domestic environment with the aim of gaining an understanding of how they could create lighting conditions suitable for this sector. It was hoped that these insights could also apply to other sectors of interior lighting. The work discussed in this chapter was undertaken by myself and funded by my own resources. In this set of practice-led experiments, the 'frames for practice' were the principles of reflection and diffusion – two principles which already have a presence in domestic environments.

Part 1 of this chapter discusses the expectations of illuminated domestic environments that developed over the 20th century. A discussion is included as to how these expectations can be challenged by other cultural traditions and lighting research. Part 2 reports on the two sets of practice-led experiments developed specifically for a domestic setting. Part 3 discusses the development of an evaluation process for the practice-led experiments which combine procedures found in conventional light quality research with approaches from the computer-human interface (CHI) area. The process developed to evaluate the experience of lay people, who interacted with the experimental light fittings, was the subject of a paper I wrote for the 2011 International Association of Societies of Design Research Conference in Delft (McDermott, 2011). Feedback from design professionals and others from the lighting industry was gathered through a separate evaluation process. Part 4 reports the results from these two evaluation processes. Part 5 discusses ways that the practice-led experiment could be developed into possible finished artefacts using LED technology. Part 6 discusses what was learned about working with LEDs through the frames of reflection and diffusion, in the course of this set of practice-led experiments.

Part 1. Challenging assumptions around domestic lighting

Actor-network theory points to the role of attitudes in technological change. In an assemblage of actors, there is always a question as to 'which meanings, attitudes and positions do the various actors have?' (Fallan, 2010 p. 69). Throughout the 19th century, artificial lighting (gas and kerosene lamps) was mediated by decorated glass light fittings. The experience of light that had been mediated in this way was taken for granted as how it should be. The

soft diffuse light created by a glass lampshade became the cultural norm for the delivery of artificial light. Other options were considered uncomfortable, unacceptable or even vulgar (Dillon, 2002).
Rybczynski (1986) notes how the word ‘comfort’ evolved from ideas of intimacy, privacy, leisure and ease in the 17th and 18th centuries to an emphasis on convenience and efficiency in the 20th century. These latter values informed the efforts of the early Modernists to improve living conditions through designs for homes with clean open spaces, communal living, sunlight and access to exercise for their inhabitants. Le Corbusier shared Walter Gropius‘s belief that this approach to housing would enhance the social and spiritual life of the inhabitants (Poppelreuter, 2011). In all of this there was an ongoing influence from Adolf Loos, who promoted free, unobstructed spaces to enlighten and liberate the modern person’s spirit (Loos, 1913). In the 20th century, the preference was for spaces flooded with bright, homogeneous light. This illuminated environment was connected with ideas of cleanliness, efficiency and freedom. Cultural norms that shape environmental experience exercise a great deal of ongoing influence, since how we interpret visual experience is affected by what we have already seen. Julian (2011) notes that the visual cortex of the brain operates efficiently when, rather than ‘seeing’, it ‘recognises’ pictures from a database of images stored in the brain. Effort is required to decode unfamiliar images into a new ‘picture’. When LEDs arrived as a new light source, they had to survive and prosper in a lighting landscape created by older technologies. They did not fit into the ‘picture’ created by 20th century lighting. The question for the 21st century is whether the 20th century experience of lit environments continues to set the cultural norms for our expectations of illuminated interiors. The following sections discuss *alternative* approaches to lighting that challenge the 20th century assumptions of how interiors should be illuminated.

Interrogating general illumination – a different type of cultural conditioning.

Certain practices around lighting in the home form connections with an older, more spiritual interpretation of the word ‘comfort’. In our age of abundant light, candles are an anachronism and yet they continue to be used to illuminate an evening meal or to signify a celebration or commemoration. The Danes call candles the ‘living light’ and use them actively to create what they called *hygge* – an intimate atmosphere for socialising with friends in the home. To create conditions of *hygge*, the lighting needs to be subdued and non-uniform; the pools of light generated by candles create a series of intimate spaces for conversation (Bille and Sorensen, 2007). While the Danes prefer candles, they will also use individual GLS lamps whose colour temperature and throw of light most closely resemble candles. Bille (2012) notes how Danes, not content with the ability of more efficient technologies to create the necessary *hygge* atmosphere, hoarded GLS lamps when they were banned. The *hygge* atmosphere is everything that the bright, homogenous light of Modernity is not – private, intimate and non-uniform.

The role of shadow

Junichiro Tanizaki, the widely-cited Japanese novelist, observed nearly 100 years ago that Westerners’ obsession with brighter lighting was part of an ongoing quest to remove even the minutest hint of darkness, noting that ‘light is not used for reading or writing or sewing but for dispelling shadows into the farthest corners’ (Tanizaki, 1932 p.17). He contrasted the Japanese approach, which is comfortable with ideas of mystery and concealment, with the Western approach, which demands that everything be exposed to the gaze of the viewer through the medium of a brightly lit interior. It could be said that the freedom gained by lighting designers may have come at the cost of atmosphere and mood.

'Impression of space' - influences from lighting research

The merits of the practice of hygge, and of Tanizaki's argument, are supported by the findings of influential lighting researchers. Professor John Flynn, from Pennsylvania State University, focused on how lighting influences a viewer's impression of a space. Flynn noted that lighting systems that flood interiors 'indiscriminately' (as with general illumination) can have advantages in space utility, flexibility and clarity. However, he argued that they can create a 'bland psychological effect' (Flynn et al, 1988 p.13). General illumination also feels public rather than private. Flynn found that higher levels of illumination were preferred in public spaces for clarity. However, in private areas, shadows and silhouettes, using a combination of uniform and non-uniform lighting as well as peripheral lighting reinforced with wall mounted lighting, were preferable (Flynn et al, 1988). Flynn's research found that light needed to be varied so that low-intensity light was in the locale of the user and higher intensity light was remote from the user (Flynn, 1977). In this lighting situation, the occupant of the space was deliberately not on display but somewhat hidden and private. There was a strong preference for peripheral rather than overhead lighting and brightness was not necessarily a decisive factor (Flynn, 1977). These findings were supported by the findings of Marsden (1972), who found that light from the side is preferred to that from directly above. Durak et al (2006) found other forms of lighting, such as wall washing, to be associated with impressions of clarity, spaciousness, pleasantness and order and to improve the visual quality of the space. The research also found that general illumination was preferred *only* when clarity was desired. General illumination is embedded within our expectations of lighting, but the work of John Flynn and other researchers point to a preference for other lighting experiences. The research suggests there could be more variation in the way spaces are illuminated and that lighting approaches could be adapted for each area. For example, long narrow corridors could be illuminated with peripheral light to create a sense of spaciousness. The use of *non-uniform* lighting to create intimate groupings in lounge or social areas could also be used, rather than a general illumination approach. This research points to the need for more flexibility in lighting schemes to better reflect the variety of activities undertaken in residences. The inability of LEDs to fit into the existing expectations of interior lighting has been seen as a challenge. However, what if the opposite were true? Previous practice-led experiments in this study led to a conclusion that LEDs need to be treated as their own light source and design processes around them should not rely on existing approaches and practices. It is possible that LEDs could lead to new lighting approaches that offer better lighting conditions. My next practice-led experiments for this research developed a specific set of LED artefacts that not only offered technical advantages but also created a different lighting effect outside the paradigm of general illumination seen in most homes.

Part 2. Practice-led experiments

The aim of the next set of practice-led experiments was to create lighting artefacts that would present a different approach to illuminating a space. This set of practice-led experiments considered how a light fitting could enhance the look of a particular space, in this instance a corridor, and would take inspiration from the lighting research discussed in the previous section.

Figure 5.5
Light seen through louvres

Figure 5.6
An early visual of a louvre-type fitting

Form of artefact and form of lighting

> Soon, we will not design light fixture shapes but only light effects. (F. Murano 2009, pers.comm., 5 September)

The mediation and regulation of intense sunlight through adjustable louvres, either by shutters or blinds, became the inspiration for the form of the LED luminaire developed for the domestic sphere. It was observed how the blades of a louvre shutter or blind can become illuminated surfaces, directing reflected light into an interior.

The design idea was to take advantage of the attractive effects created by louvres by employing a strip of LEDs to replace sunlight as the light source. It was initially planned that the principle of reflection would connect the light source to an interior wall surface, give mood and atmosphere to the space and create an effect very different from that of the even, general illumination created by a GLS light source. A deliberately non-uniform lighting effect would be created across the wall, supporting the artefact with more intense light around the fitting to form a type of ‘halo’ and the light then becoming gradually less intense as it moved away from the fitting.

The experiments would take advantage of the compactness of LEDs to create a discrete fitting that would sit neatly against the wall in a domestic interior. The aim was not to create an expressive or fashionable light fitting but an artefact that would be timeless, have a feeling of quality and fit in with the architecture.

While the principle of reflection was used as a basis for the first experiments, as the experimental process unfolded, the principle of diffusion was combined with the principle of reflection by changing the materials of the artefact. For this reason, the experimental processes of both reflection and diffusion *Lightlouvres* (as I named them) are discussed together.

Format of the mediating surfaces

In early experimentation the simple curved profile of a venetian blind louvre was adopted as the mediating shape. The curve would mask to some degree the glare from the LEDs and create a more ‘sculptural’ appearance and therefore an attractive artefact. There was a focus on using reflection as the optical principle.

This approach using rotation, illustrated in Figure 5.6, meant that the viewer could be directly exposed to the LED from either the rotated modules or the brightly illuminated underside of the louvre.

Alternative forms were explored based on a fixed louvre. Using cardboard, wire and an existing LED module from the *Isis* installation, two mock-ups were made, as shown. Figure 5.7 shows a curved louvre and Figure 5.8 the ‘gull wing’ form. The ‘gull wing’ concept created a better spread of light and so was taken further.

To get more light reflected out the sides and onto the support surface, the next mock-up needed to have a more pronounced ‘V’ shape and a 90˚ angle between the two faces. This new mock-up had the same LED module and wiring and equipment as in the models shown in Figures 5.7 and 5.8 but created a crisper mediating shape than the original curved form, as demonstrated in Figures 5.9 and 5.10. It became clear that the gull-wing shape needed to be very steep near the LED light source but as flat as possible further away to allow light out.

This design direction needed to be balanced with the requirement to mask the LEDs themselves from direct exposure to the viewer. If the module of LEDs was flat and countersunk into the wall it would assist. The addition of an ‘upstand’ around the LEDs would also help with the masking and direct the light straight up. Note the strip of cardboard acting as a shield in Figure 5.9.

The concept of using the larger reflective surface of a domestic wall to give volume to the light from the LED module remained unchanged. The shape however was

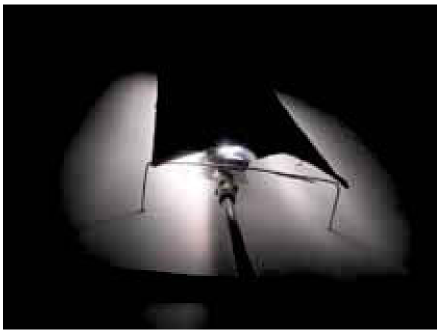


Figure 5.7
Curved louvre

Figure 5.8
Gull -wing louvre

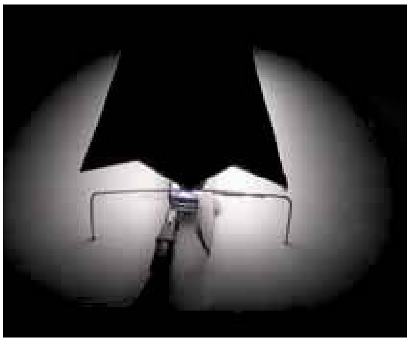


Figure 5.9
Front view of gull-wing development

Figure 5.10
Side view of gull-wing development

Figure 5. 11
Philips eW Cove modules
(Philips 2009)

Figure 5.12
Model A showing profile

changed from a single curved blade to a gull-wing profile for better light distribution.

Light sources

The second change from the early concept was the placement of the LEDs. The need to shield the onlooker from direct optical exposure to the LEDs was considered and development work continued around mounting the LEDs onto the wall surface with some sort of raised edge. In Figure 5.11, the module used in the *Isis* installation (eW Cove) is shown mounted in a support board.

Creation of effects

Following the earlier tests, a set of three more formally realised versions of the gull-wing approach were created using a range of acrylics, all mounted on a board with the LEDs in the board itself. Rare earth magnets attached to upstands at each end of the louvre mounted the louvre onto the board.

Model A was made from an acrylic sheet with a mirrored underside. The coating on the upper side was opaque and allowed no light through. Working on the principle of reflection only, this louvre not only distributed the light across the support surface but also created interesting patterns. However, the opaque coating, which was on view, was designed as a backing only and was not well finished. Consequently, this compromised the quality of the appearance of the artefact.

Another approach was taken in Model B, where clear acrylic was spray painted with white on the upper surface. This artefact reflected light out the side quite effectively and the actual louvre itself was diffusely illuminated. I considered the edge glow, which is clearly visible, to be attractive.

Model C was made with opalescent acrylic as used in light boxes. Although a diffuse lighting effect was also obtained with the louvre itself, the material did not look as attractive as Model B. This opalescent type of acrylic is used in shop fittings, light boxes and signage and had a visual connection to these sectors which did not work well in a light fitting.

The issue around the quality of materials became apparent quite quickly. Though the lighting effect from Model A was very interesting, the material was low quality. The opalescent acrylic of Model C was too reminiscent of light boxes and advertising signs. Model B was the most attractive of the materials. However, with both Model B and Model C, individual 'spots' of light were also visible, which looked 'cheap' and unattractive. Overall, the clear acrylic painted white on the upper side of Model B had a more neutral appearance and created the best spread of light of all the models. Painted acrylic was therefore taken forward into later models to introduce the principle of diffusion into this set of experiments.

Model A, which blocked all light, would be developed into a solid brushed stainless steel version to give this fitting a higher quality finish.

To create a more continuous light source, a non-standard tailored light source comprising a strip of closely-spaced LEDs was created (Figure 5.17). This light source consisted of ribbon-style Nichia LEDs mounted on an aluminium strip for thermal management, and attached to a board that simulated a flat wall surface. An escutcheon around the module prevented accidental exposure of naked LEDs to the eye. The smallness of the LEDs was important to the success of this light-louvre fitting. Using a different linear light source, such as a small fluorescent, would have necessitated mounting the louvre at a greater distance from the wall, destroying the elegant aesthetic that was sought.

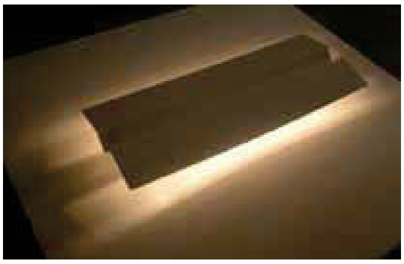


Figure 5.13
Model A whole artefact

Figure 5.14
Model A showing the mirrored underside

Figure 5.15
Model B painted acrylic

Figure 5.16
Model C An opalescent acrylic.

Figure 5.17
Custom-made LED light source

Figure 5.18
Reflection Lightlouvre with light on
(McDermott 2011)

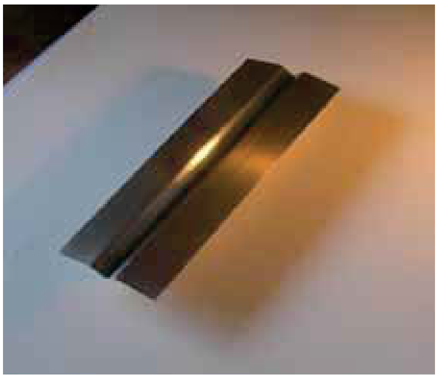


Figure 5.19
Reflection Lightlouvre with light off
(McDermott 2011)

Final artefacts

Lightlouvre using principle of reflection

The final model using the principle of reflection was made from 0.8mm stainless steel sheet. The surface towards the wall was highly polished with a brushed finish on the exterior. It was 400mm long and 145mm wide. Particular care was taken to ensure that the outer surface had a softer brushed finish that would make the stainless steel look acceptable in a variety of interior applications. This softer brushed finish in stainless steel is often associated with high quality interior fittings. This model had an acceptable appearance whether the light was on or off. Model 3B created interesting patterns on the wall but had a slightly harder, more industrial, look than was desirable for domestic situations. However, it could be appropriate for some commercial, hospitality and possibly some exterior applications. A softer looking metal, such as anodised aluminium, may have been a better choice. A matt surface on the underside would create diffuse reflection and distribute the light rather than concentrating it in an intense pattern.

Lightlouvre using principle of diffusion

The final model using the principle of diffusion was made from 2mm clear acrylic painted white on the top surface. The acrylic had a matt finish on the under surface to give a more diffuse reflective effect across the wall. It was 400mm long and 145mm wide.
The matt finish on the underside was created by using a special clear acrylic which had a matt finish on one side (usually used in picture framing to create a non-glare surface). The shinier finish on the top surface was painted white by a professional painter.

The continuous LED module gave a more consistent line of light with no hot spots. In terms of the form, the central folds of the fitting refracted the light from the LED module and therefore lessened any discomfort to the eyes from direct viewing of the light source. The thin line of light was aligned with the fold so that visually there was some continuity. The light source in format (single line) and placement (directly under a fold) worked well in the whole design, which was important as the light source was clearly visible.

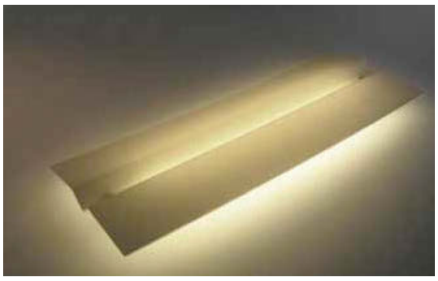


Figure 5.20
Diffusion Lightlouvre wth light on (McDermott 2011)

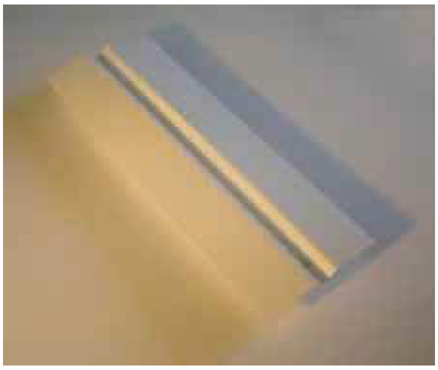


Figure 5.21
Diffusion Lightlouvre with light off (McDermott 2011)

Part 3.
Evaluating the practice-led experiments

Why evaluate this practice?

The focus of the research in this study moved from an exploration of the unique quality of LED light (in Chapter 4) to a more application-oriented approach with practice-led *Lightlouvre* experiments. The aim of the experiments, as discussed in this chapter, was to create light from LEDs with a particular context in mind, namely the domestic sphere, which is particularly sensitive to the quality of light.

The *Lightlouvre* practice came about after the refractive practice discussed in Chapter 4. In this earlier refractive practice, the artefacts themselves were on public display for a period of time. This display gave me the opportunity to personally evaluate the artefacts. In the case of the *Isis*, some useful if rather informal feedback from outsiders was able to be collected due to its exhibition context. The *Lightlouvre*s described in this chapter were neither suitable for nor intended to be displayed in an exhibition context. However, they did give me the opportunity to develop an evaluation process for domestic environments to address the following issues:

1. Were the artefacts suitable for a domestic application?

2. How could these artefacts be improved or taken forward?

The evaluation of light quality

There is an established body of literature around the evaluation of light quality that began in the first half of the 20th century, with the introduction of the fluorescent lamp. Fluorescent technology was the first artificial light source that did not use some form of incandescence and produced a higher intensity light than had been previously witnessed. This early research into light quality took an engineering approach (Guth, 1961) with an emphasis on glare control and measurement. In the 1970s, a more qualitative approach was taken by John Flynn and his colleagues around the psychology of light (Flynn et al., 1979). Flynn carried out one of the most important studies in the development of light quality evaluation. His research was undertaken in the 'laboratory' (Flynn's own description), a lighting demonstration room at the General Electric Lighting Institute, which could offer a number of different lighting set-ups (Flynn et al., 1973). In all these studies quantitative data on preferences or behaviour was produced.
Most existing research into light quality takes place in a controlled laboratory situation. Subjects are placed in a

variety of situations where they record their reactions/feedback into a matrix or questionnaire. Other studies have looked at preferences and behaviours of subjects when exposed to different lighting levels and lighting directions (Chiu and Chen, 2010, Taylor et al., 1974). Any qualitative material was limited to a pre-determined set of criteria and no open-ended questions were asked of the subjects.
The latest research looks at how lighting quality affects social behaviour, health, mood, task performance and aesthetic judgments. They are a development of the work of Flynn and they have an emphasis on comfort and productivity of people at work. This is exemplified by the work of Jennifer Veitch and Guy Newsham (Veitch & Newsham, 1996), who recently completed a large-scale study that involved more than 1700 subjects (Newsham et al., 2010). Some of the research was undertaken in a laboratory and some in newly-renovated offices that had three different but controlled types of environment. The emphasis in this research was the evaluation of productivity and worker satisfaction in relation to light quality. Although the research involved what could be considered a field study, the environment was as carefully controlled as that of a laboratory.

The importance of context

By situating my practice-led experiments in a specific environment, the domestic sphere, context became an important consideration. Studies that evaluate light quality in work situations take place during daylight hours whereas domestic lighting is most frequently used at night, when people's experience and expectations around light are different. On a physical level, our eyes will tolerate uncomfortable light during the day but are less tolerant at night, particularly in places of 'relaxation and social activity' (Hopkinson and Collins, 1970 p.70). Jennifer Veitch argues the need for knowledge of the context so

that the design can 'create luminous conditions which match what the occupants want and expect' (Veitch, 2006 p 212). David Canter notes 'the importance of context both the context within which the stimuli occur and the context provided by the particular interests or goals of the observer' (Canter, 1975 p.32) . While homes have areas for tasks (the kitchen, for example) they also need to be places of socialisation and relaxation. The variety of materials, textures and shapes within a home, which are not present in laboratories or offices, create specific challenges for lighting (McDermott, 2011). People have an emotional attachment to their homes in a way they do not have for their work areas. Any evaluation for this study needed responses that evoked *how* the subject felt about the light in their homes. With existing evaluation techniques there was little opportunity for open-ended responses to enrich the data. It was decided to develop an evaluation method that would create that opportunity to suit the requirements of this study.
In the following discussions, Section 1 discusses the methods established to evaluate *Lightlouvre* artefacts, including questions, subjects and process. Section 2 discusses the study itself. Section 3 discusses the findings from the study.

Section 1. Setting up the evaluation process

A. WHAT information was required?

An understanding of light quality in LED fittings begins with a definition of light quality factors. Drawing on the work of Veitch, Newsham and other researchers (Lam, 1977, Marsden, 1972, Rahm, 2009), the following four issues were established as key to the evaluation of light quality:

The light from the artefact is acceptable and provides comfort and satisfaction with no glare.

Glare, defined as brightness that can produce a feeling of discomfort (IES, 2009), has been identified as an issue in the use of LEDs (Reo, 2008). However, this needs to be balanced with an understanding that some sort of contrast makes schemes interesting and that the removal of glare can result in flat and mediocre lighting schemes (Marsden, 1972).

The light from the artefact creates the mood appropriate to the setting, such as a hallway, living room wall or other environment in which the light fitting is placed.

Domestic environments place great demands on light and there is an expectation that the light will contribute actively to the atmosphere of the dwelling (McDermott, 2011). This is described as a type of revelation where the lighting reveals the environment to its best advantage (Marsden, 1972). However, it is not enough for the space to look attractively illuminated; it is important that it also influences social interaction, fosters mood and atmosphere (IES, 2009) and that the mood, atmosphere and degree of social interaction are right for the context.

The light contributes to task performance and the level of light is correct for the task.

Each context in a household will have different tasks; some can be as simple as hanging a coat or as complex as cooking a meal. The right amount of visibility is required for the particular task at hand and it is important that the light allows people to gain just the right amount of information (Tregenza and Loe, 1998 p. 41); too little and the task is difficult, too much and the viewer feels fatigued and overwhelmed.

The light and light fitting complement the physical space in terms of the light created, the appearance of the fitting and their integration into the environment.

This is a more complex requirement. People select lighting on the basis that it meets all the requirements discussed above and that it complements their interior spaces. Marsden (1972, p. 139) argues that every space or building has a 'style, an ethos, a function which is communicated visually to the viewer' and notes that lighting is an important aspect of the communication. The notion that the light fitting and the light itself beautifies the space and architecture (IES, 2009) or at least complements and enhances the space, is important in the domestic sphere.

B. WHO would be the subjects?

Lay people

The experience of light is one of the key questions in my study and this could best be answered by actually living with the light in a specific context. One group of respondents would therefore be users or lay people. It was decided to use people with no professional involvement in lighting (i.e., they did not purchase, specify or design lighting as part of their professional activities). The feedback needed to reflect the common experience of lighting in the residential environment, so the evaluations took place in the subject's homes. A spread of ages in the subjects was important as research has found that the human eye becomes more sensitive to glare as people age (Hopkinson & Collins, 1970) and glare has been identified as an issue around LED lighting. The subjects selected ranged in age from early 20s to 60.

Subjects and their households were imagined in terms of archetypes, exemplified by the relatively uncluttered and controlled environments of younger single and coupled people with no children to the busier households with children.

Experts

A possible second group of subjects that presented some interesting options was the experts. These included professional lighting designers, interior designers and lighting consultants who evaluate and specify lighting artefacts as part of their professional practice. During the development process of all the practices, I had found the input of professionals or such experts to be invaluable in setting up this study. Preece et al. (2002) have noted that in the human-computer interface area, expert evaluation of new software usability has developed as a specific area of evaluation.

Sometimes users are not easily accessible or involving them is too expensive or takes too long. In such circumstances, experts or combinations of experts and users can provide feedback. Various inspection techniques began to be developed as an alternatives to usability testing. These included various kinds of expert evaluations and walkthroughs (Preece et al., 2002 p. 63).

The existing expertise and experience of professionals would be invaluable, particularly for examining the potential of these new practices in other formats, contexts or materials.

The subjects were located through professional networks, they were as follows:

	Household	Subjects and ages	Description of house
1	2 adults no children	1 x female, 1 x male 30s	Modern, minimalist and uncluttered
2	2 adults no children	2 x males both in 20s Work long hours	Softer environments More decorative aspects
3	2 adults, 3 schoolchildren	1 x female 40s 3 children involved in a variety of activities, such as music.	Older house with more simple, rustic finishes
4	2 adults, 2 university aged children	3 x male aged 60s, 20s, 18, and 1 x female 50s	Older terrace house itself full of interesting ornaments and heritage items.

Figure 5.22
Households/lay subjects for study.

