Prototyping Models of Climate Change

New Approaches to Modelling Climate Change Data

3D printed models of Climate Change research created in collaboration with Climate Scientists

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Kate Dunn

The University of Sydney

Faculty of Architecture, Design and Planning

Supervisors: Professor Michael Tawa and Dr. Dagmar Reinhardt
Declaration of Originality

I certify that the intellectual content of this thesis is the product of my own work and that all the assistance received in preparing this thesis and sources have been acknowledged.
Kate Dunn
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(Journal article)
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(Book Chapter)
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Alexandre Dubor, Gabriel Bello Diaz, Guillem Camprodon, Dagmar Reinhardt, Rob Saunders, Kate Dunn, Marjo Niemelä, Samantha Horlyck, Susana Alarcon-Licona, Dylan Wozniak-O’Connor, and Rod Watt, 2016
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Contributing Author.

As supervisor for the candidature upon which this thesis is based, I can confirm that the authorship attribution statements in this thesis are correct.

Michael Tawa

30th June 2017.
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Abstract

Prototyping Models of Climate Change: New approaches to modelling Climate Change Data, investigates a research topic with significant social and global relevance around the modelling and representation of climate change data. Specifically, the project identifies a gap in the existing knowledge on the topic of three dimensional creative visualisations of data on the impact of climate change.

Communication, visualisation and dissemination of scientific research data to the general-public is a priority of science organisations such as the Australian Commonwealth Scientific Industrial Research Organisation (CSIRO), evidenced by their employment of communication and marketing specialists. Creative visualisation projects that aim at meaningful cross-disciplinary collaboration are urgently needed, both from a communication standpoint and, to act as models for agile responsive means of addressing social and environmental change.

The visualisation of the effects of climate change in multiple ways expands the potential for understanding across a broader societal range than is possible through current pathways such as academic scientific journals. Many people find making sense of statistics or reading graphs and charts difficult. In contrast, creative visualisations, and specifically three-dimensional models of the science, can give audiences alternate and more direct means of understanding information by engaging visual and haptic experience. This project contributes new knowledge in the field by way of an innovative framework and praxis for the communication and dissemination of climate change information across the disciplines of contemporary art, design and science. The focus is on outcomes that provide enhanced awareness and knowledge of the connections between the disciplines and the potential for mutually beneficial relationships that can effectively and affectively, communicate climate science research between the disciplines and the general-public.

Through a series of collaborations with climate scientists that act as case studies, the research investigates methodologies and techniques for modelling and fabricating three-dimensional artefacts that represent climate change data. The data being modelled is sourced from climate scientists at Macquarie University, the CSIRO and the University of New South Wales (UNSW). Data is supplied in numeric, visual and textual form. The collaborations and the research outputs are evaluated using boundary object theory. Expanding on existing boundary object categories, the research introduces new categories with parameters specifically designed to evaluate creative practice\(^1\)- science collaborations and their outputs.

\(^1\) In this thesis, the term ‘creative practice’ refers to the activity of artists and designers of various kinds, including architects and visualisation experts, who produce artefacts. A detailed description is given in chapter one, section 1.6.
The fabrication methodologies of the research artefacts particularly focus on 3D printing techniques for system-inherent capabilities for accurate and repeated transfer of numeric data to 3D form and shape. A distinctive contribution to new knowledge is the development of systems and materials for 3D printing that embody principles of sustainable fabrication. The artefacts or visualizations produced as part of the research project are made from sustainable materials that have been rigorously developed and tested. This aspect is critically important to ensure that, in visualising climate change research, the artefacts themselves — in their material presence and aesthetic qualities – evidence sustainable principles and are seen not to contribute to climate change.

This research proposes that the material, aesthetic, tactile and transformative qualities of objects and the context in which they are displayed offer alternate opportunities for interactions with the data being modelled. Generally, when scientific data and research are communicated through industry and scholarly journals and textbooks, a common format used is spreadsheets of numbers or graphs followed by summary paragraphs explaining the implications of the data. The objects fabricated as part of this research project are not intended to replace numerical data, rather to supplement knowledge transfer in a suite of communication methodologies designed to advance ongoing public education and engagement with current developments in science.

The objective is to produce a series of visualisations using different scaling and fabrication methodologies, made in collaboration with climate scientists, with a focus on sustainable materials to test different modes of three-dimensional representation.
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Chapter One
1.1 Research questions

This PhD research is located at the intersection of creative practices and science, with its focus on three-dimensional representations of climate change data. The research questions that form the central core of the dissertation are:

1) Communication and Collaboration: In the current context of climate change, which tools for communication and collaboration between the disciplines of sciences and the creative practices could be mobilised to facilitate or enable innovative modes of communicating climate change?

2) Artefacts and Visualisation: What is the capacity of created (3D printed) artefacts to engage with climate change data to produce accessible forms of climate change information and visualise the effects of climate change?

3) Innovation with Processes and Materials: What kinds of processes and materials might be used or developed beyond a purely aesthetic dimension that make a connection between the materials and the data being communicated? How can the issue of sustainability be cast within the selection and development of new materials in this enterprise?

Figure 1.1 Demonstrating the three key areas the research questions investigate, and where they intersect to generate new knowledge. Kate Dunn, 2016.
1.2 Introduction

The Intergovernmental Panel on Climate Change’s most recent report stated that “Human influence on the climate system is clear, and recent anthropogenic emissions of greenhouse gases are the highest in history. Recent climate changes have had widespread impacts on human and natural systems.” This statement reinforces the urgency of action on climate change on multiple levels; however, as Willett Kempton’s *Lay perspectives on global climate change* reveals, “in general, people are concerned about climate change but the information they receive is confusing, impersonal and distant”. This statement evidences the urgent need for diverse modes of communication that inform and galvanise action in the public domain.

Scientists are looking to other disciplines for alternate means of disseminating their research. Climate scientist Dr. Caroline Lehmann, speaking about the different platforms available for disseminating critical climate change research, expressed frustration with the limited and specialised audiences for traditional communication channels such as peer-reviewed science journals. Scientific journals are a valuable way to disseminate and archive new research, but cannot contribute to a populist lay understanding of the significance, implications and urgent action needed to respond to climate change.

Dr. Lehmann’s position is supported by another climate scientist, Dr. Sarah Perkins Kirkpatrick, who researches climate extremes and states:

> Science is all graphs and numbers, and not everyone thinks that way, so it can be difficult communicating our results with these resources. Artists and designers have a different way of thinking and presenting to us, allowing us to reach a wider audience, often with using less words in the explanation.

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In this light, the dissertation hypothesizes that creative visualisations – and, three-dimensional creative visualisations produced through interdisciplinary collaborations between climate scientists and artists – can provide a viable model to affectively and effectively represent and communicate climate change. Lesley Duxbury notes:

Works of art engage the imagination and present open-ended opportunities to involve the viewing public into processes of speculation and interpretation. In an encounter with particular artworks a viewer is invited to participate, not only through sight but also bodily and imaginatively in their own perceptive processes to recall personal experiences to make sense of global reality. 6

Creative practice and science collaborations have further potential to bridge disciplines and create images and objects that illustrate complex scientific data, making it accessible to a wide range of people. These collaborations have the potential to engage people through tangible interactions and community engagement programs affiliated with the collaborative project.

This research examines creative practice and science collaborations that facilitate science communication and foster informed responses to climate change. To this extent, the dissertation will firstly describe the historical and contemporary precedents of science communication, the different modes of collaboration, and the ways resultant creative works were made. Climate change research can be communicated through innovative creative works and visualisations in a variety of contexts, and so this dissertation explores how developing new fabrication technologies for objects can support this. In extension of existing techniques, it also explores new applications and novel material hybrids. This research explores how such works can be strategised to communicate climate change and, on that basis, extend knowledge by incorporating 3D printing as a tool for accurate modelling of climate change data.

Many models of climate change education and communication to this point have enjoyed varying success in instigating action and empowered responses. Lesley Duxbury, writing about the use of artworks to provoke public and private responses to climate change, critiques the messages delivered to the general public:

Given the great range of ways of addressing climate change, we reel from apocalyptic predictions to mundane, over-simplistic solutions such as those provided in Al Gore’s list of “Things to do” at the end of his film An Inconvenient Truth. He suggests that we

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“Plant a tree” or “Use less hot water”, phrases which are quite at odds to the ominous predictions and visualisations in the film itself. If catastrophic predictions and scientists’ graphs and statistics are either not making any impact on us or causing feelings of fear and guilt or even, presenting such unimaginable situations that paralyse us then what alternatives are there to bringing climate change awareness to sectors of the community?  

In contrast to the communication strategies Duxbury describes, not all predictions are rendered negatively; rather, scientists and artists are collaborating to create additional entry points to scientific data through creative works in a positive approach to raising awareness. These entry points grant the general public more access to scientific research, without removing access to existing methods employed by other agents that promote climate science research.

Neuroscientist David Eagleman, writing about science communication, states that “scientists recognise the importance of public dissemination of science: science is not just about the generation of facts; it is about opening our eyes to the vastness of our ignorance and sharing the inspiration for further discovery”. The interconnection of art and science collaborations can promote public curiosity, thus inspiring education, discussion and innovation.

Scientists Chantal Pouliot and Julie Godbout, writing about the value for scientists in communicating their research to the general public, note that “climate change is a serious problem, but the seriousness of the language often used when addressing the issue is of concern to some scientists”. Mike Hulme, Professor of Climate and Culture at King’s College London, argues in his book Why We Disagree About Climate Change that the language of catastrophe and imminent peril “diminishes the other ways of thinking, feeling and knowing about climate which are also essential elements in personal and collective decision making”. An alternative communication strategy to this language of disaster can be achieved through a multi-faceted approach that uses artistic and creative representations and community engagement projects to raise awareness of the effects of climate change.

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7 Ibid., Lesley Duxbury, “Breath-Taking: Creating Artistic Visualisations of Atmospheric Conditions to Evoke Responses to Climate Change,” 34.
“Communicating through multiple channels and appealing to different ways of thinking and knowing about climate change may help reduce the drop-in confidence in climate change research”, as reported by CSIRO scientists writing about Climate Risk Management. This is consistent with Hulme’s assertion that “How the general population thinks about climate change plays an important role in framing personal and community responses to it”. Geoghegan and Leyson, when evaluating climate change discourse, examine how climate change as a particular environmental discourse is constructed and refer to memory, observation and conversation. They describe this response to climate change as being “simultaneously a reality, an agenda, a problem, a narrative and a discourse for the individual and the community”. Through transdisciplinary collaboration, creative outcomes can democratise scientific knowledge by creating new sites of engagement for the general population while maintaining the integrity of scientific process.

As this thesis contends, collaboration across different disciplines can alter the frameworks and formal boundaries of traditional knowledge areas. Potential for challenging traditional knowledge paradigms can stem from transdisciplinary collaboration. When experts from different fields collaborate, their distinctive research and thinking practices can produce alternate ways of exchanging, transforming and disseminating information. This occurs through the different parties forging into territory that is unfamiliar, possibly for all, often leading to reflection and reconsideration of normative parameters. When scientists are invited to speak at an event for a lay audience, they are encouraged to modify their scientific mode of delivery. This makes the content accessible to a wider audience through common language and the use of images, charts and illustrations. For instance, a prominent scientist in the field of climate change research, James Hansen, uses formal scientific terminology and structure in his scholarly publications, but more accessible language for a non-expert audience. Hansen has addressed the United States Congress and given a TED talk, and in both instances adapted the delivery of information to make it appropriate for his audience.

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12 Ibid., Mike Hulme. "Why We Disagree About Climate Change". 33.
In a similar manner to the way scientists use language and concepts, many artists use discipline-inscribed language. For example, in discourse about their work, an artist might discuss the relevance of philosophy to the conceptualisation of their artworks. However, when artists present to multidisciplinary and lay audiences, they are encouraged to do so in a more accessible mode than when communicating with colleagues, in order to ensure understanding. As with scientists adapting their mode of delivery, this may include the use of communication devices such as images or objects that facilitate understanding.

Experts cannot assume knowledge on the part of their audience; they must communicate at the level of the non-expert user or audience member. Similarly, in an attempt to expedite the communication process between two different fields of expertise such as science and art, as when any two discursive cultures meet, one would be well advised to communicate in a spirit of openness. The point where the two parties meet can create a new environment, free of the precedents and conventions of their disciplines yet bringing their wealth of knowledge to the discussion. By fielding multiple alternate perspectives on a common topic in a singular space, there is potential for that space to become charged and stimulate innovation, creating new modes of communication and collaboration. This approach to communication is a central focus of the thesis.

As with any communication strategy, it is essential that there be a range of approaches to disseminating knowledge in order to address individual preferences. Consequently, the examples of collaborative projects that the present dissertation describes provide multiple access routes and sensory pathways to take the viewer to the research or data embedded in the artworks and visualisations. An example of how the research has adopted multiple communication strategies is the exhibition at the Macleay Museum documented in Chapter Four. The exhibition employed a communication strategy involving an exhibition of visualisation objects, a series of expert talks about the exhibition, an interactive workshop for interested participants on 3D printing and a monitor displaying process documentation. This combination of communication strategies addresses the senses of sight, sound and touch, enhancing opportunities for audience engagement and stimulating curiosity about the science and the models.

1.3 Background and Context

Collaboration and Boundary Objects

One might argue that a goal of collaborations between creative practice and scientific research is to create a site for exchange, fluid discourse and reciprocity. Some collaborations can be ongoing and create self-generative outcomes, forming what sociologist Susan Leigh Star and science philosopher James Griesemer described in 1989 as “boundary objects”. Star and Griesemer described boundary objects as devices that are used to help collaborators understand each other and communicate effectively, while allowing them to work independently, and were first observed in use among scientists communicating across different scientific fields.

Since their introduction, categories of boundary objects have been developed to suit different contexts. Paul Carlile in 2002 investigated boundary objects in the context of new product development and developed syntactic, semantic, and pragmatic categories of boundary object. Charlotte Lee in 2007 built on these categories and introduced the Intermediary boundary object. Successive definitions of boundary objects developed by different authors have shown different uses within collaborations across disciplines. As integral elements to transdisciplinary collaboration between creative practitioners and scientists, the boundary object is a valuable tool for facilitating communication and overcoming disciplinary barriers. Star and Griesemer note that the major challenge in collaboration is communication between different social groups. It becomes critical to establish a means of crossing this boundary from one group to the other if they are to collaborate successfully. The boundary object establishes a clear set of methods that not only allows collaboration to take place, but also enables communication and encourages autonomous work by practitioners in their own fields.

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18 Ibid.
This dissertation documents the history of boundary object theory and develops new categories, definitions and criteria designed specifically to evaluate the nature and intent of collaborations between the creative practices and sciences. It focusses on collaborations that address new ways of communicating climate change research. The new categories that are developed through the research will then be used to evaluate the exchanges and the artefacts produced.

The role of creative practitioners in visualising information

While this thesis departs from observations of archival and museum collections such as natural history museums and older forms of scientific data collections and representations, this has been dramatically advanced by recent work undertaken on the front of visual representation of scientific data through computational and digital fabrication media. This is particularly significant, as it shifts from the scientific object itself as foregrounded in natural history museums towards representations of the science.

The visual representation of scientific data for a general audience has been termed “NEUVis: Non-Expert User Visualisation.” Representations or data are developed through direct or indirect collaborations that pass scientific knowledge from the domain-expert, such as a climate scientist, to a non-expert user, or audience. The approach advocated here stands in contrast to common approaches of visual analytics which originally stem from computer science. Visual analytics strives to automate production of visualisations for a domain-expert audience, while NEUVis are one-off representations for an audience which does not have expert knowledge in the field where the data originated.

Chaomei Chen, writing about the potential of different types of information visualisation to help communicate complex information to a lay audience, describes the field in the following terms:

> Information visualisation primarily deals with abstract, non-spatial data. Transforming such non-spatial data to intuitive and meaningful graphical representations is therefore of fundamental importance... The transformation is also a creative process in which designers assign new meanings into graphical patterns. Like art, information

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visualisation aims to communicate complex ideas to its audience and inspire its users for new connections.\textsuperscript{23}

This distinction strongly highlights the difficulty encountered by domain-expert scientists in communicating with a general audience, and suggests that creative practitioners such as designers or artists have an important role to play in disseminating information and promoting thoughtful reflection and changes in attitude. The processes of developing a NEUVIs are also more aligned with those commonly employed by creative practitioners, who are comfortable working within ill-defined problem spaces. Nigel Cross describes ill-defined problems, also known as “wicked problems”, as “fundamentally un-amenable to the techniques of science and engineering”.\textsuperscript{24} In relation to this thesis, problems being addressed in this context may include: How can we educate the general population about climate change? or What are the goals of communicating climate change science to the general public?

Such a problem would be “wicked” because it cannot be comprehensibly stated, it requires subjective interpretation, and it cannot be addressed using problem-solving methods that are familiar to scientists and scientific practice. Wicked problems are often successfully addressed by collaborations between creative practitioners and scientists seeking to leverage the expertise of both disciplines in partnership. A collaboration can produce creative visualisations that transform audiences’ understanding of information and their emotional engagement with the subject of climate change. This is an important aspect of the dissertation because communication of climate change research is critical to ensure public understanding of the science.

\textsuperscript{24}Nigel Cross, "Designerly ways of knowing: Design discipline versus design science." Design issues 17, no. 3 (2001): 49-55.
1.4 The Research Significance and Areas of Innovation

Using the research questions described in section 1.1 as the driver, the thesis works at the intersection of three key areas of research, namely, *Models of cross disciplinary collaboration; Innovation with processes and materials; and Three-dimensional artefacts and visualisations of climate change research*.

These areas have been developed by building on existing research work, precedent creative works, and scientific knowledge, and by combining the disciplines of science and the creative practices in a structured manner to facilitate innovation and the generation of new knowledge.

*Models of cross disciplinary collaboration.* This first significant area of research innovation ventures a new system of categorising boundary objects to suit a creative practice/ science collaborative context. These categories include: *Didactic Boundary Objects, Creative Boundary Objects, and Reciprocal Boundary Objects.* The context and definitions of the categories will be elaborated in Chapter Two of this thesis.

The thesis explores models of collaboration to extend and explore boundaries between different disciplines in order to visualise climate change research. Development of research on climate change communication requires considerable interdisciplinary collaboration, and is furthermore spread across the radically divergent fields of science, art, design and engineering. Research into models of collaboration was investigated and the notion of the boundary object explored and developed in order to provide a framework to evaluate the nature of the collaborations and their outcomes. Collaboration is an important term in this project given it is investigating the nexus of art and science – two historically, epistemologically and practically disparate fields. The creative practice and science disciplines have different cultures, objectives, research strategies and practices. Science has a linear, systematic approach to investigating and documenting the environment. The creative arts on the other hand explore and describe the environment and human experience in a creative, lateral trajectory that pools disparate ideas, images and sources to generate new knowledge.

The rapprochement between these two cultures has led to a range of interdisciplinary collaborations that architectural theorist Michael Tawa describes as a “multi, cross and transdisciplinary” way of working where “the value is in shuttling between boundaries – never restricting the work to one discipline, one theme, one image or one kind of thinking”.  

communication of climate change research. The participants are generally climate scientists or ecologists and artists, designer and visualisation specialists. There are numerous disciplinary boundaries defined by culture, history, language and funding models.

*Innovation with Processes and Materials.* The second significant area of research innovation is the development and application of a range of three-dimensional fabrication processes and printing techniques for making models of climate change. The processes and materials investigated range from traditional clay forming methods to three-dimensional, 3-axis printing, and 6-axis robotic deposition. There is also a focus on using environmentally sustainable materials for 3D printing so that the objects made will not contribute to climate change in their material selection and fabrication. The materials investigated have low embodied energy, maximum recyclable content and capacities for repurposing.

3D rapid prototyping printing has been chosen as the primary means of fabrication for the creative work for its capacity to accurately and repeatedly make models of climate change data. Multiple exact copies can be quickly and cheaply produced, thereby facilitating dissemination and engagement across multiple audiences simultaneously. 3D printing is also one of the most sustainable ways to make objects because of the capacity to customise individual designs virtually, through CAD modelling rather than during the production phase of fabrication. The *insitu* production of models through electronic distribution of the computer-generated files used to model them also reduces energy consumption and cost.

These 3D printed models operate as boundary objects between multiple stakeholders in the context of communicating climate change to a general audience. This research aims to demonstrate that three-dimensional creative works can create alternate access points for climate science research and actually embody the principles of the science through the use of sustainable materials in the fabrication of the creative objects.

*Artefacts and visualisations of climate change research.* The third significant area of research innovation is the development of new three-dimensional artefacts and visualisations that represent climate change data. This dissertation initially explores how three-dimensional creative representations of scientific research such as taxidermy, artworks, sculptures and 3D printed data models, produced through interdisciplinary collaborations between artists and scientists, can help communicate science to diverse audiences, stimulate interest in the science through the creation and display of creative responses to climate science research and ideally trigger reflection and consequent action. Building on this research, the thesis then produces a series of three-dimensional creative works and visualisations, in collaboration with climate scientists, that are designed to visualise climate change research.
Three-dimensional climate change data visualisation has tremendous opportunities for multi-sensory audience interactions. Objects can affect the viewer on visual, physiological, emotional and psychological levels and, in turn, influence behaviour and attitudes towards climate change. Art theorist Paula Owen, writing about objects and meaning, states that:

the object links us to memories, sensations histories and relationships rather than being an end in itself with a predetermined meaning. It is instead, a catalyst for any number of unpredictable events.\(^{26}\)

Objects such as religious icons, rosary beads, relics, or a piece of a uniform from a fallen soldier hold significant value in many institutions and help frame and communicate cultural identity across cultures, both historically and contemporarily. Objects can act as talismans, memorials, displays of wealth, trophies of war and reflections of current cultural values. Objects engender desire for ownership and investment, both financially and psychologically. Theorist Bill Brown has been writing on the role of objects in cultural memory. He uses the term “object culture”, and defines it as the “practical and symbolic use of objects”:

Object culture thus entails both the ways that inanimate objects mediate human relations and the ways that humans mediate object relations (generating differences of value, significance, and permanence among them), thus the systems (material, economic, symbolic) through which objects become meaningful or fail to.\(^{27}\)

Making objects that reflect and communicate climate change research requires a considered approach to the relationship of conceptual content to material and form. Addressing the environmental impact of both the fabrication process and the materials used to make the artefacts or visualisations is a guiding parameter of the research methodology. The dissertation focuses on three-dimensional examples of visualisations of research which include sculpture, installation, and 3D printed data visualisation. Following the precedents outlined in Chapter Two, case studies will innovate a series of models and exhibitions that investigate these ideas through collaborations with climate scientists. These case studies use sustainable materials to create three-dimensional visualisations of the scientists’ research.


1.5 Research Design and Methodology

The research presented by this thesis is threefold. Firstly, it follows a classic critical analysis of literature and relevant precedents. Secondly, a series of collaborations with climate scientists and other creative practitioners were developed in order to investigate different models of collaboration. And thirdly, using an iterative design strategy informed by design thinking, the thesis produces, in tandem with the theoretical written component, a substantial body of creative work.

The creative work utilises a practice-based research methodology whereby the research questions are addressed through the exploration and production of creative design outcomes. In Interacting: Art, Research and the Creative Practitioner, Candy and Edmonds describe how practice is central to the creative research process. In this type of research, the practitioner’s process of creation, reflection and evaluation of artefacts allows them to gain insight and use their practice to form new knowledge. In this thesis, contextual review significantly informs the creative and material outcomes, while the process itself enables exploration of ideas and theory to achieve practical research outcomes.

The design methodology builds on design thinking as described by Rowe and follows an iterative design process based on the cyclic process of evaluation of a problem by conducting research, ideation, prototyping, testing, analysing, and refining a process or design. From the results of the testing process, changes and refinements are made in order to continually get closer to answering the research questions. The refinement of the research focus is furthered through an ongoing reflective process that seeks multiple approaches and answers to the research questions. Donald Schön’s reflective practice theory opposes the idea of design as “rational problem solving”, focusing instead on honing the ability to “reflect on one’s actions so as to engage in a process of continuous learning”. Kristina Niederrrer and Linden Reilly posit that:

Creative practice can be used both as process and output, and that, as such, it can have an important role in the process of data generation/collection and data analysis/evaluation. Thereby, the creation of artefacts mostly pertains to the process of data generation, although artefacts can also be used in an analytical way for the analysis of a theoretical concept.

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The diagram in figure 1.2 by Niederrer and Reilly visualises their definition of the process of creative practice research. While this diagram demonstrates an approach related to the research methods used in this thesis, the diagram in figure 1.3 encapsulates the research method undertaken by this thesis.

![Diagram of the creative research process](image)

*Figure 1.2 Diagram of the creative research process. Kristina Niedderer and Linden Reilly, 2011.*

**Evaluation Methodology**

Each of the material and process investigations described in Chapter Three and the design research case studies described in Chapter Four are evaluated using the framework of the research questions established at the beginning of each project. Using the results of this evaluation, new research questions are generated and form the frameworks for the subsequent project. The research does not use audience evaluation, as the goals of the research are to investigate different ways climate change data can be three-dimensionally represented using sustainable processes and materials, rather than testing the impact of particular models on an audience.

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34 Ibid., Niedderer and Reilly., 2.
The design research projects are critically evaluated using a framework that differentiates:

- The scientific research or data source being investigated;
- The model of collaboration deployed and the participants involved;
- The design strategy for the physical outcomes;
- The materials being used and their relationship to the subject matter;
- The fabrication methodologies used;
- The site of display or interaction for each project;
- Reflection and design research questions generated.
1.6 Chapter Outline and Structure

In the following, the chapter outline and structure of the thesis are discussed in more detail, in order to give an overview.