Figure 5.23
Professional subjects for study.

Identifiers	Professional area
D, G	2 x interior designers in practice together for a number of years designing contemporary and traditional interiors.
M, S	Interior designer (M) and architect (S) who share an office but practice separately
K	Lighting sales consultant with a large international lighting brand with an emphasis on architectural and decorative lighting.
R	Interior designer specialising in hospitality design – has won several awards for restaurants etc.
B	Lighting designer with interior design background

Artefacts from the practice

With the understanding that the artefacts from the *Lightlouvre* practice would need to be taken to a variety of situations, the artefacts needed to be mounted on a board that would simulate a wall-mounted light. Each artefact was mounted over a strip of Nichia Flexi-ribbon LEDS 120 12Volts DC with a colour temperature of 3200 K, which is considered a neutral colour temperature. The artefact and LED array were mounted on a board approximately 600mm square with a power cord and were attached using upstands and rare earth magnets. The LED drivers were mounted internally so that they could be transported safely and easily.

C. HOW would the information be obtained?

Two separate evaluation processes were developed, one for lay people and the other for lighting or interior design professionals.

a. Field study of lighting by lay people

> The distinguishing feature of field studies is that they are done in natural settings with the aim of increasing understanding about what users do naturally and how technology impacts them. (Preece et al., 2002 p. 83)

An evaluation process was needed for this study that would take the context into consideration and would evoke the qualitative responses needed to help me understand how these artefacts could work in a domestic environment. Due to the lack of relevant precedents from the lighting world, I looked for studies in other fields relating to human-centred design. I found significant literature in the computer-human interface discipline on placing technological artefacts (new and existing) in domestic environments. The most relevant to my research was a paper by Sara Routarinne and Johan Redström, who introduce their study thus:

> What we think of a product at first sight and how we respond to it in use may be two different stories. In the design process there is a need to understand and predict how a first experience of a product may succeed in upcoming use, i.e. whether a product that seems amiable at first encounter will succeed in later use, or whether a product that makes an indifferent first appearance may redeem itself in actual use. (Routarinne and Redström, 2007 p. 2)

Routarinne and Redstrom's study focused on the 'domestication' of two experimental prototypes. They define domestication as 'an active construction of meaning in which the end users are engaged both mentally and in real time actions when they can make sense and use their material environment' (Routarainne & Redström, 2007 p.3)

Routarinne and Redström were guided by three questions:

- How will the users receive the prototype?
- Do they interpret them in accordance with the design intentions embedded in them?
- Will the prototypes find a slot in the material and social system of the house?

In their study they left the prototypes with various subjects for a period of time and documented their responses.

In terms of the practice aspects of their research, Routarinne and Redström's actions could be described as follows:

- Semi-structured interview to get subjects to describe themselves loosely in terms of household composition, education and interests.
- Placement of the prototype in a context in the house but also allowing the subjects some flexibility in where they placed the prototype – particularly after some use.
- Questionnaire and exit interview.

One of the aims of domestication, as defined by Routarinne and Redström, is to address the issue of the introduction of a new technology into an existing system. The domestication approach in this research would generate feedback on how this newer technology of LEDs would be received and used in a household with an existing lighting system involving other sources. The domestication approach would also offer a richer canvas of data than a laboratory-based experiment. While this study was undertaken from a design perspective and involved understanding how this new technology could address users' needs and desires (Hutchinson et al., 2003), there were other types of information that could be obtained from the domestication approach. According to Hutchinson et al., there is the social science goal of understanding the use of the technology in a real-world setting and a more engineering goal of testing the effectiveness of the technology itself.

Subjective responses to lighting

The key to my study was to obtain subjective responses to light quality and the experience of the light itself within a context. Most people do not examine their lighting conditions, as was noted by Stuart Lay in the discussion section of Canter's publication: 'Much lighting is below the level of consciousness' (Canter, 1974 p.32). For the group of lay subjects in this study, therefore, a method to heighten their awareness of light was needed. An approach that has appeared in most of the literature is known as *semantic differential scaling* (SDS). This method was developed by John Flynn, who was one of the first to make a connection between 'quality of light' and 'quality of architecture' and who provided new tools and methods that changed the way we look at light (McGowan and Miller, 1998). Flynn was one of the first to apply SDS to lighting research, a technique developed by Osgood and colleagues (Osgood et al., 1957). SDS has become a tool of choice for investigators interested in human responses to the qualitative aspects of the illuminated environment. Tiller and Rea (1992) describe semantic differential scaling as a series of seven-category rating scales which are defined by polar opposites, such as hazy-clear, spacious-cramped, pleasant-unpleasant etc. The subject in the study chooses a point along a seven-point continuum between the opposites that best matches his experience.

Why use SDS in this study?

The aim of the study was to elicit people's emotions and reactions to the light quality produced by the artefact. SDS is one of the most commonly used methods internationally in light evaluation, and using it in my study would help connect my research to the existing research. I was aware of the need, particularly with lay people, to look at the light quality and design of the artefact in terms other than just a personal reaction. However, because there would not be enough responses to the SDS survey to produce a meaningful analysis on their own, it was decided to use the SDS as a means of eliciting the language that would make the information from the open-ended questions most useful. SDS was to be a way of raising awareness of how lighting can influence impressions of space rather than the creation of data.

Using the four points from my previous research into light quality as headings, I planned to ask the lay subjects to rate the *light* from the artefact according to the scales which were adapted from the original literature from the work of John Flynn and his colleagues (Flynn, 1977, Flynn et al., 1979). Certain terms, that had been developed by Flynn and his associates to elicit subjective impressions of light, were found to be particularly useful in their research (Flynn et al., 1979). These terms were used under the headings developed from the research into light quality discussed previously.

Figure 5.24
SDS scale on light

1. The light from this artefact is:

Diffuse								Glary
Soft								Hard
Relaxed								Tense
Welcoming								Unwelcoming
Restful								Lively
Harmonious								Discordant
Informal								Formal
Intimate								Aloof

2. The light from this artefact for tasks is:

Adequate								Inadequate
Clear								Hazy

Figure 5.25
SDS relating to task

3. My experience of the space when this light is on is:

Informal								Formal
Private								Public
Pleasant								Unpleasant
Welcoming								Unwelcoming
Spacious								Cramped

Figure 5.26
SDS relating to experience

4. The appearance of the artefact in this space is:

Informal								Formal
Private								Public
Harmonious								Discordant
Welcoming								Unwelcoming
Focus of attention								Blends into background

Figure 5.27
SDS relating to appearance

Open-ended questions

The four light quality factors identified above were used as the basis for the open-ended questions that addressed light quality factors in terms of comfort, mood/atmosphere, task performance and the function of the artefact and light within the space. Subjects were also given the opportunity to comment specifically on the appearance of the artefact. This aspect was important to the wider research objective to explore possible typologies of form and material choice that could be appropriate for use with LEDs.

Figure 5. 28
Diffusion Lightlouvre in Household 1.

Figure 5.29
Reflection Lightlouvre in Household 3.

Figure 5.30
Reflection Lightlouvre in Household 4 in vestibule area.

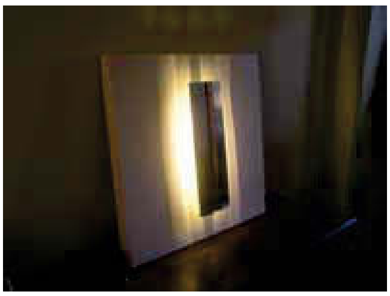


Figure 5.31
Diffusion Lightlouvre in Household 4 in television room

1. What was the experience of the space/room with this light in terms of the mood and atmosphere?
2. How did the lighting affect any tasks that you may need to complete in the area?
3. Could you live with this lighting artefact in that space long term?
4. Overall do you think this artefact suitable for your dwelling in terms of:
- light quality
- appearance of the artefact itself
- function of the artefact (i.e., the fact it is a wall fitting, the spread of light etc).
5. Are there other contexts in your home where it would be suitable – any that are unsuitable?
6. Are there any non-residential contexts where it could be used, e.g., hotel, restaurant and office?
7. Any other comments on the artefact, light or this process.
8. How would you define your overall attitude to lighting generally?

The first four questions were important issues in the study and I wanted to discuss them at the beginning while the subject had no time pressures. I framed the questions with the aim of eliciting subjective responses and with a view to encouraging the use of evocative language to describe their experience of the light in the space.

Process for lay people

The number of subjects needed to be balanced between providing enough variety in the data and the practical aspects in terms of time and resources of running a study such as this. Formosa (2009) suggests that qualitative research of this kind can be effective with around six people who represent diversity and complexity in the area to be explored. While the number could be higher, he also argues that it is hard to please even six people and that a group this size would have a diversity of views. The following discussion lists the procedure around the placement of the artefacts in the homes of the subjects:

1. Artefact would be delivered and set up in living area, hallway or any other accessible common area. The choice of placement in the home was driven by the need for visibility so a common space such as a hallway or living area was chosen. Furniture and other lighting would be rearranged to make the artefact more visible. Subjects were told to move the artefact to another area if they wished. However, in most households it was difficult to do this as the artefact was mounted on a large board and needed support and plenty of room. However, Household 4 did place the artefact in three different areas (see below). Subjects also had the opportunity to specify where the artefact would be best situated which was important information for the study.
2. The artefact would be left there for 48 hours (at least two nights) though in practice the artefact was often left on longer for logistical reasons. There was an attempt to keep the time to a few days to ensure that the subject still had a reasonably accurate memory of the space before the intervention of the artefact.
3. At the time of delivery, the researcher would explain the purpose of the semantic differential scaling and broadly the types of data the study was trying to elicit. The subject would have already received a copy of the ethics form.
4. Subjects were encouraged to move the artefact to another space in the house if they wished. Every subject would be asked to (and did) complete the semantic differential scaling before the interview.
5. Researcher would conduct an interview and collect artefact.

Figure 5.32
***Diffusion Lightlouvre* in Household 4 in television room on wall**

Process for professionals

When trying to elicit the same information from the professionals as from the lay subjects, I employed a different method. Following lighting industry practice, I brought the artefacts to their offices in the same way as all sample light fittings are brought for evaluation. Though their evaluations were made outside a domestic context, the professionals were used to undertaking such lighting evaluations of lighting for their clients in either the lighting showroom or their own office when companies lend a sample for evaluation. I did not plan to use the semantic differential scaling with the professionals, given that the professionals already work in the area and it was important to respect their prior knowledge. Time was also an issue; the professionals appeared happy to give up 45 minutes of time in a discrete concentrated block but other requests would be difficult to fulfil.

Questions for the professionals were as follows:

1. How would you describe the light from these artefacts (say to clients)?

2. Are either or both of these artefacts:
- suitable for a residential context in terms of light quality?
- can you comment on the appearance of the artefact itself?
- can you comment on the function of the artefact (i.e., the fact it is a wall fitting, the spread of light etc)?

3. Would either or both of the artefacts be appropriate for the following specific contexts:
- living room
- television room
- hallway, vestibule,
- bedroom
- other?

4. Did you find the light quality in either artefact suitable for contexts other than residential
- hospitality/hotel (foyer etc)
- restaurant
- office
- retail
- other ?

5. Are there any design alterations/development you could suggest that could widen the potential applications for this lighting artefact or improve the design, such as:
- different finishes
- different size (for example, longer)
- perforations or textures
- other?

6. Any other comments on the light quality, the appearance of the lighting artefact or this process?

I took both artefacts in, set them up in the office/studio in as good a location as possible (i.e., with as little ambient light as possible) and went through the evaluation questions one at a time for each artefact.

As can be noted, the evaluation questions were modified to place them in a user situation (e.g., How would you describe the light quality of this artefact to a client? In what context would you use this artefact?) and tapped into their knowledge as experts (What alterations could you suggest?).

Figure 5.33
Both *Lightlouvres* in professional studio

Part 4.
Feedback from the evaluation process

Originally the evaluation process was undertaken to elicit information on the current artefacts, specifically:

1.Were the artefacts suitable for a domestic application?

2.How could these artefacts be improved or taken forward?

The following discussion summarises the feedback from both professional and lay subjects. All comments are included in Appendices 3, 4, 5, 6.

1. **The suitability of the artefacts for a domestic application**

a. ***Diffusion Lightlouvre***

In terms of **light quality,** the diffusion artefact was capable of producing light quality acceptable for a domestic situation where light is experienced at close proximity and for long periods of time. Terms such as 'lightweight, soft, halo effect, glow' were used by subjects. The light was seen to have some warmth and to create a relaxed, calm ambience in the area where it was placed in people's homes. The diffusion louvre created a variety of lighting effects, namely, a strong, crisp centre line, a glowing louvre surface and a spread of light across the wall from under the louvre. This aspect did elicit some comment; some subjects commented on the effect of the light spreading from under the louvre. Another commented on the romantic effect of light from the side, 'like sunsets'. One subject (a shift worker) liked the light quality in the early morning when it was still dark outside. He felt the fitting did not bombard him with too much light and was a good transition from

dark to full light. There was positive comment that it was not possible to tell what sort of light source was used.
Lay subjects were divided on the **appearance of the artefact** itself. Some liked it, stating that the folded louvre shape integrated into the wall. Others thought it was 'architectural' and possibly too clinical with its sharp folds and that it lacked the 'homey' look suitable for domestic use. It was generally agreed that the style of the interior needed to match the artefact and there would be some interiors that it would suit better than others.
The professionals liked the appearance, saying it was an interesting sculptural form but still one that blended into the environment with an elegant simplicity. The design had a sense of logic and looked good turned off (important in a domestic environment where people can present be all day).
In terms of **placement** within the home, there was a consensus that the artefact would work in a semi-public situation. One subject described the diffusion artefact as 'a good hall light', which was supported by suggestions from both professional and lay subjects of hallways, vestibules and stairwells as contexts. One subject commented on how a confined or narrow space would suit the slim profile of the artefact and the light itself could reflect off adjacent walls. Some subjects identified the light and artefact as having a more formal, public type of appearance, which suited these placements. There was a concern that a wall light such as this would take up wall space otherwise given to artworks. However, it was also suggested that the artefact could be placed in other spaces, such as along the wall on top of a bookcase, or, in a very long version, on a stairwell wall that would connect the different floors.
Some subjects suggested placements in ceilings with the proviso that the glare from the LEDs would be managed. Four subjects suggested bathrooms as a possible placement. This was an unexpected result; bathrooms can be areas of relaxation and even luxury but are also places for detailed tasks such as shaving and applying make-up.

They thus have a variety of demands for light and at the same time require high standards of light quality. The crisp light from the artefact could be appropriate for this area.
In one household, the diffusion artefact had a journey through three different placements. The first was in a vestibule, the second was in the television room propped up on a table and the third, also in the television room, hung on the wall behind a couch. These placements were suggested by the subjects and seen as successful by the entire household and by visitors.
As far as **tasks** were concerned, the light was adequate for passing through a space and reading was possible if people were reasonably close to the artefact. It was also adequate for tasks in a vestibule, such as hanging coats or getting a dog lead. This artefact was successfully used as a television room light, giving enough light to watch television comfortably and, if its placement was correct, to read the television guide. It was agreed that more light would be required for more complex tasks. The idea of the artefact performing a transitional role was supported by placement in a vestibule, a position that another subject liked because it linked the exterior porch light and the well-lit living room.
The lay subjects were generally positive about the diffusion artefact as a real light fitting within their homes. However, they wanted control as to where and how it was placed.

b. *Reflection Lightlouvre*

As one subject noted, you either loved or hated this artefact. Despite its dramatic localised illumination, its effect on the surrounds was less than that of the diffusion artefact. This reflection artefact was less about light quality and more about **a lighting effect**. While there were some positive words ('festive', 'fancy', 'dramatic', 'complex', 'interesting') to describe the light, it was seen as more localised, less comfortable and less functional

than the light from the diffusion artefact. Many referred to this artefact as more of an artwork ('dramatic statement', 'feature light', 'attention-demanding') than a light fitting. However, the long strip of light up the wall was remarked upon as a positive by many subjects. One subject placed the reflection artefact in the hall and found that visitors asked about it much more than about the diffusion artefact. They were curious about the light source and many liked the patterns it created. Many subjects liked the artefact but did not think it would be appropriate for a domestic interior situation; instead, they felt it would suit many commercial, hospitality situations. Specific locations such as large-scale interiors in lobbies and vestibules were suggested.
In terms of the **appearance,** some liked the sculptural aspects of the folded sheet metal; others thought it was not appropriate for a domestic interior. One professional called it 'hard edges' and 'no nonsense like something out of [the film] *Metropolis*'. There was also a sense that any interior would need to be designed to suit this artefact; the artefact was too modern and severe for the average domestic interior and would be a specified product from an architect. Other comments included one that the industrial look of the brushed stainless steel limited the applications of this artefact and another that the way the solid face effectively 'blocked' the light appeared counterintuitive.

Placements suggested were hallways and public areas. This artefact was seen as a feature light, with some suggesting exterior and non-residential placements, such as hotel hallways, commercial contexts or nightclubs. One professional commented that corridors were usually quite dull, so this artefact could provide visual interest as well as illumination. Other placements described more specifically included as an example a dramatic feature light at the end of a hall to draw the eye, functioning like an artwork. In terms of **tasks**, such placements would be limited, since the spread of light was quite limited; however, it did allow some simple tasks to be undertaken.

Though the reflection artefact was seen in some ways as more interesting than the diffusion, it would be difficult to find a place for it in the domestic area.

2. **How could these artefacts be improved or taken forward?**

a. Diffusion Lightlouvre

The professionals felt the diffusion artefact needed more development and sophistication in terms of material used and better edge detail was also suggested. There were also more concerns about the detailing. Having the fixings on the existing artefact visible was acceptable but they would need to be very well handled to give a sense of quality. Both lay and professional subjects suggested that the artefact be available in longer lengths and in modular form to make a very long light. It was also suggested by one designer that white laminated glass would give a higher quality look, as some clients do not want plastic.

b. Reflection Lightlouvre

The range of alternative materials suggested for this artefact, including wood, ceramic, bronze, brass, coloured stainless steel and Corten (™) for exteriors, was very interesting and all these materials could create very flexible lighting solutions that could fit into a variety of interiors. A higher gloss front, black or white, to pick up the light was suggested and the finish could be varied across the front of the artefact. A few respondents suggested softening the severe look by having curved ‘gull wings’. Patterns on the front could also be considered. The addition of perforations to allow some light to come through was also suggested. These perforations could be customised to ensure that no glare from the LEDs themselves was visible through them. This was an option I had considered at the beginning of the process (see next discussion). Two professionals suggested that a small external spot would highlight the brushed stainless steel, as is done on other fittings on the market. Availability in longer lengths or as a modular system was mentioned for this artefact as well.

Reflection on the 'domestication' evaluation process for lay people

> Many aspects of lighting are researched in many institutions but there are very few which study the whole (Julian 1987 p. 160).

The process with lay people, in particular, was more than obtaining specific feedback on the actual artefact itself. The artefact provided subjects with an alternative method of illuminating a space and gave them an opportunity to think about previous methods and their suitability. The two-part process was able to create data that gave me a better understanding of many aspects of the performance of these artefacts in a residence. The light quality factors were covered with a type of evocative language that related to the domestic environment. There were also some interesting design directions suggested in terms of the size and materials of the artefacts. The suggestions from the subjects as to how they would use the artefacts in their home gave a sense of the effectiveness of the current design and how it could be improved.

The SDS was created to gather reflective and qualitative feedback. When asked whether the scaling assisted with the feedback, one subject responded:

> *I have to say yes, that the scaling definitely helped me to think about the different qualities/characteristics of light when evaluating it and describing the experience to you. It definitely allowed me to focus more on these different aspects of lighting and consider the experience from a much broader/richer perspective (rather than the continuum between 'I like it' – 'I don't like it').*

The domestication aspect gave a better sense of living with the light in a dynamic sense, such as entering the room, walking around the fitting, all at different times of the day. Subjects were familiar with the feeling of the space with other light sources so the intervention with the LED created a sense of difference. This two-part process also collected data for residential contexts that has *not* been covered in other studies. To create more meaningful data, there would need to be more subjects, which in turn would require more resources. When arguing for more post-occupancy evaluation of lighting, Julian (1987) points to the emphasis on the science of lighting in research and not the perceptual and aesthetic issues. Wider studies such as this evaluation process could assist in understanding what people actually want from the lighting in their homes. This information would help designers to design light fittings that would give LED technology greater penetration into the residential market.

Part 5.

Taking the practice-led experiments forward

At the end of this practice, there was a real desire on my part to go further with these designs, both in the light source and the range of materials. The feedback from the evaluation process also pointed to some interesting possible directions. However, financial resources were an issue, plus a need to work in other directions in connection with this research study. There was also the limit to the technical skills I was able to bring to this project at this stage.

The light source

The light source used in the final set of *Lightlouvre*s was created by mounting Nichia 'ribbon' LEDs on an aluminium strip (for a heat sink) and then connecting the LEDs to power through a driver. This single strip was then mounted on a board to simulate a wall with an upstanding escutcheon to block direct viewing of the LEDs. As became evident in the evaluations and my own observations, a higher intensity of light would be needed to give greater flexibility of use. There are many ways of creating higher light intensity such as using multiple strips of LEDs, larger LEDs or placing the LEDs closer together. The LEDs used in this set of practice-led experiments were chip on board (COB). They had no primary optic lens– the only light distribution was achieved through the louvre shape itself. Lens technology for LEDs was improving (Lau, 2013) and a better outcome could be achieved with lenses to assist with light distribution. The same light source was used for both the reflection and the diffusion artefacts. It may be better to customise the light source for each application and different lenses may be required.

Thermal management, in particular, is so important for LEDs that it needs to be designed and tested properly. In designing the heatsink for the *Lightlouvres*, I was using a broad understanding of how they work. I was not able, within my resources, to find out if the aluminium strip was effective in drawing heat away. Shailesh etc al (2015), note that testing for junction temperature is usually undertaken in sophisticated testing laboratories which can be out of reach for all but the best resourced companies. Given the importance of thermal management to the longevity and performance of LEDs, expertise would need to be sought to ensure optimum performance for any LED-based luminaire design in which a significant investment is being made.

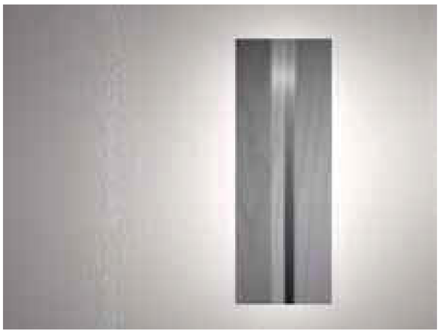


Figure 5.34
Visual of *Lightlouvre* using wood veneer

The material

For the diffusion artefact, though the painted acrylic worked well with the LEDs in terms of the appearance and distribution of the light, I was not sure that this material would have the necessary durability and quality look for a domestic application. Ceramic and laminated glass (back-painted white) that would give a high-quality appearance were suggested. One of the professional subjects, an interior designer, said during the evaluation that his clients sometimes did not want plastic light fittings. The *Lightlouvre* itself (unlike a ceiling fixture) was going to be situated very close to people's line of sight, so material quality would be important. In terms of possible metal finishes, bronze and brass were suggested as giving warmth to the LED light and a feeling of quality. Wood was also suggested as a material that could work quite well in an interior, particularly domestic, environment. Another possible finish could be clear anodised aluminium as used on the aluminium Apple Mac computers and the Artemide *Tolomeo* light, both of which are seen in domestic environments. This finish has a feeling of quality and a degree of softness even though it is a metal. Anodising can also be realised in a range of colours, including a soft white.

Artefact detailing

When the first artefacts were being developed, I considered using perforations in the reflection model in an attempt to lessen the contrast between the dark face of the artefact and the halo of light, which might create a sensation of glare. I was also interested in creating as large a lighting effect as possible; this would include allowing the light that was reflected off the wall behind the fitting to come through perforations directly to the viewer. The idea of perforations in one form or another came up during the

evaluation feedback discussed in Part 4 of this chapter. There were some practical challenges that made this difficult to do at this stage. The *Lightlouvre* could have been made out of perforated metal with some sort of masking in the middle to hide the LEDs; however, this would have created a jagged edge that could have impacted on the appearance and possibly elicited negative feedback. A custom perforation surface could have been created but it was not possible within the constraints of my own resources for this project. However, if the artefacts were developed further, the custom perforations could become part of the industrialised tooling process. These perforations could extend across the two 'gull wings' but leave the centre intact to mask LEDs. An alternative would be to have perforations at the edges to assist in the transition between light and dark. This 'eyelash' effect is seen in window treatments in cars.
Another detailing issue was the way the artefact was attached to the 'wall' (in the case of the evaluation artefacts the support board simulated a wall). The use of rare earth magnets worked well for the artefact at a model level but the practicality of this for a final version would need to be investigated. The need for sophistication in the fixings, form and the edge of the artefact had been commented upon in the evaluation. It has also been noted in previous chapters that the crisp, unforgiving nature of light from LEDs will highlight any unresolved issues in the detailing.

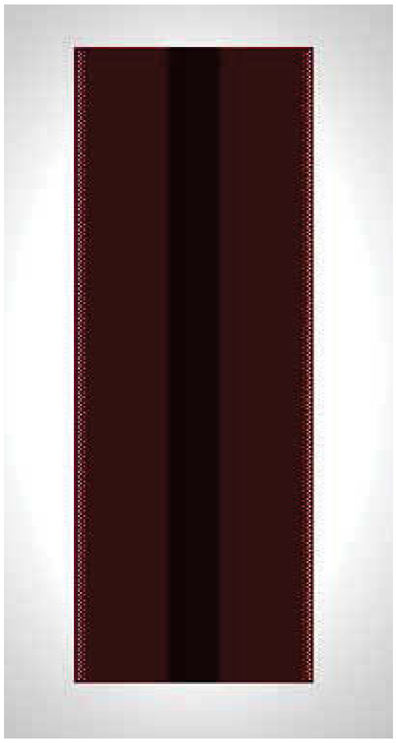


Figure 5.35
Visual of *Lightlouvre* with perforated edge

Figure 5.36
Garland Light
(Boontje 2004)

Part 6.