Chapter One Introduction
Chapter One introduces the research area, outlines the significance of the research, the research questions and the methodology employed to address the research questions. The chapter describes the context of the research and identifies key themes and areas of innovation that generate new knowledge.

The chapter is divided into sections that contribute to the framework of the thesis. Sections 1.1 identifies the research questions, 1.2. initially introduce the research, while section 1.3 contextualises the history and environment for the research. Section 1.4 defines the significance of the research and areas of innovation that make contributions to new knowledge. Section 1.5 discusses the research methodologies in two modes, a critical reflection of precedents and topics, and a creative design research component. Section 1.6 introduces each chapter, leading towards the design research outcomes. Section 1.7 introduces key terms in the context of the thesis. Section 1.8 concludes the chapter.

Chapter Two Historical and Discourse Context
Chapter Two discusses ways in which individual and community understanding of scientific research is enhanced through creative representations and collaborations between the creative practices and sciences. The chapter conceptually locates the research within the context of transdisciplinary collaborations and examines how creative works might be analysed and enhanced using boundary object theory. This chapter focuses on addressing aspects of the following two research questions:

1) Communication and Collaboration: In the current context of climate change, which tools for communication and collaborations between the disciplines of sciences and the creative practices could be mobilised to facilitate or enable innovative modes of communicating climate change?

2) Artefacts and Visualisation: What is the capacity of created objects to engage with climate change data to produce accessible forms of climate change information and communicate the effects of climate change?

Transdisciplinary collaborations between creative practitioners and scientists have produced a large body of work that visualises and communicates scientific research. This will be demonstrated in the thesis by different cases from a range of collaborative and representation models that communicate scientific data through creative representations and tangible interactions. The chapter focuses on examples from two time periods – the first is the Victorian era, selected for the societal interest in natural history at the time and secondly, contemporary responses to climate change research. There is a focus on three-dimensional examples of visualisations of science, as these inform the design research described in Chapters Three and Four.
2.1 Boundary Objects – Theoretical framework for modes of collaboration

Section 2.1 introduces the theoretical framework of boundary objects as a means of describing different models of collaboration. The section further defines the history and context of the use of the term, and determines new categories to describe novel collaborations between scientists and a range of creative practitioners, using the notion of boundary objects as a theoretical framework. These definitions are then used as critical lenses to evaluate the nature of collaborations between the artists and scientists reviewed later in the chapter.

2.2 Historical Archives from the Victorian Era conveying natural science research

This section gives an historical account of illustrations and objects by artists designed to convey Natural Science Research. These objects were primarily used as communication and educational tools. The examples are taken primarily from the Victorian era due to the tremendous interest in natural sciences during this period. Particular focus is on the influence of Charles Darwin’s *Origin of the Species* on the public perceptions of science and on the visual and decorative arts in the late 19th century, both in concept and composition. The examples given are discussed in terms of how participants collaborated and the category of boundary objects the collaboration falls into. How the science was accessed or shared, how the artist represented the science and the display context of the object or artwork. There is an emphasis on natural history and ecological research, as it is the closest precursor to climate change research.

2.3 Contemporary Creative Visualizations of Environmental and Climate Science Research

Section 2.3 discusses contemporary artists and designers making creative works or visualisations informed by environmental and climate science. The focus is on the different modes of representation used and the types of collaborations that take place between scientists and creative practitioners. There are many types of contemporary creative visualisations of science, including digital screen and paper-based works; however, the research focuses on works that use three-dimensional strategies to visualise the science as this is the mode of representation investigated in the design research described in Chapters Three and Four. The section will describe the nature of the collaboration, identify the source of the data and look at the links between the scientists, creative practitioners and artists.

The section is divided into subcategories to clarify the different structures of collaborations and outcomes. The first subcategory discusses contemporary organisations and the numerous international programs fostering collaborations between the arts and sciences, artists and scientists – including the *Cape Farewell Project* in London and Canada and the *Institute for Figuring* in the United States. These models are the most relevant for my project. The second subcategory focuses on individual artists and projects and the different modes of representation of climate change data. These are evaluated using the categories of boundary objects previously outlined. Key artists’ work and collaborations that will be reviewed include artists whose work falls into the Didactic Boundary Object category, such as *The Artist as Family* and Lauren Berkowitz. Other artists’ collaboration models and material work are categorised as Creative Boundary Objects. Relevant artists include Janet Laurence, Fiona Hall and Claire Twomey. A third division of boundary objects called Reciprocal
Boundary Objects will be used to discuss the work and relationships of artists such as Fernanda Viégas & Martin Wattenberg, Ken and Julia Yonetani and Luke Jerram.

2.4 Summary and conclusion
Draws conclusions that direct the execution of the practical research.

Chapter Three Design Research: Innovation with Fabrication Processes and Materials
Chapter Three foregrounds the fabrication processes and material investigations undertaken as part of the design research. The research in this chapter is driven by the following question:

What kinds of processes and materials might be used or developed beyond a purely aesthetic dimension that makes a connection between the materials and the data being communicated; and in particular, how can the issue of sustainability be cast within the selection and development of new materials in this enterprise?

The question is addressed by first introducing the fabrication material processes used in the design research, including 3D printing on a range of scales and materials used in 3D printing such as plaster, clay, plastic and sugar. The chapter then documents and analyses the process and material tests undertaken as part of the practical research which combine these elements to generate new knowledge in this field.

3.1 Introduction
The introduction situates the selected design research fabrication processes and materials within the theoretical paradigms of the notions of objecthood, materiality and haptic interactivity; the implications of 3D printing on the fabrication process; and addressing sustainability goals. Three-dimensional visualisation fabrication methods and materials will be outlined, together with 3D printing technologies and materials that are commercially available, as well as experimental 3D printing processes.

3.2 3D Printing Rapid Prototyping overview
This section outlines the development of 3D printing rapid prototyping technology and the current field of commercially available processes and equipment. The section also describes the applications of 3D printing rapid prototyping and the relevance to the research.

3.3 Materials for 3D Printing
Section 3.3 defines the current field of commercially available materials for 3D printing. The section then lists experimental 3D printing projects that address sustainability. There is a focus on projects that use ceramics, as much of the material and process design research described in Section 3.4 uses ceramic materials as the foundation, due to the material’s capacity to be adapted to sustainable processes and outcomes.

3.4 Selected Process and Material Investigations
This section draws conclusions from Sections 3.2 and 3.3 and outlines the technical aspects of the fabrication and material processes investigated for the case studies discussed in Chapter Four. Types of fabrication processes and materials investigated include: Hand modelled porcelain, CNC routed
timber, large-scale projections, powder-printed earthenware clay, powder-printed porcelain clay with glaze, robotically controlled slip-casting clay with waste aggregate, and robotically controlled modelling clay with waste aggregate.

3.5 Scientific Research Data
Section 3.5 outlines selected sources and types of data that are visualised in the case studies in Chapter Four. There is a focus on data documenting the effects of climate change – initially on Australian plant species, then on climate research generally. Data has been provided by climate and ecology scientists from the CSIRO, Macquarie University and the Australian Research Council’s Centre of Excellence for Climate System Science.

3.6 Discussion and Conclusion
This section describes how the processes, materials and projects outlined relate to the research and how they will be employed and combined to inform the design research case studies documented in Chapter Four.

Chapter Four Design Research: Case Studies of the Creative Works Produced
Chapter Four documents and analyses creative projects, exhibitions and artefacts produced through the design research case studies conducted in tandem with the theoretical research.

4.1 Introduction
This section introduces the case studies of projects and exhibitions produced as an integral part of this thesis. The section describes how the research on collaborations and boundary objects in Chapter Two, and the technical and material research described in Chapter Three, is incorporated in the creative works made as part of the design research in order to address the research questions. The Introduction also details the research methodologies, the participants and the types of collaborations undertaken; the scientific research or data being represented; the categorisation of creative works as boundary objects and the artefacts generated through the design research process.

4.2 Design Research, Criteria and Methodology
This section gives a theoretical framework and descriptive categories for each case study which will be outlined using the following criteria: Case study reviews introduce the project and the specific questions being addressed through the design process, they also describe the climate change research or data source being investigated in the projects and exhibitions; the participants involved in any collaborations and the types of boundary objects used; the design strategy for transforming the data or research into three-dimensional objects; the material used and relationship to the subject matter; the fabrication methods and technology used; where relevant, the site of display. Each description concludes with a reflection and lists the design research questions generated by the discrete project. These questions then lead to new research parameters for the subsequent projects.

- Introduction and research questions, the primary concerns that drive each project.
- The research or data source being investigated.
- Collaboration and the boundary object – the model of collaboration deployed, the
participants involved and types of boundary objects used;

- Design strategy for transforming the data or research into three-dimensional objects.
- The material used and relationship to the subject matter;
- The fabrication methods and technology used;
- The site of display and interaction;
- Discussion and analysis and the resulting further research questions for the subsequent case study.

4.3 Design Research Case Studies
This section documents and discusses six creative projects and exhibitions produced as part of the thesis that address different aspects of the three research aims and questions: Models of collaboration in creative interdisciplinary projects, 3D printed three-dimensional artworks and visualisations that communicate climate change research and environmentally sustainable materials for 3D printing. The case studies are produced through an iterative process whereby initial research questions or problems are introduced then systematically investigated through a process of practical research.

Using the design research framework described in section 4.2, this section discusses and documents the ways in which each case study investigates the research questions, how the project is developed, executed, displayed and then analysed. The case studies are:

1. *The Garden of Earthly Delights* at Metalab Gallery (2012);
2. *Regenerate* at Sculpture by the Sea, Cottesloe, Western Australia, and Royal Botanic Gardens, Sydney (2012-2013);
3. *3D Printed Data Models* at Research Visions, University of Sydney (2014);
4. *Fabricating Futures*, University of Sydney, Faculty of Architecture (2015);
5. *Robotic Fabrication in Architecture, Art and Design*, 2016 Conference Workshop & Exhibition (2016);

4.4 Discussion and Conclusion
In this section, the previously described research projects are summarised according to the following three key research areas:

- 3D printed three-dimensional artworks and visualisations that communicate climate change research;
- Models of collaboration in creative interdisciplinary projects;
- Environmentally sustainable materials for 3D printing.

Chapter 5 Conclusion-Chapter Structure
Chapter 5 summarises the research, draws conclusions, and outlines future directions for the research.

5.1 Research summary
The research summary gives an overview of the research undertaken during the PhD candidature and discusses how the research questions have been answered.

5.2 Research dissemination
This section outlines the dissemination that has occurred during the candidature and demonstrates the significance of the research.

5.3 Future directions of the research
This section describes the future directions of the research

Bibliography

Appendices

Appendix A
Conversations with Dan Metcalfe and Sarah Perkins Kirkpatrick about collaboration.

Appendix B
Powder Printing Research
Samples of tests.

Appendix C
Robotic 3D Printing Material Tests Samples
Samples of tests.

Appendix D
Table of Ceramic Process and Material Terms.

Appendix E
Examples of Formats of Scientific Research informing the investigations into potential three-dimensional visualizations.
Research is compiled here from:
Dr. Caroline Lehmann
Dr Dan Metcalfe
Dr. Sarah Perkins Kirkpatrick

Appendix F
Image catalogue of the Chapter Four Case Studies.
1.7 Key Terms

This thesis traverses the disciplines of design, art and science and therefore has both divergent and overlapping historical references and terms. This section defines the pivotal terms that are used for the dissertation in order to frame and contextualise their use. The particular key terms defined in the following are: Design, Art, Visualisation, Creative Practice, Aesthetics, Materiality and Material, Collaboration, Sustainability and Climate change.

Design
The word design is used in radically different settings of contemporary life, including business, management, architecture, service and object design. For example, the New South Wales government has recently declared its commitment to design-led planning;35 while the University of Sydney is driving a pedagogy of design-led innovation across all disciplines.36 In this context, understanding the term design (how one means to use it and distinguish it from art, creativity, innovation and a range of other terms and practices) becomes critical. The following paragraphs will give examples of definitions of design, then concludes with the interpretation that will be used in this thesis.

Paul Rand, writing in 1981 on the politics of design, describes design as “a problems-solving activity. It provides a means of clarifying and synthesising and dramatizing a word, a picture, a product or an event”.37 He describes the designer’s overriding motivation as art – “Art that enhances the quality of life and deepens the appreciation of the familiar world”.38 Artist/designer Andrea Zittel describes design as a hybrid between fine art and applied art.39 This definition has its foundations in the interface between the guild system of the crafts and the academy model of fine arts. An historical example of this model is William Morris, a key figure in the British Arts and Crafts movement. Morris’ oeuvre encompassed textiles, furniture, painting and sculpture and poetry. Designer and critic Kees Dorst describes the similarity between design and art:

38 Ibid., 34.
Once an artist decides on a goal to pursue, his or her creative process looks very much like a design process. Artists have effectively turned their self-made challenge into a partly determined design problem. And they temporarily turn themselves into designers. So, the border between art and design is permeable, and not just from art towards design.\(^{40}\)

Many of these descriptions describe design as a process or action rather than an outcome. Vilem Flusser, writing about the origin of the word *design*, acknowledges that it is both a noun and a verb.\(^{41}\)

As a noun, it means – among other things - intention, plan, intent, aim, scheme, plot, motif, basic structure. As a verb (to design), meanings include “to concoct something”, to simulate, to draft, to sketch, to fashion, to have designs on something.\(^{42}\)

All of these descriptions imply action or impending action. While acknowledging that there has been significant research into definitions of design, for the purposes of this thesis *design* is the process of identifying through research an issue or a problem and then systematically answering or addressing the problem using a cyclical iterative process of prototyping ideas and artefacts and testing these against defined parameters in order to arrive at a solution.

Art

There are as many definitions of art as there are artists and philosophers who write about art. For the purposes of this thesis, two definitions may be given as relevant yet opposing positions within the contemporary dialogue of representational theory. Nicolas Bourriaud states:

Art historically intended to prepare and announce a future world. However today the role of artworks is no longer to form imaginary and utopian realities but to provide ways of living and models of action within the existing real, whatever the scale chosen by the artist.\(^{42}\)

An example of this mode of praxis is the work of artist Rirkrit Tiravanija, who hosted a dinner where the act of cooking and eating constituted the artwork. Bourriaud’s philosophy promotes literal engagement over more complex and nuanced allegorical modes of expression in art. Yet

\(^{40}\) Alex Cole in *Design and Art (Whitechapel: Documents of Contemporary Art)* edited by Alex Cole. MIT Press, 2007, 12.


an alternate view is proposed by Heidegger in *The Origin of the Work of Art.* Heidegger describes the essence of art in terms of concepts of being and truth. He argues:

Art is not only a way of expressing the element of truth in a culture, but the means of creating it and providing a springboard from which ‘that which is’ can be revealed. Works of art are not merely representations of the way things are, but actually produce a community’s shared understanding.  

Building upon Heidegger’s and Bourriard’s descriptions of art, this research developed a hybrid description. This thesis contends that art is the transformative or distilling lens that happens when an artist embraces a conceptual provocation and, informed by the canon of art history, cultural influences and material expertise, experiments and arrives at a tangible manifestation of his or her response. This manifestation may be an object, a painting, an installation, a performance or any other response that is contextually considered art.

**Visualisation**

The term *visualisation* is used in the thesis in the way it is used in the burgeoning information visualization industry. This field of information visualization is developing and changing quite rapidly with the introduction of digital technologies such as virtual reality headsets, projection mapping and three-dimensional visualization made using 3D printing and CNC milling. The information represented can be scientific, financial, medical and so forth. Audience interaction with the visualizations allows data to be seen from different perspectives, making it more engaging or interesting. Examples of visualizations include graphs, pie charts and bar charts. Other information visualization experts represent the data in more creative ways, including Fernanda Viégas and Martin Wattenberg, leaders of Google’s “Big Picture” visualization group, who use accurate data to create images such as the Wind Maps series outlined in Chapter Two.

This thesis uses the term visualization in reference to the artefacts generated through this research in a range of modes to represent the data sourced through collaborations with climate scientists. These include abstract hand-modelled sculptures and 3D printing using CAD software to accurately model the data.

**Creative Practice**

There are many terms employed to describe the activities of creative and cultural sectors and the organisations that fund and teach these activities. The activities include art, craft, design, performance and visualisation. Australian federal, state and local government organizations

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refer to the cultural industries, or the creative industries, when discussing the activities of artists, designers and increasingly the innovation sector. Universities that teach art, design and architecture refer to creative practice, practice-led and design-led research to describe activities that produces creative visual and three-dimensional outcomes or artefacts within a normative research context.

As the fields of architecture, design, visual arts, interactive media and communications cement their place in the academic system, the particular characteristics of their research activities which involve making things have to be categorised to ensure ongoing competitive funding. In general, the fields listed use some version of the word *practice* to describe these activities. Niedderer and Roworth-Stokes claims that the word practice is being deployed as:

> A means of making tacit knowledge available to research, because it includes the experiential part of knowledge which evades conventional communication by verbal or textual means and which is otherwise neglected by research because of the prioritisation of propositional knowledge. 44

Niedderer and Roworth-Stokes acknowledges the uncertainty about the role of creative practice within research, and its capacity to contribute to knowledge, but they consider it essential that it be included. This is relevant to the thesis because the design research outputs include considerable practical research. These outputs are described in Chapters Three and Four.

Writing about the creative industries and their influence, Terry Flew states:

> Cultural processes such as design and signification impact upon all aspects of everyday life, particularly those related to the consumption of commodities. Culture is thus recast from being a distinct sphere of social life, to something that permeates everything from the design of urban spaces, offices, means of transport and communication. Similarly, creativity does not simply reside in the arts or media industries, but is a central – and increasingly important – input into all sectors where design and content form the basis of competitive advantage in global economic markets. 45

The term *creative practice* is used in this thesis to describe the activities of individuals or groups who engage in research or practice through the production of innovative, creative works that process and communicate information and result in visual or three-dimensional artefacts. The thesis does not distinguish between the fields of art, design and visualization; and the artefacts generated may include, but are not limited to, artworks, books, performances, sculpture, painting, design projects and outcomes or, in the case of the research here, 3D-printed data visualizations.

**Aesthetics**

German philosopher Alexander Baumgarten, writing in the eighteenth century, defined *aesthetics* as the science of how things are cognized by means of the senses. This definition attempts to apply scientific methods to something potentially subjective and linked to a general sensory perception. Jerrold Levinson, writing in the twenty-first century, refines Baumgarten’s description to a more specific meaning by referring to the notion of *aesthetic experience*.46

Philosopher Monroe Beardsley introduced the term *aesthetic experience* in 1958, defining it “as involving firmly fixed attention, relative freedom from outside concerns, affect without practical import, exercise of powers of discovery, and integration of the self. Such experiences have value in virtue of sharing the unity, intensity, and complexity of the objects—notably artworks—on which they are directed, and such objects have aesthetic value precisely in so far as they have the potential to afford such experiences”.47 Beardsley proposed that the appearance of an object or artwork can cause an experience that transcends one’s immediate environment. This transcendent quality is closely linked to the notion of affect. Sigmund Freud also referred to affect when discussing aesthetics:

> The enjoyment of beauty has a peculiar, mildly intoxicating quality of feeling. Beauty has no obvious use; nor is there any clear cultural necessity for it. Yet civilization could not do without it. The science of aesthetics investigates the conditions under which things are felt as beautiful, but it has been unable to give any explanation of the nature and origin of beauty, and, as usually happens, lack of success is concealed beneath a flood of resounding and empty words. Psychoanalysis, unfortunately, has scarcely anything to say about beauty either. All that seems certain is its derivation from the field of sexual feeling.48

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To discuss the use of aesthetics in creative representations of scientific research over the last fifty years, writer and art theorist Jacqueline Millner is particularly relevant. In her book *Conceptual Beauty*, Millner explored the contentious position of beauty in late twentieth century art history, theory and criticism, by suggesting that since “aesthetics in general and beauty specifically, were repressed on account of a series of political complaints against them, aesthetics were deemed to be extraneous to art.”49 Millner refers to movements such as grunge art in which artists declared disinterest in the appearance of artworks to the point where they could be described as anti-aesthetic.

French theorist Nicolas Bourriaud, author of *Relational Aesthetics*, takes a similar anti-aesthetic stance, asserting that “engagement is the essential component in contemporary art”. Bourriaud goes on to state that “the form of a work cannot be reduced to the simple effects of a composition as the formalistic aesthetic would like to advance”.50 These ideas and approaches are evident in the work of some artists who are making works reflecting on the impacts of global warming. An example of this approach is the Artist as Family whose work is detailed in Chapter Two. The Artist as Family focuses more on audience engagement with ideas and activities than on the aesthetic and artefactual registers of scientific research representations.

Millner contends that this focus leads to a neglect of aesthetics in contemporary art and the opportunities aesthetics can afford artists and designers as a tool in communicating concepts to an audience. Writing in 2010, Millner opines:

> more recently, aesthetics and beauty in particular have re-emerged as significant factors in understanding contemporary art, and that art that deploys beauty as a strategy has the potential for critique.51

Examples of creative practitioners who use aesthetics as a representational consideration in the context of this research include Fiona Hall and Clare Twomey, (these artists and their projects are discussed in detail in Chapter Two). Both use scientific research as a stimulus to research and analysis to engage aesthetic and material considerations and to communicate ideas about climate change. This is relevant to the thesis because the design research case studies executed as part of the thesis and described in Chapter Four use a range of aesthetic devices to describe the climate change issues informing the creative works and projects.

51 Ibid, Jacqueline Millner, 179.
Materiality and Material

The following section analyses the two terms *material* and *materiality* in the context of the research. The words materiality and material have different meanings and uses in different contexts and disciplines. “Material” simply describes what something is made of, while “materiality” is much more ambiguous and open to interpretation. An object’s perceived materiality combined with its provenance can determine its cultural value and influence. Archaeologist Tim Ingold suggests that we treat objects and the materials they are made of as blank surfaces upon which we project our ideas:

> The very notion of material culture, rests on the premise that as the embodiments of mental representations, or as stable elements in systems of signification, things have already solidified or precipitated out from the generative fluxes of the medium that gave birth to them.52

Ingold is drawing attention to the presumption of an obvious and broad understanding of the terms in the fields of archeology and anthropology and the presumption that the materiality of an object is directly linked to its materials. He urges the reader to consider the materials an object is fabricated from as an inherent component of the experience of materiality. Ingold’s observations are important to the creative works of this thesis, as 3D printing processes and materials, while new and unfamiliar to many, are still complicit in the system of cultural signifiers that he describes.

Ingold questions the presumption that constitutive materials are directly linked to experiences of materiality: “In the ever-growing literature in anthropology and archaeology that deals explicitly with the subjects of materiality and material culture, the literature seems to have hardly anything to say about materials.”53 This notion is supported in other fields – for example, when considering the ideas of material and materiality from a craft and design perspective, there is a school of thought framed around the notion of “truth to materials”. In this field, one must work with the properties of a material, such as the grain of the wood or the texture of stone, rather than against it. David Pye contends that:

> it is not really the properties of materials that an artist or craftsperson seeks to express, but rather their qualities: The properties of materials are objective and measurable. They are out there. The qualities on the other hand are subjective: they are in here: in our heads. They are ideas of ours.54

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53 Ibid., 4.
These qualities Pye describes are an object’s perceived materiality – for example, an object made of wood might attract descriptive terms such as natural, solid, antique and unique. There is a general understanding that the wood from each tree has markings and growth patterns that are individual. We expect wood products to last through generations and be passed down as significant objects with denotative value and prestige. This is evidenced by the many wooden objects found in our museums as records of past lifestyles and cultures. We invest significant cultural value in wood products because they have been part of physical infrastructure for most of human existence. A strange manifestation of this is the proliferation of materials made to look like wood. Most offices have desks surfaced in laminated plastic made to resemble wood. This is presumably to imbue the desk with the materiality and cultural value of a wooden desk. Such facsimiles can give an uncanny feeling – causing users to run their hands over the surface to test if it is real wood or not. On discovering the surface is actually wood, there might be feelings of comfort and familiarity; while on discovering it is an imitation of wood, there might be feelings of disappointment and deception.

This thesis uses the term “material” in a simple and pragmatic sense to refer to the physical substances used to fabricate objects; while the term “materiality” will be used to refer to the experience of the physicality quality and concrete presence of the objects described. This topic will be expanded upon in some detail in Chapter Three to set a theoretical framework for the materials and fabrication methodologies deployed in the design research case studies.

**Collaboration**

Collaboration between people, organisations and disciplines has numerous potential successes and pitfalls due to the vagaries of personalities, conflicting objectives and imbalance in resources and funding. The thesis will use the definition of collaboration as being two parties working together to achieve common objectives and goals. To achieve what the Cape Farewell Project describes as *the cultural response to climate change* – that is, a successful collaboration between a creative practitioner and a scientist working in the field of climate science, the research will refer to the pragmatic view of Charles Darwin: “In the long history of humankind

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(and animal kind, too), those who learned to collaborate and improvise most effectively have prevailed”.56

**Sustainability**

The term *sustainability* means different things in different industries and contexts. A summary of terms published in 2007 locates this term in the following categories: *sustainable policy, sustainable systems and subsystems, approaches and principles*.57

The thesis will discuss sustainability in the context of 3D printing as a tool for manufacturing, as this is the primary fabrication process used in the design research component of the research (described in Chapters Three and Four). The terms that are relevant to these processes and materials are:

*Recycling and Reuse-*Recovery method involving the collection and treatment of waste products for use as raw material in the manufacture of the same or a similar product. The EU waste strategy distinguishes between reuse and recycling. The reuse means using waste as a raw material in a different process without any structural changes and recycling refers to structural changes in materials within the same process.58

*Waste Minimisation*—The US Environmental Protection Authority (EPA) describes waste minimisation “as measures or techniques that reduce the amount of wastes generated during industrial production processes”.59 This can include a reduction in the total volume of waste or a reduction in the toxicity of the waste, “so long as the reduction is consistent with the goal of minimizing present and reducing future threats to human health and the environment. It is about minimising waste at source, recycling, and purifying during the production process”.60

“Sustainable Production” is creating goods by using processes and systems that are non-polluting, that conserve energy and natural resources in economically viable, safe

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59 Ibid., Paul Glavič, et al., 1881.
60 Ibid., 1881.
and healthy ways for employees, communities, and consumers and which are socially
and creatively rewarding for all stakeholders for the short and long-term future.\textsuperscript{61}

"Eco-design is a process that takes into account the complete life cycle of a product
and considers environmental aspects at all stages of a process, striving for products
which make the lowest possible environmental impact throughout the product's life
cycle."\textsuperscript{62}

"Environmental (green) technology is the systematic knowledge of, and its application
to, production processes; making efficient use of natural resources while
reducing/recycling wastes to control/minimize the risks of chemical substances, and to
reduce pollution. It includes cleaner production, supply chain management, waste
minimization and zero waste.\textsuperscript{63}

\textbf{Climate Change}

The term \textit{climate change} will be used in accordance with the meaning given to it by the
Ecological Society of Australia on Climate Change:

Climate change is likely to have significant impacts on Australia's biota and society in
the next century. The Intergovernmental Panel on Climate Change recently concluded
that there is sufficient evidence to support these predictions. Alterations in soil
characteristics, water and nutrient cycling, plant productivity, species interactions
(competition, predation, parasitism, etc.) and the composition and function of
ecosystems were identified as highly likely responses to the predicted increases in
atmospheric CO\textsubscript{2} concentration and temperature, and shifts in rainfall regimes. In
addition, impacts on biodiversity are likely to be exacerbated by changes in the
occurrence of disturbances such as wildfire and insect outbreaks.\textsuperscript{64}

There remains debate as to the existence of climate change, and climate change sceptics
continue to deny its existence. However, according to the American National Aeronautical
and Space Administration (NASA), since 2010, 97 percent of climate scientists agree that climate-
warming trends over the past century are very likely due to human activities,\textsuperscript{65} and most of the
leading scientific organisations worldwide have issued public statements endorsing this
position. According to the Intergovernmental Panel on Climate Change (IPCC), which includes

\textsuperscript{61} Ibid., Paul Glavič et al., 1884.
\textsuperscript{62} Ibid., 1881.
\textsuperscript{63} Ibid., 1882.
\textsuperscript{65} National Aeronautical and Space Administration (NASA), https://climate.nasa.gov/ accessed 2/5/2014
more than 1,300 scientists from the United States and other countries, the extent of climate change effects on individual regions will vary over time and with the ability of different societal and environmental systems to mitigate or adapt to change.

There exists a large body of information and predictive literature about the likely effects of climate change. Predictions include more frequent wildfires, longer periods of drought in some regions and an increase in the number, duration and intensity of tropical storms. This is the kind of quantitative scientific literature and data that will be used for investigating different modes of visualisations for this thesis.
1.8: Conclusion

Chapter One has systematically set the framework and context for the research by first introducing and establishing the history and current context of the research areas around creative visualisations of scientific data. This chapter has then defined the following research questions and aims in order to clarify the focus of this thesis:

1) Communication and Collaboration: In the current context of climate change, which tools for communication and collaborations between the disciplines of sciences and the creative practices could be mobilised to facilitate or enable innovative modes for communicating climate change?

2) Artefacts and Visualisation: What is the capacity of created (3D-printed) artefacts to engage with climate change data to produce accessible forms of climate change information and visualise the effects of climate change?

3) Innovation with Processes and Materials: What kinds of processes and materials might be used or developed beyond a purely aesthetic dimension that make a connection between the materials and the data being communicated, and in particular, how can the issue of sustainability be cast within the selection and development of new materials in this enterprise?

To begin to address the questions, the research defines the background, relevant literature and theoretical framework of the research with a particular focus on collaboration and boundary objects in order to set the conditions for the expanded precedent review in Chapter Two. Chapter One has described the rationale for the focus on the development of sustainable techniques and materials described in Chapter Three of this thesis. Chapter One has also introduced the design research case studies that will be expanded on in Chapter Four in order to investigate three-dimensional models of climate change research. These areas of research will be expanded on in Chapters Three and Four.
Chapter 2 Precedents

Collaborations between Creative Practitioners and Scientists to communicate and disseminate scientific research
Chapter 2 Structure

Chapter Two Historical and Discourse Context
Chapter two discusses ways in which individual and community understanding of scientific research is enhanced through creative representations and collaborations between the creative practices and sciences. The chapter conceptually locates the research within the context of transdisciplinary collaborations and how they might be analysed and enhanced using boundary object theory.

2.1 Boundary Objects – Theoretical framework for modes of collaboration
Section 2.1 introduces the theoretical framework of boundary objects as a means of describing different models of collaboration. The section further defines the history and context of the use of the term, and determines new categories to describe novel collaborations between scientists and a range of creative practitioners.

2.2 Historical Archives from the Victorian era conveying natural science research
This section gives an historical account of illustrations and objects by artists designed to convey Natural Science Research. The examples are primarily from the Victorian era due to the tremendous interest in natural sciences during this period. Particular focus is on the influence of Charles Darwin’s Origin of the Species on the public perceptions of science and on the visual and decorative arts in the late 19th Century, both in concept and composition.

2.3 Contemporary Creative Visualisations of Environmental and Climate Science Research
Section 2.3 discusses contemporary artists and designers making creative works or visualisations informed by environmental and climate science. The focus is on the different modes of representation used and the types of collaborations that take place between scientists and creative practitioners.

2.4 Summary and Conclusion
Draws conclusions that build a framework for the execution of the practical research.
Preamble

2.1 Boundary Objects – Theoretical framework for modes of collaboration

Introduction
This chapter focuses on addressing aspects of the following two research questions;

1) Communication and Collaboration: In the current context of climate change, which tools for communication and collaborations between the disciplines of sciences and the creative practices could be mobilised to facilitate or enable innovative modes of communicating climate change?

2) Objects Creation and Visualisation: What is the capacity of created objects to engage with climate change data to produce accessible forms of climate change information and communicate the effects of climate change?

To investigate the different modes of engagement and collaboration between creative practitioners and scientists working together to communicate scientific research, this chapter introduces the concept of the boundary object as a theoretical framework for analysis and evaluation. The major challenge in collaboration between different social groups in the creative practices and sciences is to discover how best to approach and achieve communication between radically different disciplines, each with its own research and procedural culture and goals. Design theorist Nigel Cross describes the differences between the cultures of the humanities and science in the following way:

“Science investigates the natural world through controlled experiments, classification and analysis, while art is concerned with investigating the human experience through analogy, metaphor, criticism and evaluation; science values objectivity, rationality, neutrality; art values subjectivity, imagination and creativity.”

Research explorations in the creative practices and science use different methodologies, impact measurement models, and dissemination sites, to name but a few considerations. The creative practices encourage lateral problem solving, while the sciences encourage linear sequential problem solving. Impact in the sciences is measured by research dissemination in industry journals and texts, while in the creative practices significant research dissemination occurs in non-traditional research outputs such as creative exhibitions. Impact in creative practices may be measured in terms of audience numbers, reception and publicity; while in science, impact is measured in terms of the quality of the journal, the number of citations and the declared impact of research in the field. For the sciences, the volume of readership is not critical, as industry publications often have limited and very specialised audiences. These disciplinary discrepancies are particularly important when creative practitioners and science researchers collaborate.

Despite these challenges, there are many successful examples of interdisciplinary collaborations that have led to new and larger audiences for scientific research. To achieve successful interdisciplinary

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collaborations, a considered approach and a range of tools or devices to encourage knowledge exchange and help achieve common goals are necessary. One such tool or device is termed a boundary object. Boundary objects mediate and help cross normative or institutionalised boundaries between disciplines, parties and individuals. Boundary objects engender understanding and facilitate effective communication and collaboration, whilst also allowing participants to work independently.

Star and Griesemer introduced the term in 1989 as a means of defining and describing objects that have different meanings to different people or parties. Maps are an example of boundary objects as they can be read and understood by people from different disciplines and can communicate diverse information in one document. In order to illustrate this, a topographical map of Sydney, Australia, is shown here Figure 2.1. The map indicates natural features such as waterways, hills, valleys and coastlines as well as manmade features such as roads, railways, suburbs and their names. The map can be used for multiple purposes including guidance for way finding, mountain climbing and boating. Its flexibility of purpose and application makes it a boundary object between different fields of knowledge. One party can use the map to explain to another how to find a particular area or to help explain the topography of different localities. The two parties do not need to have the same knowledge. By using the map as a device to help them the two groups can efficiently share existing knowledge and gain new knowledge.

(Left) Figure 2.1. Topographical Map of Sydney and Figure 2.2, Map of Aboriginal Language and Tribal Groups Institute of Aboriginal and Torres Strait Islander Studies (right).

A boundary object could take a range of forms, depending on the collaborators involved. Other examples could include books, physical models of information, artworks, performances or shared

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activities such as bush walks. Things that cannot function as boundary objects include equipment or devices that require highly specialised knowledge to operate or understand – for example, an operating manual for a spectrometer which, whilst legible in English, requires discipline-specific knowledge and language to comprehend.

In order for a boundary object to be interpretable across disciplinary boundaries, it needs to have a degree of neutrality and accessibility so that it can be relatively easily understood and yet capable of being differently invested with meaning by different players. It then needs to have a degree of adaptability so that it can be owned and spoken about differently by the different players – for example, the map in figure 2.1 can be used for a range of purposes and can be understood by diverse groups. By contrast, figure 2.2 the map of Australia that shows Aboriginal and Torres Strait Islander language groups cannot function as a boundary object because it requires cultural familiarity that might not be widely available.

Multi-disciplinary colleagues collaborating to successfully achieve shared goals must establish a means of exchanging knowledge in a generous, reciprocal manner. Collaborations can be ongoing, creating multiple outcomes, forming what is known as boundary objects. The boundary objects establish tools and processes that allow successful collaboration and communication to happen. To achieve effective ways of traversing multiple disciplinary boundaries, Paul Carlile concludes that boundary objects must establish a shared language or syntax for representing knowledge. They must also provide a means for each group to specify what they know, and what is important to them, so that the differences in knowledge are made explicit, and their collaborators can learn about their differences and facilitate the transformation of knowledge by incorporating the understandings of other fields.  

Creating the right type of boundary object for each collaboration and situation is particularly important when there are significant disciplinary cultural differences between collaborators, as is the case with art and science collaborations. These differences often require collaborators to view their own field in an objective manner and approach other disciplines with an enquiring and open-minded approach. Creative works that result directly or indirectly from collaboration between creative practitioners and scientists can also act as boundary objects, since they cross the border between the different knowledge of collaborators and their audiences. The artworks created need to speak to the audience, while also forming a bridge to the knowledge of the scientists. As the information crosses this bridge it must maintain its integrity – for instance, data about climate change must not change its intent. This is not to say that concrete, direct representations are the only valid form of visualisation. A creative work can faithfully represent data and still be abstract, culturally sensitive, interactive, physical, spatial and beautiful. Exchange and collaboration between scientists and creative practitioners can result in work that honestly speaks on behalf of the research outcomes of the data it represents.

**Boundary objects in the context of visualising science: a three-way boundary object.**

A three-way boundary object occurs when the same boundary object that is used to facilitate communication and collaboration between a creative practitioner and a scientist, is also used to communicate ideas and information to an audience. These boundary objects could be artworks or specimens or other object that does not require disciplinary expertise to be understood and yet still accurately communicates the scientific research.

In the diagram below, the first boundary object is between scientist and creative practitioners engaged in producing a visualisation. This must be negotiated so that the creative practitioner can faithfully represent the outcome of the scientific research in a way that is also able to engage the audience with data on different levels. On one side of the second boundary object is the creative practitioner and the scientist, and on the other side is the audience. In this way, the work itself acts in translation on behalf of the scientist.

![Diagram of a three-way boundary object](image)

*Figure 2.3 Diagram of a three-way boundary object. Kate Dunn, 2016.*

**Boundary Objects: Context and development**

In the following sections the different aspects of boundary objects are discussed in detail. The framework for the history of the term ‘boundary object’ and the key authors and their influence is outlined below. As part of the research, this thesis continues the lineage of precedents and categories of boundary objects, and proposes additional categories, as will be discussed (see figure 2.4).
As a first description of boundary objects, Star and Griesemer used the term when discussing the collaborations and cooperative efforts of various participants in the establishment and running of the Museum of Vertebrate Zoology at the University of California, Berkeley between 1908 and 1939. The participants included the first director Joseph Grinnell, the founder of the museum Annie Montague Alexander and many other stakeholders including “amateur naturalists, professional biologists, the general public, philanthropists, conservationists, university administrators, preparators and taxidermists”.\(^7\) The diverse range of disciplines and stakeholders represented here demonstrate the effectiveness of boundary objects in facilitating communication and collaboration in multiple contexts.

Star and Griesemer chose a natural history research museum to illustrate how boundary objects function to facilitate communication and collaboration among the vast number of stakeholders, and the diverse range of boundary objects produced, including specimens, maps, field notes and the museum itself:

\(^7\) Ibid., Star and Griesemer, *Institutional Ecology, translations’ and Boundary Objects*, 396.
“In natural history work, boundary objects are produced when sponsors, theorists and amateurs collaborate to produce representations of nature. Their boundary nature is reflected by the fact that they are simultaneously concrete and abstract, specific and general, conventionalised and customised. They are often internally heterogeneous.”72

This multiplicity of states of the boundary objects described in the collaborations at the museum provide important precedents for research into different visualisations of data investigated in Chapter four of this thesis. The museum team worked together to produce representations of the environment while the design research developed in collaboration with climate scientists produced representations of different elements of the environment 100 years later.

One of the pivotal boundary objects established in the early years of the museum was director Grinnell’s systematic records of collected samples and species data. In 1908 Grinnell hired 10 field workers to collect specimens in the San Jacinto region, together, they collected 5981 vertebrates. Along with collecting specimens and taking photographs, field workers also recorded detailed observations about the flora and fauna and their locations and habitats in notebooks. The museum director Grinnell, anticipating the different applications of the field notes, developed a system for note taking that could be followed by any of the members of the expedition team.

72 Ibid., Star and Griesemer, Institutional Ecology, translations’ and Boundary Objects, 408.
Standardising field notes also meant that anyone could read them and apply the information and research to a range of contexts. Although not every member of the San Jacinto expedition took notes, 865 pages were produced, including detailed descriptions of animals, their behaviour and abundance, vegetation, weather, and landforms. These notes act as boundary objects between diverse stakeholders and are currently being referenced by the museum for comparison with the current wildlife distribution in the area that Grinnell targeted.

Star and Griesemer’s example of the establishment of the museum and the diverse participants involved demonstrates how boundary objects can be used by multiple parties in multiple contexts to achieve effective collaborations and knowledge exchange. Subsequent analysis and development of boundary object theory by different authors has produced new categories and applications that can be applied in many different disciplines.

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**Interessement**

Star and Griesemer built their notion of the boundary object on the concept of *interessement* (mutual interest) introduced by Michel Callon in 1984 to describe the group of actions or processes of communication between parties who are collaborating to achieve an outcome.\(^{74}\) The term *interessement* can also be read as meaning ‘to be in between’ (Latin *inter-esse*), to be interposed – in effect to place a device between two things or two people. Star and Griesemer’s critique the *interessement* model as a type of funneling of viewpoints dictating that forces a story be told from only one stakeholders perspective. *Interessement* devices according to Star and Griesemer’s are objects or barriers that can be placed between participants and put them in a position of competition rather than collaboration. Callon describes his research as a study of power and of how communication and communication channels and devices affect the distribution of power.

However, boundary object theory differs in the interpretation of such devices and their application. Boundary objects are used to facilitate communication and collaboration rather than attain power. The devices work to share knowledge and increase access to multiple stakeholders. The process of translation is intended as a way of opening up knowledge exchange rather than redirecting it, as is the case with *interessement* devices. Star and Griesemer’s concept of the boundary object proposes instead a flexible object that can be viewed from multiple perspectives. Their view is that:

> there is an indefinite number of ways entrepreneurs from each cooperating social world may make their own work an obligatory point of passage for the whole network of participants. There is, therefore, an indeterminate number of coherent sets of translations.\(^{75}\)

Translation itself is defined in the context of multiple social worlds as the task of reconciling the meanings of objects, methods and concepts of these worlds,\(^{76}\) whereas in the *interessement* model translation of information is a way to withhold information and make it inaccessible to different parties. The idea of translation is an important concept in this research as the artefacts produced are experiments that attempt to translate scientific data into three-dimensional models.

In the context of the collaborations undertaken during the practical research described in chapter four of this thesis, Callon’s *interessement* model acts as a counterpoint to Star and Griesemer’s boundary object theory and stands as a warning of the dangers of using knowledge as power when trying to achieve effective collaborations. The goal of the collaborations undertaken during the research for this thesis was to achieve knowledge exchange rather than a distribution of power; they therefore adopt the boundary object model of collaboration and use the *interessement* model as a reference point to ensure translations can be understood by all parties. This is achieved by ensuring that any devices used in collaboration have meaning to and are legible to all parties involved.

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\(^{75}\)Ibid., Star and Griesemer, *Institutional Ecology, translations’ and Boundary Objects*, 390.

\(^{76}\)Ibid., 388.
Categories, types and contexts of boundary objects

The research proposes that, while boundary object theory has limitations, these limitations can be overcome with the application of context specific categories. By doing so, boundary object theory can be made a useful tool to describe the types and outcomes of different transdisciplinary collaborations. Information management theorist Adam Worrell, writing about the parameters of boundary object theory, supports this position, stating that “despite some of the limitations and criticisms other researchers have identified, boundary object theory can and likely should play a prominent role in studying the interrelations between communities, organisations, information systems and information behaviour”. The following section will document the different categories of boundary objects, their authors and the contexts of their use. The section will then go on to describe new categories determined by the research.

Star and Griesemer divide the boundary objects at play in the case study of the museum into four categories.

1. **Repositories.** These are ordered 'piles' of objects, which are indexed in a standardised fashion. An example of a repository is a library or museum. People from different worlds can use or borrow from the 'pile' for their own purposes without having directly to negotiate differences in purpose.

2. **Ideal type.** This is an object such as a diagram, atlas or other description that in fact does not accurately describe the details of any one locality or thing. An example of an ideal type is the species. This is a concept which in fact describes no specimen, incorporates both concrete and theoretical data and serves as a means of communicating across both worlds.

3. **Coincident boundaries.** These are common objects over a large-scale geographic area. The result is that work in different sites and with different perspectives can be conducted autonomously while cooperating parties share a common referent. An example of coincident boundaries is the creation of the state of California as a boundary object for workers at the museum. The maps of California created by amateur collectors and conservationists resembled traditional roadmaps familiar to us all, and emphasized campsites, trails and places to collect. The maps created by the professional biologists, however, shared the same outline of the state (with the same geo-political boundaries), but were filled in with a highly abstract, ecologically-based series of shaded areas representing 'life zones', an ecological concept.

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4. Standardised forms. These are boundary objects devised as methods of common communication across dispersed work groups. For example, the amateur collectors were provided with a form to fill out when they obtained an animal, standardized in the information it collected. The results of this type of boundary object are standardized indexes and what Latour would call 'immutable mobiles' (objects which can be transported over a long distance and convey unchanging information). The pragmatic object is often designed specifically for the situation it is being deployed in.”

Star and Griesemer’s divisions of boundary objects have subsequently been analysed, rewritten, expanded and changed to suit the context that the boundary object is operating in. Since its inception, the term boundary object has been used across a range of disciplines from sociology, the humanities and the sciences. It is often used when discussing modes of collaboration and knowledge sharing, both within a discipline and across disciplines. Boundary object theory is a particularly relevant tool for analysing the collaborations undertaken in the practical research phase of this project. In order to develop boundary objects customised to suit the collaborations between scientists and creative practitioners applying here, further research into other applications of the term were undertaken. These different models of boundary objects are described in the following sections.

Intermediary boundary objects. Another example among the diverse uses of the term boundary objects is Charlotte Lee’s case study of museum exhibition designers collaborating for a year to create an exhibition about wild dogs. In her 2007 paper on this study, Lee critiqued aspects of boundary object theory. She conducted a year-long ethnographic study of collaborative work of museum designers preparing an exhibition about wild dogs and wrote about the use of boundary objects as communication tools. Lee concluded that “artefacts can serve to establish and destabilize protocols themselves and that artefacts can be used to push boundaries rather than merely sailing across them.” Lee suggests that Star and Griesemer’s framework is merely a foundational concept and that it relies heavily on the concept of standardization. Their examples of boundary objects are typically things with a standardized structure such as forms, maps, and grades – or things with a naturally pre-determined structure such as a bird.

In writing about boundary objects, Lee cautions that the concept has been used as a catch-all for artefacts that fit uncomfortably within the definition. Lee describes boundary object theory as incomplete in that it omits artefacts that are flexible and change over time. This position is supported by Paul Carlile, whose research on boundary objects is detailed below, and who has written that:

80 Ibid., 307.
“Boundary objects are no ‘magic bullet’ because their characteristics are hard to sustain as problems and people change. For example, a CAD model can be an effective boundary object at one stage, but can falter when taken to another setting where a key functional group cannot represent their knowledge or alter the current knowledge with a CAD model.”

To overcome the limitations of Star and Griesemer’s categories Lee introduces another category, that of Intermediary objects. Lee describes them as intermediate states of a product, for example a sketch. Intermediary objects are representations, but they are also the traces as well as the outputs of a collaborative transformational process. Lee suggests that the activities of a boundary object may need to be augmented with additional contextual information in order to be effective.

**Syntactic, semantic and pragmatic boundary objects**

Another example of the context-specific use of boundary objects is given by Paul Carlile, who writes about boundary objects in the fields of product development and knowledge organisation. He presents three new and different types of boundary objects, the syntactic, semantic and pragmatic. These categories were developed to suit the disciplines he was discussing in his research.

![Figure 2.6 Paul Carlile’s breakdown of categories and characteristics of boundary objects](image)

Carlile defines the characteristics of the boundary object in each category; for the pragmatic boundary object to be truly successful, some element of transformation of knowledge must happen.
to create new knowledge. He outlines a process of transforming knowledge, “where individuals represent, learn, negotiate, and alter the current knowledge and create new knowledge to resolve the consequences identified.”

Carlile’s descriptions also help clarify the role boundary objects play in establishing an infrastructure or process where knowledge can be represented, learned, and transformed.

**Adapting Carlile’s categories for different contexts**

Carlile uses the term to define collaboration in the context of new product development; however, his category descriptions suit a range of contexts. The following definitions detail Carlile’s categories and then demonstrate how they can be adapted to suit creative practice and science collaborations.

**Syntactic boundary objects**

Syntactic boundary objects are repositories of knowledge that allow access to information without direct collaboration. The creative practitioner using this method can retrieve the scientific data for themselves; the largest concern is then how the data is processed. This may take the form of an indirect collaboration between the scientist and creative practitioner, as data can be retrieved from a repository, such as an online service. These repositories allow the group holding the knowledge to represent the data in their own terms, putting the burden of processing that data on the group that wishes to make use of the knowledge.

**Semantic boundary objects**

Semantic boundary objects involve direct collaboration between creative practitioners and scientists, allowing both parties to learn about the differences between the two groups. The semantic boundary object illuminates the differences and allows the collaborators to gain an understanding of the source of the knowledge of the other group. A creative practitioner may collaborate directly with a scientist by sharing relevant scientific publications and presentations, while also researching data and collection methods. This will help the creative practitioner develop an understanding of the data as well as its origins in scientific practice. To give the scientist an understanding of the creative processes that are used in developing an artwork, the creative practitioner may invite the scientist to be involved in prototyping, or user testing. These processes give each participant the opportunity to learn about the source of their collaborator’s knowledge.

**Pragmatic boundary objects**

Pragmatic boundary objects go further to promote the transformation of knowledge of each group, rather than just an understanding that there is a difference between them. This process will require the creative practitioner and scientist to engage in significant interaction and exchange.

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84 Ibid., Carlile. 455.
85 Phillip Gough, Kate Dunn, and Caitilin de Bérigny (These adapted definitions were co-developed and written and published in the following: “Climate Change Education through Art and Science Collaborations. “Promoting Climate Change Awareness through Environmental Education (2016): 16-36.
When defining the types of boundary objects that are generated from creative practice / science collaborations, the existing terms outlined by Star and Griesemer, Lee and Carlile fail to address and describe the influence of aesthetics, models of representation or the transformative qualities of creative works, on the output of these collaborations. Star and Griesemer designed their categories specifically for the museum context, hence the reference to species, museums and forms used to record specimens. Lee expanded on these categories for a museum context and introduced Intermediary Boundary Objects to include those items or artefacts that changed over time, suggesting that contextual information is necessary to make the boundary objects effective.

Another example of boundary object theory being adapted for discipline and context specific cases is Paul Carlile’s introduction of the Syntactic, Semantic and Pragmatic Boundary object categories. Carlile introduced these categories to address the nuances of the fields of product development and knowledge organisation. His new categories and their parameters meant that the activities of the relevant parties and the outcomes of their collaborations were able to be identified and described in detail, in language that was able to be understood by the relevant disciplines and the general public.