What was learned from the practice

Artefact - material

In Chapter 4 the experiments revealed a need to use appropriately chosen materials to give LEDs a sense of warmth and personality. The material itself needs to have a feeling of quality as the light from LEDs can make materials look cheap. The findings from the practice-led experiment highlighted that the *Lightlouvre* fitting needed a quality material to add to the look of both the light created and the artefact itself. This is in contrast to designing for GLS sources, where a wide range of materials can be used very effectively. A cheap finish such as vacuum metallising (usually seen on Christmas decorations) can look good with GLS lighting and there have been several successful examples of this during the 20^{th} century, perhaps most notably, the *Garland Light* by Tord Boontje. It has been noted that LEDs lack intrinsic beauty as a light source and so the choice of materials to use with LEDs is critical.
It also emerged from the practice discussed in Chapters 3 and 4 that LEDs have a particular strength in lighting *other* things – materials, surfaces, shapes etc. With LEDs, slight changes in material can significantly influence the lighting effect. In the series of experiments in this study, different types of plastic were tried for the diffusion model, before deciding upon back-painted clear acrylic. One material was rejected because it looked low quality with this light source. Similarly, different finishes were tried for the metal louvres. The early examples used a softer metal finish on the underside. The final version had a highly polished finish that created a more spectacular light spread, but,

as the feedback showed, was too hard-edged for some applications. A more precise balance between specular and diffuse reflection would need to be found to take this project forward. LEDs will also highlight any faults or inconsistencies. The generosity of the abundant light from GLS means that precision is less necessary. The pleasant quality of GLS lighting makes the material look good, whereas LED lighting needs sensitive material choice; it does not on its own enhance the appearance of materials. Unlike incandescent light, there is no intrinsic beauty in the light from LEDs – no 'incandescent coziness' (Kellog) or 'warm restfulness' (McComrie). The designer needs to 'help' the LEDs by understanding their strengths and weaknesses.

Light source and lighting effect

With this set of experiments, the researcher took a 'back-to-front' approach to the design of the *Lightlouvre* with lighting effect being the prime consideration in giving shape to the light fitting. As Fredrik Nystrom from Danish lighting manufacturer Louis Poulsen commented, when designing with LEDs you can 'design the light source' (F. Nyberg 2009 pers. comm., August 20). This approach is also suggested by Italian designer Michele de Lucchi, who has recommended that designers working with this technology should create a system of light, which then creates the shape of the light fitting (Artemide, 2014). LEDs are essentially a formless light source, and the designer must group or manipulate them to achieve a desired effect. While this quality created great opportunities in the design, it also created challenges. Questions arise such as which LEDs, what luminous output and colour temperature and what spacing (if they are linear), to use. It is not just a matter of grouping the LEDs; better understanding of optics is required. Experiments need to be undertaken to maximise

the lighting effect while limiting viewers' exposure to the direct light. The requirement for technical expertise constrains easy entry to the field of designers who have no specific training in lighting design.
Artefacts such as these would need to exist in a system of other LED lights; cove lighting, portable work lights, wall lights, suspended lights and other, yet-to-be-developed typologies of light fitting, each catering to a specific lighting need within the space. With the ongoing advancements in control and sensors, the *Lightlouvre* artefacts could also become part of a wider system of illuminating the home.

Designing the light source

With their greater flexibility and small size, LEDs do offer the opportunity of 'designing the light source'. This practice-led experiment included a custom-designed light source. LEDs offer an advantage in that they can be reformatted into non-standard formats to work with different light mediating forms. However, creating new typologies using non-standard LED light sources requires a high degree of knowledge and understanding which is different to that required with previous light sources. Designers who wish to design an LED light source will need to assemble a team that has expertise in optics, thermal management and electronics. This represents a shift from the expectations of lighting designers working with GLS technologies. While the latter might consult technical experts, for the most part they would expect to master any necessary technical knowledge themselves. Working with LEDs, by contrast, demands more precise calculations across a range of complex and rapidly developing technical fields.

Summary

The practice-led experiments in this chapter were based around designing a set of artefacts specifically for a domestic interior environment. The artefacts were then evaluated by both lay people in their own homes and professionals working in the field of design or architecture.

- LEDs are able to create lighting conditions which are more in tune with both the findings of light quality research and other cultural traditions and challenge the bright, even light which became common over the 20th century.

- The design methodology which involves visualising the lighting effect first and then designing the luminaire meets the need of LEDs for greater optical control. With this approach, the luminaire became more of a creator of lighting effects than simply an object carrying a light source.

- LEDs create the opportunity to 'design the light source' and while this offers the designer a wider range of opportunities there are also are technical challenges associated with this process.

- The evaluation process undertaken in this stage of the study demonstrated that lighting designers could obtain quite rich and varied data from both lay and professional subjects, which may be of useful in the development of new applications of LEDs.

- The importance of material consideration was emphasised with the crisp, intense light of LEDs highlighting even small differences in materials, form and detailing.

Chapter 6.

Adding dimension and control to light

Chapter 6.

Adding dimension and control to light

The practice-led experiments in this chapter incorporated aspects of LED technology that had *not* been explored before in this study. The first area of investigation was around the possibility of creating *three-dimensional* volume for LEDs. The other area of exploration was the incorporation of *digital control* into the experiments. The first experiments discussed in this chapter were connected with the creation of a light art piece for *Vivid Sydney 2012*. This was funded by the festival. The second set of experiments scaled down the light art piece to a smaller artefact suitable for interiors. This second set was funded from our own resources. Both sets of experiments were collaboration with Ben Baxter. The 'frames for practice' which were explored were obstruction, reflection and, with the second set of experiments, diffusion.

The module nature of LEDs can create challenges in generating forms for light fittings. To create a significant lighting effect, a number of what appear to be small points of light are required in some sort of matrix. Then the light from the matrix needs to be enhanced, mediated and given 'volume' at the same time as managing the glare produced by the LEDs. This management in previous practices centred on hiding the light source by either pointing the LEDs away from the viewer, as in the *Web of Light*, or countersinking the light into a wall or plinth, as in the *Isis* and the *Lightlouvres*. With these approaches, it had been difficult to move away from a two-dimensional form.

The second area of exploration in this chapter was *flexibility* in the colour and intensity of light through a control system. While this characteristic of LEDs was discussed in Chapter 2, it was not incorporated into this study up to this point. However, the ability to control LEDs digitally has important ramifications for the future of the technology and it was important that at least some of the practice worked with digital control.

A different approach to an older typology

The focus in this study has been to look at different ways of delivery light outside existing approaches. However, it may be possible to use LED technology to re-imagine older approaches. The amalgamation of three-dimensional form and control was used as an opportunity to investigate how the *typology* of the suspended ceiling light could be reformatted. The aim of this was to explore the particular characteristics of LEDs, not to simply mimic an existing approach.

The suspended light fitting (or pendant light) has antecedents in older typologies such as the Dutch *lustre* from the 17th century (Figure 6.1), the lead crystal chandelier in the 18th century and the 19th century gasolier.

Figure 6.1
Lustre
(Anonymous c1690)

The pendant light became a dominant typology during the 20th century, particularly in the way it embodied particular fashions or approaches in design. The omni-directional GLS lamp led quite naturally to three-dimensional responses (McDermott and Stewart, 2015). A suspended light fitting can make a statement about an interior and define an aesthetic in a way that is hard for other light fittings to do. Designer Qui Sing Tran stated:

> ... The pendant serves far beyond the function of illumination. A highly visual sculpture that changes its characteristics and presence as time tracks through day to night. It holds a commanding presence as a way-finding element within an architectural space and interiors context, at the same time, when appropriately appointed, completes the overall statement of the building/structure/interior/space. (Q. Tran 2013, pers. comm., 15 July)

Suspended light fittings can define smaller, possibly more intimate, spaces within a larger space, hence their role over dining tables in homes and restaurants. Interior designers in the hospitality area often talk about the rule of low/low/low lighting to create engaging illumination. With this approach, the light is *low* in intensity, the colour temperature is *low* (i.e. quite warm) and the position is *low* in relation to the ceiling or people's viewing angles. As well as fulfilling these functional roles, suspended light fittings have connections to the realm of the spectacular. Their ongoing presence in new buildings would suggest that they still have an important role in interiors.

Part 1
Cumulus

The first practice was the *Cumulus*, a large scale outdoor suspended light piece created for *VIVID Sydney 2012*. We developed a narrative for the practice based on stormy weather and used the programmability of the LEDs to create spectacular lighting effects.

Figures 6.2 –6.4
Cumulus
(McDermott & Baxter 2012)

Cumulus Mediation technique	Mediation of light	LEDS
	Mediation technique: Obstruction and Reflection	**Name:** Philips Color Kinetic iColor LMX modules x 50 nodes
	Medium: 3mm perforated aluminium sheet	**Lumen output:** 300 lumen per node
	Surface for generating lighting effects: 40% open area 6.4mm holes x 9.5mm staggered pitch	**Mediating lens:** Standard clear cover for IP rating only - no lensing was used though this is possible
		Colour: RGB
	Technique for modifying medium or surface: Mill-finished aluminium sheet	**Configuration:** LMX nodes in a continuous 'necklace'-style string
	Configuration of mediating surfaces: Laser-cut pieces interlocking to form a larger matrix	**Spacing of LEDs:** 305mm centres

Tabel 6.1 *Cumulus summary*

Management of LED	Effects	What was learned
Mounting: Each node mounted on an individual bracket with diagonal direction for light **Housing:** Standard DMX housing **Thermal management:** Within the system. Each node is not extremely bright and nodes were not enclosed. Outdoor product **Cabling:** Continuous 'necklance' of DMX nodes **Location of driver:** exterior to Cumulus array on other infrastructure **Data enabler:** Standard DMX data enabler and iPlayer controller for programming	The *Cumulus* became a glowing object The light was given volume by a combination of the reflective surfaces in each 'square' which created an internal illuminated effect and the perforations which allowed the light to flow around the structure. Individual LED nodes were perceivable but the light was broken up by the perforations. Variations in light intensity due to layers of perforations. Programming creating coloured effects which appeared to move through the ligt sculpture. Unintended side effect was one side was not fully illuminated as all the nodes faced the same way. No sensation of discomfort glare from the light sources.	1. It is possible to create three-dimensional volume with LEDs. 2. In a 3D structure LEDs need careful placement and angling otherwise dark areas will be created. 3. Using the structure to be a carrier of LEDs as a system can also offer advantaged in programmability and, in the future, other forms of intelligence such as sensors etc. 4. Combining optical principles can be more effective in light mediation and enhancement. 5. Challenge with LEDs is the light needs to be both mediated and enhanced (given volumne).

Figure 6.5
Early visual of *Cumulus*

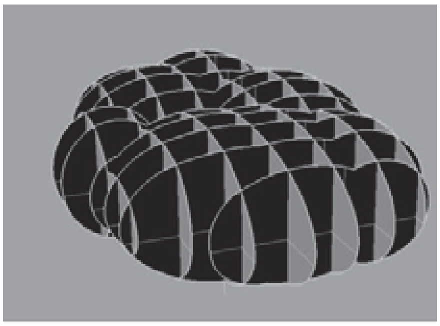


Figure 6.6
Screen shot of 3D model

Figure 6.7
Card models

Cumulus experimental process

Format of the mediating surfaces

There is a practice amongst industrial designers and sculptors of creating three-dimensional forms from interlocking two-dimensional planes. Often the effect of overlapping and intersecting planes creates a powerful visual statement. This approach can be used as a quick way of exploring forms before formal model making commences. The human eye can scan the outline of these shapes and make sense of them as a final three-dimensional form. One of the outcomes of this approach is the creation of many individual 'cubes' in a matrix, each of which could hold one LED. We adapted this approach for *Cumulus*. Our first thinking was to use a solid material such as plywood and paint it with gold leaf to create a slightly uneven, diffuse surface which would reflect light up and down.

From the first visuals, the form was further developed to make it more compact in footprint but rounder to emulate the form of a cumulus cloud more closely. A variety of techniques were used in the development, including visuals generated by 3D modelling software and scale models. At this stage, it was envisioned that each 'cube' in the matrix would have an LED mounted within to fill it with light, which, depending on the angle of the LED, could be reflected downwards towards the viewer. However, we realised that plywood was too heavy and expensive for a suspension and might not work well as a lighting piece. We looked at the following materials as alternatives:

- solid aluminium sheet
- lightweight aluminium composites, the disadvantage here being that cutting out shapes would reveal the composite structure on the edges, which would be aesthetically unattractive
- polycarbonate roofing material sheeting

We wanted to stay with the idea of a lightweight suspended structure, which had been part of our practice with *Vivid Sydney* 2011 (*Web of Light* discussed in Chapter 4) and true to the concept of a cloud. The architectural approach using solid material such as plywood or aluminium sheeting was therefore now thought inappropriate for a suspended light sculpture. The idea of using perforated metal came initially from concerns about the weight; however, we quickly realised that the perforations would allow some light through while also breaking up the glare. The approach would use the optical principle of *obstruction* as seen in the *moshabak* and similar screens in the Middle East and described earlier in Chapter 3. While previous practice-led experiments had a degree of obstruction to mask the lights, obstruction had not been used as a leading principle up to this point.

Regarding choice of material, perforated aluminium was not only lightweight but also offered a good reflective surface that would work with the obstruction principle. We obtained a number of small samples of differently perforated sheets. The final choice of Pattern 234 (which had 40 per cent perforation) was a compromise between the strength of the material and its degree of light transmission. The *Cumulus* crisscross matrix was intrinsically strong, so we could afford to go with a high level of perforations. However, the engineer and metal worker who made the *Cumulus* indicated the need for enough solid material for fixings an internal bracket. Pattern 234 was thought to have the right balance of material and perforation.
A decision needed to be made on how the mounting of the light sources would be detailed. We designed a small bracket (to be made from the perforated metal) and made a mock-up of the detail in cardboard (Figure 6. 9). Note the position of the large rectangular aperture through which to thread the LMX nodes.

Figure 6.8
Perforated aluminium
(Arrow Metals 2012)

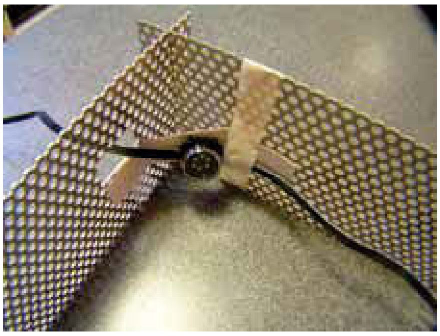


Figure 6.9
Corner detail

In order to understand how the *Cumulus* would be built, we had a full-size prototype of four 'squares' made from the 234 perforated aluminium sheet. The fabricator made the joining brackets from the same metal to keep the lightweight look. This also provided apertures for the connectors, avoiding the need for additional drilling and speeding up the manufacturing process. The full size mock-up was also used for lighting experiments.
Individual laser cutting files were developed for the *Cumulus*. Great care was needed at all stages as a small misalignment would mean the pieces of the 3-metre long *Cumulus* would not fit together. These pieces needed to be accurately connected so a system of triangular, square and circular cut-outs was designed into the file. The fabricator could align these apertures to create each larger piece.
The cut-out approach was based on the system used in dressmaking where pieces of garment are sewn tougher by matching notches. Apertures (which were rectangular to differentiate them from the notching system) were cut so that the 50 nodes could be threaded through them.

Light source

Our requirement was for a system of individual lights, each of which could be programmed to collectively create storm, sunrise and sunset effects. The most appropriate light source was the Philips Color Kinetic LMX system. This is a technology usually seen in media façades, where each node forms a pixel for a large composition or effect. It had not, to our knowledge, been used in a suspended three-dimensional form. There was a continuous string of 50 nodes, like a necklace, that needed to be threaded into the structure. To match the number of light sources we also had to manipulate the format of the fitting itself. Each 'node' was 40mm in diameter and could be programmed for dimming and for a wide variety of colours.

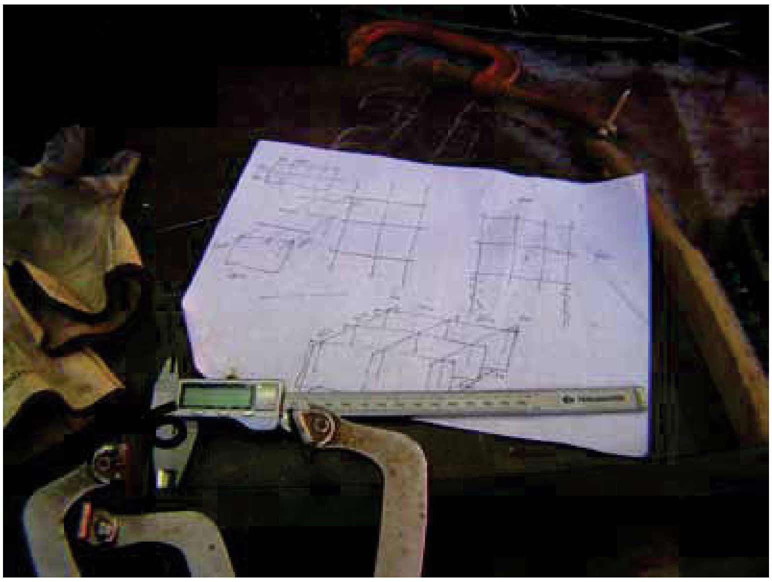


Figure 6.10
Workshop drawing of mock-up

Figure 6.11
Full view of mock-up

Figure 6.12
Lengthways pieces for
Cumulus

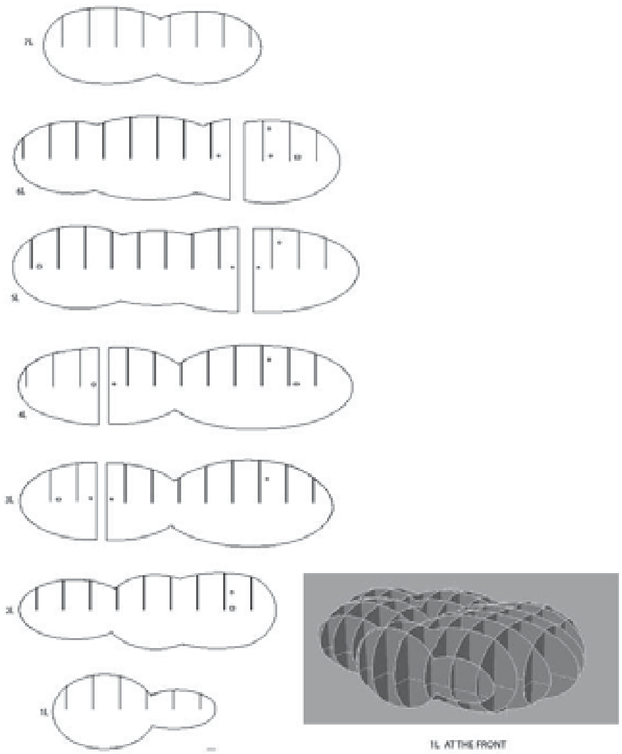
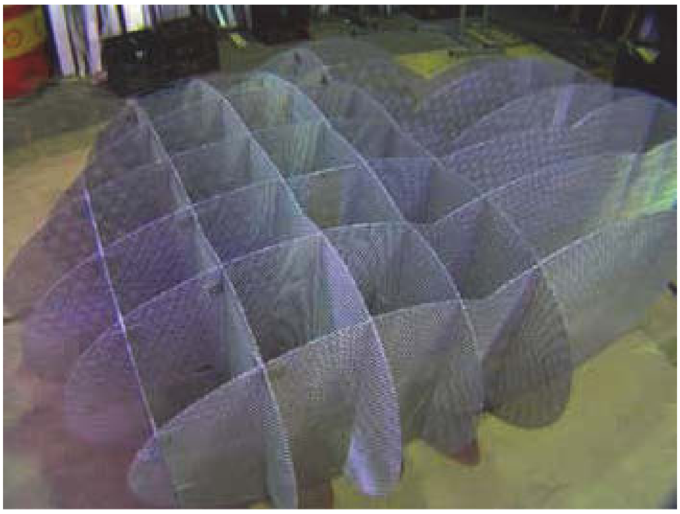


Figure 6.13
View of manufacturing



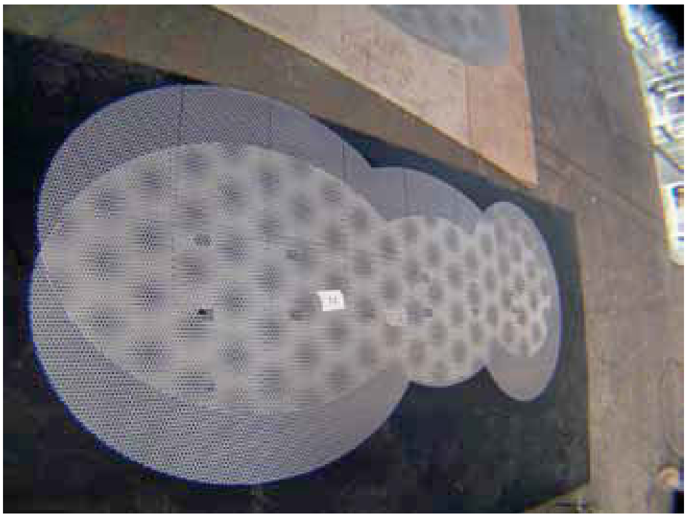


Figure 6.14
View of laser-cut pieces

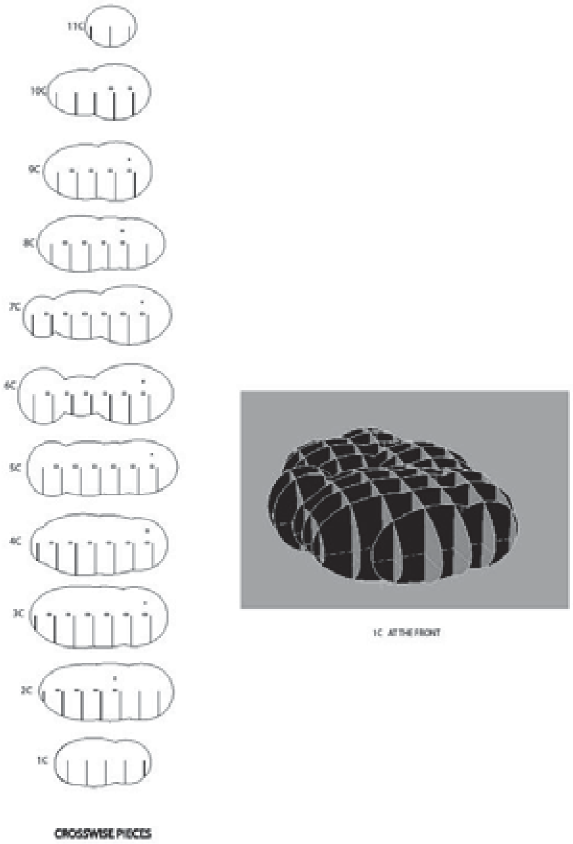


Figure 6.15
Crossways pieces for *Cumulus*

Figure 6.16
Image of LMX system
(Philips 2012, p.12)

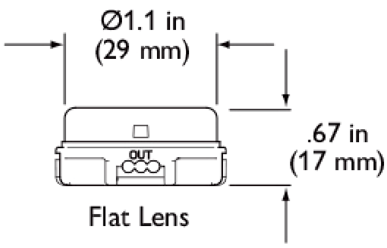


Figure 6.17
Individual LMX node
(Philips 2012, p.13)

We tested our first mock-up at the workshop of Xenian Light, our lighting supplier and sponsor. We connected four A4 samples of the perforated metal that we had been given by the metal supplier to form a square. The lighting supplier advised us to mount the LED facing across the diagonal to ensure the light filled the area.

Creation of effects

In order to program the LMX nodes, we needed to lay them out in the same position relative to each other as in the final *Cumulus*. With this system, each node would have an 'address' and the program would tell each 'address' what to do, in terms of changing colour and/or intensity and how quickly or slowly to make that change. We had to develop a five-minute 'show', i.e., a cycle of colour and dimming, working only at night to ensure we achieved the required effects. Given the infinite possibilities of colour and speed with this technology, it was important to have a concept behind the show, since without this, it could look uncontrolled. We developed a loose narrative of sunrise (with pink tones based on colours from Monet paintings), day (with blue tones), storm with dramatic white effects and sunset with deeper oranges and reds.

Final presentation

We had previously worked with engineers and riggers to work out the best way of suspending the *Cumulus* at the site, which had been specifically chosen for its darkness and good proportions.

Reaction

Cumulus won an award at the Illuminating Engineering Society (IES) NSW State Awards in 2012 and the project was published in *Superlux: Smart Light Art, Design and Architecture for Cities* (2014).

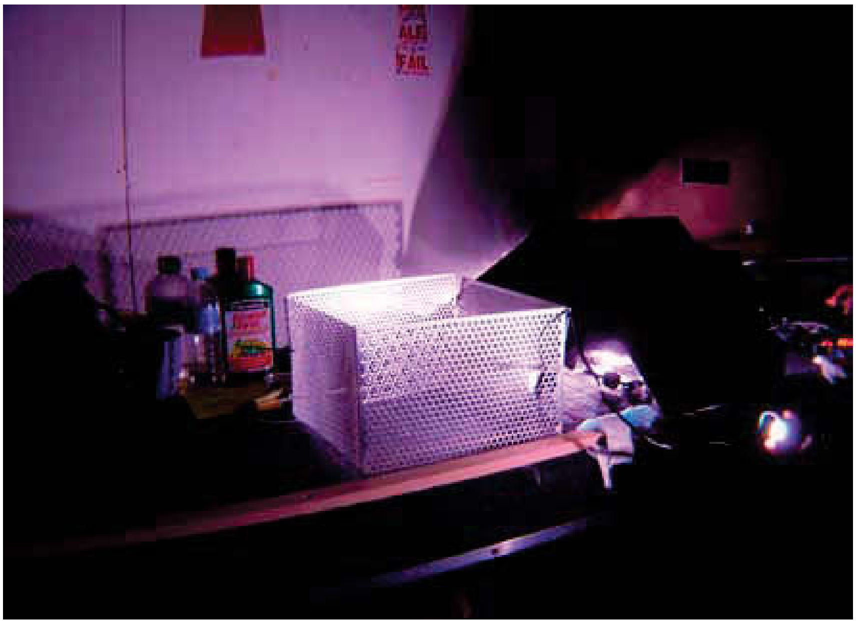


Figure 6.18
Mock-up to test lights

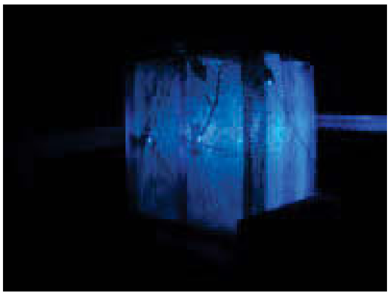


Figure 6.19
Image of full-size model
used for light testing

Figure 6.20
Close-up of lighting effect
in mock-up

Figure 6.21
Laying out modules to get the correct shape

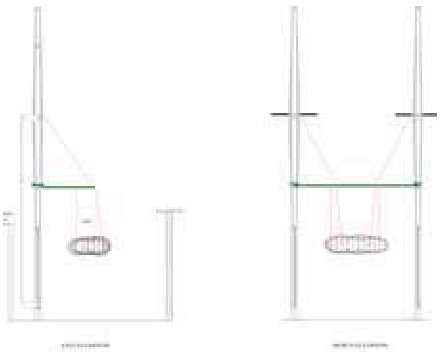


Figure 6.22
North and east elevations of rigging to be constructed for *Cumulus*

When asked about *Cumulus,* the *Superlux* editor, Davina Jackson, replied via email:

> McDermott Baxter's *Cumulus* installation is a notable contribution to the 'smart light cities' movement that has galvanised public art, urban design and architecture via electroluminescent (digitally controlled) systems of illumination. This inflated, colour-changing form, representing a cloud and suspended above historic stone steps in central Sydney, alludes to both today's challenges of reforming human destructions of natural environments and the globally dominant wireless networking paradigm of 'cloud' computing. (D. Jackson 2015, pers. comm., 16 December)

What was learned from the *Cumulus* practice

A new way of giving volume

LEDs are basically pinpoints of light and the perforated metal 'squares' gave volume to the light from each LED module. *Obstruction* was seen in the way the perforations allowed the light to flow through the fitting, but it also broke up the light, which was the aim of this approach. The mill finished aluminium provided a diffuse reflective surface, so that light was reflected within each cube and through the perforations.