Carlile’s categories were in turn adapted by the author in collaboration with Gough and de Bérigny in three case studies of artists’ projects to describe their work about climate change. However, Carlile’s categories, while effective at a shallow depth of enquiry in the context of three case study projects all from Sydney that were executed at approximately the same time, became awkward to use when applied to the breadth of projects described in this thesis.

Carlile’s categories, originally designed for product development and knowledge organisation, do not have the detail needed to ensure an accurate and detailed description of the boundary objects generated by collaborations between artists and scientists described in this thesis. These span across more than two hundred years and take place in Europe, the Americas and the Pacific. The collaborations traverse different contexts and models of collaboration as well as producing quite different types of boundary objects and physical artefacts.

**New categories of boundary objects generated by the research**

As with other researchers developing categories of boundary objects for specific contexts, this thesis proposes new categories of boundary objects specifically for collaborations between creative practitioners and scientists and for the material outcomes of their collaborations. Three new categories were developed, together with associated parameters, to enable accurate analysis of the nature and outcomes of the collaborations:

1. Didactic Boundary Objects;
2. Creative Boundary Objects;
3. Reciprocal Boundary Objects.

The categories defined by the research and the parameters are outlined below.

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86 Ibid., Phillip Gough et al. 23.
Using Carlile’s template for the type, category and characteristics of boundary objects, the following table outlines the parameters of each new boundary object. This is followed by a detailed description of each with examples in section 2.2 and 2.3.

<table>
<thead>
<tr>
<th>Types of Boundary Objects</th>
<th>Categories of Boundary Objects</th>
<th>Characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Didactic</td>
<td>Activities, artworks and botanical plants</td>
<td>Representing and often enacting elements of the science</td>
</tr>
<tr>
<td>Creative</td>
<td>Artworks in galleries</td>
<td>Representing and transforming</td>
</tr>
<tr>
<td>Reciprocal</td>
<td>Artworks in a range of contexts</td>
<td>Representing, transforming reciprocal, ongoing</td>
</tr>
</tbody>
</table>

*Figure 2.7, Types, Categories and Characteristics of Boundary Objects. Diagram by Kate Dunn, 2015.*

**Didactic boundary objects**

A didactic boundary object describes artefacts generated by collaborations between artists and scientists that have had little or no creative transformation applied to the object’s aesthetic and physical form. They function as boundary objects because they help translate information from one party to another. In this case the parties are the artist and an audience viewing a presentation of the artist’s work. The process of translation is critical to being categorised as a boundary object.

A common manifestation of didactic boundary objects involves scientific research findings prepared in a form suited to display in an art gallery, for example, rather than a scholarly journal are one common manifestation of a didactic boundary object. The goal of this type of boundary object is to draw attention to the science and reach new audiences who may not read science journals or have access to science labs. The translation or passage of information occurs through the shift in context, making information available to new audiences.

This mode has informed many museum displays; for example, taxidermy specimens with identity tags are in most natural history museums. There is often no analysis with the specimen other than a species name and a location where the specimen was caught. The Harvard Natural History Museum has a large collection of taxidermy and skeletal specimens; however, whales are in the same room as giraffes and koalas. The animals are crowded together and the logic of the display resembles a trophy cabinet rather than a considered communication of deep scientific research.

Contemporary examples of didactic boundary objects include Lauren Berkowitz’s work *Manna*, and the Artist as Family’s piece *Food Forest*, both of which include live plants; these were displayed as part of the 2010 *In the Balance* Exhibition at the Museum of Contemporary Art (MCA), Sydney. Detailed descriptions of didactic boundary objects will be presented in section 2.2 and 2.3.
Creative Boundary Objects

Creative boundary objects are described as objects or events generated by an artist creatively interpreting scientific research and using it to inform their creative practice. A scientist is not necessarily involved, and the data can be sourced from public sources such as newspapers. The translation occurs through the artist interpreting the scientific research and applying a series of creative devices to render the information in a new form. Examples of the forms include botanical illustrations, sculptures, paintings and installations. The context for display of a creative boundary object is generally a cultural institution such as a gallery or a museum.

The intention of creative boundary objects in the context of communicating climate change science is to draw attention to the issues; it is not to accurately convey a particular scientist's research. The creative boundary object may engage a range of emotive techniques such as dramatising elements to enhance the transformative effects of the creative works or to stimulate a response in an audience. Techniques could include editing, framing, up- and down-scaling or otherwise modifying or exaggerating the scientific data so as to more effectively and powerfully communicate the scientific research. This is arguably a method used in the most effective kinds of documentary that, while using accurate information, assemble and represent it in such a way as to amplify the desired message.

There are limitations on the impact of works displayed in cultural institutions such as galleries and museums. These institutions can have limited audience appeal and visitation numbers for several reasons. Some members of the public can be intimidated by the formality of traditional gallery and museum architecture, while others can find galleries and museums inaccessible due to location and admission costs. Museums and galleries also have protocols of preservation that can restrict the type of work to be exhibited there.87

Despite the limitations of an arts context, this type of work is critical as it allows the artist to respond to climate change data in a creative, interpretive manner that can give new insight into the scientific research informing the work. The artist can distil the information into images and objects that are quickly interpreted by viewers, while also potentially triggering an emotional response in the audiences – ideally triggering a curiosity about the science as well as a desire to make changes in their activities. For example, works about climate change may prompt audiences to reconsider their own energy usage. This type of creative work forms a boundary object between the scientist and the public as well as the artist and the public.

Reciprocal boundary objects
A reciprocal boundary object describes relationships and outcomes where an artist and scientist have

87 For example, when installing the Rapid Prototyping: Modelling Climate Change exhibition (2016) at the Macleay Museum, Sydney University, I was prevented from using some organic materials such as sugar because of the insects that might be attracted. This is a problem because of the rare specimens kept in the cabinets in the museum.
an ongoing dialogue and exchange and rely on each other to complete their research. The scientist relies on the artist to record the information and the artist relies on the scientist to supply the subject of their practice. This is an ongoing relationship that develops over time and is interdependent. An historical example is the relationship between zoologist Francois Peron and artist Charles-Alexandre Lesueur. Peron and Lesueur travelled together on-board the *Geographe* during the French circumnavigation of Australia and worked closely together documenting and preserving the specimens they found. Lesueur’s drawings along with the preserved specimens acted as proof of or evidence for scientific theories. The products of the collaboration can be described as reciprocal boundary objects since Lesueur responded to Peron’s research while his drawings educated the next generation of scientists about that research and formed a database for Peron to reflect on.

Their work resulted in some critical records of research that were used to communicate to each other, the broader science community and the public. The specimens and records have ongoing value as boundary objects, being able to overcome boundaries of time and place. The objects have recently been used by curators from the Museum of Victoria to assess both the effects of time on the distribution of species in the Southern Ocean and the impact of changing water temperature on specimens of invertebrates dredged from the reefs off Tasmania. The framework for a reciprocal boundary object builds on the definition of the pragmatic boundary object determined with Gough and de Berigny in the context of collaboration between an artist and a scientist – a process that required creative practitioner and scientist to engage in significant interaction and exchange.

A reciprocal collaboration establishes multiple modalities for exchange, influences the participating disciplines and social groups and creates outcomes that effectively communicate contemporary science. Reciprocal boundary objects are often purpose-built to address the context of the collaboration. A contemporary example is Luke Jerram’s models of disease, created through a process of collaboration and consultation with virologist Dr. Andrew Davidson from the University of Bristol. Using a combination of different scientific photographs and objects, Jerram made large-scale glass models of significant viruses. The works have been made to facilitate the study of the global impact of each disease and are used in multiple disciplines such as medicine, art and design. These works are detailed in the section 2.3 of this chapter.

**Summary**

Each of these categories has different uses within transdisciplinary collaboration, and all can be found in the examples presented in this chapter. The examples demonstrate that the artworks produced through collaboration can also be considered boundary objects, helping an audience understand the science informing the artwork.

Reflecting on concepts of “creative” and “reciprocal” boundary objects, sometimes, an artist might interpret scientific data in personal or coded ways that do not amplify its understanding for a public

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89 Ibid., 16.
audience. However, understanding can be defined in numerous ways, for example it could be a literal understanding of how many species have become extinct due to climate change within a given area. This could be communicated using an object that uses the numerical data supplied by the scientist to create an object which uses these numbers as exact design parameters. Like all contemporary art and design objects the system of cultural, material and aesthetic semiotics applies. This ensures that the object will still communicate ideas, concepts and responses to the scientific research that the scientist and audiences can recognize.

What then of a situation when a scientist, who produces data used by an artist to make a creative boundary object, cannot decipher the meaning from the resulting artistic work? Creative boundary objects are designed to draw the attention of an audience to the issues being researched by the scientist. The intention of creative boundary objects in the context of communicating climate change science, for example, is to draw attention to the issues; it is not to convey the specific quantitative data which forms part of the scientific research.

Understanding or impact could also occur through stimulating emotions by using dramatising devices and techniques that enhance the transformative effects of the creative works or stimulate a response in an audience. Despite the limitations of an arts context, as noted earlier, this type of work is critical as it allows the artist to respond to climate change data in a creative, interpretive manner that can give new insight into the scientific research informing the work.

The notion of a boundary object and in particular a reciprocal boundary object, is that it facilitates exchange of knowledge, and thereby contributes to the generation of new knowledge. The boundary object is not necessarily new knowledge as it could be as familiar as an object as an instructional diagram or a map, rather it is through the cross disciplinary exchange and collaboration that knowledge can be generated. This occurs by incrementally building on what already exists and combing it to generate new knowledge through iterative prototyping and testing, be it an object or an idea.

Collaboration across different disciplines can challenge and alter the frameworks and formal boundaries of traditional knowledge paradigms. When experts from different fields collaborate, their distinctive research and thinking practices can produce alternate ways of exchanging, transforming, and disseminating information. This occurs through the different parties’ forging into territory that is unfamiliar, possibly for both parties, often leading to reflection and reconsideration of normative parameters. The point where the two parties meet can create a new environment, free of the precedents and conventions of their separate disciplines, yet bringing a wealth of diverse knowledge to the discussion. By fielding multiple alternate perspectives on a common topic in a singular site, there is the potential for the resulting space of exchange to become charged and to stimulate innovation, creating new modes of communication and collaboration.\(^{90}\)

\(^{90}\) Ibid., Phillip Gough, Kate Dunn, and Caitilin de Bérigny. "Climate Change Education through Art and Science Collaborations." Promoting Climate Change Awareness through Environmental Education.
2.2 Historical Archives from The Victorian Era
Conveying Natural Science Research
Introduction

This section will give an overview of the types of collaborations and objects employed to communicate natural science to the general public during the latter half of the nineteenth century. Victorian-era Britain saw some of the first widespread communication of scientific research, through events such as the Great Exhibition of 1851, the emergence of public museums, and advances in publishing through the industrialisation of the printing industry. An interest in the natural sciences dominated many areas of culture, a factor attributed to Charles Darwin and his publishing of the *Origin of Species* and his theory of evolution. Darwin’s friend Thomas Huxley went so far as to describe “The philosophy of Evolution” as the most portentous event of the nineteenth century.91

The dominant understanding of species development in Darwin’s time was that each species had been independently created and did not change – for example, each dove would be virtually the same as the first dove, with no change in size or adaptations for specific environments. At the same time as Darwin was building his theory of natural selection and adaption, other naturalists such as Alfred Wallace were comparing living species with a growing collection of specimens and fossils and drawing similar conclusions. Despite competition Darwin’s name is the one affiliated with the theory of evolution.

Darwin’s controversial text, the theory of evolution and stories of his voyages sparked the imagination of everyday people; “Darwin’s books could be understood and their implications could be absorbed by any educated person at the time – and those implications were such as to change fundamentally the readers’ view of nature and mankind.”92 In some ways, the Victorian era was a golden age of collaboration between the arts and sciences, something that was subsequently lost with the segregation of disciplines during the early twentieth century in universities. The constructive approach to collaboration common in the Victorian era is slowly being reclaimed as the urgency of climate change calls for new ways to communicate scientific research. Of particular relevance to this thesis is the prior example of seismic shift in social and cultural values and approaches to the environment. These dramatic shifts in attitudes to nature, and the controversies and practices that ensued, provide a useful comparison in the current era of climate change.

The wide influence of Darwin’s writings led to significant collaborations between scientists and creative practitioners that generated what were early examples of three-dimensional boundary objects to facilitate science communication – for example, taxidermy, sculpture and biology models in a range of materials. The examples from the period – as well as the sites of display such as natural history museums, art galleries and large public exhibitions – have influenced the modes and locations of display for the material research outputs detailed here in chapter four.

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92 Ibid., 1.
Methodologies
This section uses the categories of Didactic, Creative and Reciprocal boundary objects outlined in section 2.1 to analyse collaborations between different stakeholders such as scientists and artists to communicate natural science in the Victorian Era. The categories are used to identify the model of collaboration and describe the boundary objects and the material outcomes they generated. While acknowledging the wealth of examples from the period, the research will focus on key examples that are relevant to the thesis. The section is divided into broad categories such as museums and illustrated books, with examples of individual collaborations, projects and boundary objects detailed within each category. Particular focus will be placed on the significance of:

- Charles Darwin’s research and publications;
- The Great Exhibition of 1851;
- Natural history museums;
- Illustrated books and decorative arts.

The Victorian era was a time of intense interest in the sciences, particularly natural history. Many countries were conducting exploratory scientific voyages during the period, including the French, the Spanish, the Americans and the British. One of the most famous voyages is Charles Darwin’s voyage of the Beagle. The Beagle as with other research voyages, travelled around the globe collecting samples and conducting research. On board these ships were botanists, biologists, artists, taxidermists and geographers working together to collect, store and record the plants, animals and landscapes they came across.

Materially, texts such as Darwin’s and objects such as taxidermy specimens and zoological and botanical illustrations were the primary means of communicating natural scientific research to the general public. These objects, the places where they were viewed and the means of disseminating the information (for example illustrated books) functioned as boundary objects between scientist, artist and the public. There were multiple types of boundary objects being made and used to facilitate communication of science at this time. Many would fall into the category of a reciprocal boundary object, as artists were often instrumental in the representations of the science. A close and mutually beneficial relationship between the arts and the natural sciences developed during this period.

The relationship flourished within an interdependency specific to the period. Scientists relied on artists to draw or paint the specimens they collected on field trips as cameras during the Victorian era were primitive and certainly not transportable; and other means of recording species such as taxidermy required specialised equipment and materials. Artists and scientists would often travel together on field trips and voyages such as that of the Beagle. Artists’ work, along with text, were the primary means of documentation and communication of the scientific research from the period.

Artists also relied on the relationship for inspiration and as a source of income. Due to the widespread interest in natural science in the Victorian era, many artists referenced natural science in
their work and indeed, many artists made their living illustrating for scientific publications. Ornithological artist Edward Lear spent much of his career creating images for John Gould’s well-known series *Birds of Europe.*

Displays of Scientists and artists research and practice were often grouped together in museums, galleries and at events such as the Great Exhibition of 1851; these events ensured regular opportunities for dialogue and exchange across the different fields. This relationship, while constantly changing, is still critical today as scientists continue to seek to communicate or visualise their research and artists continue to draw inspiration from scientific research. The following section will detail examples of different types of collaborations from the Victorian era, (Contemporary collaborations and exchanges will be expanded on in section 2.3).

**Didactic boundary objects from the Victorian era: Charles Darwin’s research and publications, didactic boundary objects between science and the general public**

Charles Darwin published *Voyage of the Beagle* in 1839 and *On the Origin of Species by Means of Natural Selection or the Preservation of Favoured Races in the Struggle for Life* in 1859. The books proposed the revolutionary concepts of natural selection and survival of the fittest and documented the research outcomes of Darwin’s field trips. The books were highly controversial at the time because they challenged the existence of God. They acted as a didactic boundary object between Darwin and the general public. The science was communicated in text form with no opportunity for exchange of opinion between disciplines or response from the reader back to Darwin.

Upon publication of *Voyage of the Beagle*, Darwin had completed his nearly five-year voyage around the world visiting many sites including Australia and the Galapagos Islands, conducting his research, collecting specimens and documenting the landscapes, fauna and flora of the places visited. The books were written for lay readers and were widely distributed. The texts and theories became hugely influential in the sciences and culture generally. Darwin’s texts are relevant to the thesis and material outcomes described in chapters three and four because they demonstrate an early example of a scientific theory or discovery that had a large impact on contemporary society.

In a similar manner, climate change research is currently having a large impact on society, culture and the creative practices as people grapple to understand the implications of the science. While Darwin’s books acted as a didactic boundary object, the influence of Darwin’s theories and research on Victorian culture, society and attitudes to nature caused many other collaborations to take place and boundary objects to be created. The arts played a critical role in communicating both questions and ideas in Darwin’s science because they were able to visualise ideas embodied in the text. The arts currently have a similarly valuable contribution to make in visualising climate change research and making it accessible and comprehensible to the general public and experts alike.

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Creative boundary objects from the Victorian era- creative works made by creative practitioners to communicate natural science, focusing on those made in response to Darwin’s writing

The creative works made in response to the themes in Darwin’s texts became creative three-way boundary objects between science, the arts and the general public. The artists may have had no contact with a scientist before making the works and have had little understanding of the scientific theory, but even so they were able to capture the essence and drama of the ideas in the works through their creative ideas and material skills.

There has been a great deal of analysis by art critics such as Julius Bryant and Diana Donald of the pivotal influence of Darwin’s research on the way nature was represented in the visual arts.94 Others, such as Patricia Mainardi, suggest the changes can also be attributed to a general naturalist movement of which Darwin was perhaps the figurehead but certainly not the only member.95 Other significant figures in the naturalist movement included Alfred Wallace96 and Joseph Hooker97; however, neither of these men enjoyed nearly as much public attention and, unfortunately for them, Darwin is the one immortalised in history as the father of evolutionary theory.

In 2009, the exhibition Endless Forms, Charles Darwin, Natural Science and the Visual Arts was held at the Fitzwilliam Museum, University of Cambridge, and the Yale Centre for British Art to celebrate the bicentenary of the birth of Charles Darwin and the 150th anniversary of the publication of On the Origin of Species. An extensive catalogue was published with a series of essays that analyse Darwin’s

97 “Australia’s flora as well as fauna were important to Darwin in developing his theory of evolution by natural selection. The adaptation and the distribution of Australia’s native flora were of great interest to Darwin. A source of information, encouragement and critical discussion was the botanist Joseph Dalton Hooker. Hooker spent two periods in Australia, in 1840–41 and 1842, while serving with James Clark Ross’s 1841 Antarctic voyage, which was the first to penetrate the Antarctic pack ice south of New Zealand. Hooker worked at Kew Gardens, where his father was Director, and retained close links to a network of local naturalists in the Australian colonies. Darwin had extensive correspondence with Hooker from 1843 until 1882 (over 400 items) and from the mid-1850s onwards was able to make use of this network of naturalists in the Australian colonies”. Berry, R. J. “Joseph Hooker: one of Charles Darwin’s best friends.” Curtis's Botanical Magazine 26, no. 1-2 (2009): 142-174.
influence on the visual arts in great detail.\textsuperscript{98} Of particular relevance are the essays by Julius Bryant, \textit{Darwin at Home: Observations and Taste at Down House} and, \textit{The ‘Struggle for Existence’ in Nature and Human Society}, by Diana Donald. Donald and Bryant propose that the stylistic and thematic changes in visual arts during the latter half of the nineteenth century were brought about by Darwin’s writings in \textit{On the Origin of Species}.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{image.png}
\caption{The struggle for Existence, George Bouverie Goddard 1879.\textsuperscript{99}}
\end{figure}

Donald writes extensively on the influence of Darwin’s theme of the “survival of the fittest”. This can be seen in paintings of the period such as George Bouverie Goddard’s \textit{The Struggle for Existence} (1879), which depicts a pack of wolves in a battle for supremacy. Some of the wolves are in various aggressive poses with their lips curled back, their teeth bared, on their hind legs in attack; others are obviously in pain, lying in a submissive position implying defeat; yet others seem injured beyond return. There is a sense that the viewer is in the wilderness and has happened upon a pack of wolves in the midst of a violent battle. The poses are dramatic and imply fast movement through the corresponding flurry of snow swirling around the wolves’ feet. Donald attributes the visceral domineering nature of the painting to the influence of Darwin’s \textit{Origin of Species}.\textsuperscript{100} The painting is a creative response to Darwin’s theory of survival of the fittest and functions as a creative boundary object between the science and the general public.

Other examples of artworks where the influence of Darwin’s theories is apparent include scientific models and taxidermy scenes portraying battles to the death of different species, for example John Hancock’s taxidermy hunting compositions exhibited at the Great Exhibition of 1851. Figure 2.9


\textsuperscript{100}Ibid, Diana Donald, 91.
shows Hancock’s *Struggle with the Quarry*. The piece portrays a falcon attacking a heron, whose torn flesh Hancock has chosen to show after being ripped apart by the sharp beak and talons of the falcon. The heron appears crushed and broken in response to the relentless onslaught of the falcon’s attack, one claw raised in attempted defense, the neck bent at an ungainly angle. Feathers near the wound appear damp as if soaked in blood. The wings of the heron and falcon are outstretched despite the setting of leaves and sticks, implying the pair have fallen to the earth, and we have happened upon the last moments of battle.

The dynamic and dramatic composition of the piece revolutionised approaches to taxidermy at the time as it was in contrast to the usual style of taxidermy portrayed in figure 2.10. Figure 2.10 shows taxidermy Great Kiskadees at the Museum of Wildlife and Fish Biology, at the University of California, Berkeley. Multiple birds from the same species lie flat on their back with a tag identifying their specifications tied to their legs. The similar positioning allows for comparisons to be made between the different specimens. There is no attempt to relay to the viewer anything about the bird’s behaviours or natural environment. The taxidermist has not employed any of the devices used in creative practices such as design elements and principles or dramatising compositions. The intention is simply to preserve scientific specimens.

(Left) Figure 2.9 John Hancock, *Struggle with the Quarry*, taxidermy, exhibited 1851 at the Great Exhibition in London, and (Right) Figure 2.10 demonstrates taxidermy used to archive a species for the purposes of scientific research.

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101 Image sourced from the Natural History Society of North Umbria, The Hancock Museum Newcastle upon Tyne.
102 The Museum of Wildlife and Fish Biology, ‘Taxidermy Great Kiskadees from Southern Texas’ (bird collection: University of California, Davis).
Hancock changed the perception of taxidermy from that of a tool for recording scientific specimens to one of a high art by consciously introducing composition devices traditionally used in art. These included consideration and exploitation of design principles and elements such as contrast, balance, movement, repetition, colour and texture. Another factor that changed the work from a mere record of two bird species to a work of art was the attribution of a title. The words Struggle with the Quarry imply action and lend a narrative to the scene, allowing the audience to use their imagination and visualise what had happened right before the moment Hancock was portraying.

Hancock received rave reviews for his exhibits of birds and small and large game specimens, which at the time were amongst the finest examples of group taxidermy ever put on display to the public. According to an illustrated record of the Great Exhibition called a Reports by the Jury, “these impressed visitors by their faithful and spirited adherence to life and nature. But also by their skillful and harmonious combination of forms and colours, such as to raise the status of taxidermy to a higher level of artistic esteem”.\(^\text{103}\) This shift from using taxidermy to display an individual of a species for the purposes of communicating or recording it for scientific purposes towards creating poses and interactions between characters or animals in the mounts meant that they became sculptures or artworks in their own right as well as tools or objects for communicating science. This places them in the category of creative boundary objects.

Another taxidermist exhibiting at the Great Exhibition was Abraham Dee Bartlett; he is relevant because of his prolific practice and his relationship with Darwin. He corresponded regularly with Darwin, offering information on the habits, anatomy and breeding of animals. He had detailed knowledge of different species and their habits through his various roles as taxidermist and superintendent of the natural history department at the Crystal Palace between 1852-9 and later as Superintendent of the Zoological Gardens in London.

Hancock and Bartlett illustrated Charles Darwin’s survival of the fittest philosophy in arranged scenes incorporating taxidermy animals in various hunting positions, with some animals obviously, victors and others victims. They incorporated a latent violence simply by the arrangements of the forms, differing from prior styles of taxidermy primarily designed to serve as specimens for scientific research.

The work of the artists described all demonstrate a creative, interpretive and transformative approach to portraying the powerful or weak positions in which animals found themselves in their fight for survival. Techniques employed by artists included dramatising the poses and expressions of the animals to emphasize their respective roles; the use of dark backgrounds in paintings to emphasis the gravity of the victim’s situation; and the placement of figures in perilous positions such as on the edge of a cliff or dangling from the mouth of an opponent. These devices were used to amplify the power of the stronger and the imminent danger of death for the weaker.

\(^{103}\) Ibid., Diana Donald, 92.
These creative, dramatising devices were used not only to communicate natural science but also to engage audiences and generate interest in science generally. The way animals were represented in response to Darwin’s writings meant that these creative works and many others of the period fell into the category of creative boundary objects in that they used a series of creative devices to communicate the science informing scientific theory. The creative works described in this section are relevant to the thesis because they involve artists and creative practitioners collaborating with or responding to scientists to make objects and images that convey scientific research. The examples are also critically relevant to the research because the works attempt to embody ideas through their material composition and manner of portrayal. For example, Hancock’s taxidermy displays used the physical body of the animals that Darwin was discussing to illustrate his theory.

**Reciprocal boundary objects from the Victorian era**

The following examples of reciprocal boundary objects include environments, devices and objects that facilitate collaboration and exchange between disciplines and stakeholders during the Victorian era. Reciprocal boundary objects are the most effective collaborative model as they can be ongoing and all parties benefit from the exchanges. The examples addressed in this section are:

- The Great Exhibition of the Works of Industry of All Nations, 1851;
- Reciprocal boundary objects drawn from the British Museum, the Harvard Museum of Natural History and the Macleay Museum;
- Botanical and Zoological Illustrations;
- Three dimensional models in Victorian museums.

**The Great Exhibition of the Works of Industry of All Nations, 1851**

The Great Exhibition took place in the purpose-built Crystal Palace in London. Opened by Queen Victoria, it was attended by over 6 million people during its six-month run. The exhibition is pertinent to this research because it was one of the first large-scale events displaying and communicating new scientific knowledge using a range of modes. The patrons were largely from Britain, and represented a fifth of the British population at that time. The exhibition consisted of 13,000 stalls displaying art, science, technology and industry from around the world.
The exhibition operated as a reciprocal boundary object in that it created an interdisciplinary space of exchange where different stakeholders and practitioners could meet, see each other’s work and draw from the experience – be it an artist encountering new scientific discoveries or a scientist seeing a new way to communicate research to colleagues and the public. This was also a social space that – largely due to the somewhat chaotic nature of the categories of display – did not impose a hierarchy of disciplines, allowing exchange and observation to take place on relatively neutral territory. Geoffrey Auerbach, author of *The Great Exhibition of 1851: A Nation on Display*, describes the exhibits as “a hodgepodge at best and severely criticised in many quarters”.105

The organisers of the event, including Queen Victoria’s husband Prince Albert, were more concerned with displaying the British Empire’s superiority over other nations than in disciplinary organisation. The *Illustrated London News* declared that the London of May 1851 was not simply "the capital of a great nation, but the metropolis of the world".106 Auerbach states that, “historians have described the great Exhibition as the pre-eminent symbol of the Victorian age, boldly asserting Britain’s position as the first industrialised nation, as the workshop of the world, and as the most powerful and advanced state, a paragon of liberalism”.107 Auerbach questions the way history has recorded the event, contending that recording to have been inaccurate, so as to glorify Britain, aggrandise the exhibition and exaggerate its impact.

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107 Ibid., 453.
In a subsequent book with Peter Hoffenberg, Auerbach claimed that event presented the world as reproducible and consumable, and the exhibition as fundamentally illustrative – as demonstrated by its prominent exhibition slogan; “explore the world in a day”.\textsuperscript{108} The promotion enticed audiences to willingly suspend disbelief and enter a world of imaginative travel to the geographically remote locations represented. Auerbach and Hoffenberg described this goal as “initiating interconnections between reality and representation, where representation appears more believable than the reality offered by the city outside”\textsuperscript{109}. While not using the term boundary object, Auerbach and Hoffenberg may well be describing a transmutation or representation of information into another mode that renders it accessible to the general public, much in the way of a boundary object.

Arguably, the Exhibition had more of an impact on raising interest in the natural sciences among the broader British population than Darwin’s \textit{Origin of Species}, despite Darwin’s easy prose. The exhibition was seen by over six million people\textsuperscript{110} whereas by the end of 1859, \textit{Origin of Species} has sold just over 3000 copies across two editions. While the readership would likely have included influential thought leaders such as clergy and politicians, working class citizens had limited literacy.\textsuperscript{111} Seeing displays of science such as taxidermy and exotic representations of other cultures was a potentially much more effective means of communicating ideas to a larger and broader cross-cultural and cross-linguistic audience than an English text. The Great Exhibition and the objects it displayed fall within the reciprocal boundary object definition, since it required collaboration between different stakeholders and communicated scientific research to a diverse and large audience of professionals and lay people.

**Significance of natural history museums**

Natural history museums during the Victorian era performed a critical role in facilitating collaborations between a large range of interested parties, including the public. They were also one of the primary means of communicating scientific research. Natural history museums have a quality of framing nature and making it comprehensible, scalable and accessible to people. Nobody wants to meet a grizzly bear in nature but most people are happy to get very close to one in a museum. People can go indoors to understand nature, in a systematic, still and contemplative environment. Nature is frozen in space and time, allowing the viewer time and proximity to reflect and understand its relevance to them. In this way, the museum and its displays become boundary objects between man and nature. Scientists are then boundary riders who go out and bring back information about

\textsuperscript{108} Ibid., Jeffrey A. Auerbach and Peter H Hoffenberg, 9.

\textsuperscript{109} Ibid.,10.


\textsuperscript{111} Levels of working class literacy during the Victorian Era, while increasing, were still rudimentary. Educational opportunities expanded during the period 1750-1858, so that by 1840 between 67% and 75% of the British working class had achieved only rudimentary literacy - Schofield, R. S ‘Dimensions of Illiteracy, 1750–1850’, \textit{Explorations in Economic History} 10, no. 4 (1973): 437–54.
nature that is stuffed, displayed, drawn, described or otherwise transmitted by artists, taxidermists and writers.

Like the Great Exhibition, natural history museums acted as large-scale boundary objects by facilitating research and conservation and providing a physical space where collaborations between multiple disciplines could take place and develop over time. Collaborative activities undertaken by these great public institutions included research expeditions, archaeology, anthropology, cartography, conservation and heritage, science, as well as the commissioning, collection, curation and display of fine and decorative arts. Such collaborations crossed disciplines, counties and cultures and thus required the kinds of intermediate forms of communication that could be provided by boundary objects.

The Victorian Era was a time of imperialism in many parts of the world militarily through colonisation and culturally through a jingoistic framing of history, culture and nature. One of the ways patriotism and national pride were displayed was through objects and icons taken from other cultures and places and exhibited as trophies or international treasures in collections, both private and public. Museums functioned as repositories of imperialist appropriation made publically available in one location.

As with the Great Exhibition of 1851, the collections in museums contributed to the construction and portrayal of national identity, and to the conspicuous consumption of the nation's sophistication and civilising mission through diverse cultural and scientific pursuits. The collections influenced and reflected their nations' perceptions of their own history and culture as well as the world around them. As the British colonies developed, a symbol of their maturity was the establishment of cultural institutions including natural history museums. In the formative years of Australia's museums, "British museums solicited specimens from Australia, provided exchanges and arranged purchases, assisted in publishing new material, and recommended scientific staff for the colonies. In the early years of colonisation, expertise was, by definition, an import".112 This importation of expertise and exchange of materials and specimens meant that the formula for a successful natural history museum was very much based on the British model. "Interdependence and collaboration with British and colonial museums was accepted easily even as the museums gradually asserted independent initiative in administrative and scientific matters."113

The physical qualities of museums were also transferred - imposing stone facades, wooden and glass display cabinets and the means of displaying works were all standardised on the basis of British models. Museums of the period facilitated the global networked activities of the naturalist movement in a systematic, structured way, and built a large body of specimens and archives that all acted as reciprocal boundary objects.

113 Ibid., 1.
Many natural history museums were founded on personal collections that were subsequently gifted to the nation. These collections were also being developed and expanded during the Victorian era in line with the large interest in the natural sciences throughout all levels of society. The British Museum was founded on the collection of Sir Hans Sloane, a physician, naturalist and collector who had acquired more than 71,000 objects – books, manuscripts and natural specimens which he sold to the British nation in 1753. The Macleay Museum in Sydney was also founded on an individual’s collection. Alexander Macleay came to Australia as the Colonial Secretary of New South Wales in 1825. He brought with him a large library and an extensive collection of insects. Alexander formed crucial relationships with the Sydney scientific community that continued down the generations of the Macleys. William John Macleay took possession of the Macleay natural history collections in 1865, enlarging them considerably to cover most areas of natural history. He funded and organised the first Australian scientific expedition to the Torres Strait and New Guinea, when he amassed what he described as “a vast and valuable collection” of fish, reptiles, corals, vertebrates, invertebrates and birds as well as ethnographic artefacts.114

By the 1880s the collections had outgrown the capacity of the Macleay family home, Elizabeth Bay House, and posed a serious conflict of interest as the Macleys were lobbying government to fund a public museum. Macleay offered to donate the collections to the University of Sydney as soon as a suitable building was ready; and thus, the Macleay Museum was born, becoming the teaching environment for the natural sciences at the University. Many museums were founded in this way, and became organised and accessible sites for the public to interact with the sciences.

The Harvard Natural History Museum was established in 1859 by an act of the Commonwealth of Massachusetts. This foundational structure is quite different from the Macleay and British museums but, like them, it served multiple functions. It was a primary repository for zoological specimens collected by past and present Harvard faculty curators, students, staff, and associates conducting research around the world. It was connected to laboratories where research was being undertaken and it offered a physical space where collaborations could take place. From its inauguration, the Harvard Natural History Museum was affiliated with academic research, which in principle should dictate a collection strategy geared to pedagogy and pure investigation, rather than to the accumulation of wealth. Despite this, the effect of the museum is much like a vast cabinet of curiosities or trophy room. The collection of taxidermy includes endangered animals from all continents, from mice to whales. There is an extensive geological collection and a substantial collection of scientific models. The most significant of these is the Blaschka glass flower collection whose relevance to this thesis will be described in the following section.

Figure 2.14 The Mammal Hall - Interior of the Harvard Natural History Museum.

There are many examples of museums during the Victorian era serving as an organised and accessible way for scientists, artists and the public to interact and share knowledge about natural history and nature in general. The museum structure became a clear reciprocal boundary object facilitating knowledge sharing across disciplines and countries and continues in that vein to this day. The museum and its role as a venue for disseminating the material results of research has influenced the presentation of the artifacts generated by this research project. This is particularly evident in the

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rapid prototyping models of climate change exhibition held at the Macleay Museum describe in chapter four of this thesis.

**Three-dimensional models used to communicate scientific research in the Victorian era**

This section details the objects displayed in museums and at events such as the Great Exhibition of 1851. Because of their influence on the design outcomes of this thesis, the section is structured around the methods of fabrication and materials of the models, their material innovation and their context of use for education and communication.

Generally, the objects fall into the category of creative boundary objects in that an artist or model maker has taken a specimen and creatively interpreted it to render it in 3D form. There are many Victorian examples of three dimensional models and artworks used to represent and communicate science to the general public and as a teaching tool to students studying natural science and art. One of the most common in natural history museums in the Victorian era was taxidermy, which was detailed earlier in chapter two. Other model making methods from the period included objects made of plaster, wax, glass, and papier-mâché.

(Left) Figure 2.15 Sowerby’s models from British Natural History Museum\(^{118}\) and (Right), Figure 2.16 Hand-painted papier-mâché mushrooms made for the Museum in the nineteenth century by Heinrich Arnold and Co, Gotha, Germany.

English naturalist and illustrator James Sowerby, who studied painting at the Royal Academy of London and produced many illustrations of aspects of natural science, is also well known for a series of illustrated works and models called “Coloured Figures of English Fungi.” These were produced in the early nineteenth century to educate the British public about poisonous fungi. Sowerby made 193 models and displayed them at his house. He would open his home twice a month for public tours.

The collection is of particular relevance to this research because of the material innovation and the use of three dimensional models to communicate scientific information related to public health. The models were made using materials such as wire, unfired clay and dried plant matter. Unfortunately, Sowerby’s unconventional experiments with materials were prone to fairly rapid deterioration, and his models were subsequently repaired by Worthington Smith approximately 50 years later for the British Natural History Museum. There remains to this day a total of twenty-nine models – an interesting experiment that crosses into the areas of creative visualisations.

Other examples of hand painted papier-mâché models from the Victorian era include the works by Heinrich Arnoldi, made for the Museum of Economic Botany in Adelaide. Arnoldi’s pieces are brightly coloured and defy belief in their possible relationship to reality. The bright colours and forms attract the attention of the viewer, causing them to contemplate the science behind the forms.

Glass models
One of the most famous examples of glass used for scientific model making is the Blaschkas’ glass models of flowers. Leopold and Rudolf Blaschka were German glass makers who were commissioned by a wealthy family to make models of different plant species for Professor George Lincoln Goodale, founder of the Botanical Museum Harvard.

![Blaschka glass models of plants from the Harvard natural history museum.](image)

Goodale taught botany and struggled to find accurate models in other materials. The glass models were very accurate, colourful and always in bloom. Life sized, the models represented 847 different species. The glass flowers were fabricated using techniques such as glass blowing, and cold work as well as glass annealing. The collection is still on display at the Harvard Natural History Museum.

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**Wax models**

Wax was used extensively for botanical models in the Victorian era. The most well-known exponents were the Mintorns, appointed by Queen Victoria as the Queen’s Modellers. The technique involved casting from real flowers, providing an exact replica. The wax was susceptible to heat damage and remained relatively fragile; however, it could record detail very accurately.

![Image of orchids and apples](image)

*Figure 2.18 Mintorn wax model of orchids and apples, made by Mrs. Mintorn in 1899.*

The Great Exhibition featured numerous displays of wax flowers, presented both as representations of science and as decorative displays of craftsmanship. This ambiguity or slippage of intent was noted by Ann Shteir: “wax flowers found a place in the parlour and the lecture hall, as ornament and as visual aids in teaching.”

Shteir drew attention to the Mintorns, who exhibited “flowers modelled in wax, showing their applicability as ornaments for the drawing-room, as well as rare and curious botanical specimens modelled in wax from life, showing their growing state, and exhibiting the varieties and phases of their existence.” Shteir attributes the multiplicity of intents or uses of the wax models to the unusual culture of Victorian natural history, “Migrating back and forth between the drawing-room and the artisanal world of museum display, Victorian wax modelling represents mid-century interest in material objects as well as preoccupation with nature's beauties and wonders.”

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120 Image Sourced: Amy Mechowski and Andrew McRobb, ‘Mintorn Wax Model of Orchids and Apples’ (Kew Gardens Collection, n.d.).


122 Ibid., 651.

123 Ibid., 655.
Wax flower maker and Artiste in Wax Flowers to Queen Victoria, Emma Peachey wrote and illustrated a book called *Her Royal Guide to Wax Flower Modelling*. The book was not a botanical work and was not written for experts in either craft or botany. However, according to Shteir, Peachey “attempts to bridge a growing divide between art and science by calling on the languages and techniques of each”.124 Peachey integrates some botanical knowledge and thereby cultivates some knowledge in her audience. The book demonstrates the fluidity of knowledge of nature across different areas of culture at the time and is in contrast to the siloed nature of disciplines common throughout the twentieth century.

Model making was an element of many museums’ and botanic gardens’ infrastructure. The Mintorns and their descendants were involved in model making and communication departments of many of the world’s established natural history institutions – notably the Natural History section of the British Museum, the American Museum of Natural History and the Royal Botanical Gardens at Kew – and they made elaborate teaching and decorative displays for them, for the scientists working in them and for the public audiences attending them. Museum modelling workshops such as the one at Kew Gardens provided a location for reciprocal collaborations between botanists and artists. The models themselves operate as boundary objects in that they facilitate knowledge transfer between a range of stakeholders such as other botanists, artists and the public. “As might be expected the most useful though not necessarily artistic contributions to the task of recording pictorially the plants of the world have been made by artists who worked in collaboration with eminent botanists, and were therefore well acquainted with the scientific needs of the time.”125

**Botanical and zoological Illustrations, drawn from three dimensional specimens.**

One of the original models for communicating scientific research were botanical and zoological illustrations, whether hand drawn, painted or etched. They resulted from critically important collaborations between artists and scientists; however, as with any collaboration, a series of boundary objects to ensure successful and clear communication of research were required. These boundary objects were generally the specimens themselves. During the eighteenth and nineteenth centuries, due to the rapidly expanding interest in the natural sciences, there was a great deal of funding for voyages and expeditions such as the voyage of the *Beagle*. Often funded partially by private collectors, these expeditions could travel great distances and be away for long periods of time.

Illustrators did not always go on the journeys; rather, they would receive specimens that had been preserved – in the case of animals, often taxidermies. Preservation techniques could render specimens in unnatural positions and colours. Illustrators who used taxidermies as models could record colours and positions that were incorrect – for example, certain species of crayfish are naturally brown but were cooked to survive the journey home, changing their colour to pink. This

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124 Ibid., Ann B. Shteir, 652.
was problematic in that the information being communicated was often wrong, at least in part. For example, Mark Catesby (1683-1749), an English illustrator who focused on Florida and the Bahamas, wrote *The Natural History of Carolina, Florida and the Bahama Islands: Containing the Figures of Birds, Beasts, Fishes, Serpents, Insects and Plants*, with descriptions of the specimens in both English and French. Catesby made etchings primarily of animals and the plants that host them. He would have specimens delivered to him, often dead. Consequently, many of his illustrations, while accurate in form, were often in very contrived positions and in unlikely settings. Not having seen the specimen in its natural setting, Catesby would combine elements from the same region. Below is an example of a pink flamingo’s head with a backdrop of black coral.

![Image](image.png)

*Figure 2.19 Catesby’s illustrations of specimens from similar regions – a flamingo head with black coral and the North American robin.*

To overcome inaccuracies prone to arise when drawing from dead specimens, a range of approaches were used. Maria Sybilla Merian, a renowned entomologist and illustrator of both insects and plants, she went on many field trips with much of her work focused on the process of metamorphosis. Merian’s work was renowned for the accurate scaling of her drawings, the lifelike colours and the portrayal of growth and decay. Another method was used by Jules Dumont d’Urville, who drew from live specimens before they were killed and their parts drawn. John James Audubon, famous for his

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126 Image Sourced: Mark Catesby, "The natural history of Carolina, Florida, and the Bahama Islands: containing the figures of birds, beasts, fishes, serpents, insects, and plants; particularly the forest-trees, shrews, and other plants… together with their descriptions in English and French, to which are added observations on the air, soil, and waters, with remarks upon agriculture, grain, pulse, roots,[et] c. to the whole is prefixed a new correct map of the countries treated of; Vol. I [-vol. II]." (1754).
The Birds of America, was a hunter who would take home specimens, mount them while fresh and then draw them based on memory.127

These models of collaboration, where the research and illustrations are done side by side, led to more accurate communication since, as reciprocal boundary objects, they had become the main form of instruction for the general public and the next generations of scientists.

Representations of natural science in the home

The public were also able to experience and view scientific research through limited edition books of natural history illustration as well as the decorative arts of the latter half of the nineteenth century. Every day dinnerware, furniture and commemorative items incorporated many aspects of natural science in a range of modes: as decorative motifs, as documentation of plant and animal species and as illustrations of Darwin’s theories and associated ideas, in particular the notion of the survival of the fittest.

Limited edition natural history books

As printing techniques improved and interest in the natural sciences developed following Darwin’s Origin of Species, illustrated natural history books became more accessible for the middle class to

128 Maria Sybilla Merian, ‘Maria Sybilla Merian’ (Historisches Museum, 1997).
read about natural history, and to own and collect as desirable objects. For Nicola Gauld, "the natural history books of the Victorian era aimed at a lay readership whose members are presumed to be middle class, reasonably wealthy and educated. These publications were often offered as an alternative to visiting a natural history museum and were designed to be read by families within a domestic setting."¹³⁰ One of the most widely distributed was John James Audubon’s *Birds of America*; another was Reverend John George Wood’s *Illustrated Natural History*, whose objectives Wood described as “anecdotal and vital rather than merely anatomical and scientific”.¹³¹

Wood’s books acted as a boundary object between scientists and the general public, offering access to scientific research in a manner accessible to a wide range of people. Generally, a book on natural history could be presumed to fall into a literal category of boundary object; however, once creative representational devices such as vitality and narrative come into play, the books move clearly into the category of a creative boundary object.

**Decorative arts**

The interest in natural history also manifested in the decorative arts in domestic settings. Objects such as cabinets of curiosity or wunderkammers, containing exotic objects or artefacts, became points of interest in homes. One well known example was the Macquarie Chest (Figure 2.24) created for New South Wales Governor Macquarie, which featured drawers of collections of Australian native flora and fauna.

Images of plants and animals and repeated designs based on plants and animals lent themselves naturally to motifs in decorative arts and became symbolic of first the Arts and Crafts movement and then the Art Nouveau Movement, which followed in the decades after Darwin’s publications. Examples include William Morris wall papers and textiles pictured in figure? and the insect-inspired coloured glass ware of Louis Comfort Tiffany. The manufacturers of porcelain and ceramics such as the Meissen porcelain of the period created not only functional pieces but also decorative items such as models of birds in semi-natural positions, and silver presentation pieces such as those made by the English silversmith Robert Garrard.

¹³¹ Ibid., 128.
The ownership of decorative art objects incorporating natural science motifs reflected a family’s prestige and demonstrated education and worldliness. Wedgewood produced dinnerware incorporating elements of natural history such as the Brown Water Lily set pictured in figure 2.25. This particular set was in Charles Darwin’s childhood home. Donald speculates that the Wedgewood dinner service in Darwin’s childhood home influenced his career; “it was the first Wedgewood pattern to be derived from identifiable botanical prints and represents an important strand of Darwin’s cultural inheritance and his visual experience as a child.” The Wedgwood Company supported Darwin’s work and helped fund the voyages of the Beagle. Darwin was a first cousin to the Wedgewood’s and married Emma Wedgewood.

2.2 Summary

The communication of science in the Victorian era took many forms due to the large interest in the natural sciences at the time. The interest is largely attributed to Charles Darwin, his theory of evolution and the accessibility of his writings. The theory and its communication and understanding had many ramifications across the fields of religion, politics and culture on a global scale – notably in its irreversible impact on peoples’ perspectives on nature and their place with in it.

The examples given in this section investigated different types of collaborations between scientists and artists working together to communicate natural science during the Victorian era. The research described and analysed objects used to facilitate collaborations and communicate scientific research using three categories of boundary object. The three categories are:

**Didactic boundary objects**, such as Darwin’s books *Origin of Species* and the *Voyages of the Beagle* series, gave clear outlines of the theory of evolution but offered no opportunity for collaboration or feedback.

**Creative boundary objects**, including specimens of animals preserved by taxidermists in dynamic poses such as Hancock’s *Struggle with the Quarry*; artworks such as paintings; illustrated books; decorative arts such as wunderkammers and functional objects including dinnerware and furniture decorated with motifs drawn from the natural sciences.

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135 Image sourced: State Library of NSW archives. 

136 Image Sourced: Ibid., Diana Donald, 36
Reciprocal Boundary Objects, such as museum displays and events such as the Great Exhibition that provided a physical space and systematic context for collaborations between artists and scientists to occur over an extended time period. The museum structure encompassed many activities including expeditions, research, conservation and display of artefacts generated by scientific research.

The three types of boundary object outlined above cover the primary tools and artefacts used in the Victorian era to communicate natural science across disciplines and to the general public. The examples are relevant to the practical outcomes of this research in that many of them are three dimensional in form, come from collaborations between artists and scientists and are displayed in public spaces such as museums.

The study of these examples provides a framework for analysing contemporary collaborations between scientists and artists working together to communicate climate science. The framework will also be used to evaluate practical elements of the research output outlined in Chapter Four. This thesis suggests that climate change research is having as great an impact, or greater, on society, politics and culture than Darwin’s theory did at the time. Climate change is experienced by anyone in their everyday lives as they interact with the environment – be it in the wilderness or simply breathing the air outside their house. This evident, ever-present reality is changing the way we live, consume and interact. With the urgency for change, creative practitioners and scientists are collaborating to find innovative ways to communicate the research, promote better understanding of the evidence and encourage responsible action.
2.3 Contemporary Creative Visualisations of Environmental and Climate Science Research
Introduction- Climate change visualisation through transdisciplinary collaboration

This section investigates contemporary modes of representation of climate change research in the form of artworks, exhibits and projects. Modes of delivery include museum and gallery environments and public art festivals. These events attract significant audience numbers and promote community awareness of climate change. This section discusses different case studies of artworks that use either direct or indirect collaborations with scientists. The output of each collaboration is a boundary object through which knowledge about climate change can be shared with each other and the audience.

The examples given focus on artists and creative works that engage haptic and material elements in both the fabrication of the works and the way they are presented. Some of the projects invite audience members to touch the works, others lead the audience to imagine the physical sensation of the work. Lesley Duxbury, writing about immersive haptic artworks, notes that “the physical body is central to the spatial and temporal construction of the world in which it is located and engaged.” The works discussed have influenced the design of the process and outcomes of the practical research project described in chapters three and four.

The contemporary projects featured here will be evaluated using the following boundary object categories:

- Didactic Boundary Object
- Creative Boundary Object
- Reciprocal Boundary Object

Many contemporary artists make artworks that engage with climate change and ecological conditions (previously described as natural history) in the contemporary world. The conceptualisation, format, presentation and purpose of these works take different forms. Artists such as Janet Laurence make individual artworks to be shown in galleries; others such as the Artist as Family use practices of engagement to investigate principles of environmental science within localised community contexts. The science informing artworks is also sourced in a variety of ways. Some artists such as Clare Twomey build on a tacit, personal understanding of the issues involved, other artists interpret climate change research and produce artworks about them, forming creative boundary objects.

Others such as Luke Jerram consult with scientists about the issues and make artworks that develop out of such conversations to produce reciprocal boundary objects. Yet another group of creative practitioners, such as Ken and Julia Yonetani and Fernanda Viégas and Martin Wattenberg, collaborate directly with scientists to visualise and communicate scientific information and data so as to make it accessible to the public. The artists work in scientific contexts such as the Commonwealth Scientific and Industrial Research Organisation (CSIRO) and generate work that informs the scientific community as well as the general public.

137 Ibid., Lesley Duxbury 36.
Generally, current artworks about the environment and climate change are characterized by being reflective of particular issues; based on research; incorporating evidence based, informed responses and focusing on the educational value of the work. Artists include Fiona Hall, the Wertheim sisters, Janet Laurence, Laurence Berkowitz and The Artist as Family.