Managing the light from LEDs

The directional nature of the light from the LEDs highlighted the importance of angling the modules correctly; from some viewing angles, there was a clear variation in illumination levels. This orientation could be addressed in further developments. Overall, however, the areas of lower illumination were not necessarily a negative; rather, this more varied effect contrasted favourably with

Figure 6.23
Arrival of *Cumulus*

Figure 6.24
Raising of *Cumulus* on
a scissor lift

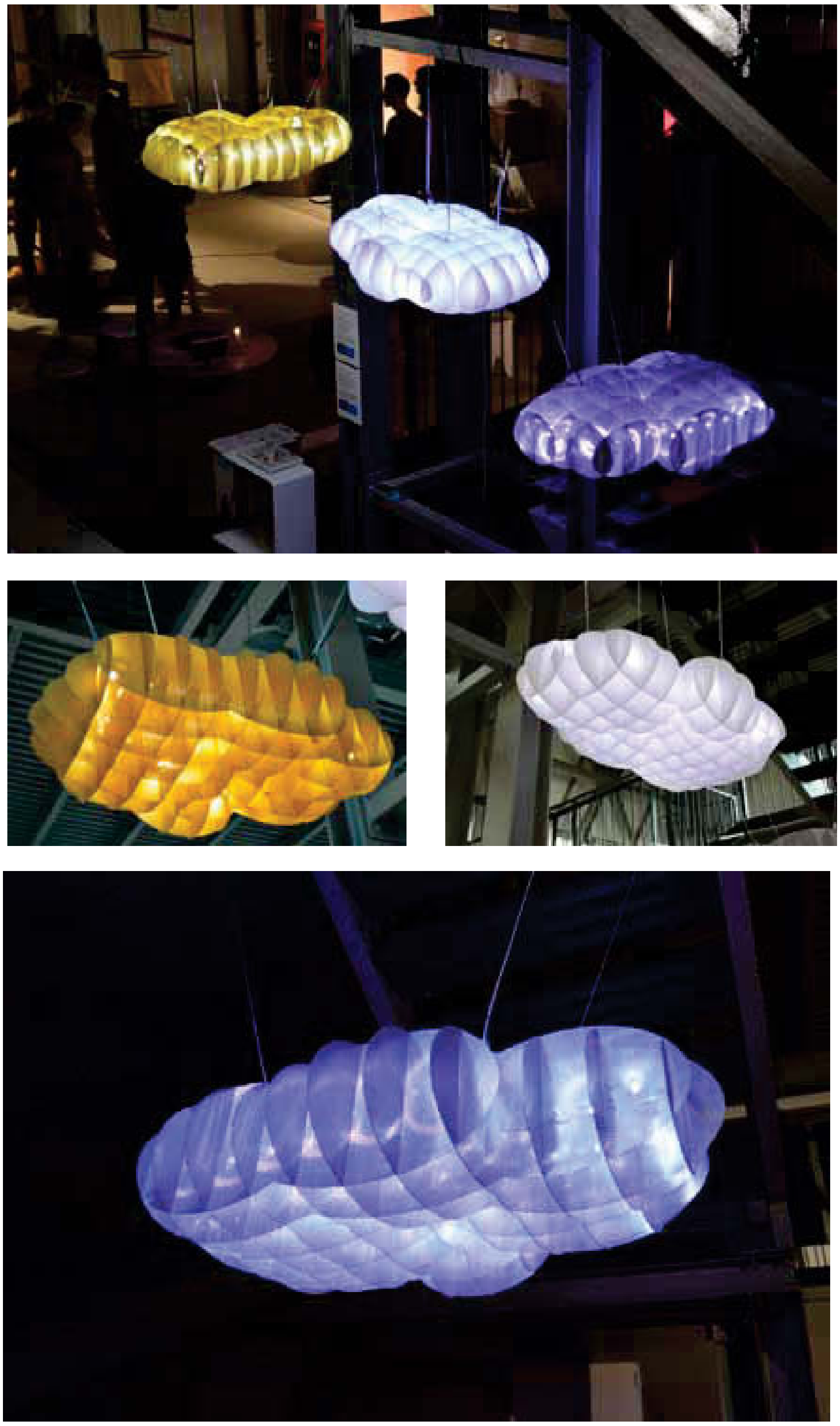
Figure 6.25
Daylight view of *Cumulus*

Figure 6.26
Sparkle

the uniformly glowing GLS-type light fittings. The fact that each LED was embedded in the structure created a more seamless relationship between the light source, material and form. The colours and programming complemented the overall shape and effect and the three-dimensional form and the cycle of lighting effects offered something new to this typology.

Cumulus functioned in the realm of the spectacular, so issues of glare were perhaps not as relevant as to a domestic light fitting. The highly perceptible spots of light were not unpleasant, they added a necessary 'sparkle'. If this practice were to be taken into a smaller scale for interior applications, however, the angle of the LED nodules would need to be much more carefully considered.

The issue of the relationship between the pinpoint LED and the actual size of the perforation would also need to be resolved. Some glare is acceptable for a large-scale lighting sculpture but this glare needs to be minimised for internal use. In the case of *Cumulus*, a naked LED would be seen directly only if a viewer stood underneath it and looked directly up; this is uncommon to exterior applications, which people view from a distance. However, in the case of interior applications, the fitting could be suspended above a dining table or in a living room. In such a case the LEDs would be seen through the perforations and may need to be angled upwards away from the viewer with a small shield. Some light spill could go onto the ceiling but this could be reflected downwards, since most ceilings are white and using the ceiling as a reflector is quite common in architectural lighting design.



Part 2.
The *Nimbus*

Figure 6.27-6.30
Views of *Nimbus* installation
(McDermott & Baxter 2015)

Nimbus gold

	Mediation of light	LEDS
	Mediation technique: Obstruction and Reflection **Medium:** 2mm perforated aluminium **Surface for generating lighting effects:** 40% open area 2.4 mm holes x 3.6 mm pitch **Technique for modifying medium or surface:** Perforated aluminium sheet with gold anodised finish **Configuration of mediating surfaces:** Laser cut pieces interlocking to form a larger matrix	**Name:** Tridonic nodes on custom made **Lumen output:** 50 lumen each node **Mediating lens:** COB (chip on board) with no lens **Colour:** 3000k **Configuration:** COB LEDs in a continuous 'necklace' style string **Spacing of LEDs:** 150mm

Table 6.2 *Nimbus summary*

Management of LED	Effects	What was learned
Mounting: LEDs on the outside of Nimbus were aligned and screwed into place according to light plan. Those towards the centre were not attached relying on stiffness of cabling for support. **Housing:** no housing. **Thermal management:** Within the system. Each node is not extremely bright and nodes were not enclosed. **Cabling:** Continuous 'necklace' of nodes. **Location of driver:** exterior to Cumulus array on other infrastructure.	**Data enabler: Not applicable** Gold *Nimbus* became a glowing object. As with the *Cumulus,* the light was given volume by a combination of the reflective surfaces in each 'square', which created an internal illuminated effect, and by the perforations, which allowed the light to flow around the structure. Individual LED nodes were perceptable through the material; however the light was broken up by fine perforations. Individual LEDs were directly visible if the viewer was directly below the fitting - due to their angle and low intensity this was not problematic in terms of the lighting effect. However, the LEDs did not have the neat professional appearanc of a standard system. No 'dark side' as with *Cumulus*. Variations in light intensity due to layers of perforations - 'moire' type effects were visible when perforated surfaces appeared in front of each. The light was not uniform - it varied depending on the orientation of the internal reflecting surfaces in relation to the viewer. Slightly more sparkly effect than with mill-finished aluminium of both *Cumulus* and silver *Nimbus*. The gold finish was more noticeable in a daylight situation than other materials, as was intended. No sensation of discomfort glare from the light sources.	1. Matrix system can create volume for LED light even at this smaller scale and non-standard level of light. 2. More careful placement and angling of LEDs can lessen 'dark spots", however, with this matrix approach there will always be some variation in the lighting level using perforated metal. 3. Whilst it is possible to custom-make an LED system, the issues around finish became a problem when the LEDs themselves are visible. 4. The warmer finish of the gold anodising created an interesting visual effect.

Nimbus Satin Ice White	Mediation of light	LEDS
	Mediation technique: Diffusion with some reflection	Name: Philips Color Kinetic MX system
	Medium: Satinice acrylic	Lumen output: 6 lumen
	Surface for generating lighting effects: 2mm satin ice acrylic sheet	Mediating lens: MX standard nodes with standard diffusing lens
	Technique for modifying medium or surface: Surface unmodified	Colour: RGB
	Configuration of mediating surfaces: Laser cut pieces interlocking to form a larger matrix	Configuration: 50 nodes in continuous strand
		Spacing of LEDs: 150mm

Table 6.2 *Nimbus summary*

Management of LED

Mounting: Led nodes were integrated into the structure of the white *Nimbus* with specific notches. This is accomplished during the actual assembly. All nodes were angled as per light plan

Housing: LEDs housed in individual sealed nodes

Thermal management: Within the system. Each node is not extremely bright and nodes were not enclosed.

Cabling: Continuous 'necklance' of nodes

Location of driver: exterior to *Nimbus* array on other infrastructure

Data enabler: Iplayer

Effects

White *Nimbus* became a glowing object.

The LED light was given volume by a combination of the reflective surfaces in each 'square' which created an internal illuminated effect and the translucency which allowed the light to flow around the structure.

When the colour system was set to white the lighting effect was more uniform than the metal versions of *Nimbus* without the variation in light and dark.

When the system was set to its colour program (through cool and warm colours plus with dimming storm effects) the colour and effects were noticeable though the white softened the intensity.

Individual LEDs were faintly visible from the side - they were seen as glowing small area rather than more defined 'spot'in the metal versions.

Because light could actually travel within the material itself surfaces which were not directly illuminated still glowed.

Individual LEDs were not directly visible from the side but were visible if the viewer was directly below the fitting.

The LEDs had the neat professional appearance of a standard system the connecting cable between nodes was quite thick and bulky due the system being IP rated.

No sensation of discomfort glare from the light sources.

What was learned

1. The use of diffusing material created a more even lighting effect when the system was on white. Matrix system can create volume for LED light even at this smaller scale.

2. The angling and placement of LEDs resulted in an even effect with no dark side.

3. The small size and flexibility of LED nodes means they can be integrated into the actual structure of the fitting without additional fixings.

4. The use of a standard existing system of LED nodes solved some problems. However, the thick cabling and the 'bulky' look of the individual nodes could be problematic in an interior situation where a more refined look would be preferable. However, this is the only system available which offered colour and control.

Figure 6.31
Early visual of small *Nimbus*

Figure 6.32
3D modelling render of *Nimbus* in a plastic finish

Part 2. The *Nimbus*

There had always been an intention to take the *Cumulus* forward into a smaller version for interior applications. My collaborator on the *Cumulus*, Ben Baxter, and I were further encouraged to undertake this next stage by a colleague who remarked that a scaled-down *Cumulus* would have the advantage of offering the consumer a chandelier-type fitting that was flat and suitable for modern dwellings with lower ceiling heights. However, we did not have the resources to undertake this process until three years after the original *Cumulus*.

The *Nimbus* (named to differentiate it from the large *Cumulus*) was created in three different materials. We generated some visuals of possible set-ups, thinking at this early stage of using only perforated metal as the material. We decided to develop the *Nimbus* for exhibition in Milan (*Salone Del Mobile*) but would explore different materials, possibly acrylic and some sort of natural material, such as thin plywood.

The *Nimbus* was to be one metre long, which while possibly too large for some smaller scaled interiors would meet our need for an impressive exhibit in a large space. Like a chandelier, this type of product needs to be large to work effectively. Each 'square' needed to be a certain size to utilise the LED light and create a type of mediation. We also planned to develop more than one *Nimbus* to see how different materials and effects would work.

We found early in the process that it would be difficult to get the type of fine tolerances necessary for this product using wood or similar product such as bamboo sheet. However, it was something that could be pursued in the future with more research and development. For the purposes of the the Salone del Mobile exhibition, however, the *Nimbus* was realised in mill-finish perforated aluminium, an acrylic Plexiglas material called 'Satinice' and gold anodised perforated aluminium.

Our early planning took into consideration a few things we had learned from the *Cumulus*. We wanted to avoid the creation of a 'dark side' of the *Cumulus* when all the light sources were pointed in one direction. We also needed to consider the issues around exposure to glare in a potentially smaller interior environment.

Nimbus experimental process

Format of mediating surfaces

Full-size models were made from card (to check the form) and paper (to explore the flow of light). We viewed a 1:1 cardboard model of the *Nimbus* and started to experiment with the digital MX system of LED nodes.
From the start of the process we had been investigating the possibility of making the *Nimbus* from acrylic. It is a very traditional lighting material and if used in a conventional way as a flat plane for diffusing, the individual spots of light would be obvious. However, when using this 'waffle' design in a matrix, it would perform differently. The Satinice acrylic by Plastral was chosen for its high transmission values and good quality matt diffusing surface. It was also available in a range of attractive colours, including a white named 'Snow'. Our modelmaker was not able to take samples away from the shop and had to send us the images, shown in Figure 5.35 and Figure 5.36.
Satinice has a range of beautiful colours which we did consider using. However, as the RGB programming with the white paper created a sufficiently spectacular effect, we felt coloured material for the light fittings would be unnecessary. An additional disadvantage with the coloured Satinice was its relatively low light transmission. In choosing the colour 'Snow', we gained a white with a 73% transmission (according to the technical infomation

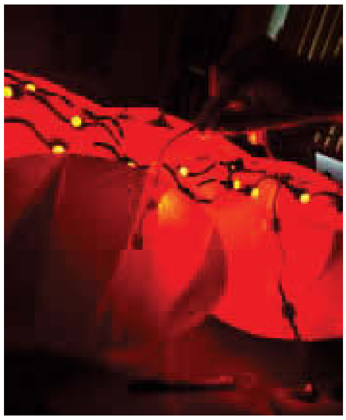


Figure 6.33
Cardboard model of *Nimbus*

Figure 6.34
MX lights with model

Figure 6.35
Samples of white Satinice

Figure 6.36
Sample of colour Satinice

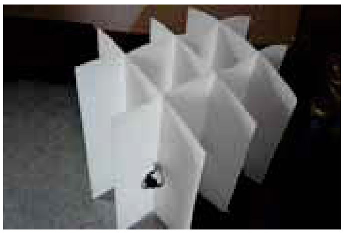


Figure 6.37
Small plastic mock-up

Figure 6.38
Mock-up with lights

Figure 6.39
Sample of different cuts for notching detail

Figure 6.40
Pieces of mock-up

brochure), thereby balancing the dual requirements of transmitting and diffusing light. Following the precedent of the *Cumulus*, a series of mock-ups were made.

Test rig for plastic version

Having finalised the material, we then investigated a new approach to holding the acrylic *Nimbus* together. Instead of internal L-shaped brackets (as used with the *Cumulus*) we examined integral notches, a detail that had been observed in flat pack furniture. These notches could be laser cut into the material, and the acrylic's natural spring would enable the individual elements to be inserted into each and to hold. In terms of managing the continuous string of lights, Matt Webster, our development assistant, suggested that the intersecting slot in the vertical plane could be shaped to include a 'mouse hole' to hold the cabling. This would provide more support for the cable and possibly negate the need for separate LED supporting brackets creating a cleaner look.

Development of notching details

In further developments, laser-cut samples were made of the notch detailing for assembling and mounting the LEDs. We now had to make final decisions on the number of *Nimbus* light fittings to be exhibited in Milan and what material they would be made of. The exhibition space we were to use was an industrial staircase (see Figure 6.43) in the Ventura Station exhibition venue in the Lambrate area of Milan. The extremely bright interior, and consequently the challenge of so much competing light was a concern and influenced the choice of the materials and placement within the area. To obtain the best effect, we decided to mount three installations, each in a different material, namely Satinice plexiglas, perforated aluminium and gold anodised perforated aluminium. The finishes are indicated by the colours on the 3D modelling visuals shown in Figures 6.43 and 6.44.

Figure 6.41
Image of site in MIlan

Perforated aluminium

The use of white Satinice with colour changing lights allowed us to experiment with perforated aluminium as a second material. We knew from the *Cumulus* that this material had a spectacular appearance. Perforated aluminium would provide a good contrast to the more subtle tones of the Satinice and would be effective in an exhibition context. With the perforated aluminium we investigated using the same 'locking' method for mounting the LED nodes as with the acrylic version. However, there were concerns that the metal edges may damage the cabling so the perforated metal *Nimbus* used the same joining method using 'L' brackets as the *Cumulus*. We chose a 2mm perforated aluminium sheet with 40% open area which had 2.4mm holes x 3.6mm pitch. We asked the laser cutters to give us any left over pieces of sheet metal which I guillotined into strips to make the brackets. We could then thread the LEDs through, as we did with the *Cumulus*.

Gold anodised performated aluminium

The decision to exhibit a gold anodised version of *Nimbus* was driven by the exhibtion context in Milan which would have a fair amount of competitive daylight. Gold reflects light very well day *and* night. We were interested in introducing a warmer tone as a counterpoint to the cooler Satinice snow and perforated aluminium. At this time, there also was a revival of interest in materials such as brass, copper and gold in light fittings. We briefly considered making a *Nimbus* out of perforated brass. The contrast between brass (one of the oldest materials for light fittings) and the high-tech aspects of LED lighting would

Figure 6.42
3D Model of site

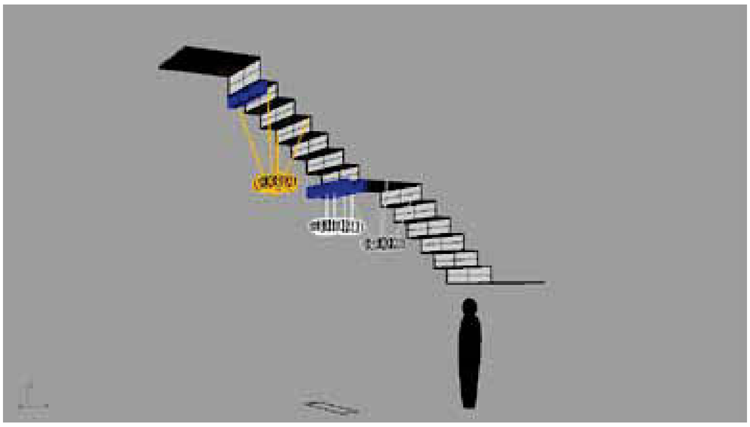
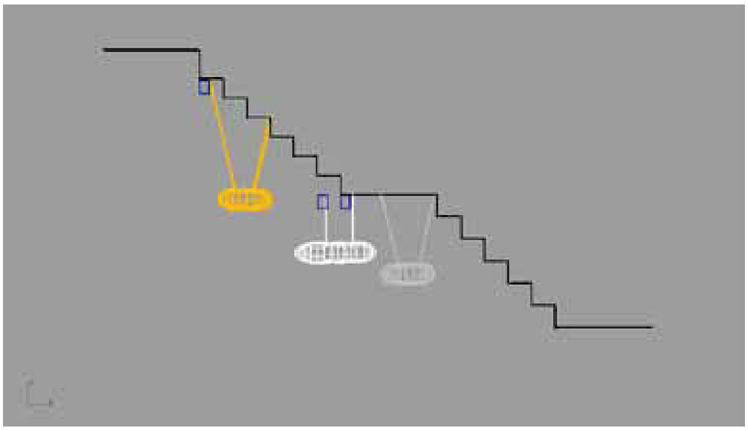


Figure 6.43
Showing suspension heights



have been interesting. However, there was not enough time to do the necessary experimenting with a material we had never used. Brass is soft and heavy - two things that may make it difficult to use in an application that needed materials that were both robust and lightweight. Brass is not an easy material to obtain and sheet-perforated brass would need to be specially made to order.
Gold anodising the perforated aluminium was then investigated. The actual colour was an issue – too yellow and it could look cheap and too white and it would not have the necessary brilliance and start to resemble plain perforated aluminium. It was planned that the gold *Nimbus* would be placed at the front and in the highest position to atract attention.

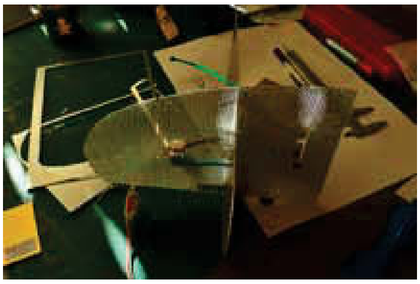


Figure 6.44
Mock-up of perforated metal detail

Figure 6.45
Samples of gold anodised pieces

Figure 6.46
Testing the gold with lights

The light source

As we needed to procure another light system, we looked at a scaled-down version of the LMX we had used for *Cumulus*. This system, called MX, offered the same ability to change the colour of the lights and, also like the LMX system, was packaged so as to make it waterproof and hence suitable for outdoor use. While this waterproof aspect was crucial for the LMX (the *Cumulus* being an outdoor installation), for the *Nimbus*, this was not as important. The reason we chose the MX system over others we found during our product research was that, despite its expense, no other system could offer us the same colour control in interior-only applications. An upside to the expense was that the system itself - nodes and flex - was neatly packaged in black or white plastic so that it looked quite professional. This was important, as from certain angles the viewer would probably be able to see the nodes. The MX system is usually applied to large-scale media facades and outdoor applications, as can be seen from the brochure images reproduced in Figures 6.47 and 6.48. It

Figure 6.47
iColor Flex MX
(Philips 2014, p.2)

Figure 6.48
Application of MX brochure
(Philips 2014, p.3)

Figure 6.49
Tridonic LED system

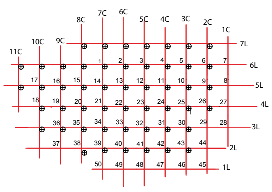


Figure 6.50
Plan of LED lights

was instructive to read the information on the data sheet about the use of MX system:

> iColor Flex MX gen2 can be used in a wide range of two-dimensional and three dimensional configurations, including portable video screens and permanent building covering displays. Planning includes understanding how to position strands in relation to power / data supplies and the number of strands each power / data supply can support. All installations involve three main steps: 1. Create a lighting design plan and layout grid 2. Mount fixture strands 3. Address, configure, and test fixtures. (Philips, 2014)

This was a good summary of the complexities of engaging with controlled LED systems. There needed to be a driver for the LEDs and an iPlayer or similar device on which the control program would be installed.

For the gold *Nimbus* we chose to go with white lights only, using a custom-made 50 node network of Tridonic LEDs; a control system was not required.

Creation of effects

Previous experience with LEDs had revealed that the position of the LEDs, the direction of their light beams and the relationship between form material and light source is critical to the final effect. To get the best distribution of light we planned to position the LEDs as shown in Figure 6.51. There was discussion as to where the LEDs would be located vertically, i.e., at what heights through the array. The LEDs needed to be on the same plane, due mainly to cabling issues; however, we were also aware that we did *not* want the LEDs to be too visible from below. Testing with a light metre showed that LEDs positioned half way up the *Nimbus* created the maximum light spread and offered some shielding from direct viewing.

Assembling the silver perforated *Nimbus*

Figures 6. 51 – 6.54
Assembly of silver *Nimbus*

Assembly of white *Nimbus* — a practice for Milan

Figures 6.55–6.56
Assembly of white *Nimbus*

Figures 6.57–6.58
Illuminated white *Nimbus*

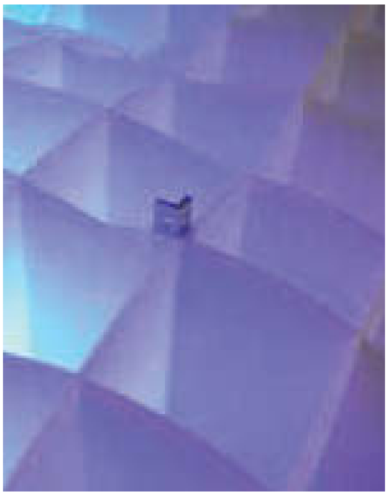


Figure 6.59
Assembly in Milan

Assembly and installation in Milan.

The pieces for all three *Nimbus* light fittings were carried to Milan as flat packs in our luggage and assembled in our accommodation an onsite.

Part 3.
Taking practice forward

The light source

For both *Cumulus* and *Nimbus*, existing systems of LEDs (LMX and MX systems respectively) were used. These systems gave us the colour we wanted and were packaged together to look neat despite the thick cabling between each node. However, there was a trade-off using RGB LEDs for colour and then white as they did not produce as high a luminous flux as white LEDs alone would have. We were aware that this was not an ideal situation and therefore attempted to design our own light source, using individual Tridonic LEDs as in the gold anodised version. Even though the LEDs performed well, this customised system did not look professional. The best way forward would be an integrated approach where the LEDs would be already mounted on the individual pieces before assembly. Any mounting and connection details could then be laser cut or stamped into the piece. Even with wireless control, power would still be needed to each LED. Given the low voltage, it was possible that the structure itself (if metal) could be used, as Richard Sapper used the structure of the *Tizio* light, to carry power to the light source (Hoger, 1997).

Figure 6.60
Installation in Milan

Materials and finishes

Often new light sources seem to ‘find’ the right material, either by adapting an existing material or finding a new one. Examples are lead crystal and candles, paper shades for Argand lamps, frosted glass for gas light and modern plastics for electric lighting (Bluhm Lippincott 2000; Dillon 2002; Duncan 1978). What could be the material for LEDs? Current designs for LED use fairly conventional materials such as translucent plastic and perforated aluminium, however new materials incorporating nano-technologies, bioplastics or sensor technologies, may be a better fit for this digital technology. Ongoing developments in 3D printing point to another approach to mediating light through more complex shapes. My experiments using conventional materials delivered understandings about the kinds of texture, reflectivity, opacity or translucence, that are effective in mediating LED light. Ongoing practice with LEDs would need to extend this set of material understandings to include newer materials.