Materially, many of the works incorporate a pseudoscientific or museological aesthetic in that they give the appearance of being scientific, and may involve a method or mindset that “appeals to observation and experiment’, but which 'nevertheless does not come up to scientific standards”.138 This approach uses a wide range of techniques for communication, including visual, auditory and tactile tools.

The artworks reference the aesthetics of science by incorporating elements that you might find in a science laboratory, including live plant specimens and scientific equipment in the case of the Artist as Family and Janet Laurence. Other artists arrange displays in a structured format that references the aesthetics of nineteenth century specimen testing and comparative study environments. Lauren Berkowitz arranges her objects, be they plants or plastic bags, in orderly rows with carefully placed lighting as if to facilitate close inspection. These devices, familiar to audiences from natural history museums and high school science classes, lend the artworks a quality of scientific research and add layers to possible interpretations of the work. The creative practitioner’s aesthetic choices and compositions translate the ideas informing the works, namely concern and data about climate change, into embodied and engaging experiences for audiences. Unlike with a graph or text which could communicate the same ideas and information, the viewer has the opportunity to contemplate the significance of the ideas informing artworks as they walk around and observe.

While artists are looking to the sciences to inform their work, contemporary scientists are equally turning to the arts to visualise crucial data and make it accessible to the general public. In principle, this is so as to find effective ways of informing, influencing and transforming attitudes and behaviours towards climate change. With the urgency to disseminate research, scientists are recognising the emotive power of art to communicate information. Some theorists argue that, in comparison to conventional discipline-based practices, art and science collaborations can produce more effective outcomes for communicating accurate data and triggering informed responses from the public. Michael Hohl notes, for example:

“Visualisations of data may become memorable and meaningful experiences as a result of inter-disciplinary collaboration. Crucial in this process appears to be the evocative manner of presentation and a combination of intellectual together with embodied experience which also addresses multiple sensorial modalities, such as sound and touch.”139

Collaboration between artists and scientists can deploy different models – for example, an exhibition of artworks may be accompanied by a talk from a scientist on the data informing the artworks, effectively producing a cross-pollination of information and audiences. An example of this model is the Cape Farewell Project where artists and scientists travel together on a boat to the high Arctic, conducting their research alongside each other and helping each other. Artists work as assistants to scientists and scientists participate in the artists’ projects. These projects and others will be described and evaluated in this section.

**Contemporary organisations fostering collaborations between artists and scientists**

One of the most effective modes of establishing collaboration is through a parent organisation that forges links between disciplines, provides neutral sites for ongoing engagement, and moderates discourse around the data being represented and the models of representation. The parent organisation can also evaluate effectiveness and impact through structured formats. Numerous international programs currently foster collaboration and communication between the arts and sciences. Some focus predominantly on communicating all types of scientific research, such as ANAT (Australian Network for Art and Technology); others on communicating climate change, such as *The Cape Farewell Project* and *The Institute for Figuring*.

These latter models are the most relevant for this thesis. Precedents have been selected for their success in generating reciprocal collaborations and boundary objects. A reciprocal collaboration establishes multiple modalities for engagement; influences the participant disciplines and social groups through the experience of the collaboration; and creates outcomes that effectively communicate contemporary climate science.
The Crochet Coral Reef is a project developed by the Institute for Figuring that “resides at the intersection of mathematics, marine biology, handicraft and community art practice, and also responds to the environmental crisis of global warming and the escalating problem of oceanic plastic trash”. Started by two mathematicians, Margaret and Christine Wertheim, the large-scale crochet coral reef is a series of works made initially by the two sisters to investigate the mathematics informing the structure of coral reefs.

The hyperbolic crochet technique was originally developed by Cornell University mathematician Diana Taimina as a means of creating a visible, tangible model of hyperbolic geometry. In this context, the crochet works form a reciprocal boundary object as they are used to facilitate the communication of complex ideas across several disciplines and as a teaching tool.

The Wertheim sisters adopted Dr. Taimina’s approach of using the very simple techniques of crochet to communicate complex ideas. While Taimina used the techniques to illustrate a mathematical principle, the Wertheims used them to explain and communicate a global environmental problem.


They elaborated Taimina’s techniques to develop a taxonomy of reef life-forms:

“The basic process for making these forms is a simple pattern or algorithm, which on its own produces a mathematically pure shape, but by varying or mutating this algorithm, endless variations and permutations of shape and form can be produced.”

These teaching techniques evolved into large community-based artworks that were then exhibited in significant galleries around the world. The familiarity of a process we are all taught as children combined with the tactile nature of the finished works has made the series hugely popular. These have become a portal for developing climate science literacy in the general public; and the works often have very large audiences in museum contexts.

(Left) Figure 2.27 Crochet Coral Reef on Display. The Institute for Figuring and (Right), Figure 2.28 Detail of the Crochet Coral Reef.

The hyperbolic coral reef project is an example of a creative boundary object for the following reasons. The form of the works is a creative interpretation of the science informing it and serves to draw attention to the effects of climate change and ocean trash. The workshop model of the project can operate with instructions anywhere in the world and involves community participation, communication of complex ideas and the facility for multiple social and cultural boundaries to be crossed. The final works communicate to a non-participant audience in multiple mediums; images of the works are widely disseminated and are always accompanied by text explaining their source and inspiration, as well as how they were made.

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143 Ibid., accessed 12/3/2014.
Based in London and Toronto, the Cape Farewell Project is an international organisation bringing together and fostering collaborations between artists, scientists and communicators to “stimulate the production of art founded in scientific research”\textsuperscript{146}. There are numerous boundary objects developed and used in these projects.

Established in 2001 by artist David Buckland, the project is framed around interdisciplinary collaboration and communication with a series of journeys to sites where evidence of climate change is very apparent, such as the Arctic Circle. This framework of a journey with multiple disciplines involved has expanded over time to include expeditions of all kinds “Arctic, Island, Urban and Conceptual – to interrogate the scientific, social and economic realities that lead to climate disruption, and to inspire the creation of climate-focused art which is disseminated across a range of platforms – exhibitions, festivals, publications, digital media and film”\textsuperscript{147}.

An example was an expedition to the Arctic in 2007. The journey brought together twenty artists and scientists from seven countries as well as twelve students. The participants sailed from Greenland to Iceland over a three-week period, working as crew and conducting research of all kinds. While on

\textsuperscript{145} Ibid.
\textsuperscript{146} Ibid.
\textsuperscript{147} Ibid.
board, scientists measured the temperature and salinity of the Gulf Stream and the Greenland current to see how they compared to previous measurements. Scientists also measured the polar and glacial ice melt. The science crew onboard included marine and coastal geoscientist Dr. Carol Cotterill and oceanographer Emily Venables.

The vessel also carried a team of artists who not only worked as crew and assisted scientists with their research but also created artworks which documented the journey and the scientists’ research. Creative outcomes included musician Liam Frost recording songs on the ice; while artists such as David Buckland, Cathy Barber and Brian Jungen made works in response to the experience of working with the scientists and the icy environment they found themselves in. These works were then exhibited in galleries all over the world, thereby disseminating the research informing the creative works.

Another Cape Farewell expedition journeyed to Noorderlicht locked in ice at Tempelfjorden, just north of the 79th Parallel. On board were artist Antony Gormley and architect Peter Clegg – two creative practitioners collaborating on a series of artworks called Three Made Places. The works were informed by data on CO₂ emissions. Clegg describes trying to define a kilogram of CO₂ (approximately the exhaust gases of a 2-litre car travelling 10 miles) as a space rather than mass. One kilogram of CO₂ at atmospheric pressure occupies 0.54 of a cubic metre; “It is roughly the volume occupied by a coffin, which is perhaps an appropriate symbolic unit when we are talking about the destruction of the planet”.148 Informed by this notion, Gormley and Clegg set about carving these structures out of hard snow and ice. The structures reference the body only in scale, not in form. The artists rely on the material for colour and texture. The hollowed forms suggest containment, much like a coffin. As with many environmental works, the only interaction an audience has with them is through photographs and they must imagine the cold, the dark and the sounds of a windy icy environment they cannot feel physically. This space for the imagination is an important part of the transformative element of artworks and one of the reasons that works such as Gormley’s and Clegg’s can be an affective creative boundary object to facilitate communication of climate change research.

The experience of the journey became a reciprocal boundary object for the artists and scientists on board the vessel. The participants were able to actively contribute to and witness each other’s research and to draw influences and techniques from the experience. Both groups developed new ways of collaborating to communicate and disseminate their research to new audiences, thereby increasing its impact. The relationships that developed through the process of collaborating built a foundation for ongoing exchange.

Individual creative practitioners whose research investigates representations of climate change and environmental issues

The boundary object categories and relevant creative practitioners, include:

- Didactic Boundary Objects; The Artist as Family and Lauren Berkowitz.
- Creative Boundary Objects; Janet Laurence, Fiona Hall and Claire Twomey.

Didactic Boundary Objects

The Artist as Family

The Artists as Family is literally a family of artists who make works about environmental and sustainability issues using the act of gardening and incorporating social engagement. The group created a work called Food Forest at St Michael's Anglican Church in Sydney's Surry Hills as a satellite event of the In the Balance, Art for a Changing World exhibition at the Museum of Contemporary Art in Sydney. This artwork was a garden that the artists describe as a “statement about the environmental harm caused by shipping food from distant locations; It's a highly political work,” states artist Patrick Jones; "it's saying the transportation of resources is central to [the] global ecological crisis. And if we keep going like this, we're going to be in real trouble." Jones wants to encourage social warming, "If there's a positive spin-off to global warming, we call it social warming – that is, grassroots movements becoming active.”

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While this project does address elements of arts practice to communicate issues around climate change, the project is in the model of a community engagement and development project. No traditional arts objects or images are generated. The artefacts of the project are photos documenting the process, which are then displayed on a wall in a gallery or on the group’s website. There are no direct links with scientists; rather the artists are enacting scientific principles of successful horticulture and social activism. The Food Forest project falls within the didactic model of a boundary object established through both the model of social engagement and the archives generated recording the project. The boundaries traversed are between artists and the community or audience; there is no crossover between climate scientists and the artists or science. The project does succeed in drawing attention to sustainable food production and the role individuals can potentially play in addressing this issue.

Lauren Berkowitz

Lauren Berkowitz is an Australian installation artist working mostly with ephemeral and site-specific works that evoke the passage of time and our place within it. “Often inspired by the landscape but troubled by its degradation, she recycles materials and themes into environmental narratives as an act of regeneration”\(^1\) Berkowitz’s piece *Manna*, exhibited at the MCA as part of the 2010 *In the Balance, Art for A Changing World* exhibition, contains various medicinal and edible food plants grown in New South Wales displayed in plastic containers on a large table under lights. The plants grow in the gallery during the course of the exhibition. Berkowitz describes the work as “a symbolic map of Australian history, pre-and post-European colonisation”\(^2\). However, these themes are very

\(^{151}\) Lauren Berkowitz, ‘Manna’ (Museum of Contemporary Art, 2010).
\(^{152}\) Ibid.
hard to discover by viewing the work. Berkowitz claims in her artist’s statement that the themes are inherent in the plant diversity on display and that their links to the preservation of the environment are evident through the use of recycled plastic containers to hold the plants. The work operates on a didactic level and seems instructional on the conditions necessary for growing plants rather than a commentary on colonisation and environmental degradation.

The Artist as Family and Berkowitz enact the principles of sustainability in their works, which become art through their relationships to context and intent. However, there is no transformative element in their work which would give it the quality of creative boundary objects. The audience is left little room for interpretation. These artists are demonstrating aspects of the science informing their ideas in order to direct audiences towards practical ways of addressing climate change, much like visiting an educational facility in a national park or plant nursery. The Artist as Family and Berkowitz’s projects are displayed in a scientific and explicit manner, accompanied by texts that dictate what the viewer is to take away from the experience. As such, the works function as didactic boundary objects between the artists and the public.
Creative boundary objects
This section analyses projects made by individual artists and designers whose creative works result from collaboration with a climate scientist or draw inspiration from the field of climate science research. The projects described all fall within the category of creative boundary objects in that they use transforming and dramatising devices such as exaggeration and interpretative representation to emotively portray the climate science they are referencing. The works have been selected because they are all three-dimensional and thus have the potential to engage the sense of touch, real or imagined, attracting or repelling. Objects allow the viewer to experience the kinaesthetic dimension of the information being communicated. This is relevant to the design research component of this PhD as a key area of experimentation is different ways to represent climate science using three-dimensional forms.

Janet Laurence

Figure 2.34 Janet Laurence, Cellular Gardens (where breathing begins) 2010.¹⁵⁵

Janet Laurence is an Australian installation artist whose work moves fluidly between different modes of representation; some incorporate living plants; others make allegorical reference to environmental issues. Laurence often uses plants as a metaphor for the environment generally; however, unlike the pieces by The Artist as Family and Lauren Berkowitz described earlier, her work integrates plants in carefully staged environments that lead the viewer to moods of reverence or empathy. Laurence often uses medical and scientific equipment in her work – materials such as delicate laboratory glass vitrines, fine white netting, mirrored shelving and transparent structures with hard sterile surfaces that imply quarantine and critical observation. These materials reference a scientific, calculating world view but counterpose it with a presentation of the endangered and fragile condition of nature. Waiting – A Medicinal Garden for Ailing Plants, created for the 2010 Sydney Biennale, incorporates such elements and houses them in a glass house that indicates a rarefied atmosphere of preservation and recuperation necessary to sustain life. Laurence is often

pictured wearing a laboratory coat, as if she is the steward or carer of the environment she is referencing. When viewing the works the audience feels compelled to whisper, as if visiting a relative in the intensive care ward of a hospital. Laurence describes her works “as a place between evidence and imagination”.\textsuperscript{156}

Art if it engages, can linger in the mind the way that pure information can’t. As artists make work addressing environmental issues, it finds a place in culture. So, while artists may not have the capacity to directly effect change, they can certainly contribute to the political sphere by reaching people in more inviting and imaginative ways than scientists and politicians can.\textsuperscript{157}

Laurence’s works generally form creative boundary objects. They are exhibited in arts contexts and draw attention to contemporary climate and environmental science. Her collaborations with scientists are often in the form of a residency program with a science organisation or a museum. Her practice has been influential in the development of this thesis. Many of Laurence's works communicate the same message, consistently drawing attention to the fragility and temporality of the environment and trying different modes and scales of creative representation to suit the contexts of display and move her audience. Chapter four will detail the material investigations undertaken in the research that also trial different modes and scales of representation.

\textbf{Claire Twomey}

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure1}
\caption{(Left) Figure 2.35 Claire Twomey Blossom, installed at the Eden Project 2010\textsuperscript{158} and (right), Figure 2.36 Specimen, Clare Twomey 2010. \textsuperscript{159}}
\end{figure}

\begin{footnotesize}
\begin{itemize}
\item \textsuperscript{156} Felicity Fenner, “A Hospital for Plants: The Healing Art of Janet Laurence,” \textit{Art and Australia} 8, no. 1 (2010), 67.
\item \textsuperscript{157} Ibid., 67.
\item \textsuperscript{158} Image Sourced: Claire Twomey, ‘Blossom’ (Victoria & Albert Museum, 2010). Accessed 10/11/2016
\item \textsuperscript{159} Image Sourced: M.J. Kelly, ‘Specimen’ (The Royal Academy, 2010).
\end{itemize}
\end{footnotesize}
Claire Twomey uses creative boundary objects to draw attention to environmental and climate issues. In 2007 Twomey created Blossom at the Eden Project in Cornwall, England. The Eden Project is an educational charity and social enterprise dedicated to creating science-based events and long-term creative projects. These are aimed at producing cultural shifts in attitudes to climate change and empowerment through community engagement. Twomey’s Blossom was an installation of seven thousand unfired handmade china clay flowers scattered throughout the central pathways of the horticultural displays at the Eden Project. Blossom is primarily intended to remind the audience of the potential fragility of the environment under the influences of a rapidly changing climate. This is achieved by the audience seeing the flowers deteriorate by the hour and day in response to ambient weather conditions.

The material choice of Twomey’s work is significant. The raw clay flowers are appealing to touch, the viewer is attracted by the objects’ resemblance to flowers (delicate, light weight, living and decaying beings) while also knowing that these will eventually return to the soil out of which they were made. Despite their appearance, the clay flowers weigh considerably more than real flowers, a factor that renders what is seen and what is known as fundamentally ambiguous and dichotomous. The ephemeral nature of deteriorating clay provokes curiosity and triggers a series of questions around the fragile nature of different life forms and the effects of climate change on the environment.

The display lasted for a month with a team of horticulturalists replacing the flowers as they deteriorated. The other significant layer to Twomey’s work is the relationship of the works to the history of the site. The Eden Project is constructed on what was once a china clay pit that supplied the Stoke on Trent Pottery. Twomey commissioned twenty women who worked at the Pottery to create the flowers using models that had been used for centuries in decorative porcelain ornaments. The association with preciousness and the appreciation of the time and effort spent in creating the handmade flowers contribute to the audiences’ sense of loss as they see them disintegrate into the earth. Ian Wilson has noted that Blossom underlines the question of ecological interdependence and is a reminder of “how seemingly disparate, wholly unrelated places – in this case pottery factories and a country’s major environmental undertaking – are intimately connected”. As with any project that discusses climate change, the environmental effects of the artworks must be considered, and responsibility for the effects taken. In this case, Twomey is putting a material directly into the environment, having first investigated likely effects of the decomposed blooms on the soil and determined that the material would have no detrimental effect.

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Fiona Hall's *Paradisus Terrestris* is a series of twenty-three works. Small and mounted on the wall, they initially resemble opened sardine cans. On closer inspection, each one is seen to contain a small figure which is paired with a plant carved from the aluminium can. The plant names are given in Latin and the local aboriginal language. The works describe the body’s relationship to nature. In effect, the works become a Garden of Eden with the naked eroticised bodies framed inside the tins like a tiny theatre set. The figures are surrounded by plants chosen because of their relationship to paradise and the divine. The scale of the works draws the viewer closer and the intricately rendered forms engage the audience through what art theorist, Jacqueline Millner calls *Conceptual Beauty* – the use of seductive aesthetic devices to provoke curiosity and illicit engagement with the underlying ideas of an artwork.

While not specifically aiming to visualise scientific data, Hall does investigate relationships between nature and culture with recurrent references to the natural sciences. She undertook considerable research in the botanical gardens of the world to accurately inform these works. Ewington describes her work as “simultaneously emulating and parodying a notional botanical collection”. Hall cleverly layers’ concepts, intertwining them into unexpected and at times shocking, assemblages of textures, images and words. The image of a tongue licking the tip of a penis within the sharp edges of a sardine tin while nestled under the generous branches of a native plant is an immediately arresting composition. The work reminds the audience of humanity’s delicate relationship with nature and our shared vulnerability through the portrayal of the most intimate sexual acts. These works also function as creative boundary objects since they investigate and interpret the boundaries between culture and nature, between commonplace and scientific knowledge. As Millner notes, “in recent times artists have been less concerned to reproduce nature or interpret nature’s beauty and awe

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163 Ibid., Jacqueline. Millner.
than to inquire as to how nature is represented and to explore the status of nature vis-à-vis culture”.

Reciprocal boundary objects

Fernanda Viégas & Martin Wattenberg

Fernanda Viégas and Martin Wattenberg are leaders of Google’s Big Picture visualisation group. For them, data has become part of cultural discourse. “Real-world data and issues such as climate change, human development and disease are of concern to all. Artists are turning to science to accurately inform their practice as they seek to raise awareness of pressing global issues. Abstract visualisations can be informed by accurate research data, even if the presentation is not literal.”

Wind Maps is an artwork of the wind landscape over the USA created by Viégas and Wattenberg and exhibited at the Museum of Modern Art in New York in 2012. The work is based on accurate meteorological data, yet the maps eclipse the data by taking on their own identity as artworks so as to amplify and capture the intensity of changing weather patterns. While not a three-dimensional work, Windmaps is relevant to the design research as it is one example where an artist works directly with accurate scientific data to produce representations with a high degree of realism.

Figure 2.38 Wind Maps by Fernanda Viégas & Martin Wattenberg.

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167 Ibid.
Ken and Julia Yonetani have been making work in collaboration with climate scientists since 2008. Their works harness an emotive, and material response to public anxiety about climate change in a series of carefully rendered sculptural installations. The artworks such as *Sweet Barrier Reef* and *Still Life: The Food Bowl*, explore perceptions of materiality to convey important messages about climate change to the public. *Sweet Barrier Reef* was a large installation exhibited at the Venice Biennale in 2009. Made of sugar, the work referenced the threat posed to the Great Barrier Reef by climate change and the destructive effects of chemical run-off from the sugarcane industry on the Queensland coastline. The sugary sculptures are attractive, both aesthetically and also conceptually - the viewer questions their understanding of what coral might feel like to touch. Most of us are familiar with the texture of sugar, we imagine that the textured sculptural forms could be parts of a reef dug up and transplanted to the gallery and yet we know they are made of a material that we consume on a daily basis. There is a slippage of perception and knowledge between the material and materiality of the object that stimulates curiosity and a sense of the uncanny; leading us to engage with the ideas informing the installation. We are provoked to think about the effects of the sugarcane industry on the reef.

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171 Ken and Julia Yonetani, ‘Sweet Barrier Reef’.
172 As described in the section on materials and materiality in chapter one.
Subsequent works by the Yonetani’s discuss and investigate human caused climate destruction using a range of materials, often employing the device of material sublimation as a means of engaging curiosity.

Examples include the large artworks made from salt shown in figure 2.40. The piece, *Still Life- the Food Bowl* references the increasing salinity and turbidity of the Murray River system that threatens Australia's food production and imperils a significant source of the nation’s potable water. The Yonetani’s work closely with climate scientists through a series of formal collaborations such as the Murray-Darling Freshwater Research Centre\(^\text{173}\) to ensure their representations are accurate and to give voice to the critical research being undertaken in this field.

Both the *Sweet Barrier Reef* and *Still Life- the Food Bowl* artworks are creative responses to the scientific data. The objects the Yonetani’s have made use of dramatic devices such as exaggerated scale in the case of the *Sweet Barrier Reef*, or composing a life size three-dimensional renaissance still life scene from river salt in the *Still Life- the Food Bowl installation*. In this way, the works could be a creative boundary object however because of the Yonatani’s ongoing commitment to collaborations with scientists and working process of being embedded at Scientific Research Institutes, the artworks they have made form a reciprocal boundary object between the scientists and the artists, and the scientists and the general public. The collaborative approach demonstrated by the Yoentanis has resulted in significant creative projects with global impact – notably *Sweet Barrier Reef* which drew an audience of over half a million at the 2009 Venice Biennale.

The Yoentanis’ projects described here are particularly relevant to the practical research discussed in chapter four due to their focus on representing climate change using carefully considered material choices. The works demonstrate a clear link between the materials used and the subject matter discussed. This ensures a clear communication of the scientific research informing the works and allows audiences to contemplate their role in climate change and the potential effects on their lives.

Luke Jerram is a British artist who makes three-dimensional data visualisation objects informed by consultation with scientists and by scientific data. One of the best known is Glass Microbiology (2009), referencing studies of the global impact of disease. Jerram consulted with virologist Dr. Andrew Davidson from the University of Bristol. Using a combination of different scientific photographs and models, Jerram made large-scale glass models of significant viruses in collaboration with both scientists and scientific instrument and vessel glass blowers Kim George, Brian Jones and Norman Veitch.

Materially, the works are reminiscent of the glass flowers made by Leopold and Rudolf Blaschka. However, the scale of Jerram’s models is of cells magnified many times, while the Blaschkas modelled their specimens at 1:1. Jerram chose to use clear instead of coloured glass as he questioned the impact of colour in the representations of data and its likely prejudicial reception by an audience for whom colour might have unpredictable subjective registers. While visualisations of scientific data intended for a science audience are generally intended to be faithful, many are brightly coloured – often using the CMYK palette\(^{175}\) – to create contrast and better identify different components of the forms represented. The colouring of visualisations in scientific imaging actually has no relationship to the data being represented and is generally left up to the preference and skill set of the person creating the visualisation.

By creating works with no colour, Jerram is questioning the impact or effect of colour in scientific imaging of data. He notes that “viruses have no colour as they are smaller than the wavelength of


\(^{175}\) CMYK palette refers to the four coloured inks used in most colour paper printing. The colours are cyan, magenta, yellow and key (black).
light. By extracting the colour from the imagery and creating jewel-like beautiful sculptures in glass, a complex tension has arisen between the artworks’ beauty and what they represent”. Jerram stimulates curiosity and inquiry around verisimilitude by contrasting his own monochrome works with familiar artificially coloured scientific imaging, together with how the latter affects a viewer’s reception and understanding of natural phenomena and science.

Jerram poses several questions: “If some images are coloured for scientific purposes, and others altered simply for aesthetic reasons, how can a viewer tell the difference? How many people believe viruses are brightly coloured? Are there any colour conventions and what kind of ‘presence’ do pseudo coloured images have that ‘naturally’ coloured specimens don’t? How does the choice of different colours affect their reception?”

The models are exhibited in galleries and museums and are perceived as fine art objects. Concurrently photographs of Jerram’s glass artworks are used widely in medical journals and textbooks, and are seen as useful representations of virology within the scientific community. The collaboration between the scientists, Jerram and the glass blowers requires ongoing exchange and communication. The models become reciprocal boundary objects between different stakeholders and disciplines.

Figure 2.42 Luke Jerram Tōhoku Japanese Earthquake 2011

Another of Jerram’s artworks also can be described as three-dimensional data visualisation. Jerram created a sculpture to contemplate the 2011 earthquake and tsunami in Japan. A seismogram of the earthquake was rotated using computer aided design and then printed in three dimensions using rapid prototyping technology. The data was converted into a physical object that can be held and explored so as to more forcefully and haptically communicate the enormity of the event. Further, 3D

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177 Ibid.
printing technology enables simultaneous mass production and therefore reach and access to the works by a global audience.

Jerram’s 3D printed sculpture *Tōhoku Japanese Earthquake* is made of off-white 3D printed plastic. The plastic filament used in 3D printing has no cultural or historical significance due to its relative newness as a fabrication material. Most materials have their own histories and semiotics – for example glass is associated with hygiene and purity, porcelain is considered valuable and strong; however, 3D printed plastic does not yet have particular associations. So, despite Jerram’s goal of making objects to hold, the material quality of *Tōhoku Japanese Earthquake* is such as to compromise the desired tactility. The materiality of *Glass Microbiology* appears more alluring due to the visual and perceived tactile qualities of the material and form. The viewer imagines the smooth texture of the surface and how it might feel to touch, thereby inspiring curiosity, both about the object and the data determining its form.

Jerram has used different approaches to accurately three dimensionally representing scientific research and data. The works described here explore materiality in the case of the glass works, to create objects that attract attention and visualise the science informing the works. While the 3D printed *Tōhoku Japanese Earthquake*, accurately three dimensionally represents data.

Jerram’s work along with the other significant precedents described in this section have demonstrated innovative ways to has outlined innovative methods of visualising scientific research including climate change. Three different types of boundary objects were discussed in order to reveal how transdisciplinary collaborations between creative practitioners and scientists can facilitate engagement with climate change research. Scientists recognise the need to enhance their skills for more effective interaction with the public. Articles in scientific journals are mostly aim at informing other scientists; and scientific conferences and symposia are attended only by scientists and scientific editors. Creative practitioners, with expertise in communicating through art to a general audience, can offer valuable skills in developing successful boundary objects that devise a new syntax for communicating climate change data to an audience; that allow individuals to share their knowledge and learn about other sources of knowledge; and that facilitate the process through which audience and researcher can jointly transform their knowledge.179

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Section 2.4 Summary and conclusion

Chapter two investigated the following two research questions:

1) Communication and Collaboration: In the current context of climate change, which tools for communication and collaborations between the disciplines of sciences and the creative practices could be mobilised to facilitate or enable innovative modes of communicating climate change?

2) Artefacts and Visualisation: What is the capacity of created objects to engage with climate change data to produce accessible forms of climate change information and communicate the effects of climate change?

The research questions were investigated through a series of precedent studies that reviewed collaborations between creative practitioners and scientists working together to visualise and communicate scientific research. The precedents were analysed using boundary object theory as described in section 2.1. This chapter has introduced new categories of boundary objects that are appropriate for the fields of creative visualisations of climate science. Building on the research conducted by Stars and Greasier, Calllon and Carlile the research has introduced the following categories:

- Didactic Boundary Objects;
- Creative Boundary Objects;
- Reciprocal Boundary Objects.

Each of these categories has been used to describe the nature of the collaboration between scientists and creative practitioners as they work alongside each other and together to communicate the natural sciences in the Victorian era and then climate change research contemporarily. These categories are now used to describe and analyse the collaborations undertaken with different climate scientists during the design research described in chapters three and four. The categories are also used to analyse the artefact generated through these collaborations.

Precedents discussed in chapter two have influenced the form of the three-dimensional objects developed through the design research to communicate and represent scientific research. This chapter has reviewed historical examples of visualisations of science in three-dimensional form, such as taxidermy and cabinets of curiosity, and investigates contemporary examples of creative works that communicate climate change research. A particular influence from the Victorian era case studies is the mode of display of artefacts generated through the design research. The Victorian displays of natural history described in section 2.2 influenced the display of the design research in the Macleay Museum described in case study six described in chapter four. Contemporary influences on form of the objects include reciprocal boundary objects such as Luke Jerram's 3D printed data models of the Tsunami pictured in figure 2.41, where the source data is an integral element of the aesthetic of the work. The research builds on these precedents in order to develop a series 3D printed models based
on collaborations with climate scientists. It does so with the aim of testing different ways to three-
dimensionally visualise a particular scientific data set.

The artefacts described in this chapter have also influenced the choice of materials and processes
investigated and developed during the design research phase of the thesis. Processes and materials
from the Victorian era that have had influence include the innovative use of simple materials such as
wax, glass and paper. These materials, can all be recycled, are easily sourced and can be manipulated
into a wide variety of three dimensional forms. These precedents have demonstrated that combining
materials and molding them in innovative ways can provide a sustainable means of three
dimensionally representing scientific research. Contemporary material and process influences
include, the materially focused works of artists such as Clare Twomey and the Yonetani's who used
materials such as clay, sugar and salt. Again here, these artists have used simple materials that can all
be recycled, are easily sourced and can be manipulated into a wide variety of three dimensional
forms. This application of sustainable materials is pertinent to the material investigations described
in chapter three which focus on clay, sugar, sawdust and recycled paper as the primary materials for
fabrication.

Scientists and the creative practitioners can include in their professions, transdisciplinary
collaboration that work together to help audiences understand complex messages. As institutions
globally, are moving away from a siloed model of education towards a transdisciplinary model, there
is potential for innovation through the meeting of and knowledge exchange between these critically
important fields. The representation of scientific research findings in effective and affective visual
and interactive creative works provides a platform for the disciplines to learn about each other,
facilitate access to scientific data and, most importantly, build resilience and stimulates empowered
responses to climate change. A shared understanding between scientists and creative practitioners -
and in a larger context, between creative practitioners and audience, or content and audience - is
critically important in the context of climate change communication. Three-dimensional creative
works generated through these collaborations and exchanges can act as boundary objects to
facilitate communication, visualise data and raise awareness. They can thus have cultural impact.

The design research described in following chapters investigates all of the three research areas and
uses the research questions to drive the iterative process of developing and testing different types of
collaborations, materials and fabrication processes, and ways to three dimensionally visualise
scientific data.
Chapter 3
Design Research
Innovation with Processes and Materials
Chapter Three Structure

3.1 Introduction
This section introduces the theoretical framework and methodology for reviewing and analysing the fabrication processes and materials investigated as part of the design research.

3.2 3D Printing Rapid Prototyping Overview
This section outlines the development of 3D printing rapid prototyping technology and the current field of commercially available processes and equipment. The section also describes the applications of 3D printing rapid prototyping and the relevance to the research.

3.3 Materials for 3D Printing
Section 3.3 describes the current field of available materials for 3D printing, and lists experimental 3D printing projects that address sustainability and then focuses on ceramic 3D printing.

3.4 Selected Process and Material Investigations
This section draws conclusions from sections 3.2 and 3.3 and outlines the technical aspects of the fabrication and material processes investigated for the case studies discussed in chapter four. Types of processes and materials investigated include: Hand modelled porcelain, CNC routed timber, large scale projections, powder-printed earthenware clay, powder-printed porcelain clay with glaze, robotically controlled slip-casting clay with waste aggregate, and robotically controlled modelling clay with waste aggregate.

3.5 Scientific Research Data
Section 3.5 outlines selected sources types of data that are visualised in the case studies in chapter four.

3.6 Discussion and Conclusion
describes how the processes, materials and projects outlined relate to the research and how they will be employed and combined to inform design research case studies documented in chapter four.
Preamble

Section 3.4: Selected process and materials for the design research case studies-technical descriptions: Design Research Case Study Four: Free Form Clay Deposition, Robotic 6 axis 3D printing, producing sustainable fabrication processes; contains substantial content from the following book chapter of which I was lead author.

Kate Dunn, Dylan Wozniak O’Connor, Marjo Niemelä, and Gabriele Ulacco.

Section 3.4: Design research case study five; Robotic Fabrication in Architecture, Art and Design, Conference Workshop & Exhibition Pier 2/3 Walsh Bay, Sydney (2016) contains limited content from the following book chapter of which I was a contributing author.

3.1 Introduction

This chapter initially describes the context of the fabrication and material investigations undertaken as part of the design research. It then goes on to describe the design research processes and materials investigated in order to address the research question;

Innovation with Methods and Materials: What kinds of processes and materials might be used or developed beyond a purely aesthetic dimension that make a connection between the materials and the data being communicated and in particular, how can the issue of sustainability be cast within the selection and development of new materials in this enterprise?

A key contention of the thesis is that the material, aesthetic, tactile and transformative qualities of creative artefacts, designed to communicate climate change data, can enable expanded audience interactions and insights into the data being modeled. The artefacts are not intended to replace traditional communication modes of numerical scientific research data such as graphs and charts; rather to supplement these in a suite of communication methodologies designed to advance ongoing knowledge exchange between disciplines and promote public engagement with climate science.

The precedent studies reviewed in chapter two included three dimensional objects designed to communicate scientific data. Examples from the Victorian era included taxidermy animals, decorative art objects and realistic models made of materials such as paper, glass and wax. Contemporary means of visualising scientific data that were reviewed, included art installations, collaborative engagement projects such as those conducted by the Cape Farewell Project and the Artist as Family, and objects such as the clay flowers made by Clare Twomey. The precedent studies reviewed in chapter two demonstrated the significant historical and contemporary ways in which science can be communicated through creative projects and artefacts.

While acknowledging the merits of all modes of visualisation for communication, this thesis primarily investigates and conducts inter-disciplinary design projects resulting in three dimensional artefacts that visualise climate change science. The resulting processes, methods and creative outputs of the research and its case studies are thus situated at, and focused on, the nexus of objects as relevant for tangible interaction, embodied experiences, art, design and science communication. This is based on the concept that three-dimensional visualisations have the potential to reflect data and facilitate communication through haptic, material and visual experiences.
The boundary objects made through collaborations with climate scientists described in this thesis can make knowledge memorable and tangible and promote understanding of climate change. 3D printed data visualisations, made using sustainable materials and designed in collaboration with climate scientists, are the primary vehicle for producing the creative outputs of this thesis. Considerable material and fabrication research was undertaken to support this objective, as will be discussed in the following.

Process and material sustainability
As 3D printing advances and becomes a ubiquitous fabrication tool, the development of sustainable materials for 3D printing, becomes a pressing social and environmental issue. Consequently, it is imperative that the materials of objects visualising climate change data are themselves sustainable and do not contribute to the problem in their sourcing, fabrication and disposal. Existing 3D printing technologies, materials and processes are thus described here, then followed by case studies and experiments undertaken as part of the research, with a particular focus on sustainability.

Multiple strategies are needed to address sustainability in the process of making three dimensional objects designed to visualise climate change data. Because the thesis discusses climate change by making or manufacturing objects, there is the potential for the perception of the outcome being at odds with the intent, in that the manufacturing of objects and the consumption of goods is a known contributor to global warming due to carbon emissions produced through the sourcing, manufacturing, distribution and disposal of goods. While acknowledging this danger, the research has chosen to pursue this means of visualising data for the inherent capacity of objects to embody and reflect climate change information in multiple accessible ways that, traditional means of scientific visualisation such as graphs, charts and screen based modes, cannot.

A further validation of the importance of the design research conducted into sustainable 3D printing processes and materials described in this chapter, is the direct positive ramifications for the growing 3D printing industry. The authors of a 2015 paper titled Does Material Choice Drive Sustainability of 3D Printing? concluded that:

3D printing does not commonly use “green” materials which cause few ecological impacts in their extraction or production. The possible exception is PLA bioplastic, which is commonly

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used, and which this study shows to lower printer energy use as well as having lower embodied impacts than ABS plastic. Innovative approaches, such as printing salt with an inkjet 3D printer, can lower ecological impacts per part even further. Other low impact materials could include sawdust, plaster, or other relatively inert substances that can be bonded with low toxicity adhesives.\textsuperscript{181}

Faludi et.al., further recommend, “Future work should experiment with and measure the impacts of 3D printing with more alternative materials that both have low environmental impacts themselves and also enable low-energy printing processes”.\textsuperscript{182} The recommendation to experiment with materials in order to address goals of sustainability in 3D printing is supported another significant study titled “A global sustainability perspective on 3D printing technologies” which states that in order to address sustainability in the 3D printing industry, “the range of applicable materials has to be broadened to enable printing of advanced materials, high-performance alloys, nano-materials and hybrid material structures”.\textsuperscript{183} The practical process and material research conducted and described as part of this PhD project, builds on these recommendations and develop sustainable 3D printing processes, thereby making an important contribution to this field of knowledge.

It is important to note that the term sustainability means different things in different contexts, and is interchangeably applied to environmental, business, financial and social resources. While acknowledging the inter-relatedness of all these factors, the framework used in the research focuses on environmental sustainability. To achieve environmental sustainability, materials will have low toxicity, have a minimum production of waste in manufacture and can be either recycled or disposed of in a manner by which the materials can be absorbed into soil with no negative environmental effects.

The implications of 3D printing on the fabrication process and dissemination of data

3D printing is the primary focus of the fabrication processes investigated in the design research conducted as part of the thesis. The process has been selected for its capacity for repeatable accuracy, relative low cost and potential to be a sustainable manufacturing technology.\textsuperscript{184} The controlling mechanism for 3D printing is based on the Cartesian coordinate system whereby each movement and placement of material is mapped and sequenced using X, Y and Z geometry. This

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\textsuperscript{182} Ibid.

\textsuperscript{183} Gebler et al., "A global sustainability perspective on 3D printing technologies", 166.

\textsuperscript{184} Ibid.
system enables accurate fabrication of 3D printed models that also accurately reflect climate change data. Because of digitisation and networked information technology such models can be made repeatedly and disseminated in multiple places at the same time. Together, these measures constitute a valuable tool for the communication of scientific information, increasing the reach of scientific research and improving the chances of that research producing a transformative impact on audiences.

**Three dimensional objects and their materiality**

Three dimensional objects have been selected as the primary mode of representation in the design research. This is because such objects have a capacity for interaction and engagement that two dimensional forms do not. Objects can potentially stimulate audiences through different combinations of visual, material, tactile and spatial experiences. Even when objects cannot be touched, such as is the case in a museum, one can still move around the object and understand its physical form in relation to other objects, understand its scale measured against our own body, and imagine what the object might feel like to touch or hold. We imagine the weight of an object depending on what we perceive it to be made of. We imagine the heaviness of a stone artefact in a museum, the lightness of a remnant of paper. We also imagine the texture against our hands, the coarseness of brick, the smooth coldness of bronze. These qualities that we imagine can be described as an object's materiality, their materiality is intrinsically linked to our perceptions, expectations and experience of objects.

However, the materials and processes used in 3D printing thus far have little cultural value other than their novelty and their indication of future possibility. 3D printed plastic objects may not be considered intrinsically valuable, as their material and materiality, once transformed by the printing process, are unfamiliar and have no provenance. This can distract from the desired message. An object designed to raise awareness of climate change and stimulate constructive responses may be inherently confusing if made from a material known to contribute to climate change in its sourcing, fabrication and disposal - as is the case with plastics. Unfamiliarity with the materials, and the transformations that occur through 3D printing, can however register haptically in the viewer as uncanny, which can then trigger curiosity, doubt and reflection.

These expectations of objects and their materiality are important considerations when selecting materials and processes to make objects that communicate information. The development of materials for 3D printing that can assuage these concerns is critically important. Hence the imperative for the development and use of sustainable materials for 3D printing in the material outcomes of this thesis described in Chapter Four.
3.2 3D Printing, fabrication and rapid prototyping

The material and fabrication processes used in the design research build on analogue material and fabrication experiments in clay, plaster and wood. The techniques used in forming clay include coil building - where long extruded coils of material are layered and compressed to form objects and structures - much like 3D printing. Another analogue technique is carving - where a tool is used to remove material to articulate a shape, pattern or form. This process is also used with wood and has the same workflow as laser cutting or CNC routing. The process of slip casting has also informed some of the processes developed through the research. Slip-casting involves pouring liquid clay into plaster moulds to form a skin. Here a liquid material state is mixed and exposed to another material - plaster; and an atmospheric element - in this case air - causes it to change state and solidify, much the way plastics solidify from a viscous liquid to a solid once exposed to a cool room temperature after being extruded through a hot metal nozzle using a 3D printer.

Background of 3D printing

This section defines the current field of 3D printing processes, commercially available materials for 3D printing and the environmental implications of their use. The section will then go on to list experimental 3D printing projects addressing sustainability in the processes and materials used. There is a focus on projects that use ceramics, as it is the primary material investigated in the practical material research undertaken and therefore most relevant to the research goals of the thesis.

Development in 3D printing materials is diverse and constant. Variations of plastics, ceramics, metals and more recently organic tissues have been added since the innovation of 3D printing in the 1980s. Current innovations that are changing the way we live include the ability to 3D print live tissue and cells for medical purposes. This research project, while acknowledging the value and innovation in these areas is focused on 3D printing for the purposes of making creative three-dimensional data visualisations, therefore the focus will be on non-living materials used in 3D printing. The goal of 3D printing material development has been in general to produce a material that is stable in that it does not change its chemical properties with the effects of time, heat, cold or moisture during the prefabrication period. The material must also perform well during the 3D printing process being used. For example, in plastic filament depositing, it must heat consistently and extrude smoothly without blocking and most importantly, it must adhere to the previous layer as the object is systematically built. The build material should ideally be affordable and the end result durable, well bonded across all layers, attractive and fit for purpose.

Current commercial material products for 3D printing are supplied in a range of physical states
including powder, filaments and resin. One of the critical issues that must be addressed as 3D printing materials develop is the sustainability and safety of the materials as they go through the process of being printed. For example, some plastics emit fumes when heated that are potentially toxic to user and environment. The sustainability of materials will be evaluated for their relevance and suitability for the thesis topic of visualising climate change data using experimental three-dimensional digital fabrication techniques.

3D printing - also called additive manufacturing - uses a machine to build up parts in very fine layers using CAD (Computer Aided Drafting) software to determine the form. The way in which material is built up depends on the type of 3D printer used, examples include FDM printers, powder printers and laser sintering printers, (the range of different types of 3D printers is detailed in section 3.2.2).

3D printing as an additive fabrication technique, differs from other additive methodologies such as casting or injection moulds, in that the form does not require a skin or master to determine the final product. In 3D printing, the form is either self-supporting as it builds or, it is supported by a nominal sacrificial scaffold. This development in fabrication processes has tremendous consequences for achieving a more sustainable means of making objects while reducing waste in the production process - This occurs because 3D printing removes one of the stages in previous additive fabrication processes entirely, thereby reducing time and waste. 3D printing technology also offers manufacturing industries potential to adapt their workflow in an agile manner because the process of taking a product from design through the testing phase is greatly simplified. In traditional additive manufacturing a product required both a master and mould to be remade each time a change in design is required. With 3D printing a change in design can occur in the CAD model and printing phase rather than discarding entire systems that are set up for each product.

The most common type of digital file used to 3D print is an STL file (STereoLithographic) originally developed by the firm 3D Systems specifically to support 3D printing, and which can now be generated by all standard modelling software such as Maya, Rhino and Solidworks. 3D printing or rapid prototyping technologies were originally developed with the aim of further
automating manufacturing. The first patent was filed in 1981 in Japan by Hideo Kodama\textsuperscript{190}, and included designs for solid printed models that used an X, Y and Z-axis.\textsuperscript{191} Kodama’s designs showed the object being built up in layers, each of which corresponded to a cross-sectional slice in the model. The technology continued to develop until it was commercialized by 3D Systems in 1986.\textsuperscript{192} In the 1980s and 1990s the process was deployed in response to research and development needs of government sectors such as the military and multinationals such as General Electric. However, early machines were very large, expensive and somewhat unreliable - making the process a risky investment for manufacturing.

The cost of high-end printers is still prohibitively expensive for manufacturing that requires large volumes of one type of shape, such as car parts. Another limitation to widespread use of the process is that to date, most printers have restricted build size. This is because they rely on a gantry system corresponding to a particular print bed, to control the deposition of material. Recent developments challenging this limitation of scale include robotically controlled 3D printing where the size able to be printed is only limited by the reach of the robotic arm. This process is developing constantly and has yet to be commercialised, primarily because the consistent supply of the build material has not yet been technically resolved. Another field that has embraced 3D printing is the medical industry, typical uses are titanium bone and joint replacements such as hip joints. The cost of metal 3D printing setup and machinery can be very expensive; however, the needs of the medical industry are generally very precise and small parts and the expense can be transferred to the consumer, unlike other fabrication industries.

**Types of 3D printing and how they work**

There are constant innovations not only in 3D printing materials but in the technology and processes used in 3D printing.\textsuperscript{193} Below is an overview of the primary types of 3D printing processes and their

\begin{footnotesize}
\begin{itemize}
    \item \textsuperscript{189} Defined by Rene Descartes in 1637, the Cartesian coordinate system is a means of locating a point in space in relation to a point of origin using numerical coordinates.
    
    \item \textsuperscript{190} Robert Bogue, "3D printing: the dawn of a new era in manufacturing?" Assembly Automation 33, no. 4 (2013): 307-311.
    
    \item \textsuperscript{191} X, Y and Z axis is based on the Cartesian coordinate system and locates points and objects along vertical and horizontal planes.
    
    \item \textsuperscript{192} 3D systems patent. https://www.google.com/patents/US4575330# . Another system being developed was Fused Deposition Modeling (FDM) by a company called Stratasys Inc Many of these technologies and patents built upon the research of others; nevertheless, the patent holders were the ones able to profit and expand from the research.
    
    \item \textsuperscript{193} Kaufui V. Wong and Aldo Hernandez, "A review of additive manufacturing," ISRN Mechanical Engineering 2012 (2012).
\end{itemize}
\end{footnotesize}
relationship to the design research described in Section 3.4, Selected Processes and Materials. The processes described do not address all the types of 3D printers ever made, and some processes have different names depending on the manufacturer or country of origin.

Particular processes will be discussed in detail here, namely, Stereo Lithography, Direct Metal Laser Sintering, Electron Beam Melting, Selective Deposition Laminating, Laser sintering powder printing, Binder Jet Powder Printing, Material Jet Printing, and Fused Deposition Modeling (also called Free Form Fabrication) Extrusion 3D printing.

**Stereo lithography**

Stereo Lithography relies on the effect of laser beams on photopolymer resin - a material that changes its physical properties when exposed to light. When exposed to the laser beam the resin cures and forms a solid. Stereo lithography apparatus (SLA) stores the resin in a vat that has a movable platform inside it. The platform lowers as each predetermined layer of the object is exposed to light and bonded. The area to be bonded is determined by an STL file supplied to the machine, which separates the object into very fine slices. This process continues until the object is completed. The platform is then raised and the object can be removed. The materials are expensive and toxic and the bed size is very small. Consequently, Stereo Lithography is a very accurate process, suited to prototyping but not to manufacturing.

**Laser sintering powder printing and direct metal laser sintering**

Laser sintering powder printing and Direct Metal Laser Sintering are 3D printing process relying on

the use of lasers to fuse or sinter material and bond them together, rather than a liquid binder. Laser sintering works with a range of powdered materials including metal and glass. Laser sintering 3D printing machines are divided into two platforms or beds; one is a feed bed or platform and the other, a build bed or platform. The powdered building material is swept in incremental layers by a roller from the feed bed to the build bed by a gantry-style arm. The laser is projected in the pattern determined by the STL file input into the machine across the X-Y axis. The laser causes the powder to sinter or fuse to a solid, much like welding - however with much greater accuracy.

After each layer is fused the build bed drops incrementally to allow for the next layer of build material to be swept over from the feed bed in preparation for the sintering of the next layer of the form being built. The build bed or platform is contained in a chamber that is completely sealed to

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ensure accurate temperature control necessary to facilitate fusion. Upon completion, the entire build bed is removed from the machine, with the fused object still embedded in the layers of powder. The excess powder is then removed and the printed object is left on the build bed. The process of fusing material while it is encased in the unfused powder around it means that the object is fully supported as it is formed. Most materials which can be bonded by heat are particularly weak and prone to slumping when subject to increased temperatures. Because the object is surrounded by powder, fine details that are either suspended or would be undercuts in another process are held in place as they fuse and then cool.\textsuperscript{196}

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure3_1.png}
\caption{Laser sintered gold.\textsuperscript{197}}
\end{figure}

**Electron beam 3D printing**

Electron beam melting 3D printing technique is a recent development and builds on direct metal laser sintering techniques. The process uses metal powder with an electron beam instead of laser beam heat source. The electron beam requires a vacuum environment to operate. The technique produces high-grade prints with very low porosity; a problem with many of the other processes where, as materials are laid down, air bubbles can be trapped between the layers. This technology is now being used in the medical industry for implants.\textsuperscript{198}

\begin{itemize}
\item \textsuperscript{197} Image Sourced: \url{http://www.professionaljeweller.com/how-to-print-your-own-jewellery/accessed 10/08/2015}.
\item \textsuperscript{198} Wong and Hernandez, "A review of additive manufacturing."
\end{itemize}
Binder jet powder printing

Binder jet powder printing uses the same powder material delivery mechanisms as laser sintered powder printing. However, this type of powder printing relies on a liquid binder to fuse the powder, rather than heat as used in laser sintering. The binder is jetted into the pattern designated by the STL file, layer by layer, until the object is fully printed. The jetting technique is adapted from that used in two-dimensional ink jet paper printing. As each layer is built the build bed lowers incrementally to allow room for the next layer of powder at the top. The object is supported as it is formed by the unused powder that is swept over from the feed bed for each layer. Once printing is complete the object can be removed - in this case the feed build bed can be raised to the surface of the machine and the unfused powder removed by vacuum. This process can be used with multiple types of powder such as gypsum and clay. Colour can be added to the binder. This type of printing is one of the primary processes selected for material experimentation in this thesis because of the capacity to vary and test materials whilst maintaining optimum printing performance.