Looking at the existing material choices for *Cumulus* and *Nimbus:*

1. using perforated metal allows light to flow around and out of the fitting (in a horizontal axis) while the matt surfaces also reflect light upwards and downwards. The disadvantage is that the LEDs themselves can become visible through the perforations and therefore need very careful placement
2. using translucent plastic results in lower levels of glare; however, it also results in a loss of light intensity

As was found in the practice-led experiments described in this thesis, there is a requirement with LEDs to mediate their glare while losing as little light intensity as possible. The major selling point of LEDs is their efficiency; at the same time, they need to deliver a good outcome in terms of lumen-per-watts performance.
The optimum situation in a *Cumulus*- style fitting is

where the light that flows around the fitting, is mediated to manage the glare from the LED source and is surrounded by surfaces that reflect the light up and down. Manufacturers are now experimenting with moulding refractive lenses in material so that the light is mediated but the loss of light is as low as 10% (Lau, 2013). *Cumulus* and *Nimbus* could be made from a new sheet material that combines reflecting surfaces (to force the light up and down) and lenses in the perforations that allow 90% of the light through while mediating the glare. By combining the principles of reflection and refraction a new material can be created for LEDs.

Flat pack

In order to exhibit the *Nimbus* in Milan, the pieces were all carried flat pack and assembled on arrival. This was a complex and time-consuming process that involved attaching the individual brackets and threading the lights. However, the detailing of the acrylic *Nimbus*, which did not need brackets or LED mounts and used laser-cut shapes to assist with its assembly, points to future developments. With a more integrated lighting system, the *Nimbus* could be developed as a flat pack product to be assembled *in situ*, thus saving costs, and fixings could be integrated into the design. The smallness of the LEDs also means they could be integrated into the structure in advance.

Introduction of control

The *Cumulus* saw the use of a control system to create a spectacular lighting show for a festival. The idea could be taken forward to a *Cumulus*-style fitting as part of a wider control system in a building or an urban environment. A *Cumulus* or *Nimbus*-style fitting could be programmed to respond to different times of the day with different colour temperatures or to have an 'event' mode with brighter colours. It could be sensitive to the levels of light required and even turn itself off if people are not present.

The need to design the light source was identified in Chapter 5, and a ribbon-type array of LEDs was created. However, with the perforated metal and Satinice acrylic *Nimbus,* we had to adapt an existing system to obtain the necessary degree of colour control. Even though the cables and nodes were all neatly enclosed, the cabling itself was thick and less flexible because of the water-proofing aspects as it was designed for outdoor use. This thicker cable was acceptable in the *Cumulus* as it was quite large. However, in the *Nimbus* it was not as elegantly resolved as we would like. The system was quite expensive as it offers this waterproofing which was not needed for this interior application.

Assembly

We had aimed, when assembling the gold *Nimbus* with the Tridonic system, for each node to be attached by screws to the metal using the existing perforations. However, we found this was a very time-consuming process in Milan and were unable to attach all the LEDs properly within the time constraints. We ended up attaching all the LEDs that were around the four edges and leaving the internal LEDs unattached – using only the natural stiffness of the cabling to support the nodes. From the outside the effect was quite acceptable; however, if one looked up into the fitting, it seemed unfinished. To take this forward, a better detail and system would need to be developed.

With the perforated material there was the great advantage that the perforations already existed and there was no need for extra holes to be drilled. A clip-on detail could be developed, possibly using 3D printing, to attach the LEDs to the metal quickly. In addition, the spacing between the nodes could custom made so that they all sat more neatly, with no excess cabling.

Summary

The practice-led experiments in this chapter focused on the creation of a three-dimensional artefact incorporating LED technology as a way of moving forward from the two-dimensional approach to formatting LEDs used previously.

- The process of re-imagining a traditional light fitting of the suspended pendant typology revealed a different method of creating volume for LED light involving a matrix of reflective and diffuse surfaces.

- The small size of LEDs and their modularity meant that different formats and assembly methods could be explored in three-dimensional as well as two-dimensional forms.

- This combination of optical principles brought forward the idea that a new material could be developed, particularly for LED technology.

- Incorporation of control through the use of an existing commercial light system from the media facade sector meant that skills around programming were acquired as part of this design process. In terms of the knowledge of designers, this is part of an inevitable process where control and sensor technology will become integrated with LEDs.

Chapter 7.
The unexpected gifts

Chapter 7.
The unexpected gifts

Earlier chapters have outlined how LED technology was introduced because of its energy efficiency. With the development of LED technology over the past 20 years, other advantages and possibilities have emerged that are not necessarily connected with their energy efficiency and longevity. This next section discusses some of the unexpected gifts of LED technology to see how they may impact the future adoption of the technology.

Part 1.
The ‘dark side’

When LED technology became available for architectural lighting around 2000, there were concerns that this energy-efficient light source would lead to a diminution of light quality. So much so that the Commission Internationale d’Éclairage (CIE - the International Commission on Illumination), which sets international standards on lighting, devoted its 2010 conference to the theme ‘Lighting quality and energy efficiency’ (CIE, 2010). It has been noted previously in this thesis that the experience of GLS-type lighting conditions and even the format of the lamp itself created certain expectations which have proved hard to change (McDermott & Stewart, 2015). It is difficult for LEDs to replicate the GLS-type experience of light. The practice in this study has in part been exploring what lighting effects are possible with LED light, with an implicit acceptance that new typologies and ways of delivering light may be required in the future. However, it has also emerged that LEDs may offer aspects of lighting that older light sources cannot offer and may indeed point to better ways of illuminating interiors.

Ways of seeing 1 - the visual system

The ability of eyes to operate over a wide range of light levels, to distinguish wavelengths of light as colours and to resolve very small detail in objects of regard is explicable in terms of the characteristics of their receptors and their distribution over the retina (Julian, 2011).
As a species, humans have spent the majority of their evolution in conditions where light has varied throughout the day and even at night (with the old flame-based light sources), utilising the ability for the human eye to adapt to a range of lighting levels. Humans can function effectively at varying levels of light thanks to certain aspects of

the visual system and the way sight works. Sight occurs when certain parts of the eye are stimulated by light, the critical part of the eye being the retina, which is a surface at the back of the eyeball. The retina contains two types of photoreceptors, named rods and cones because of their shape, which are key to the operation of the visual system (Julian, 2011; Rea, 2000). At very low levels of light, only the rods are sensitive to light. This vision is called scotopic and as the rods have little or no wavelength discrimination, colour appears almost absent. Only coarse detail can be detected under scotopic conditions. With slightly higher luminance, the rods are still conveying information but the cone receptors begin to operate, colour appears and finer detail becomes more apparent. This is mesopic sight, which, it should be noted, is not stable, as colours can change. This type of vision occurs in low lighting conditions such as dusk.

Interior lighting is designed to produce lighting conditions in the photopic range where luminance levels are high. In photopic vision the cones are fully operational and can detect details and colours more accurately. The rods are 'saturated' and for practical purposes cannot contribute any more to vision (Boyce, 2014).

Although the eye can function over a wide range of luminance levels, it needs time to become accustomed to each level. This process is called 'adaptation' and is due to chemical changes in the photoreceptors. There is a time lag involved; when we move from light to dark, the adaptation is slower than when we move from dark to light (Julian 2011, Boyce, 2014). The manner in which our eyes adapt to the low lighting in cinemas, from experiencing total blackness to a gradual visual perception of the people and shapes around us, is one of the more common examples of this adaptation. What needs to be understood from this discussion is that humans can function at lower levels of light for many (though not all) tasks. It is therefore the

cultural norms and practices discussed throughout this study that dictate how interiors are illuminated, not our biological needs.
Recently there has been a move in lighting design calling for the appreciation of darkness and shadow in lighting schemes, playfully called 'darkitecture' (Maloney, 2015b p. 17). On the 50th anniversary of the death of Junchiro Tanizaki, a section of his seminal book *In Praise of Shadows* was printed in *Lighting* magazine. Distinguished lighting designer Mark Major wrote in his introduction how Tanizaki:

> … introduces us to the idea not only as to how the mere suggestion of form can be satisfying but also how darkness can provide stillness, quiet contemplation, privacy and concealment in a busy world otherwise bathed in the full glare of electric light. (Major, 2015 p. 52)

When both Tanizaki and Major were referring to the electric light source they were referring to the GLS incandescent lamp, a technology that was able to create the even, homogeneous light of the 20th century interior. However, as noted in Chapter 5, there exists a body of lighting research that questions this approach (Flynn, 1977; Marsden, 1972; Durak et al, 2007) as well as cultural practices that exist outside this paradigm, such as the Danish *hygge* (Bille & Sorensen, 2007). Perhaps at issue is not so much the quality of 20th century light but its homogeneity and ubiquity. It is everywhere and more or less the same. In the domestic sphere, the lighting in the kitchen, the dining room and the living area can be similar and often resemble the lighting in the workplace.

Homogenous light

> …in many areas the idea of uniform light is relentlessly pursued with little understanding of

> the consequences. This approach means our world becomes like an overcast day — gloomy, drab and monotonous — devoid of contrast and definition. Shadowless. This is curious because there are few who would prefer this condition in the natural world over a sunny day when contrast is high, shadows are strong and we are constantly stimulated by the shift of texture and pattern. (Major et al, 2005 p.50)

Around the mid-20th century, evenly-illuminated ceilings became common thanks to the invention of fluorescent light. The Illuminating Engineering Society (IES) mandated standards and the ability to integrate other systems such as air conditioning made this approach quite popular (Marsden, 1972). However, as architects found, the evenly-illuminated ceiling, unless very carefully used, could be too monotonous and too diffuse for sharp perception (Neumann, 2010). This tendency to monotony in lighting schemes has been criticised by various researchers. Lighting historian Alistair Laing said the 'constant level of artificial lighting in modern office blocks is the visual counterpart of the psychologically calculated use of Musak' (Laing, 1982 p.57). The uniform level of lighting plus the need to avoid uncomfortable glare resulted in what many saw as fairly bland general lighting schemes. Marsden rather humorously agreed with Laing, saying that 'glare limitation has led to commercial lighting descending globally to the same level of harmless mediocrity requiring rubber plants for salvation' (Marsden, 1972 p.143).
By suggesting three elements of lighting interiors, i. e., focal glow, ambient luminescence and play of brilliants discussed in detail in Chapter 2, mid-century lighting designer Richard Kelly showed the need for differentiated lighting experiences in an interior (Neumann, 2010). In his TED talk, then Chief of the Design Office of Philips lighting, Rogier Van Der Heide noted the role that LEDs could play in reducing light pollution in the night sky

because they could be placed exactly where needed (Van Der Heide, 2010). Perhaps this role could also be translated into interiors. Some aspects of LED technology previously seen as a challenge in LEDs - pronounced shadows and directionality for example - could, with appropriate design approaches, create the more varied luminous environments where some degree of darkness would have a role.

Ways of seeing 2 – the circadian system

> Technology has effectively decoupled us from the natural 24-hour day to which our bodies evolved. (Czeisler, 2013 p. 13)

The 2002 discovery of photosensitive ganglion cells in front of the human retina indicated that there were photoreceptors that worked independently of the visual system (Donoff, 2008). These photoreceptors are not about seeing things but are connected to the endocrine system as part of the circadian system that governs the 24-hour internal clock of all living beings. Just as we as a species evolved under a certain spectrum of natural light with variations during the day, we also evolved with a cycle of light that governs our internal clocks (Veitch et al., 2010). In summary, the cooler colour temperatures of daylight stimulate our system and the more warm tones of the late afternoon prepare the body for the evening's rest (Czeisler, 2013). Another key difference of the circadian system from the visual system is timing; the visual system is almost instantaneous but the circadian system is extremely slow to respond (Rea et al., 2004). With the advent of more intense (often blue-toned) artificial light which prolongs exposure to bright lighting, there are concerns in the scientific community about the effect of these new ways of living on our health. Research is being undertaken into how exposure to certain types of light in the evening can have detrimental effects on both sleep patterns and health overall (Rea et al., 2010; Czeisler, 2013). There is also concern that this effect is being exacerbated by exposure to the luminous screens of computers, tablets, televisions and mobile phones (Wood et al, 2013).

For thousands of years we humans were ruled by the natural day-night cycle relieved by small amounts of flame-based light at night. Modern light has untethered itself from this dynamic cycle of natural light. This cycle involves exposure to both warm-toned light at the end of the day and enough blue-toned light in the middle of the day to stimulate the circadian system. Sometimes society's desire for energy efficiency has resulted in misplaced lighting strategies. In an interview, Dr Mariana Figuero, Professor and Light and Health Program Director, Lighting Research Center, Rensselaer Polytechnic Institute, NYC, said that the amount of exposure to bright blue-toned light in work places can be insufficient to stimulate the circadian system. This is associated with energy efficiency guidelines that mandate lower levels of light (Figuero, 2010). In many situations, a neutral colour temperature may be selected (3500k) to create a pleasant luminous environment for the *visual* system but the constancy of this colour temperature does not reflect the dynamic quality of natural light which, in the middle of the day, is quite cool (around 5000k) and at the end of the day drops to a warm 2800k.

Several low-tech solutions could be tried to ensure our circadian clock is correctly attuned, such as 30-minute walks at lunch time or red lights at night. The idea of 'darkitecture' mentioned earlier in this chapter could also provide more appropriate environments at night. Better integration of daylight into architecture could also be explored. The role LEDs can play in certain scenarios could also prove to be important, as LEDs are both dynamic in terms of spectrum and controllable in a way that no other light source is. There are already moves to use LEDs to simulate the dynamic quality of daylight. NASA spent more than $11 million replacing fluorescent lighting on the International Space Station with LEDs, so it can control the colour, intensity and timing of lighting to help astronauts sleep better and awake refreshed (Bain & Trevett, 2015). It is important to remember the slowness of the circadian system. Short exposure for a few minutes to red or blue light will not significantly alter the circadian response. In-built systems and better light planning (which could be part of a wider system of control in a household) could also have a role to play. When commenting on lighting design for the future, Dr Mariana Figuero said:

> Lighting design has been focused on vision, but we now know that doesn't meet the needs of our circadian rhythms. The idea is that you would do a full 24-hour scheme that meets the needs of both those systems at once. Circadian systems are more sensitive to blue light. Visual systems are more sensitive to yellow light. We have to start combining lights to achieve a compromise. (Figuero, 2010 p. 43)

Light and architecture

Architects have long held the integration of light and architecture as a kind of 'holy grail'. Recent movements in technology, most obviously LEDs, have the potential to make this connection even stronger. Kjetil Traedal Thorsen, from the internationally-known architecture practice Snohetta and recognised for his redesign of Times Square in New York, believes that 'technology is redefining the relationship between light and architecture' (Halper, 2015 p.8). Architect Daniel Libeskind is also interested in the possibilities of new lighting technologies and feels that this is a good time to be designing buildings with the capacity to harness and create light. It is not about the big fixtures but really about 'a very poetic technology that can help us create something beautiful' (Entwistle, 2015 p. 24). In a recent issue of *Lighting* magazine, lighting designer Doug James discussed 10 key methods for integrating lighting into architecture: the slot, spots in slot, the raft, the back-lit panel, the skylight, the turrell (named after artist James Turrell), the overlap, the wall graze, the skirting wall wash and the floor edge slot. In all applications, LEDs were discussed as a preferred option (James, 2015). The small size and longevity of LEDs make them ideal for a variety of applications, particularly where they are built into the fabric of the building.

How far can the integration between LEDs and the fabric of the built environment go?

> If we could step away from standard practice and conventional applications, we would find that smart materials present unprecedented opportunities to challenge the accepted, and unquestioned, beliefs about how building systems should perform. (Addington, 2007 p. 161)

Writing in 2007, when LEDs were beginning to make an impact in the built environment, Professor Michelle Addington from Yale University charted how the technology had moved from disco floor novelty to a viable architectural lighting source. Addington claimed that the ability of LEDs to convert electrical energy into radiation put them in the category of smart material. She further argued that conventional classifications of materials used in architecture were challenged by the way smart materials behaved. The characteristics of LEDs, namely their narrow spectral bands, precise angles and directionality, tiny size, discrete addressability and reliance on DC power, were at odds with a general lighting system based on a wide spectral bandwidth, diffuse spreading of the light over large surface areas and an AC power supply. Despite this seeming disjuncture, LEDS can actually match the way the eye performs. Addington claimed that lighting design for the eye rather than for the building would result in radically different locations and distribution of LEDs, away from the ceiling and discretely placed within certain angles of view. Architects would ‘be able to “script” the view field, and in so doing, meet visual needs with dramatic reductions in energy use’ (Addington, 2007 p. 161).

New types of lighting scenarios

LEDs are offering new ways of lighting, illustrating that sometimes it is a matter of stepping outside what feels instinctively correct and looking anew at lighting problems. We feel intuitively that large windows are good and our knowledge of the circadian system would confirm the importance of exposure to natural light. But we also have a *visual* system for perceiving light and then glare becomes an issue with large windows. Bright daylight brings too much contrast into the space so we use overhead and task lighting to ‘even things up’ (Stallwitz, 2008). A study found that as window illuminance increases, the probability of switching on lights will also increase by up to 60 per cent to reduce luminance contrast between the window and surrounding areas, resulting in an actual increase in electricity consumption (Heschong et al., 2005).
Another study (Amirkhani et al., 2015) used LEDs to improve user acceptance and visual comfort of typical day-lit offices, and to reduce negative occupant interventions in these spaces by reducing the luminance contrast between the window and the wall. This was achieved by increasing the luminance of the areas surrounding the window using supplementary lighting. A strip of LEDs created a kind of ‘halo’ around a window, thereby increasing luminance on the wall and reducing the contrast between wall and window. Through using a supplementary LED strategy with about 18W luminaire power, the users’ intention to switch on ceiling lights diminished by about 27 per cent and to

roll the blind down by more than 90 per cent. This new approach to solving a lighting problem was made possible by the very specific characteristics of LED technology.

The Trojan horse – LEDs and the Internet of Things

> Imagine a world in which all of a building's subsystems can talk to each other along a unified protocol, and integrate together in a seamless intuitive interface, reacting to the needs of users with minimal effort. (Routlege 2015 p. 1)

The Internet of Things (IoT) refers to a situation where not only phones and computers are connected to the internet but so are many other things, including lighting. LEDs are crucial to this implementation; new installations of LEDs could be installed with necessary sensors to enable IoT systems. In an article in *Lux Review*, Dr Ted Konnerth, a former Vice President of Cooper Lighting, suggested that Stage 1 of LED adoption, where the light source becomes bright enough to supplant other technologies, is over. The next stage is when LED lighting becomes part of the building management system (Konnerth, 2013).

> Lighting is physically distributed across an enterprise, as such it's a perfect vehicle to accommodate other devices that can be integrated into the lighting PC board. So lighting will become the 'great enabler' of other things; which also means the manufacturers of 'other things' will want to have a say in the specification of lighting (T. Konnerth 2015, pers. comm.,12 December)

In a webinar on the IoT run by *Lux Review* (Bain, 2015), it was claimed that 80 per cent of energy consumed to produce lighting could be saved with properly integrated control systems. The IoT can offer many other benefits in terms of controlling building systems, including air conditioning, day lighting, security, motion sensing, monitoring energy consumption, predictive maintenance and many other aspects. The IoT could also be used to control the various lighting scenarios, such as changing colour temperature throughout the day, as discussed here previously.

Various control systems already exist; the IoT is not only about bringing them together but also about generating information, or Big Data, to gain better information about the built environment. It is the Cloud, operational from 2000s, that enables IoT, as the data involved needs to be stored. The key is creating wireless mesh networking where each node can relay data and messages. An example is a network of light fittings with built-in sensors that talk to each other and share data about temperature, light levels, occupancy and so on. These networks can be large or small and can be adapted to generate many different types of information (Maloney, 2015a).

More recent discussions have begun around Li-Fi (data through lighting) where data will be delivered through lighting fixtures. Mark Halper writing in *Lux Review* noted that Li-Fi offers significant benefits as it will use the wider frequencies of light rather than the narrow frequencies of radio in Wi-Fi. This is another technological advance that is still in the early stages but will probably grow as quickly as LEDs themselves (Halper, 2017).

The discussions around IoT, Li-Fi and LEDs have been happening only since 2014. Many more developments, technically and in infrastructure, will be needed before IoT and Li-Fi become widely used. However, there are already many companies that are developing expertise and products in these areas. While the emphasis will initially be on large commercial operations, the movement to small-scale domestic applications will follow. Having followed the history of LEDs as the technology has come to dominate lighting over the past 10 years, I understand that change will come sooner rather than later.

Back to the future with DC.

In the very early days of electricity there was a great deal of disputation as to the type of current to be used. Edison and other distinguished scientists such as Lord Kelvin advocated direct current (DC) and others advocated alternating current (AC). DC was considered safer as the voltages were low (which was all that was needed at that time) and it could be stored in batteries. The disadvantage was the system lost power over distance. AC could not be stored but transformers enabled the current to be transported over long distances with minimal loss of power. Eventually, AC was preferred for large scale generation but DC was used for smaller individual installations (Dillon, 2002 p. 174). Like gas, electricity was initially confined to urban areas. If there was demand for electricity in more remote areas it could be met by the purchase of installations from companies set up for this purpose, but this tended to be for the wealthy. For example, in the United Kingdom, the famous architect Edwin Lutyens installed sophisticated electrical technology into Castle Drogo built for the Drewe family in the early 20th century. The DC electricity was brought to the castle directly from two turbines on the River Teign (Dillon, 2002).
In Britain in 1925 the Weir Committee recommended standardisation and the creation of a national grid, which saw the end of the large number of small DC installations throughout the country. This process involved the conversion of three quarters of a million DC consumers and two and a half million non-standard AC consumers (Dillon, 2002). Electric lighting made its way into middle class homes after 1900. It was not until 1934 with the establishment of the national grid that electricity became available to those on low incomes. Steam and gas tended to be used for industrial purposes until about 1900 and electricity for lighting. Electricity was *invented* for lighting and adopted for industry with innovations, one of the most important being the Tesla AC polyphase motor. The

development of power stations made electricity a more commercially viable energy source for industry. In the United Kingdom, when a standard current was agreed upon, it was 200 – 250 voltage electricity, due to *industrial* demands for higher voltages (Dillon, 2002).
Direct current has made a reappearance in the 21st century, as we are living in a world where DC powers many of our everyday items. LEDs (and tungsten halogens), computers, mobile phone chargers and tablets all use DC. Solar panels generate DC power which can be stored in batteries. To this list could be added solid state refrigeration, heating and air-conditioning, entertainment systems, water treatment and pumps. Even heavier production machinery can be converted to DC devices at a reasonable cost. Ted Konnerth (2015 pers.comm., 19 December) noted that the past few years have seen a few factors which make the 'DC house' a viable option in the near future and listed the following:

- Improvements in battery technologies to store electricity
- solar panels are at a historically low price
- semi-conductor technology has improved so that system losses for charging and discharging batteries are low
- many devices are internally DC
- lighting is moving towards LED, which is DC driven

A DC infrastructure with a battery system would lend itself to a direct feed from an alternative energy source such as solar or wind. This is more efficient than feeding generated energy into a grid. There are energy losses involved when DC devices need to convert to AC for use, so using DC to power DC devices makes sense from an efficiency point of view (Bollmann, 2013). The role that LEDs will play in a possible DC house is critical. The implementation of new infrastructures around lighting and the energy saving possibilities will make economic sense for the transfer to DC. The combination of solar power and LED light is being used in various programs around the world to create light equality. Communities in sub-Saharan Africa or Asia that do not have access to a grid can now use LED products which are directly and individually powered by micro solar panels (Niethammer & Alstone, 2012).

Although a pure DC home could exist off-grid, there is a belief that utility companies will still have a role in providing back-up AC power as well as providing and maintaining DC systems. DC power makes it possible to move into micro-grid construction and eliminate the cost and environmental impacts of huge utility generation (T. Konnerth 2015 pers. comm., 19 December). In a case of 'back to the future', the Edwin Lutyens-type installation that is DC, with AC back-up, may actually reappear.

If the arrival of LEDs could precipitate a change in the way power is generated and provided, there are implications for the building industry itself. Ted Konnerth (2014) sees a change in the structure of buildings (for example, smaller fixtures could result in lower ceiling heights). The need for items such as conduits, steel boxes, transformers and switches will come to an end and trades such as electrical contracting for lighting will cease. The lighting installers of the future will be more aligned to network interface people, possibly using innovations such as Power over Ethernet instead of conventional electrical infrastructure, thus creating another new constellation of actors around the delivery of lighting.

LEDs came from the world of electronics, and their influence on, if not total domination of, the lighting world will continue to grow. The advantages they offer are considerable but people still need to live and work in the environments in which they are installed. What will these environments look like? What will the ways of delivering lighting look like? Will they resemble in any way what we currently understand to be a light fitting? Whilst Konnerth (2013) pointed out the many advantages of the changes created by LED technology, he was also aware of the downside, principally the possible demise of good lighting design. Design was front and centre of the lighting industry in the 20th century but now its role is less defined.

Summary

This chapter discussed the benefits beyond energy efficiency and longevity offered by LEDs.

- In terms of the visual system, LEDs used correctly can offer an escape from the homogeneity of modern light, creating situations of light and shadow.

- In terms of the circadian system, LEDs offer a dynamic spectrum and programmability to create lighting conditions more akin to those in the natural world.

- LEDs offer a closer relationship between the built environment and lighting by having the LED nodes able to be integrated into the building fabric itself.

- LEDs offer innovations outside the realm of lighting. They can be in effect a 'Trojan Horse', whereby their incorporation into buildings can bring internet control (IoT and, in the near future, LiFi) into the building system.

- LED will enable technologies that control data relating not only to lighting but also to other aspects of building management (such as temperature control and power usage).

- A building-wide system of LED lighting, with the energy efficiencies it can offer, can enable the use of DC power for all the power needs of a building. DC can operate directly off renewable sources of energy and offer the possibility of distributed rather than centralised power sources.

Chapter 8.
Findings

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Findings

This research has focused on the role designers can play in the evolving technology of LEDs, exploring the specifics of LED design practice through practice-led experiments. This led to a growing understanding that the type of technological change represented by LEDs raises challenges for both the design and lighting sectors. A series of specific questions were raised in the Introduction. These were: What new design approaches are required to work effectively with LEDs? What is the potential for new lighting applications using LED technology which can make best use of their attributes? What is the nature of the transition to LED technology? What are the implications for the lighting sector of the transition to LEDs? What role will product design have in the future of LED lighting? Chapter 8 discusses the findings in relation to these questions and finishes with a short reflection on the research.

Part 1 of this chapter focuses on design approaches and the potential of design with LEDs. More specifically, Part 1A discusses the findings around a new design approach to work effectively with LEDs. Part 1B discusses the potential for new lighting applications using LED technology that make the best use of LED attributes. Part 2 discusses the impact that the digital technology of LEDs has had on the lighting industry. Part 3 discusses the role of design in the unfolding LED lighting sector.

Part 1A.

New design approaches

The knowledge connected with designing light fittings throughout the 20th century was acquired through working with a set of assumptions, as discussed in this thesis. Designers were able to assume that the light source used would have a pleasant quality without mediation or control and that direct viewing of the light source was acceptable. It was assumed that glare was not experienced by most viewers. Perhaps the most influential assumption was that the light was omni-directional and flowed out evenly in all directions from the light source, illuminating rooms evenly throughout the space. Often a room could be illuminated with one light source, its generous quality creating a soft transition between any differing levels of brightness. If directionality was required it was achieved with reflectors. The practice and research undertaken for this study point to a new set of assumptions that need to be considered when designing with LEDs.

Design approaches for LED

a. Designers need to understand the challenges with LED light

While light over the 20th century needed minimal 'help' to look good (Johnstone, 2007), LEDs have more requirements than other types of light to create pleasant lighting experiences. The light source itself is usually too glary for direct viewing, particularly in interior applications. However, if LEDs are to be viewed directly, it is important that they are not too powerful and are placed appropriately to mitigate the glare. Designers need to understand not only the quality but the shape of the lighting effect. LEDs can direct light over 180 degrees with the use of lenses; however, the 'throw' of the light tends to be long and thin and at 90 degrees to the chip. LED light needs to be given a sense of quality, as it can look cheap and unpleasant if not handled with care. It has a particular strength at illuminating individual items, such as materials, shapes and textures, rather than functioning as a primary light source.

The use of optical principles in designing with LEDs is very important. These principles can mitigate the unwanted effects of LEDs and enhance its illuminating function to create a pleasant light. Dr Ted Konnerth has suggested that as lighting in the future will interface with control systems, there needs to be a close dialogue between the fitting designer and the architectural lighting design (Konnerth, 2013). It would certainly be useful for luminaire designers to think in terms of an architectural lighting design rather than the design of an object alone.

b. Designers need to develop an innate knowledge of LEDs

The question of innate knowledge is more complex with lighting than other areas of technology. As noted by Julian (2011), how we interpret visual experience is strongly influenced by what we have already seen. Everyone experiences light in one form or another from the moment of birth and this experience can be very evocative. During the 20th century, designers working with light sources such as GLS could draw on their everyday experience of artificially-lit environments as well as the tacit, intuitive knowledge built up *within* their own design practices. This combination of everyday experience and expert know-how fed the development of unreflective intuitions and expectations concerning the behaviour of light that are unconsciously held, and therefore difficult to recognise, let alone displace.

LEDs are a new light source and we have not yet acquired intuitions as to how they will behave; we have no history

or tradition of light fittings using LEDs from which we can learn. Hence the designer needs to start from scratch. The way forward requires an awareness and understanding that designers not only need to develop new skills and approaches but also an acknowledgement that we cannot rely on our intuition. In this context, an actively reflective experimental practice can support the development of new intuitions appropriate to this new technology.
The research practice undertaken for this thesis delivered two kinds of knowledge: specific knowledge about how to work with LEDs as a lighting designer, and knowledge about how to acquire such knowledge. The guidelines below focus on the latter. They set out specific knowledge, distilled from the experience gained through this research project, concerning how designers new to this technology can best set about acquiring a feel for working with LEDs as a light source.

1. Sourcing LEDs.

LED suppliers have a great deal of knowledge about available products and future options. There is only a very limited array of LEDs available through conventional suppliers such as electrical wholesalers. Sourcing LEDs through the internet may be a possible first step, however, it is more useful to develop relationships with LED suppliers, as their expertise can be a key input into the experimental process. The sector is rapidly changing and connections with suppliers and keeping abreast of new developments is important.

2. Start with small experiments

It is best to start with small-scale experiments using different materials and examples of LEDs. It is best to keep each experiment simple in order to focus on accuracy, as small changes in the placement and angling of LEDs significantly impact the final effect. It is also advisable to be reasonably methodical. Plan a series of experiments using the same lighting set-up but with different materials substituted to explore different effects, or a series using the same material but with different lighting set-ups. Record every experiment so the different effects can be compared. Being methodical in this way allows the researcher to understand the range of effects that can be produced through small variations to particular configurations. This helps to engender a feel for nuance in working with the technology. It is important that these early experiments are understood as experiments, rather than expecting them to lead directly to the production of a designed outcome. Expectations need to be oriented to learning, not creating, at this stage.

3. Documentation

All experiments must be documented in a methodical manner using photographs, drawings, models and CAD programs. Photography is useful as it exaggerates contrasts in light so can alert the experimenter to the presence of glare. Within a set of experiments, all photography needs to be from the same angle and produced under the same conditions and should be catalogued with accompanying notes of what material and light source were used.

4. Skills

Being able to wire up LED arrays (which are low voltage so reasonably safe) is useful, particularly to get started with small experiments. If the experimenter does not have this skill, they should try to learn from the person that they find to do the wiring for them. Skills in manipulating materials and form are necessary. Computer skills in CAD and 3D modelling can give the experimenter options of exploring different ways of manipulating form in relation to the LEDs using digital manufacturing capabilities.

5. Know what you don't want

Glare and 'hotspots' are associated with LED lighting and it is important to understand where these problem effects are likely to occur in relation to different light source placement and light mediation techniques. The experimenter needs to find ways to mediate the LEDs whilst still enhancing the lighting effects. Any experiments should be viewed from different viewing angles as LEDs are highly directional.

6. Learn by observation

Take active note of LED use in interior lighting installations (foyers, public areas in building, corridors, public restrooms). If a lighting environment is uncomfortable, the observer should question why this is the case and what could be done to improve (e.g, more indirect light using reflective surfaces, lower intensity light in some parts of the area, different finishes). A lot can be learned about the more playful capabilities of LEDs from light art installations at Light Festivals. It may be possible to modify these effects for use in interior contexts.

7. Engagement

The LED industry is developing rapidly. Stay abreast of new developments through the media, conferences and product development presentations.

c. Designers need to work with certain technical skills

LEDs have moved lighting outside the design area and into the engineering and electronics area. (B. Baxter 2014, pers. comm., 5 July)

The freedom created by GLS electric light allowed designers to create interesting light fittings and take risks with form and materials. LED technology, on the other hand, places more demand on design skills and needs more complex technical expertise. A list of the skills needed is given below:

1. Optical control of light

Knowledge of optical principles to optimise or mediate light was not required in legacy sources, due to the intrinsic qualities of the light itself, particularly the light produced by GLS technology. With LEDs, designers need to mitigate certain lighting effects (mainly glare) whilst still creating a usable amount of light suitable for the purpose. Awareness of how the optical principles of reflection, refraction, diffusion and obstruction can be used to control light is necessary to accomplish this outcome. In some cases, the designer may wish to incorporate lenses to provide optical control of the light, so a working knowledge of different lenses and the ability to source the correct model are necessary.

2. Awareness of heat sinks

Unlike legacy light sources such as GLS and fluorescent light, LEDs do not perform efficiently when subjected to internal heat. Without effective thermal management, they will not deliver the benefits of efficiency and longevity, which were the main reasons the technology was introduced (Shailesh et al., 2015). Managing heat with LEDs does not involve the simple approach of allowing an air gap; it requires actively designing a heat sink as part of the LED unit.

According to light fitting designer James Price, from SJB Lighting, designing heat sink size and shape into the design early in the process gives the most effective result. Price notes that while the final heat sink design is a specialist area, there are ways in which designers can build up knowledge by experience, which can then make the final incorporation of thermal management into the LED fitting more seamless. He suggests that mock-ups and experimentation with some commercially available heatsinks are the best start. When the design is developed further, it is advisable to engage specialists in 3D CAD thermal simulation or using an LED whose performance parameters are well known. Laboratory testing is also a possibility, but this process is often expensive and time consuming (Shailish et al. 2015). In addition, well established companies in the LED field, such as Xicato, will often supply specifications for heat sinks. Through the iterative process of designing an LED light fitting, designers can build up a knowledge base of how to incorporate thermal management into their LED designs (J. Price 2017, pers.comm., 7 Nov).

3. LED Drivers

An LED driver needs to be matched exactly with the characteristics of the LED or LED array. Companies that manufacture drivers provide technical specifications for their products and designers must understand how to use this technical information and how to apply it to different configurations. It is not a 'one-size-fits-all' approach. For example, driving a large array of a certain LED will require a different driver to that which powers a smaller array of the same LEDs. Designers also need to consider the design hardware aspects of drivers, such as their placement (for example, remote from the fitting or integrated into the fitting) and issues around both mounting the driver and the final appearance (if remote) of the driver enclosure.

4. Skills in programming

To work with control in LED technology, some programming skills and a knowledge of DMX control are useful. Designers need to understand all the hardware components and how they all work together. Knowing how to work with sensor technology and the Internet of Things (IoT) will be increasingly necessary as lighting design becomes integrated into complex digital systems.

Designers will need to be active in seeking technical support from suppliers and other technical experts, as technologies will change constantly. This means a shift in the self-understanding of the designer from ‘independent creator’ to ‘team-builder’.

A suggested method for designing with LEDs

A back-to-front approach is suggested when using LEDs in the design of a luminaire. The required lighting effect should be considered very early in the process, and the form and materials later. For the purposes of this discussion, I have called the carrier of the LED light source a ‘luminaire’, with the understanding that LEDs can become integrated into the building fabric in a way that may not resemble a conventional light fitting. Based on the experience gained through my research practice, I suggest a process that steps the following questions:

What is the purpose of the luminaire?

LEDs need to be given a specific task, and the luminaire needs to be designed for this task. The designer needs to bear in mind that there is no ambiguity about LED light. It does not flow out to fill a room as do omnidirectional light sources such as GLS.

Five broad functions for lighting can currently be identified:
1. general light
2. background (or transitional) lighting
3. task lighting
4. mood lighting
5. lit objects

LEDs are not well suited to the provision of general lighting; however, because of the assumed need for general lighting, LED light sources have been developed to fulfill this function. An example of this application is the E27 LED bulb. There are, however, issues around the optical distribution of light with the E27 LED bulb, and other technical problems as noted in Chapter 2. To address the needs of a general lighting environment, designers may wish to use a combination of many sources of light distributed around the interior to create an overall illuminated effect. LEDs can perform in transitional and background applications, as the light can be localised, which suits the characteristics of LED light. Volume can be created by using optical principles such as reflection. As noted in Chapter 4, peripheral lighting such as wall washing is associated with impressions of spaciousness and pleasantness (Durak et al., 2006). The crisp light of LEDs is ideal for tasks but needs to be balanced with the need to mitigate glare. Conversely, can the unforgiving nature of the light of LEDs create mood? With the use of dimming systems and effective light mediation techniques it is quite possible. A better match, however, to the modular characteristics of LEDs may be found in the Danish notion of hygge (Chapter 4). Mood and intimacy can occur with the creation of several small, subdued and non-uniform lighting effects working together. Lit objects may include spectacular light fittings or light art – this second area, in particular, is a sector where LEDs can excel.

In designing for these different functions, designers need to be aware of the role of colour temperature. Task light may suit a cooler colour temperature, whilst mood light needs a warmer colour temperature.

The designer needs to consider that LEDs are a digital technology and are naturally suited to a digitally managed system of lighting. This means that LED installations performing each of the functions above can be linked into a system, and dynamically adjust to shifting requirements within a space. Working with LEDs in this way shifts the designer away from the kinds of practice that worked best for GLS and utilises the strengths of LED technology.

a. **What is the lighting effect required?**

The answer to this question needs to be very specific. The following list of considerations provides a guideline:

- how big?
- how intense?
- how sharply defined?
- how mobile or static?
- how controlled/influenced?
- where does it appear?
- what its specific purpose is?
- how it relates to other sources of illumination in the space?

It can be helpful to visualise the interior and the lighting effect, as I did when developing the *Lightlouvre;* I thought about the wash of light along a wall before designing the actual fitting. It is important to be aware of the potential for negative effects to be generated by the LED luminaire, and to plan in advance to mitigate these effects. Negative effects that need to be considered include:

- crispness (where details are highlighted)
- glare
- defined border between light and shadow with no soft graduation
- long light 'throw'
- intensity and directionality (though for some purposes this can be an advantage)

Designers need to consider what combination of optical principles allied to material and form may mediate the negative aspects of LED light.

b. Organise the light source

LED light has a better spread if it is distributed at the source. Where a single LED is used, the negative effects of the sharp shadowing and dramatic highlights become more obvious. If a matrix of LEDs is used, the designer is able to 'design the light source' which may involve organising existing light sources into a particular format. The designer will need to consider how the LEDs can be arranged, in which direction they are pointed, and how they are oriented towards each other. The roles played by the different types of optical control of the LED need to be considered. The designer needs to consider how the primary optic of an LED such as a lens (if there is one) could work in a larger fitting that provides the secondary or tertiary optical control (such as louvres or refractive material). Thermal management also needs to be considered. Designers need to have an awareness that the LED light source will drive the agenda; the luminaire needs to suit LED technology, not the other way around. Throughout the design process, the mock-ups and models need to be created with great care and accuracy as even small changes in the placement of LEDs can make a difference to the final lighting effect.

c. Design/ find best material and form

The combination of technology and aesthetics can make the design of luminaires difficult, even without the particular challenges of LED technology (Tregenza and Loe, 1998). The intensity of light produced by the LED means that material choices for use in mediating this light source are more limited than when working with earlier lighting technologies. The unforgiving, crisp light of LED light will highlight any faults or discrepancies in the material and design. The light itself will certainly not add any warmth and the materials need to give the LEDs a feeling of quality and appropriateness for location. Designers may need to consider using higher quality materials they may not have used before, such as gold plating, brass, bronze, ceramic or wood veneer.

New materials enabled by 21st century technologies, such as nano-composites, and bioplastics may offer opportunities to mitigate the negative effects of LEDs in clever ways. The designer needs to actively experiment with new materials to explore their potential in conjuction with LEDs. Integrating LEDs with 3D printing technologies may create a new relationship between light and form.

In the case of LEDs, the narrow distribution of their light means the light sources themselves need to be placed differently compared to other light sources in interiors. In most situations, designers will need to consider how they can give volume to the LED light. At the same time, the relationship between the LEDs and their mediating form needs to be seamless; the two elements must be considered together.

Historical research into the mediation of earlier light sources through application of the optical principles can provide guidance, but few easy answers. What LEDs require is not the magnification of light (as in conditions of scarce light in pre-industrial times) nor gentle moderation (as in conditions of the abundant light of GLS). What history reveals is the ingenuity involved in the creation of artificial light and illuminated interiors with relatively simple light sources. These older methods may offer some pointers to new design approaches. As previously noted by Konnerth (2013), designers need to think about how light functions in an interior space: shift their approach from that of a light fitting designer to that of architectural lighting design.

Section 1B.

New lighting applications using LED technology

This discussion will include an overview of new applications for LED technology that have been revealed by this research. Each of the practice-led experiments uncovered a number of possible future ways in which LED technology could be used. Chapter 7 discussed innovations offered by LEDs that were, perhaps unexpected but are starting to exercise an influence on the technology.
The practice-led experiments in Chapters 4, 5 and 6 described in detail a number of ways that LEDs could be applied. New applications included an illuminated screen typology which could be integrated into buildings. Traditional material such as lead crystal beads could be illuminated to create bright, glowing shapes which could refract LED light using a custom designed shape of each bead. LED modules could be integrated into a built fabric and then used to create particular effects using the wall as a giant, diffuse reflector. In addition, all these effects could be manipulated, depending on the material used. For example, LEDs can create large three-dimensional shapes and incorporate digital control to create a variety of lighting effects. There were limitations created by our financial resources and the availability of LEDs to suit our specific needs, as noted in the discussion of the practice-led experiments. In all these experiments, however, the challenges of creating acceptable lighting conditions with LEDs were addressed through the use of optical principles as 'frames for practice'.
Chapter 7 discussed the wider potential of LED technology that was *not* recognised when the technology was developed for the lighting market. These potential benefits included a more nuanced approach to lighting, using both light and shadow, and the possibility of including controls

to help create better conditions for circadian rhythms.
New scenarios where LEDs are integrated with both the fabric of the built environment and used with daylighting techniques are other advantages of LED technology that were outlined in Chapter 7. The role of LEDs in the future in terms of the Internet of Things (IoT) and the possibility of a more seamless relationship with direct current applications was also noted.

As noted previously, what was revealed from this is that the real strength of LEDs, as a light source and its capability, lies in using it as a *system*, rather than as an individual light source. If LEDs are used as one bright individual light source (for example, one LED bulb), the designer is likely to default to approaches and outcomes more allied to legacy light sources such as GLS incandescent. The ‘unexpected gifts’ outlined in Chapter 7 cannot be used with the single LED bulb. A *systems* approach is where the innovation will lie. LEDs in the future will work together and with other technologies to offer artificial light, as outlined in Chapter 7.

Designers need to embrace a method that considers the architectural lighting effect as well as the individual light fitting. A variety of lighting approaches is needed, as discussed in Chapter 5, so that in the future, all these light sources will be able to work together in concert, not individually.

Whatever the ongoing developments in LED technology to improve technical and aesthetic performance, the quality of the basic light source will not change. It will still be directional, glary, crisp and hard. The light from LEDs, whether it is delivered via a recognisable luminaire or integrated in some other manner into the built environment, still needs skills around mediation and enhancement. That is because this is a light source that needs *more* design intervention than previous light sources, not less.

Part 2.

Implications for lighting

Early investigations alerted me to the contrast between the enthusiasm exhibited by governments and media around the introduction of LEDs and the *lack* of enthusiasm exhibited by the manufacturers and designers in the lighting industry. Chapter 2 discussed the emergence of LED technology in a framework of different innovation scenarios. Terms and concepts from Actor-network theory were used to delineate the different amounts of disruption and change caused by each innovation scenario. Within this framework, LEDs were identified as causing a major change, as potentially dramatic and far-reaching as the industrialised production of light and the creation of physical distribution networks in the early 19th century. The following discussion is based around the questions about the nature of LED technology and the implications for the lighting sector of the transition to LEDs.

A clash of cultures

> The lighting industry had stagnated for decades, fixated on technologies and typologies primarily innovated during the 1960's. (Koerner, 2012 p. 2)

From the outset, electricity was developed specifically for artificial lighting (DiLaura, 2009, Dillon, 2002, Brox, 2010). Eventually electricity did move into wider industrial applications with innovations such as the polyphase AC motor by Nicola Tesla (Dillon, 2002) but these were by-products of the initial developments. The lighting manufacturing industry stems from a craft-based background. While interested in launching new and novel light fittings for market share, the lighting industry is slow to change fundamental design approaches; rather, it prefers to evolve as fashion, interior design or other influences

dictate. The industry as a whole is by nature conservative and averse to change. The product life cycles have been very long with little difference in product offerings, aside from adventurously designed light fittings, from one year to the next (Johnstone, 2007) Lighting is allied to the building industry which has long lead times on new buildings and works within a set of mandated standards.
On the other hand, LEDs were first developed for direct viewing applications such as indicator lights on machines, traffic lights and score boards. It was with the advent of high intensity blue and then white LEDs in the late 1990s that their applications for architectural lighting became common (Johnstone, 2007, Dowling 2008). The semi-conductor industry comes from a high-technology background that is driven by Haitz' Law (named after Roland Haitz, a scientist from Agilent Technologies). This law forecasts that every 10 years the amount of light generated by an LED increases by a factor of 20, while the *cost* per lumen falls by a factor of 10 (Graydon, 2007). To put it more generally, there is an expectation that the technology will grow in performance at a rapid rate. Standards are not important, it is all about relentless improvements in performance in as short a time as possible. It is a sector known for its aggression and ability to transform industries, the mobile phone industry being a current example.

Evolution vs revolution

> They [the lighting industry] just see the LED as the next lightsource, comparable to halogen 30 years ago, and CFL 15 years ago. They do not realise that they are looking at a new platform (lighting professional R. Geerts 2014 pers. comm., January 21)

Evolutions in technologies have happened before; there are many examples of new technologies being quickly adopted and developed from within the lighting and other sectors. Industry consultant Dr Jack Curran mentioned the invention of the camera and how, once photography was established as a creative area, developments in cameras were more seamlessly incorporated into the photographer's practice. There appeared to be a closer relationship between the artists and the camera manufacturers. Curran maintains that while LED technology offered advantages over existing light sources, it did not appear to be as drastic a change as that of the camera. As a result, lighting designers and manufacturers were able to ignore the technology for many years (J. Curran 2010, pers. comm., October 5).

The lighting industry was also caught by surprise at the speed of LED development. In the early days the lumens per watt (amount of light created related to the power input) was not very high. However, following Haitz Law, LED performance increased exponentially and became a competitive light source very quickly (Graydon 2007); the growing efficiencies of LEDs are noted in detail in Chapter 1 . The rapid innovation caught the industry off guard, a situation likened by Dr Jack Curran to a runaway train, with the semi-conductor industry on the train and creating LEDs with no reference to the form, factors or terminology of the lighting industry. He added 'the LED train pulled out of the station without them. Now the lighting folks are hearing this whistle off in the distance...' (J. Curran 2010, pers. comm., October 5).

The lighting industry's seeming complacency may also be based on past experience of bringing new lighting technologies into the existing infrastructure. As noted in Chapter 2, halogen technology was simply added to the network, offering better performances in certain areas. A similar situation existed with the development of fluorescent technology earlier in the 20th century. What is different about LEDs? I put this question to Dr Geoff Archenhold, a technical writer from *mondo arc* magazine, who responded by saying that with halogen and fluorescent lighting, the technology was essentially the same as before, no new skills were needed and it was ‘evolutionary’. He said:

> … it’s a lamp source that has mains voltages applied to two electrodes and to make a fixture it’s just the design of reflectors and metal work, so all the people working on HID, incandescent, plasma etc could easily understand and design fluorescents into new products. (G. Archenhold 2015, pers.comm., 21 January)

‘Creative destruction’

> With the transformation to LED, there is creative destruction going on. Established players have come into more challenging situations because of this huge transformation that’s not only a technology transformation but it’s also the supply change, it’s cultural, it’s design. Everything’s changing (Pierre van Lamsweerde, CEO of Nordeon Group [Halper, 2017b p. 38]).

> The way to avoid dead ends is to ‘bust your blinders’ or remove the blinkers that will force a company to see the future from the rosy lens of its past success. (Chopra, 2010 p. 10)

The introduction of LED technology could see the end of many existing business models and, in this, the story of Kodak and Polaroid are instructive. Both were companies that relied on consumables (camera film) for the majority of their profits. When digital technology came along they did not respond quickly enough or followed ‘dead ends’ in terms of technology. As a result Kodak as a company was much diminished and Polaroid went out of business (Chopra, 2010).
Similarly, many parts of the lighting sector have been built

on a consumable, the GLS incandescent lamp. With new light sources promising a new type of longevity, this is one of many parts of existing lighting infrastructure that will need to change. In 2014, Philips announced that it would separate out its lighting business, giving it 'independence'. Industry observers were divided as to what this meant, but the consensus was that Philips had wanted to move out of lighting for a while, finding it hard to maintain profits in the face of intense international competition in the light bulb area from new companies that cut costs aggressively to enter new markets (Maloney, 2014). A variety of buy-outs, mergers and sell-offs (including the sale by Philips of its LED chip business Luminleds) were noted in *Lux Review* (Halper 2017). The 'creative destruction' in the lighting landscape continues today and gives little indication of stability any time soon.

Changing business models

There is no doubt that LEDs have posed many challenges for lamp suppliers. The actual manufacture of the LED light source is outside any expertise the lighting industry already possesses. LEDs are basically crystals which are grown (literally) in a mysterious black box to form what is known as a chip or die. This raw chip is then turned into a light source (called an emitter) by being mounted onto a circuit board and often covered with a simple lens (known as a 'primary optic'). These are two separate steps. The third step is when this chip on board (COB) is put into a luminaire that provides secondary or even tertiary optics. The GLS lamp by comparison is a simple piece of technology, a heated filament in a vacuum (Julian, 1987). The creation of LEDs is a more complicated process than the mass production of the GLS lamp and requires new investment and expertise in diverse areas. An additional complication for manufacturers is to decide at what point to get involved in this process, to purchase the basic die or at a later point. If they purchase the die from another maker they then lose control of part of the process.

'Too hard basket'

The lighting industry invested in the retrofit approach where LEDs, CFLS and A type halogens are shaped into incandescent bulbs. The retrofit approach offers advantages in that these products conform to the existing assemblage, that is, the way lighting is sold, and the way it fits into existing light fittings (though often heavily compromised in terms of lighting effect and performance). It will be very difficult and take many years to dismantle and reform this assemblage of actors. However, industry experts are concerned that this retrofit approach is not utilising the benefits of LEDs and is in fact a step backwards. I identified these early concerns at the beginning of the study, as noted in the Introduction (Koerth-Baker, 2009). This situation has not changed over the years, and money and time continue to be invested. Kevin Willmorth (2014) expressed concern as to the cost benefit of this approach, saying that once an investment is made in the retrofit (which would offer some energy savings), the client would be reluctant to invest further, even if a better solution appeared on the market. He also felt that the real culprit were the existing sockets and the need for the lighting industry to keep them. This approach slows down innovation and prevents the LED technology from finding a form that is correct.
He is advocating for a move to fully-integrated fixtures as an alternative to retrofit. The LEDs (sometimes with a primary individual optic or lens) could then be integrated directly into the luminaire without being reshaped into an intermediary form of GLS substitute. In this way, the heat can be managed properly and without compromise, and the LEDs could fulfil their promise of long life. The optics could also be designed to give the best possible light distribution with a combination of primary and secondary

optics, including lenses, reflectors, refractive materials and so on. With newer technologies, the LED modules could be individually controlled wirelessly and change colour and/or intensity on command. They could become nodes in a wider network for IoT or other control systems, as discussed in Chapter 7.

Two networks

> …as firms try to go beyond the socket, they may aim at opportunities both close to, and far from, the traditional industry boundaries. Home automation, fixtures, data networking, and services will all be up for grabs, and the collective effort of firms will determine the new industry boundaries (Chopra 2010 p. 10).

Looking at the current lighting landscape, there are two approaches to supplying lighting, each with their own constellation of actors. One is the legacy network based around LED bulbs, CFLs and A-type halogen light sources that maintain the existing networks in terms of design, marketing, distribution and manufacture. The attempts to delay the phasing-out of the A-type halogen lamp are but one strategy to keep this network of actors intact.
The conventional lighting industry has maintained its dominant place in this assemblage of actors and still relies on designers to produce interesting new products for customers. As time goes by, this assemblage appears to be less and less relevant to the future of lighting.
The second network, the LED network, is forming around the creation of an integrated LED approach that comes from a technology background and does not rely on a single 'bulb' approach. As discussed in parts of this section, the LED network has never been fully integrated with the traditional lighting industry, even from its early days. Now it has developed in a different direction and is

recruiting powerful players from outside the traditional realm of lighting into a new assemblage around artificial lighting. As one example, both Apple and Google are now becoming involved with lighting through the agency of LEDs. The LED network is still in a state of flux, as noted in the previous section, and its final form is unknown.
The traditional lighting industry will find a place in this network, even though sell-offs and buyouts are indicating that the influence of the traditional lighting industry will wane. The role of the lighting industry's great ally – design – is also not certain.

The tipping point

History tells us that sometimes an innovation or development in a new technology can deliver a final knock-out blow to a pre-existing technology that has lingered on, providing unwanted competition. With the development of the tungsten filament in 1910, electricity was finally able to provide illumination levels equal to that of gas (Bijker, 1992). While other developments were also in place, this technical advance made it possible for electric light to replace gas lighting.
LEDs were introduced to save energy; however, to save the *most* amount of energy it would be optimal to have control and data on the environment and how the LED is performing. The IoT (or other forms of systematic control), as discussed in Chapter 7, is considered the way forward not only to harness its advantages but also to introduce other benefits. Will the IoT and associated developments be the knock-out blow to other light sources, including retrofit bulbs? Alex Makdessian (2015) in *Electronics Weekly* makes the point that previously successful technologies, such as desktop computers, digital video recorders and smart phones, reached their individual tipping points with the development of an easy-to-understand user interface. He then asks whether the ability to monitor and control

lighting and IoT devices with smartphones (which is currently being developed) is sufficient to push connected LEDs into general adoption in more appropriate forms. Will these advances provide the tipping point to ensure that LEDs will finally be able to fulfil their full potential?
The emergence of IoT as an example is fairly indicative of the speed with which LED technology has advanced. When checking literature and online resources two or three years ago, I found little discussion about the IoT in regards to lighting. Now the IoT is starting to have an impact, as can be seen in the following examples. In the two-day *Lighting Fixture Design Conference* (organised by *Lux Review*) held in London in February 2017, most of the second day was devoted to the IoT. Industry writer Mark Halper, contributing Editor, *LEDs Magazine,* reported in January 2017 how Acuity Brands (a particularly aggressive player in the LED market) had deployed 40 million square feet of retail space illuminated by IoT lighting. This project was completed in collaboration with Microsoft (Halper, 2017
Given the past behaviour of the lighting industry, I was curious to see how it would react to IoT. Not surprisingly, it has not been particularly quick on the uptake, although many other sectors have been. In a recent interview in *LEDs Magazine*, Paul Hussey, CEO of Harvard Technologies, advised the lighting industry to not 'put off' involvement with the IoT. Hussey said:

> I think the lighting industry needs to pay a lot of attention here. The Googles and the Verizons have deep pockets and they have cottoned onto the fact the IoT is something they need to invest in. Does the lighting industry really want to end up at the very end of the supply chain, where they become a commoditized fixture? Or do they want to own the firmware and hardware that captures more of the value? If you don't invest against commoditization, you will be commoditized (Maloney, 2017. p. 27).

When I wrote the first draft of this chapter, the scenarios around the IoT and the DC house seemed to be something in the future. However, if there is one thing that the history of LEDs tells us, it is that with this technology the future tends to arrive very quickly.

The intrinsic difference in LED technology

What has emerged from this research study is that LEDs are not just a new lighting technology, they are a new *type* of lighting technology. To understand *how* they are a new type of technology, it is useful to look at Hubert Dreyfus' discussion about the internet. Dreyfus points to internal combustion cars as being a technology that, though refined in many ways, still offer the same benefit as when first introduced around the late 1800s. In contrast, the internet has moved beyond its initial purpose of enabling email communication through computer-to-computer connection (Dreyfus, 2009). The internet is now about viewing content in films or music, e-commerce, data storage and in current times the Internet of Things, as discussed in Chapter 7.

LED technology has some similarities to the internet in that its function as a light source is going to be just *part* of the technology's final capability. LEDs will be an intrinsic part of a new world of smart controls, cloud computing, networking, Li-Fi (data through lighting) and generating Big Data. Providing illumination will be just part of the technological offering. In other words, LEDs are a completely different type of lighting both in terms of the light that is produced (noted in Chapter 1) and the nature of the technology itself. The issue for the lighting industry and the design profession is that the network developing around LEDs is being influenced by actors coming from sectors with *no* relationship with design or lighting. The whole aim of the assemblage around LEDs will be different to that of legacy light sources which was focused on providing artificial illumination. The challenge for design is to ensure that its practitioners have a voice in the new world of LEDs, otherwise the illuminated environment will be all the poorer.

Part 3.

How the game has changed for design

With an awareness of the advances offered by LED technology comes the need to understand challenges that a closer relationship between lighting and high technology will bring for designers. This section discusses likely shifts in the role played by the designer, when working with this technology.

Industry expert John Moran, in *Lighting Talk,* lamented that designers had ‘lost that ability to see and understand The Whole Product’ (Moran, 2015). He then listed the different kinds of specialist called upon in the design of LED luminaires, including specialists who work with LEDs, such as an electronics specialist to design the driver, an optical specialist to design the spread of the light, a packaging specialist to design the enclosure and a thermal specialist to control the heat issues.

Moran speculates as to what that consummate designer of the late 19th and early 20th century, Charles Rennie Mackintosh, would think of such a distributed process of design decision-making (Moran, 2015). While Mackintosh regularly worked with craftsmen such as silversmiths, lead-lighting specialists and cabinet makers to realise his designs, the actor-network that the designer of LED luminaires must work with is populated by technical, rather than craft, expertise. Laboratories and measurements, rather than workshops and embodied know-how, provide a significantly different context for design collaborations (Moran, 2015).

Moran's list is concerned with the design of the light source, but the actor-networks supporting LED design will increasingly include technologists concerned with the generation of lighting effects, such as software engineers and interaction designers. The designer has always worked within actor-networks that include multiple areas of expertise and practice but, as Moran has indicated, the new network associated with LEDs is one that feels foreign to designers trained to work with GLS technologies.

The train in the distance

Gas and electricity networks were developed for lighting purposes; their entry into other areas such as heating or electric motors for industry came as by-products well after the initial developments (Dillon, 2002). Whatever the early difficulties with infrastructure, technological issues and 'design lag', lighting always drove the agenda. Design was able to find a place in the actor network by making the technologies acceptable and saleable to the consumer and by managing the complexities inherent in the design of lighting fixtures (Duncan, 1978, Hansen et al. 1994). LEDs, by contrast, come from a high-technology area outside the considerations of illuminating spaces or interiors, and the lighting industry did not engage in the early days of their development. The lighting industry is still using legacy light sources to keep current actor networks, product distribution methods, existing light fittings and even the sockets themselves, intact. As a result, the role of designers seems to be limited to reinventing previous typologies of light fitting. Concurrently, however, other actors are shaping the new network around LED technology and innovation is lying in areas *outsid*e the lighting industry and certainly outside design itself. As Jack Curran noted rather colourfully, the train has not only pulled out of the station but is far in the distance with other [non-lighting] people on board.

Where are the sexy light fittings?

A review of the history of 20^{th} century light fittings tells us that design was at the forefront of creating and innovating in lighting (Hoger, 1997, Hansen et al. 1994, Maurer 2007). Light fittings become fashion statements (Verner Panton), explorations of new technology (*Tizio* light by Richard Sapper), or celebration of the poetic aspects of light (work of Ingo Maurer). The industry has become used to seeing innovative and novel light fittings from *Euroluce, Light and Build Frankfurt* or other major lighting trade shows that have become akin to the annual fashion shows of Paris or Milan. There is also still a desire on the part of consumers for the new and novel, as noted by Oliver Buchan from lighting company Luxiotronic in December 2013:

> I heard more than a couple of comments after *LuxLive* [a lighting show in the UK] about a perceived lack of new and exciting things to see - I suppose such things are subjective. I also get a bit frustrated when people say 'Where are all the sexy fittings? (Buchan, 2013)

Buchan went on to make the point that there was an expectation of the 'new and novel', which may not be appropriate for LEDs. He felt that the focus should be on meeting needs with the best technological and aesthetic solutions (Buchan, 2013). The higher cost of lighting fixtures that integrate LEDs (and possibly other technologies, as noted above) properly, and the longevity of the light source, could mean an emphasis on long-lasting classic designs of high quality materials, perhaps with some modular variation. The use of 3D printing technology to customise may become a way forward to connect lighting and design styles. As lighting becomes more integrated into building control systems, the whole design and delivery of light will change. While there will always be a role for a feature or spectacular light (such as the *Nimbus*), LEDs have a strength as a *system* of lighting rather than as individual sources of light, and the concept of an individual light fitting as we know it may be challenged.

The new sexy

> Groundbreaking stuff has been a bit thin on the ground. Especially when you compare what's happening in other industries. Think of the sophistication of modern cars, smartphones, computers and music. In the lighting industry, we've just got rid of the incandescent light bulb. After, oh let me see, 136 years (Maloney, 2015).

When I started this research study, I assumed that all that was required was a creative practitioner with enough skill and knowledge to break LEDs out of their 'design lag' stage and realise their full benefits. New approaches would be uncovered by the practice-led experiments and lead to the sort of lighting innovations suggested as possible and desirable by many commentators. Readings, interviews and my own practice-led experiments ensured I was aware from the beginning that LEDs created different lighting conditions and offered new possibilities. However, in the early stages of the study, I did not fully comprehend that LEDs were in fact a different type of lighting technology. To use a prior example, GLS, despite its beauty and ease of use as a light source, is in reality a cleaner, brighter and more instantaneous version of gas lighting. Like gaslight, it is an individual, stand-alone light source constantly connected to industrialised supply. Cleaving to this light source (and the copies such as LED bulbs, CFLs and A-type halogens) when other sectors have moved on to a digital world has been detrimental to lighting design and the lighting industry is in catch-up mode. The innovation in LED lighting – its 'sexiness' - now lies with areas such as control, sensors and cloud computing, leading to the question about the role of design in the new assemblage of actors forming around LED technology.

Where is design in the evolution of LEDs

> Leaving aside the locomotive, there is no other instance where form and function are so difficult to combine as in the lamp – but, unlike the lamp, one is not forced to look at a locomotive day and night (Bluhm and Lippincott, 2000 p. 228).

While there is a great deal of discussion and investment in IoT and systems of control, there is very little discussion about what these illuminated environments might look like or how the LED light will be delivered. An internet-based seminar conducted by *Luxlive* magazine and technology company Gooee featured discussion around the advantages of these new systems of control and information for energy saving and other advantages and how LED lighting was integral to this development (Bain and Trevett, 2015). However, this presentation had no discussion of what LED luminaires would look like or what the user experience would be. There was no indication of whether LED light would be delivered through a recognisable luminaire or in some other way (e.g., integrated into the built environment). This is concerning as we are dealing with a light source which by its very nature has some challenges in terms of creating good lighting experiences.
Alec Makdassian (2015), who was cited in Part 2 of this chapter, may indeed be proved correct in his comparison of the adoption of LED technology with laptops, smartphones and video recorders, which became successful once they had better user interfaces. But in some ways he misses the point. Better and more easily understood interfaces may indeed be helpful, but we live in light and with light. Light is experienced in a way that no other technology

is experienced. User experience of light, aesthetics and design will have a role to play in the future illuminated environment. The focus on technical aspects of lighting without understanding the experiential side can still be seen in commercially-available products. There is still commentary on glare and other unwanted aspects of LED technology. John Bullock, technical writer with *Lux Review,* commented rather colourfully in his round-up of the 2016 Frankfurt *Light and Build* exhibition on the 'angry' looking street lights on display. According to Bullock, the street lights were very glary 'directly attributable to the point-source nature of the individual LED module' (Bullock, 2016).

'How Design can Save Lighting'

In his presentation 'How Design can Save Lighting' at the *2014 LED Show* conference, Dr Ted Konnerth argued that lighting designers needed to take their rightful place in the world of LEDs as 'guardians of the bastions of lighting quality' (Peters, 2014 p. 10). He pointed to the great number of new companies involved with LEDs and with these new entrants and the predominantly technical approach to lighting, designers needed to play an active role. Part of this would be a requirement for designers to understand the capabilities of LED systems. The need to define the essential qualities of lighting as it gets integrated into building automation systems, energy management systems and security systems remains (Peters, 2014). In the world of LEDs, it would seem obvious that designers become an advocate for what is desirable from a user's perspective. However, there is no doubt that for designers to earn their place in the conversation, an understanding of what is technically feasible is also necessary. The challenge is that what is technically feasible is becoming more complex very quickly.

What can design offer?

GLS lamps relied on the beauty of the light and the industry relied on the 'sexiness' to keep that assemblage profitable. Purchasing decisions around LEDs will be influenced by factors such as efficiency or system requirements, which are outside the realm of aesthetics and user experience. What will this world look like? How will it be experienced? Whether or not in the future we will be dealing with light fittings or a 'delivery point' for light within a system, many of the issues around light quality, fixture design and appearance in an interior scheme that were discussed in previous sections will still need to be addressed. The comparatively greater complexity of LED technology probably requires a team approach; however, many individual professionals in these future teams may not have the experience, training or even desire to focus on integrating competing interests into a whole.
The ability to bring disparate and sometimes competing aspects together as a coherent whole is something that is part of a designer's training and practice; it is also something that they aim for in their activities, for 'there is a glimpse of perfection in an integrated design' (Lawson and Dorst, 2009 p. 44). As well as working with new assumptions and developing new skills and knowledge around LED technology, designers can use this ability to develop a stronger voice in the new world of LEDs. What has to be recognised, however, is that the voice will be different to that of previous times.

Part 4.

Reflections on the research

I came to the practice for this study with a background in industrial design and experience in designing light fittings. What was useful in the practice-led experiments was my expertise as a *designer* in general, rather than my expertise as a *lighting* designer in particular. The process outlined in the practice-led experiments did not come as a natural development of my prior lighting work but rather represented a complete break. It also represented a move from working alone (my position at the beginning of this study) to working with a more team approach, not only with my design collaborator but also with lighting experts and other professionals associated with LEDs.

The 'frames-for-practice' approach was useful not only for giving structure to the practice-led experiments but also for pointing to a way of designing with light sources that was particularly suitable for LEDS. As noted in Chapter 1, the light from LEDs needs optical control in a way that no other previous light source has done. Using optical principles means that a designer will focus on the area where LED light is the most challenging.

Discussing light

We exist *in* light and, while it is necessary for everyday existence, there is a certain lack of awareness *about* light. This lack of awareness appears to be reflected in the small amount of scholarship around the history of light – something that was noted in some of the sources I drew on. In their forward to their comprehensive catalogue of the exhibition *Lamps of Other Days* at the Smithsonian Institution, Bluhm and Lippicott (2000) mention that there are no 'all embracing histories of light'. This was corroborated by many other writers, including F.W. Robins, who said, 'Having regard to the intimate part artificial lighting plays and has played in family, social and even ceremonial light, it is curious how little attention has been given to its history'. (Robins, 1939 p. 64)

Lighting also appears to be given little importance in histories of architecture or associated areas. Distinguished lighting designers Mark Major and Jonathon Speirs have commented on the shortage of discussion about light in buildings seen in architectural histories (Major et al., 2005). Laing (1982) alludes to the five-volume *Illustrated English Social History* by G.M. Trevelyan, which has *one* line devoted to lighting. This paucity of discussion flows into contemporary times. For example, of the 80 papers presented at the 2015 conference of the Architectural Science Association, there were only *four* presentations that discussed light. One was on daylight, two presentations discussed daylight and artificial light. The presentation I co-authored with Dr Susan Stewart was the *only* presentation to focus solely on artificial light (McDermott & Stewart, 2015). This is surprising as, aside from aesthetic and experiential issues, the whole question of sustainability would appear to make lighting (a great consumer of power) a topic of great importance in the ongoing development of our built environment. The revolution going on in the world of lighting in order to introduce a more efficient light source into the built environment was largely ignored at this conference. I am hoping that this study – and other studies around light– will put issues around lighting in a more prominent place in discussions around the built environment. We have an important technology that offers energy efficiency, longevity and more, as outlined in this thesis. We can only begin to imagine what the long-term future of LED light will be. It is a technology that needs design more than any other light source. I believe design has an important role to play in the future evolution of LEDs, a technology that will always challenge us but can, in the right hands, also delight us.

Appendices

Appendix 1

Figure A.1
Christ in the Carpenter's Shop
(de la Tour 1645)

The age of scarce light

Despite a great deal of ingenuity in the generation of artificial light, it is remarkable how little lighting technology changed from ancient times until the mid-18th century (Laing, 1982, Hayward, 1962, Thwing, 1938). Torches, lamps and candles (using either tallow (animal) fat or beeswax) , which provided portable light sources, were in common use from ancient times (Laing, 1982, Major et al., 2005). In all these applications correct preparation of a light source involved labour and time.
The effort and expense involved in the creation of artificial light meant that many, especially the less well off, went without; for example, Thwing (1938), using data he collected from inventories of wills and inventories of estates, reports, in Essex County, New England, in the 1600s, no less than 40% of homes were without implements for artificial light. Even among the better off, artificial light was considered a luxury and therefore was used sparingly (O'Dea, 1951). Lavish lighting of interiors was reserved for occasions of significant display, such as public assemblies or private parties (Crowe Leviner, 2000). The experience of artificial light in an era of scarce light was quite particular, not only in the lighting effect, but also in the closeness and prevalence of shadows. The light from these pre-industrial sources was only able to illuminate specific areas as is beautifully illustrated in the de la Tour painting Figure A . Pre-industrial artificial light sources provide limited defence against the engulfing shadows and even the wealthy could only buy so much artificial light. With the best light sources (candles and oil lamps), people were still surrounded by 'shadows and darkness after sundown'. (Crowe Leviner, 2000 p.17).

Appendix 2

Why do chandeliers sparkle?

This brilliant lighting effect is due to the chemical make-up of the material and the way it interacts with light. Whilst the speed of light is constant within a vacuum (Maxwell, 1881), it will be retarded in media where there are atoms present. Most clear and colourless objects will not retard light a great deal. On the other hand, diamonds and lead crystal are so densely packed with atoms that the light travels at much slower than in air (Hazen, 1999). When white light enters a refractive material such as lead crystal and slows down, each of the constituent colours that make up white light slow down to a different speed. The light will reflect internally within the medium (TIR) until it is able to escape from a surface. On its escape, the light is often perceived as coloured sparkle (Pedrotti, 2009). Lead crystal beads and diamonds are deliberately cut into shapes with many surfaces to allow the distribution of light and the creation of sparkle. Chandeliers do appear to enhance the light ie. create a greater lighting effect. However, they are really acting as a distributor of the amount of light present – giving volume to the amount of light present.

Figure: A.2
Lead crystal
(Kentfield Lighting 2010, p.5)

Appendix 3 ***Diffusion Lightlovure*** **with feedback from professional subjects**

Categories	**D and G**	**K**	**M and S**	**R**	**B**
	Interior designers	Manager at lighting showroom with background in interior design.	Interior designer (M) and architect (S)	Interior designer specialising in hospitality.	Lighting consultant with interior design background
Describe Light quality produced by artefact generally (As they would describe to clients)	**G** Warm, diffuse light. The softness of the halo versus the crispness of the centre was good. **D** There were three levels of the light particularly seen at oblique angles. One was the halo on the wall, the next was the centre of the fitting with a strong light, the third was the rest of the louvre surface. The graduation between the three was satisfying.	Warm even glow around fitting.	**S** Has glow looks ethereal. **M** Has a halo effect.	Lightweight, soft especially for a LED fitting. LEDs often have a green cast (*this one did not)*.	The light is OK for domestic situation. Not a task light more hallway or mood light. Decorative light.
Light quality in relation to residential	**D** Suitable for contemporary (residential) contexts. Could not tell what sort of light source was used which was good.	Light quality has warmth to it. This fitting has good skin rendering which is surprising for a LED fitting.	OK for high end residential. **M** Ok for residential but depending on cost. M MM Concerned about glare.	OK ambient light for walls. May not be as effective as a ceiling light.	Suitable for domestic residential situations.
Appearance of artefact	**G** The softness of the halo versus the Crispness of the centre was good.. Pleasing to see evidence of the fixings – they were obvious but still quite subtle. The look logical in their placement. **D** It is OK to see fixings coming through (if they were well handled). GF Appearance of artefact is elegant, fresh minimal.. There is a sense of logic to the design.	For a real product the support pins would need to be more professional and resolved. People like simplicity in wall lights. The idea works well. Turned off the fitting blends into the wall. Sculptural. The current fitting blends in with the architecture.	**M** Liked the continuous light – no individual 'spots'. **M** Would prefer no 'V' just floating square.	Liked folded shape.	Liked the form has a sculptural 3D effect. Looks good night and day – it would be OK to leave it on during the day.
How does it function/ work in space. what type of fitting is it.	**G** Could go on the ceiling.	People like simplicity in wall lights. the idea works well. If the light is recessed into the wall it will need longevity as it is hard to replace. Turned off the fitting blends into the wall. Sculptural.	**M** Not a task light – could perform in a hallway by casting light on a person. . **S** Shape lends itself to corridor application in vertical format. There is a dependence on available space.	Liked the effect on the ceiling created by the light fitting .	Not a task light more hallway or mood light. Decorative light.
Specific residential contexts	**G** Could be OK in heritage context as artefact is not 'overdesigned' and fussy in appearance.	Bathroom either side of the mirror. Hallways. This fitting has good skin rendering which is surprising for a LED fitting. Secondary light in living room. Light to watch TV with.	**M** Halls, living rooms. **S** Nightlight, ambient light in bathroom.	Up the stairs, hallways, bedside.	Best for hallways but could work in dining or living room

Potential non-residential contexts	**D** Very good in hospitals - would run it wall to wall in a strip along the top of the wall. Very good in hotel corridors – ceilings in corridors.	Hospitality would love this fitting as it is easy to keep clear. Dust would drop through. Corridors in hotels. Office lobby.	**M** Restaurants. Office reception area – but offices need pendants to give scale	Lobbies, foyers, hotels, lift lobbies. Not in hospitality (restaurants).	Could work in commercial/ hospitality contexts. Maybe not retail.
Critique of fitting (inc. LQ, artefact and how it works in a space.	**D** Could not tell what sort of light source was used which was good. Would not suit single light in middle of room. Need to make sure that the light intensity matched the need of the context. G.	Liked the white no other colour necessary. Edge detail needs to become more sophisticated.	Liked the continuous light – no individual "spots". Was impressed with the amount of light for the length of the fitting.		
Suggestions for design improve - ments , possible placements etc.		Integrate bolts and fixings. They need to become a design feature. Longer lengths might be good for commercial applications. The fitting should definitely not be smaller than current. Horizontal applications could be different.	**S** Could use texture of brick to enhance throw of light.. Modular sizes would be good. **M** Changing RGB colour could work for restaurant. Colour changing to different types of white and cream could be good as well. *Both S and M, when asked specifically, flexibility in length would be good.*	Should offer in any length. If used in a ceiling context open the centre (with small perforations or slots) to transmit more light through centre. Combine with halogen spots and pint sources are other luminaires are doing. If it was suspended from ceiling would need to block ends to mask glare from LEDs. Try and keep clean look.	Need to be longer – more drama and statement. Many of the Belgium and European lights are quite long. There is a need for longer lights.
Any other comments		LEDs (**K** had a look from the side to see if she could see the actual LEDS themselves).	**S** asked about the wattage – he had a metre and we measured it at 7 watts. **M** was curious about how the light would look on a dark wall and brought out a large dark paint sample to see the effect. Both seemed to be concerned about the cost issue – they have tried to sell LED type lights to clients but cost was a barrier.	**R** suggested a type of housing for a suspended version which could mask the LEDs as drawing.	

Appendix 4 *Diffusion Lightlouvre* with feedback from lay people

Question	House hold 1: G & H	Household 2: D & A	Household 3: P	Household 3: P, S, H, Se	Household 4: S
	Located in middle of living area propped up on coffee table.	Located In dining area on top of bookcase	Located in vestibule on hall table.	Located in television room	Located In front room of traditional terrace house
What was the experience of this space with this light in terms of mood and atmosphere?	**G** During the day found it a bit harsh. Too white.	**D** Experience did not change **A** The light was too dim on its own. Liked the light quality better in the morning when it is dark. He was not bombarded with too much light – it was a good transition light from dark to full light. D On its own you notice how cool the light is.	The light redefined the space Created a different lighting environment.	**S** Big difference from the naked bulb. Warmer gentler – something oppressive about overhead lighting. Light coming from the side more romantic – something to do with sunsets. **S** Experience of the room is Calmer with this light - less harsh than previous. Suits this room. P More lighting to create an atmosphere. Creates an effect without dominating	Creates a mood (**S** then referred to her SDS scaling) Pleasant but she was not drawn to it. Ambient. This was not the right space for this light *The space was the front room of a terrace house and full of musical instruments and ornaments. There was an old chandelier hanging in the space.*
How did the lighting effect any tasks that you may need to complete in the area?	**G** On its own not enough for reading but Ok for watching television. **H** in particular likes high levels of light – bright but diffuse. LL was OK as a third light (he had two bright floor lights in the room). **G** felt it worked from certain angles better than others. Having lived with the fitting she liked the different levels of light from different viewing angles. Might suit more confined spaces .Very good hall light. Light would also bounce off other walls.	**D** When they were dining needed to use the overhead pendant.	The light was adequate for passage through to other areas – strong light is not critical. Other tasks in the area such as hanging coats and getting dog lead – light is OK. (the vestibule has a hanging pendant light at the moment) P does not normally have that light on – likes to emphasise the 'outside and inside'. By this **P** meant she has an outside light and a living room light and the vestibule connects the two so doesn't need full light.	S Light is localised – able to ready by it if sitting directly adjacent. P The level of lighting was good to watch TV by but not enough to read TV guide unless you are close to the light.	Not sure the space for tasks (which were usually music practice) or reading. The light was OK for moving around the room on its own.

Could you live with this lighting artefact in that space long term?	G Live with it in hallway.	**D** Need more output – possible make it larger? Likes the way it washes light across the wall. **A** Would prefer a warmer light particularly for tasks such as studying. **D** Did not like the texture of the louvre itself when it was lit up – had some odd colour tones (he mentioned pink tones that became obvious when the light was the focus ie. no other lights were on).	Yes but wonder if the diffuse light would be enough for some extra tasks. Occasionally need a brighter light for older people (parents) find walking stick etc. The light seems an atmospheric light.	Se Would be very happy to have something like this. Imagine is in a few spaces – hallway and staircases.	Not in this room. Stylistically not appropriate.
Overall do you think this artefact suitable for your dwelling in terms of Light quality	Light quality OK but needs to be warmer for living areas.	**D** Not in the lounge area **A** More in the vestibule or entry area	Light quality OK.	**S** Light quality was the best thing about it. Light is diffuse pleasant. Light fitting radiates light – not bright, 'sheds light'. **H** More for a modern house. More for a house that has sharp lines, clean surfaces, no cracks in the wall. Sets a mood for a modern house.(LQ and shape).	Yes like diffuse softness. Appearance of the artefact. Stylistically too modern does not suit interior. Function as a wall light – OK in hallways In living areas prefer unfixed light sources (floor or table light).
Do you think this artefact suitable for your dwelling in terms of appearance artefact?	**G** Felt it had a 'clinical' appearance with the sharp folds. She described it has having a 'modern architectural Look' not 'homey'. H Did not think it would suit a restaurant.	D It looks good turned off too. Liked the "halo" effect but would prefer more uniformity over the spread of light. Andy: likes the variation with the different levels of light.	Appearance of artefact OK. Liked the "folded" louvre shape and the way it integrated into the wall.	S Folds add interest. The way it is folded emphasises the vertical dimension. Likes the way it works in the room – room is a bit of a 'crappy old room'. Artefact adds a classy dimension. Ups the ante.	Stylistically no - too modern does not suit interior
Function of the artefact		D Would like to see it horizontal (he was keen to see it horizontal across the top of the bookcase which was "dead" space). Concerned that vertical louvre may monopolise a wall which could have an artwork. Doug did concede that this was more of an issue in their apartment which was small and did not have a lot of wall space.	But would also like to be able to hang paintings in this area so would need to accommodate this.	S Place light where you did not want a blast of light. Create an effect in a room. Lighting panels in a restaurant – would need candles as well. Not a sole light source.	Could look good in longer lengths and arrange the artefact in multiples. Should have not too many joins Should have not too many joins if it is in larger lengths.

Are there *other* contexts in your home where it would be suitable – any that are unsuitable?	G Could be OK for bathroom in terms of light quality.	D Good for the entry area if large enough (D did try to put the artefact into his entry area as a trial but there was no place to put the board).	Other suitable areas – in stair well where there is a need for some throw of light. Television room – have the *Lightlouvre* plus the television. Don't need bright overhead light. Would be a good alternative to overhead light.	S. Anywhere else – in hallways, sitting room. bedside lamps – either side of the bed. Would be nicer if a bit warmer – definitely not too cold. Don't like the fluoro look. this one has just the right amount of yellow H Imagine it in a corridor - because of shape – lighting is not strong – ok for directing you through the space.	Outdoor . Hallway. Bathroom – because bathrooms can have different styling to rest of house.
Are there any non- residential contexts it could be used in	H Looks formal – could see it in a doctor's surgery.	D Public areas. Possible bathrooms with the crisper cleaner light. (D also mentioned how he liked the earth magnet method of attaching the louvres). A Hallways. Too harsh for restaurants. Sees it more as a utility or public type of product. Doug: liked the 'sci-fi' look – the idea of the light coming out from under objects.	Could see it in a hotel corridor. Areas that need some illumination but not too much. Bedrooms – when not too much light is needed (changing etc).	H Put writing on the gull wings – house number, advertising. Not in a shop – too relaxing. Perhaps in upmarket boutique – 'chill area'. where you did not want a blast of light. Create an effect in a room. Lighting panels in a restaurant – would need candles as well. Not a sole light source.	Entertainment foyers. Opera house, concert hall. Staircases
Any other comments on the artefact, light or this process	G The artefact is too formal for this space – but needs more form to be a feature light.	A found some of the SDS a bit difficult – not quite understanding the terms etc. *(perhaps more briefing is needed)*. Found the use of terms like artefact which could be 'jargonistic'.	Quality of light is OK not too bright or dim.	This light has made S rethink the idea of an overhead light.	Could work in arcades and walkways.
How would you define your overall attitude to lighting generally. It is of some interest in your own home or in other interiors that you may visit?	G and H bought two new floor lights when they moved recently. H likes light to complement the space. Likes hard light in kitchen as it is a work space. H likes a brightly lit ambience – with warmer lights in the living room and bedroom. He feels it is important to for the light to feel right for the space.	A Considered himself a 'light novice'. He had never really interacted or thought about lighting until recently when they started living over a lighting showroom. He liked the lights that had interesting form (mentioned the Ross Lovegrove Mercury light). D Had some exposure to lighting with his work in exhibition and environmental design but does not specify or buy lights professionally.	P feels that lighting is important in a house. She has bought lamps etc for the house but has not invested in serious lighting (except for parts of the house where there are new renovations such as bathroom and studio at back). She feels that people don't tend to light their houses well – she would like to get professional advice.		S described herself as very interested in lighting and how different lights work. Has purchased lighting pieces including the large scale Artemide light in the corner which she sees and as investment piece which could last for many years.

Appendix 5 - *Reflection Lightlouvre* with feedback from professionals					
Categories	**D & G**	**K**	**M & S**	**R**	**B**
	Interior designers	Manager at lighting showroom with background in interior design.	Interior designer (M) and architect (S)	Interior designer specialising in hospitality.	Lighting consultant with interior design background
Describe Light quality produced by artefact generally (As they would it describe to clients).	D Hard edged. More complex and interesting than plastic louvre. The play of light and shadow adds a layer of interest. No nonsense, like something out of [the film] 'Metropolis'. G Cold Hard	Dramatic, 'love it or hate it' K did not like the streaks of different coloured light. Preferred the halo effect from the previous light. Could be difficult to sell. Possible outdoor application.	M Would describe it as a lighting feature – interesting play of light and shadow effect' of light on the wall. S Material was harder – light quality harder.	Like the variations – stripes. The distortions on the wall are good. Perforations would be good.	More of a dramatic statement. The metal louvre more commercial however, it could be specified as a feature light but the interior would need to be designed around it. Metal version more for the architectural/ designer market – it would be a specified product.
Light quality in relation to residential			S Not as successful as the first light – 'strange warm band'. Variation in reflections and the uneven aspect a problem. M Would prefer without the yellow light. Likes the contrast between the front and the reflected light. Could go outside – external wall.	Interesting pattern could work well.	The metal louvre more commercial however, it could be specified as a feature light but the interior would need to be designed around it.
Appearance of artefact		Likes the metal Sculpture rather than a fitting.			Metal version could do with a tiny external spot to highlight the brushed stainless.
How does it function/ work in space. what type of fitting is it.	G Appeal is the amazing reflections up the wall. The light could also show up irregularities in the wall. Extra bang for buck in terms of light on a wall. Can do different lighting effects would be a good feature light.				One off dramatic feature light.

Specific residential contexts	D Less likely to use in residential contexts. Use in all sorts of commercial contexts.	Would only suit a very modern project with the light 'stripes' and stainless steel. Hard. Could work outdoors – night light for front door or corridor.		Suitable for exterior if IP rated (water-proof).	
Potential non-residential contexts	D Suitable for commercial contexts Look good at the end of a corridor in an ad agency. Generally very good hall light There is a problem with corridors which are usually quite dull so this light could provide some options.	It does not give out as much light as previous diffusion. Restaurant mood lighting. Corporate look. Where you don't need much light – decorative aspect. Elevator lobby Need vast space / high space.	M Restaurant – you don't see the glare. 'comes alive at night'. Could be used anywhere. Would prefer the louvre to have some curves.	Hotel applications (same as diffusion louvre). In common areas. Commercial building – entry into car park. Way finding. Mirror finish not necessary on underside (from her experience). Good to offer options on finish.	Metal version more for the architectural/ designer market – it would be a specified product.
Critique of fitting (inc. LQ, artefact and how it works in a space.	Need to design context around fitting.		S mentioned that he liked Louis Poulsen designs with the curves. *(I mentioned that the original concept had curved 'gull wings').* He liked that idea.		Metal version could work in hospitality – also in horizontal format around the top of banquette seating etc.
Suggestions for design improve - ments , possible placements.	D Decorative context may be with bronze or different finishes. G Could do bronze. Bright chrome front would break up the dark face and lighting the appearance. Mix the plastic and metal louvres in an installation. Also have some sort of slot to break up the dark surface. Must allow interior designers to 'play' with different lengths. Turn it into feature lighting – could have a connector piece. Could also fit into niches in hallway.	Suggested playing with perforations to relieve the front. Higher gloss front. High gloss white or black. Perforations can create a 'reveal' – great potential for perforations as the currently light is not getting through. Bronze for residential. *(Wood was suggested).* K liked that but it would be good to keep crispness. Also, vary the finish across the stainless steel eg. matt finish in V , highly polished on wings.	*(In response to the suggestion of perforations).* S Did not like the idea of perforations thought it would look "tacky". Worried about the 'pointyness' of the metal – looked a bit dangerous. Not friendly. *(I mentioned that to get the curved effect you could put on a separate 'cap).* S This would not be truthful to the design. Louvre could be painted white. M Suggested timber veneer (she brought some timber samples out). *(I suggested that you could put a high gloss finish on the underside of the timber louvre to give the specular reflections).* S Corten TM could be interesting as well.	Perforations. Bronze, brass all metal finishes. Coloured stainless steel *(R showed some samples).* Perforated steel For ceiling applications perforated down the middle (in the V) as the glare from the LEDs would not be apparent unless one looked directly up which is rare.	Metal version could be customised with perforations etc as an option only. Metal one could also have numbers cut into it as door numbers.
Any other comments			Both M and S did not like the fact that the reflection either side of the louvre was not exactly the same either side.		

Appendix 6 ***Reflection Lightlouvre*** **with feedback from lay people**

Question	**House hold 1: G & H**	**Household 2: D & A**	**Household 3: P, S, H, Se**	**Household 4: S**
	Located in middle of living area propped up on coffee table.	Located In dining area on top of bookcase	Located in vestibule on hall table.	Located in front room of traditional terrace house
What was the experience of this space in terms with this light in terms of mood and atmosphere?	Liked the light quality (she then referred to the SDS she had completed). She described it as relaxed and soft. At the time of our discussion G had the metal light louvre and one other floor light – she found that relationship worked well. She felt it was not as strong as the diffusion light – she found it more appropriate. Not in your face!	D Likes it off as an object A Less functional than previous (diffusion) light. More interesting light effect. Did not emit enough light to change room.	The spread of light was not as effective as the first model – the light was localised. More of a dramatic statement. P has many people (family and friends) that pass through the vestibule area. She stated that people tended to comment on the light more – they stopped and looked. They were curious about the light sources (what was it etc). They were interested in the pattern created.	Liked shape. Had a strong reaction – less inviting that previous. Drew you in less. Liked the reflection effect up the wall
How did the lighting effect any tasks that you may need to complete in the area?	G saw the artefact as a night light and felt that for that task the light would be adequate and appropriate (ie not too bright to dazzle the eyes). She would have it on all night.	D With television on, if this is the only light it is OK. Needed to put on more lights on for dining.		Able walk into the space but play not instruments.
Could you live with this lighting artefact in that space long term ?	Light quality OK for the space.	D Visually like it but too severe for lounge room. But Ok as feature light – could contribute to built environment. AR Could not live with it prefer diffusion model.		No
Overall do you think this artefact suitable for your dwelling in terms of Light quality	Prefer it to be warmer looking but it is atmospheric. Ok for watching TV or similar.	A Interesting but not functional. D Cool patterns but light quality not comfortable.		OK in certain areas More of an outdoor application Feature light in stairwell Or anywhere you need a feature light.
Do you think this artefact suitable for your dwelling in terms of appearance artefact	Needs to look less industrial , more domestic particularly for during the day . Could look good with pattern or in white. Would not purchase it in current metal version	D Likes appearance when off. Folded surface had nice shadows.		Does not like solid metal Screens the light More formal/ more public

Function of the artefact	Ok but wondered about cleaning – particularly as I used gloves to put it on the magnets.	D Could be outdoor or feature light, Dramatic effect.	.	Likes the shape and lighting effect but more public setting would be better.
Are there *other* contexts in your home where it would be suitable – any that are unsuitable?	Hallway – and would leave it on all the time.	D Suit a big place. Alcove or hall – would draw eye to the end of the hall. Attention demanding Clash with domestic . Styling of house needs to be more severe to suit it. A The stainless steel appears to block the light it is counter intuitive.		Outdoors Feature light more than the diffusion model. The diffusion louvre blends in more.
Are there any non-residential contexts it could be used in	Nightclubs Definitely not a doctors surgery (like the previous one). Looks festive, fancy, atmospheric. Could be in upscale modern restaurant. Demands attention	D Public walkway, corporate lobby if matched decor. After hours Light. Change of material at front could change the mood. A Cinema in the foyer		'Long strip' like an artwork Feature light in a restaurant. Corridor, staircase on its own or multiples dispersed. Reminded S of Daniel Behrans (Burrans) who is a light sculptor in the manner of Dan Flavin.
Any other comments on the artefact, light or this process	Light looks good from all angles. G thought it could look good but need to watch angle so no glare spots appear from LEDs. G liked the light quality from this artefact more than the previous one – the light was more even.	D Perforations could relieve the dark rectangle. Feather perforations to the edge. Laminate a softer material on top – a softer texture. Curved instead of straight gullwings. Separate reflector from cover for great flexibility.		Using wood would be interesting but could be too fashionable. Metal too corporate. Suggested it could be painted white but SP did not like painted metal. Ceramic would be interesting - give warmth – for example unglazed porcelain. She also mentioned that she does not like acrylic in the diffusion louvre but in that context it did work. Stainless steel ok but not in living room context. Adding perforations could look too 'techo'. Marine ply a possibility.

Glossary of lighting terms

AC (alternating current): reverses direction a certain number of times per second (100 in Europe) and can be converted to different voltages relatively easily using a transformer. AC power can be 'stepped up' and transmitted over long distances on suspended wires and then 'stepped down' for usage.

A-type halogen lamp: a small glass capsule with a halogen light source mounted in a larger globe that is the same shape as a GLS lamp. A-type halogen lamps were created in the 1970s and have been used in the early 21^{st} century as a GLS lamp replacement. See also Halogen lamp.

Adaptation: the process by which the retina becomes accustomed to more or less light than it was exposed to during an immediately preceding period.

Addressability: the process by which individual LED nodes are addressed (like computers and printers in a network) and can be controlled as separate entities. This allows precise control of large numbers of LEDs in an array.

Arc lamp: a discharge lamp in which the light is emitted by an arc discharge.

Ballast: a device used with an electric-discharge lamp to obtain the necessary circuit conditions (voltage, current, and waveform) for starting and operating.

Binning: a physical sorting of LED lamps of similar voltage, lumen output and colour temperature. The individual bins are then priced and sold commercially based on desirability and availability. See also SDCM

CFL (compact fluorescent light): fluorescent lamp designed to fit GLS lamp holders.

Chip on Board: a bare LED chip that is mounted directly onto a printed circuit board (PCB).

Colour rendering index (CRI): the degree of colour distortion under a given light source in comparison with a reference light source. The optimum colour rendering index is Ra = 100.

Colour temperature (CCT): measures colour temperature of a light source according to Kelvins (k). 4000K is cool and 2700–3000K is warm.

Contrast: the difference in the luminance or colour of two objects or of one object and its surroundings. A visual task becomes increasingly difficult as contrast decreases.

DC (direct current): where the electric current flows in one direction only and is used in low voltage circuits. DC is used to power low voltage devices such as computers, LEDs, solar cells and electric vehicles. Direct current is not easily converted to higher or lower voltages and was considered not suitable for transmission of power over long distances. However, methods have recently become available for converting direct current to higher and lower voltages.

Diffuse light: the light emitted from large, luminous surfaces to produce a soft, uniform lighting with low modelling and brilliance.

Diffuser: an optical element for dispersing rays of light in order to give a soft light beam. Fitted to a luminaire, the diffuser reduces the lamp luminance and can reduce glare.

Digital lighting: lighting that uses electronics (similar to those used in computers) rather than either incandescent or discharge technologies to create light. LEDs are an example of digital lighting.

Diffuse reflection: The process by which incident flux is redirected over a range of angles resulting in a soft, reflected light.

Disability glare: the effect of stray light in the eye whereby visibility and visual performance are reduced. A direct glare source that produces discomfort can also produce disability glare by introducing a measurable amount of stray light in the eye.

Discharge lamp: a lamp in which the light is produced, directly or indirectly, by an electric discharge through a gas, a metal vapour or a mixture of several gases and vapours. The fluorescent lamp is an example of a discharge lamp .

Discomfort glare: a type of glare that produces discomfort. It does not necessarily interfere with visual performance or visibility.

DMX (digital multiplexed): the digital control protocol most often used in lighting control.

Downlight: a small direct lighting unit that directs the light downward. It can be recessed, surface mounted or suspended.

Driver: see LED driver

Efficacy: see Luminous efficacy

Electroluminescence: the non-thermal conversion of electrical energy into light energy. This phenomenon is used in LEDs, OLEDS and EL lamps.

EL Lamps (also known as high field electroluminescent lamps) use current through a phosphor to create light. This technology can be formed as a flat plane and is used in display applications.

Fluorescent lamp: a low-pressure mercury electric-discharge lamp in which a fluorescing coating (phosphor) transforms some of the UV energy generated by the discharge into light.

Gasolier: A gaslight chandelier from gas + -elier (as in chandelier). Alternative form gaselier.

GLS (general lighting service): see Incandescent lamp

General lighting (or general illumination): lighting designed to provide a substantially uniform level of illuminance throughout an area.

Globe: a transparent or diffusing enclosure intended to protect a lamp, to diffuse and redirect its light, or to change the color of the light.

Haitz's Law: named after Dr Roland Haitz. Long considered the parallel of the semiconductor industry's Moore's Law, Haitz's Law asserted an exponential increase in lumen output from packaged LEDs and a corresponding reduction in dollar per lumen. Roland Haitz first publicly postulated Haitz's Law at the Strategies in Light conference in 2000.

Halogen lamp: an incandescent light source made of a tungsten filament within a small glass envelope filled with halogen gas. Halogen lamps have a slightly higher luminous efficacy and longer functional life than GLS incandescent lamps.

Heat sink: a metal heat management component for LEDs which uses convection heat transfer from a solid to a moving fluid (the fluid being air) to dissipate heat from the LED.

Incandescent filament lamp: a lamp in which light is produced by a filament heated to incandescence by an electric current.

Internet of things (IoT): this term refers to the connectivity of a variety of devices through internet-based control.

IP Rating: Ingress protection rating refers to as specific set of numbers that refer to a products ability to prevent intrusion from water, dust and solid objects.

Junction temperature: the temperature at the p-n junction (see p-n junction below) in an LED. Desired light output and service life can be ensured for a LED luminaire if the p–n junction of the LEDs is maintained within a specified temperature band and the heat generated is dissipated away from the p–n junction to the heat management system (see heat sink).

Kelvin: see Colour temperature.

Lambertian surface: a surface that emits or reflects light in accordance with Lambert's cosine law. A lambertian surface has the same luminance regardless of viewing angle.

Lamp: a generic term for a source created to produce optical radiation. By extension, the term is also used to denote sources that radiate in regions of the spectrum adjacent to the visible.

Lamp cap: lamp component through which the electrical connection to the lamp holder of the luminaire is made.

LEDs (Light Emitting Diodes): solid state diodes (active devices with two electrical terminals) made of p- and n-type semiconductors operated on low-voltage DC power. LEDs produce a narrow band spectral range of light.

LED driver: device that acts as a power supply for LED modules, regulating output voltage or current for the light source. It transforms and conditions incoming power (typically AC, but it may be DC) and drives the current to the LEDs. The driver is a critical component of the LED lighting system as its design affects operation, presence of flicker, service life, controllability and ability to withstand power surges.

Lens: A glass or plastic element used in luminaires to change the direction and control the distribution of light rays. The radius, curvature and surface texture of the lens determine its optical properties.

Li-Fi (or visible light communication, abbreviated to VLC): process whereby LEDS (which can switch on and off at a high rate) are used as a medium to communicate data. This method overcomes the limitations of wi-fi communication which has to fit in with existing radio frequency availability.

Light fitting: see Luminaire.

Lighting control: enables the lighting of space or the creation of an effect to be adjusted to suit different 'scenes' or patterns. The information is stored electronically (sometimes using DMX).

Light mediation: process whereby light is redirected, redistributed or altered, usually by using the optical principles of refraction, reflection, diffusion and obstruction. Light mediation is often used to make light more acceptable to the viewer.

Local lighting: light that provides illuminance over a relatively small area or confined space and with little if any significant general surrounding lighting.

Louvre: a single opaque or translucent element to shield a light source from direct view at certain angles, to absorb or block unwanted light, or to reflect and redirect light.

Lumen, lm: unit of luminous flux.

Luminaire: an object containing a lamp to provide artificial illumination. The luminaire gives the lamp physical support and protection, encloses any electrical gear and provides optical control.

Luminous efficacy: quotient of the luminous flux emitted and the power consumed. A unit of luminous efficacy is expressed as lumen per watt or lm/W.

Luminous flux: expresses the total light power emitted by a light source. It is calculated from the spectral radiant power by evaluating this with the spectral brightness sensitivity of the eye. A unit of luminous flux is expressed as lumen (lm).

Matte surface: a surface from which reflection is predominantly diffuse, with or without a negligible specular component. See Diffuse reflection.

MR-16 downlight: a type of lamp, specifically a low-voltage halogen reflector lamp sealed in an exterior, parabolic reflector. The lamp and reflector form an integrated unit and are frequently track mounted.

OLED (organic light emitting diode): a light source made of a layer of organic (carbon) electroluminescent material with a p/n junction sandwiched between two electrodes. Light is created in the same manner as LEDS, albeit with a flat plane format rather than points of light.

Optical control: the means by which light output from a light source has the required distribution. In luminaires this is achieved by one or more of the following principles: obstruction, diffusion, reflection and refraction.

Photometry: the measurement of quantities associated with light.

Photopic vision: (or day vision): This involves adaptation of the human eye to high luminances. Photopic vision is performed by the cone cells and is therefore concentrated on the area of the fovea. The visual acuity is high and colours are perceptible.

Power over Ethernet (PoE): a method of providing power through Ethernet cabling (known as Cat 5 or Cat 6 cables, often blue but can be grey, green, white or yellow in colour) and normally used to connect the internet to routers or computers. These cables were designed to carry data but if the electrical load is low enough they can deliver power and communicate with fixtures – such as LEDs - at the same time.

Recessed luminaire: a luminaire mounted into the ceiling or behind a wall or other surface so that any visible projection is insignificant.

Reflector: a device used to redirect the flux from a source by the process of reflection.

Refraction: the process by which the direction of a light ray changes as it passes obliquely from one medium to another and in which its speed is different.

RGB (Red Green Blue): the RGB colour mixing used in lighting technology is based on additive colour synthesis to produce light of different colours.

Standard Deviation Colour Matching (SDCM): a method for perceiving and separating different colours developed by Kodak scientist, Dr David Macadam, in the 1950s. His work characterised human population variation and individual temporal variation in colour perception, along with mapping these differences onto the colour space.

Scotopic vision: night vision involving adaptation to low luminances through the rod cells that are mainly in the periphery of the retina. With scotopic vision, visual acuity is low and colours cannot be perceived, but there is high sensitivity to the movement of observed objects.

Solid State Lighting (SSL): see LEDs.

Spectrum: distribution of the radiation intensity of a light source over a specific range of wavelengths. Both colour of light and colour rendition are a result of the spectrum.

Specular surface: surface from which the reflection is predominantly regular. Specular surfaces tend to be shiny and smooth.

Suspended pendant luminaire (or pendant): a luminaire that is hung from a ceiling by supports.

Task lighting: in general, this refers to the lighting of workplaces to suit visual tasks.

Thermal management: refers to the practical steps taken by designers of LED lighting products to ensure that heat is conducted away from the light producing junction (p-n) within an LED.

Translucent: transmitting light diffusely or imperfectly.

Transmission: a general term for the passage of radiation through a medium without change in frequency. Transmitting materials range from clear to diffusing.

Transparent: having the property of transmitting rays of light through its substance so that bodies situated beyond or behind can be distinctly seen (as opposed to opaque and usually distinguished from translucent).

Tungsten-halogen lamp: see Halogen lamp.

Typology: organisation of products according to classes or categories of specific types.

Visual comfort: describes lighting quality in terms of parameters such as illuminance, elimination of glare and colour rendering.

Volt: unit that indicates the difference in electrical potential between two points in a circuit. It is also called the electromotive force.

Volume: in the applications discussed in this study, means the amount or quantity of light as perceived by the viewer. To give light 'more volume' means to make it look larger or to illuminate a larger area.

Watt: physical unit of power. One watt is the power produced by a current of one ampere across a potential difference of one volt.

Organisations

CIE: International Commission on Illumination (French title, the Commission Internationale de l´Eclairage). It was established in 1913, is devoted to worldwide cooperation and the exchange of information on the science and art of light and lighting, colour and vision, photobiology and image technology. It is recognised by the International Organisation for Standardisation (ISO) as an international standardisation body for lighting. The CIE holds conferences, symposiums and presentations and publishes standards. Further information is available at http://www.cie.co.at/cie

IESNA: The Illuminating Engineering Society of North America. It was founded in New York City in 1906 and its stated mission is to improve the lit environment by bringing together those with lighting knowledge and by translating that knowledge into actions that benefit the public. Members of the IESNA are regarded as professionals in their industry and are globally respected for their knowledge Other countries have set up similar societies, such as the Illuminating Engineering Society in the United Kingdom. Further information is available at www.ies.org

IESANZ: the Illuminating Engineering Society of Australia and New Zealand, established in 1930s during the Great Depression. IESANZ public policy efforts involve uniting the voices of lighting professionals to contribute to practical energy policies in Australia and New Zealand. Further information is available at http://www.iesanz.org/

IALD: the International Association of Lighting Designers, founded in 1969 in the USA. It is an internationally recognised organisation dedicated solely to the concerns of independent, professional lighting designers. The IALD strives to set the global standard for lighting design excellence by promoting the advancement and recognition of professional lighting designer. Further information is available at https://www.iald.org/

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