Figure 3.2 A Binder Jet Powder Printer showing the feed and build bed. Zcorp 510 printer.

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Selective deposition laminating (SDL)\textsuperscript{202}

Selective Deposition Laminating printers use layers of material glued together in a pattern determined by the 3D data inputted into the machine. A common build material is standard photocopier paper. Each layer of paper is glued using an adhesive put down in the designated pattern. The process is similar to binder jet printing in that the material is altered by the addition of a binder. As with a copier, the SDL machine has a feed mechanism that places a piece of paper on top of the previous one on the build plate. The machine moves the most recently placed sheet up to a heat plate, further solidifying the adhesive. The design is cut into each sheet of paper using a tungsten carbide blade that ensures the final part is easy to remove from the waste paper. When this cutting sequence is complete, the 3D printer deposits the next layer of adhesive and so on until the part is complete. Colour can also be added to the paper. The process is one of the more environmentally friendly alternatives in that the feed material can be recycled. While SDL printing addresses the research criteria of sustainability, there is limited opportunity to alter the materials as the entire system has been developed for standard copying paper. There is also limited flexibility in the size of objects that can be built.

Material jet printing

Material jet printing jets or sprays the build material rather than the binder. The material is in a molten or liquid state and can be delivered using multiple jet heads allowing for a part to be produced from different materials at the same time. It is also possible to deposit the scaffold material to support the different build materials using multiple binder heads. The most common materials used in this process are liquid photopolymers. These are then cured by passing UV light over the layer as it is deposited. Material jetting is a very precise 3D printing method, producing accurate parts with a very smooth finish. Common materials used in Material Jet printing include wax and photo curable plastic resins. This type of printer has a small print bed and is often used for jewellery. There is no potential to alter the way the process works or to investigate sustainable materials with this process; consequently, it is not investigated further in this thesis.

FDM (Fused Deposition Modeling) FFF/ (Free Form Fabrication), Extrusion 3D printing

FDM (Fused Deposition Modeling) FFF/ (Free Form Fabrication) and Extrusion 3D printing are similar processes with different names attributed by different printer developers. It is the most common type of 3D printing and can be at an industrial scale or a domestic desktop scale. The process relies on extruding a material through a hose and nozzle in a pattern determined by an STL file. The material is extruded onto a bed or plate of some kind depending on the particular characteristics of

the material being extruded. Many of the cheaper FDM 3D printers use a plastic filament that is heated in the extruder head and then extruded onto a slightly warm platform. The material builds up in fine layers supported in places by a scaffold made of either the same material or another that can be washed away or chemically dissolved after the printing is complete.

This printing process relies on the material bonding with the layer beneath as it is printed to ensure the structural integrity of the final printed object. This process requires fairly stringent temperature or other environmental controls such as moisture or air movement to ensure layers’ bond at the correct rate. FDM / FFF/ Extrusion printing is relatively easy to adjust for different purposes as some printers are designed for use with different types of filaments and many of the mechanisms can be easily hacked or altered. It is also a process that can be scaled up by introducing large gantry frames and robotic arms for delivering materials. To date this has not been commercialised by any one company however there are numerous research projects investigating the potential of 3D printing different materials using this process. Developers of large scale FFF, include DUS Architects from the Netherlands, Win Sun from China Enrico Dini’s D-Shape project, B Behrokh Khoshnevis’ Contour Crafting project, and Audrey Rudenko, who are all experimenting with largescale FFF using extruded concrete and plastics. James Gardiner with Laing ORourke Construction is developing 3D printed wax for the purposes of large scale concrete casting.

These projects listed above are pioneering applications of the process however, 3D printed concrete and wax are not relevant to the material processes investigated as part of this thesis. FDM / FFF/ Extrusion printing is a suitable process for investigating different sustainable 3D printing materials and is used in the design research for a range of material and process experiments, these are detailed in section 3.4.

203 Hacking: Many participants, whether they are volunteers or corporate employees paid to work on free software, refer to themselves as hackers – computer aficionados driven by an inquisitive passion for tinkering and learning technical systems. E. Gabriella Coleman, Coding freedom: The ethics and aesthetics of hacking (Princeton: Princeton University Press, 2013), 3.
204 Ibid., Robert Bogue, "3D printing: the dawn of a new era in manufacturing?".
3.3 Materials for 3D printing

In the following section the raw materials used in 3D printing are discussed. Materials described include different metals, plastic, paper, clay or ceramics. The section then goes on to describe experimental projects that address sustainability in both the material and processes researched.

Metals

The most common metals used for 3D printing are aluminium, cobalt, steel and, most recently, titanium. Aluminium is desirable because it is soft, powders easily and has a relatively low melting temperature of 660.03 degrees. Cobalt is combined with other metals to produce a high strength alloy - though it is also toxic during melting. Stainless Steel is one of the strongest metals used in 3D printing. It has qualities that are very useful in a range of industries including medical and precision tooling. The benefits of stainless steel are that it is a very hard, dense material which is relatively impervious to rust. It has a high melting or sintering temperature of between 1370 and 1560 degrees.

Titanium has similar properties to steel in that it is very hard, relatively impervious to corrosion caused by other elements such as air and water and can be used in powder form. Gold and Silver are also being used for small parts, particularly jewellery. While metals have great potential in 3D printing, they are not relevant to this thesis because they require elaborate, expensive processes to recycle; the machinery is difficult to access; their materiality communicates a permanence which does not reflect the constantly changing circumstances of climate change; and their aesthetic qualities are redolent of a machinic technology which could render the printed objects ambiguous and the likely message self-contradictory. 3D printing with titanium has been explored by the aeronautical and medical industries, it has not been taken up by many creative practitioners at this stage because the cost of the materials is prohibitively expensive. One example however is Eleanor Gates Stuart, (artist in residence at the CSIRO) who produced a series of titanium 3D printed insects in collaboration with CSIRO’s Information, Mathematics and Future Manufacturing divisions.

212 These alloys are used in the “Aerospace, Electrical Energy, Electronics, Oil & Gas Industries.”
214 Ibid.
Plastics are the cheapest and most common type of 3D printing material available. They are used in filament form in the Fused Deposition Modelling process. The most common types include Nylon, supplied in filament form for FDM 3D printers and ABS - another common plastic widely used on entry-level FDM 3D printers. Both of these plastics can be recycled and reused using a filament recycler - however, they both give off fumes when heated and during fabrication and recycling. The equipment necessary for recycling is considerably more expensive than the printer or filament. Consequently, most users do not recycle the plastic, which ends up in landfill, leaching toxins into the soil. Research conducted by Wojtyla, Klama, and Baran has shown that ABS plastic does not break down in the environment. "The conducted study has shown that ABS is significantly more toxic than PLA." ABS is unsustainable yet is frequently used by schools, universities, and individual consumers. The resultant familiarity of a generation of students with environmentally harmful plastics rather than sustainable alternatives is of significant concern. 3D printing with plastics is

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220 Ibid., 1.
industry standard and widely applied. In creative works, and particularly relevant to this research, aspects of plastics printing have been explored by many creative practitioners, significant examples include Louis Pratt\textsuperscript{221}, Maria Fernanda Cardosa\textsuperscript{222} and Luke Jerram.\textsuperscript{223}

**Paper**

Paper is currently used in standard A4 copying paper format as discussed in the section on SDL (Selective Deposition Laminating) printers in this chapter. However, it has tremendous potential as a sustainable 3D printing material because it is easily sourced, recyclable, nontoxic - and it absorbs moisture easily, facilitating bonding with other materials. Some of the design research experiments described in Section 3.4 include the use of recycled unbleached paper in combination with other materials for robotic 3D printing. 3D printing with paper has been explored by Ronald Rael and Virginia San Fratello and Anthony Giannini from *Emerging Objects*.\textsuperscript{224}

**Plaster**

Plaster is made from gypsum or hydrated calcium sulfate. It is used to make casting plaster, gyprock wall boards and is in fertilizers and is the primary ingredient in commercial powder for printing such as Z print.\textsuperscript{225} Gypsum is widely available and is nontoxic; however, it's very small particle size renders it a hazard for inhalation. Once printed, objects cannot be recycled and must be disposed of in landfill. 3D printing with plaster has been explored by James Gardiner in his series of works modelling artificial reef systems.\textsuperscript{226}

\textsuperscript{222} The current state of 3D printing for use in construction\textsuperscript{222} Maria Fernanda Cardoso, ‘It’s Not Size That Matters, It’s Shape’ (The artist, 2011). Accessed 03/03/2017.
\textsuperscript{224} *Emerging Objects* 3D printing with paper http://www.emergingobjects.com/2012/08/01/paper/
\textsuperscript{225} ZPrint is the commercial product designed for ZCorps Powder Printers.
\textsuperscript{226} James Gardiner, “Exploring the emerging design territory of construction 3D printing-project led architectural research.” Theses, Architecture & Design, RMIT University (2011).
Food: chocolate, sugar and pasta

3D printed food is a recent development and lends itself well to FDM and powder printing processes. Many foods such as chocolate and sugar can be altered in their consistencies to work effectively with the 3D printing extrusion method. 3D Systems\(^\text{228}\) has collaborated with food companies such as Hershey’s chocolates\(^\text{229}\) and the culinary Institute of America, while Barilla pasta has developed a project with 3D Dutch non-profit company TNO\(^\text{230}\). These have been showcased at industry events but are still somewhat of a novelty, functioning like an automated icing piping bag. Yet the projects are relevant to this thesis because they adapt an everyday material and use 3D printing technology to deploy the material in new ways.

Sugar is the most successful food material to be utilised in the 3D printing industry. It is a single ingredient that can be easily controlled by varying temperature and adding water, makes it able to adhere to other layers. Sugar is also nontoxic, cheap, has a consistent neutral colour depending on

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\(^{228}\) http://www.3dsystems.com/de/node/7563. Accessed 06/05/2015.

\(^{229}\) Ibid.

\(^{230}\) TNO participates in a growing international network comprised of leading scientific institutes, companies with ambitious development profiles, universities and other partners in knowledge. They have a focus on creating ensuring positive economic and social impact in their practice. -https://www.tno.nl/en/about-tno/. Accessed 6/8/2016.
how it is refined and can be easily coloured using nontoxic cheap food colouring. Some early innovators of 3D printing with sugar were Liz and Kyle Von Hasseln, two architecture graduates who experimented with different materials before testing sugar in a powder printing machine adapted to become food safe. Sugar has a great potential as an ephemeral material for artworks, as demonstrated by Ken and Julia Yonetani in their Sweet Barrier Reef project, exhibited at the 2009 Venice Biennale. While not 3D printed, the material bonding qualities of the sugar are demonstrated in the Yonetanis works shown in figure 3.6. Sugar can be sculpted into almost any form using a range of processes, including 3D printing.

Figure 3.6 Sweet Barrier Reef Materials: Sugar, vegetable gum, polystyrene foam (2009).

Sustainable filaments for fused deposition printing
As FDM 3D printing becomes a universal fabrication tool, new sustainable materials are being researched, commercialised and distributed for mainstream consumption. The most common is PLA or Polylactic acid. PLA is a bio-degradable plastic material that has gained market share with 3D printing for this very reason. It can be utilized in resin format for DLP/SL processes as well as in filament form for the FDM process. However, it is not as durable or as flexible as ABS. As with ABS

231 While sugar is non-toxic for the consumer, the research notes that the farming of the sugar can have detrimental effects on certain environments where it is grown. The thesis does not suggest that the use of sugar is without environmental impact; however, during processing and 3D printing production, relative to the other material listed such as plastics, the negative impact both on air quality and human health is considerably lower.
232 http://the-sugar-lab.com accessed 08/05/2015.
and nylon, the recycling process requires an expensive filament recycler, which consequently results in similar unsustainable impacts as for plastics such as disposal of waste scaffolds and unwanted prints in landfill. PLA takes up 15 years to break down in soil.\(^{234}\) Disposed of in plastic bags, however, the process could be indefinite.

**Experimental sustainable filaments for FDM printing**

A number of specialty sustainable filament products are commercially available; however, these are expensive compared to plastic and have supply and performance problems. Commercial products include recycled wood filaments, recycled brick filaments and, recently, an algae filament.\(^{235}\) These products rely on a certain percentage of base bonding material such as plastic or PLA to ensure fabrication stability during printing - as the base materials melt at a consistent temperature, ensuring consistent bonding of each subsequent layer. There is opportunity for considerable material development in this field. The principle of having a base material with different additives has informed material investigations undertaken in this thesis. Using a base material of clay, different additives were added and subtracted to achieve sustainable and functional outcomes.

**Experimental sustainable materials for powder printing**

Considerable research has been undertaken in this area by Professors Mark Ganter and Duane Stori from the Solheim Rapid Manufacturing Laboratory at the University of Washington.\(^{236}\)\(^{237}\) Ganter and Stori have researched different recipes for powder printing since 2009 and published them in a blog called Open 3DP. Their research approaches 3D printing from an engineering framework focused on materials, rather than on potential objects that can be manufactured from those materials. Materials include sugar, salt, clay and different binders. Their research has been globally influential and many others have built on their research including the design research conducted as part of this thesis. In particular, *Process and Material Investigation three, Powder printed earthenware clay*, described later in this chapter, built on Ganter and Stori’s research and sought to adapt processes and materials to suit local Australian materials as well as add new ingredients.

Another group conducting research into experimental materials is *Emerging Objects* introduced earlier in this chapter lead by Ronald Rael and Virginia Fratello.\(^{238}\)\(^{239}\) *Emerging Objects* have


experimented with salt, sand, tea, sugar, clay and plastics. Their focus is on sustainability and materials development as well as potential uses in architecture. This research is particularly relevant to this thesis as it demonstrates radically innovative and experimental approaches to combining unexpected materials for 3D printing and then applying them in different creative contexts.

3D printing with ceramic materials

Much of our built environment is fabricated from some variation of clay or ceramics. Applications include bricks, roofing and flooring tiles, mud brick houses, rammed earth houses, bathroom fixtures and dinnerware. But like any material, ceramics has limitations and strengths. The precedents discussed here draw on research undertaken in traditional forming techniques such as wheel throwing, hand building and manual extrusion, to inform 3D printing and robotically controlled investigations in scale, free form deposition and push the potential of the material. Ceramics is a relatively new area of 3D printing material research and is developing with mixed success for different types of printers. Martin Bechthold, a leader in the field of large scale ceramic 3D printing notes: “3D printing, while still at the development stage for larger elements, shows promise as a strategy for special pieces in the near future, and in the long term, for highly varied modular designs that cannot be produced with traditional manufacturing techniques.”

Ceramic 3D printing has been commercialised by companies using ceramic powder printers such as Figulos and Shapeways. Shapeways is in the process of converting an SLS (Selective Laser Sintering System) to use with ceramic or porcelain materials - however results are not available at the time of writing.

Because of the cost of the process and the instability of the material it is yet to be used in large-volume production by anyone. Precedents of small-scale production by artists and designers do exist - for example Australian Rod Bamford’s MakerBot printer that uses a gantry moving on XY and Z axes. Bamford substituted the printer’s standard roll of filament for a tube of ceramic slip which deposits onto a bed. Bamford observed that his “experiments did reveal a language of contours that recalled miniature clay coiling, and also a similarity to the layered clay nests extruded by the mud wasp’s abdomen.”

The limitation of this technique is that the size of the gantry frame controls the size of the final work, unless it is built in components. Another limitation is that the clay has to be of a very fine particle size to fit through the custom nozzle of the depositor. To achieve a fine particle size all grog or aggregate

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is removed, yet grog or aggregate - generally made of bisque fired clay that has been crushed and then added to the material - is what gives clay its structural integrity and strength. The removal of the grog causes the clay to slump. To compensate for the slumping, the forms had to be built slowly to allow the clay to harden enough to support the next layer being deposited, making the process slow and prone to cracking during the drying process due to the uneven moisture content.

Figure 3.7 Unfold- Original printer in l’Artisan Électronique Figure - Artefacts of a new history, 2009.244

A similar project to Bamford’s was developed in 2009 by a Dutch Design company called Unfold. Unfold developed a small range of semi functional and decorative ceramic items. Much of their work questioned how 3D printing could change the way things are made rather than attempting to create a product. In writing about their process for an exhibition L’Artisan Electronique author and designer Clair Warnier declares that;

“From knife to hammer to 3D printer, the influence of tools on a design is not to be underestimated. Yet for a long time the instruments of production were closed systems. This is now changing. Following the personal computer and a range of digital advances, the advent of the personal fabricator has provoked a revival of the idea of `making your own things.”245

Unfold’s 3D printing process for ceramics not only harnesses the potential of new technology and materials but also projects the past history of specific techniques into the future. The layering of the clay material by the printer harnesses the same material properties as a traditional potter might use in building a coil vessel. The clay is built up sequentially, relying on the previous layer to support the weight of the next, while the moisture in the clay helps it adhere. Where the process differs is the ability to create very fine layers that are not possible by hand – thereby enabling complex structures to be repeated. As with Bamford’s project, the size of the printer’s output is limited by the size of the frame of the printer.

Olivier van Herpt, another Dutch designer has greatly increased the scale of the gantry and facilitated much larger 3D printing, as seen in figure 3.8. Van Herpt uses the printer to make a range of functional works that investigate the potential of the printer and move towards a “human scale”\textsuperscript{246} of work. Van Herpt used an iterative design strategy to resolve the design of the printer and the composition of the clay - moving from mixing clay with water, to extruding clay that has a high grog component, thus removing the problem of slumping.

\textit{Image 3.8 Oliver van Herpt 3D printed ceramics using high grog clay.}\textsuperscript{247}

Other examples of 3D printed clay include \textit{G Code Clay} by Emerging Objects\textsuperscript{248}, a series of smaller 3D printed components intended to fit together to form a larger customised structure. Likewise \textit{Print

\textsuperscript{247} Image Sourced: Ibid.
\textsuperscript{248} http://www.emergingobjects.com/project/gcode-clay accessed 10/10/2015.
and Burn\textsuperscript{249} and Shelter\textsuperscript{250} by El Studio- a collaborative design studio for architecture, urbanism and research based in Amsterdam founded by Erno Langenberg.

The examples given here, are a cross section of the innovations in the field of 3D printing with ceramics at the time of writing. They investigate different types of 3D printing, different consistencies of clay and increasing scales of print volume. The examples given inform the process and material investigations conducted as part of the design research and described in section 3.4 of this chapter.

**Ceramics for large scale free form fabrication (FFF)**

Ceramics is also being used in large scale free form fabrication, using robots as the primary means of controlling where material is deposited or formed. This is a new field exemplified by international precedents including Roboscult\textsuperscript{251} a robotically fabricated project using clay as a mould to sculpt fibreglass chairs. The process involves manually packing clay into position, then using a series of robotic tool paths to subtract clay into a shape.

A significant body of research has been generated by the Material Processes and Systems Group (MaP+S),\textsuperscript{252} led by Professor Martin Bechthold from the Harvard Graduate School of Design. Over a six-year period the MaP+S group have investigated numerous industrial and robotic applications of ceramic materials including large scale clay 3D printing. These Projects include, Objects of Rotation\textsuperscript{253} which uses a series of clay hand tools in a collet chuck attached to a robot arm. The tools are used to mark or shape columns of clay secured onto a clay throwing wheel. The novelty here is in the integration of digital automation that allows for clay modeling techniques and methods to be scaled, thus providing control in the production of small and large objects.

\textsuperscript{249} http://www.elstudio.nl/ accessed 12/10/2015.
\textsuperscript{250} Ibid.
\textsuperscript{251} Mathew Schwartz and Jason Prasad, "RoboSculpt," in Rob/Arch 2012 (Springer Vienna, 2013), 230-237.
\textsuperscript{252} http://research.gsd.harvard.edu/maps/ accessed 10/11/2015.
Woven Clay\textsuperscript{254} uses clay to extrude a woven pattern onto an undulating foam bed, which causes the clay to set or dry in a form that replicates the undulating bed surface. The clay deposition technique is undertaken through robotic extrusion by depositing a clay paste. The undulating forms are created using a router subtracting material from a piece of styrene, and then a second robotic application is applied in the form of the extruded pathways rather than strata deposition. In the context of large-scale precedents, there further exist a number that use ceramic material deposition, and which apply different fabrication methodologies for objects and structures.

Another project by the MaPS team is the Printed Clay: Micro Extrusion.\textsuperscript{255} This project investigated the potential to simply workflow and customise the production of exterior ceramic louvers using robotic 3D printing. Clay was 3D printed using a custom-made extrusion system incorporating a single cylinder motorised piston. The nozzle extruded beads of clay from a milled aluminium mouthpiece on to different surfaces and moulds.


\textsuperscript{255} Martin Bechthold, “Ceramic Prototypes.”

\textsuperscript{256} Collaborative ceramics 3D printed projects led by Martin Bechthold: image source: http://research.gsd.harvard.edu/maps/portfolio/printing-ceramic-louvers accessed 11/05/2016.

\textsuperscript{257} Image sourced The Institute for Advanced Architecture of Catalonia (IAAC), https://iaac.net/research-projects/large-scale-3d-printing/pylos accessed 11/05/2016.
Another significant example is the *Pylos Project*\(^{258}\) undertaken by the Institute for Advanced Architecture of Catalonia (IAAC), with Alexandre Dubor and Sofoklis Giannakopoulos. This project focused on using soil mixed with clay for 3D printing and depositing using a KUKA robot. *Pylos Projects* shown in Figure 3.10 is ongoing and focuses on the potential for sustainability in housing futures.

Other examples of large-scale ceramic 3D printing include WASP 3D printed *Zero-Mile* homes.\(^{259}\) *Zero-Mile* homes are large in scale but still rely on gantry frames to control the deposition of material.

![Figure 3.11 WASP 3D printing clay and soil on a large scale.](https://iaac.net/research-projects/large-scale-3d-printing/pylos/ 10/06/2016)

The projects and processes described in this section do not cover all of the research in the field of large scale ceramic 3D printing and fabrication, however the examples given show the innovations that have taken place in the field. Together, these precedents demonstrate the potential of incorporating traditional knowledge of ceramics with new technology to address global issues such as sustainability in the case of the *Pylos Project* and the *Zero Mile Homes Project*, where locally sourced materials contribute to the deposit materials.

Other projects such as those conducted by Martin Bechthold and the MaPs group have made

\(^{258}\) [https://iaac.net/research-projects/large-scale-3d-printing/pylos/ 10/06/2016.](https://iaac.net/research-projects/large-scale-3d-printing/pylos/ 10/06/2016)

\(^{259}\) WASP (World’s Advanced Saving Project) was founded in 2012 by Massimo Moretti. *Interview with WASP by 3dprintingarchitecture.net (Erno Langenberg).* [http://www.3dprintingarchitecture.net/?p=521 accessed 5/06/2015.](http://www.3dprintingarchitecture.net/?p=521 accessed 5/06/2015)

significant contributions to innovations in fabrication processes for the built environment. The projects described here demonstrate that through collaboration across disciplines and knowledge boundaries, new knowledge can be generated that can solve complex problems. The process and material investigations described in section 3.4 of this chapter build on this research and investigate new ways to three dimensionally model and represent climate change data, using a range of fabrication processes and sustainable materials.
3.4 Selected process and materials for the design research case studies-technical descriptions

Introduction
Section 3.4 describes the technical, material and process design research undertaken as part of this thesis. Building on the 3D printing processes and materials described in section 3.2 and 3.3, the design research uses this information to inform and conduct a series of case studies that address the research questions. The conceptual framework, the types of boundary objects used and the collaborations engaged in to make these test cases are described in chapter four.

The types of processes and materials investigated in the case studies and discussed in this section include:

- Process and Material Investigation One; Hand modelled porcelain;
- Process and Material Investigation Two; CNC routed timber;
- Process and Material Investigation Three; Powder-printed earthenware clay;
- Process and Material Investigation Four; Powder-printed porcelain clay with glaze;
- Process and Material Investigation Five; Robotically controlled slip-casting clay with waste aggregate;
- Process and Material Investigation Six; Robotically controlled modelling clay with waste aggregate.
Process and Material Investigation One: Hand modeled porcelain

This process was used in Case Study One, The Garden of Earthly Delights at Metalab Gallery (2012) and discussed in chapter four.

The first material investigated in this research was unfired white porcelain. Unfired, porcelain is malleable and plastic, lending itself to both additive and subtractive processes. The processes investigated in the Garden of Earthly Delights project were hand modelling and carving. The act of shaping and modelling materials by hand meant that no piece was exactly the same. The translation of visual information to three-dimensional form, relied on the human senses of sight and touch to achieve a resemblance to the original form of the endangered plant species being depicted. The limitations of the process were that only one piece could be made at a time. The process was very slow and fragile; and the final shape relied on the artist’s subjective judgement to determine appearance, volumes, dimensions and textures.

The hand modelling clay techniques used in the Garden of Earthly Delights project set the framework for approaches in subsequent projects. Both additive and subtractive processes were employed. While subsequent projects all used digital means of fabrication, the haptic and tactile understanding of material and materiality gained in the Garden of Earthly Delights did influence the selection of materials, processes and three-dimensional forms in those projects.

261 Image sourced: Kate Dunn 2012.
Process and Material Investigation Two: CNC routed timber

This process and material was used in Case Study Two, Regenerate at Sculpture by the Sea, Cottesloe Western Australia and Royal Botanic Gardens, Sydney, (2012-2013). This case study is discussed in detail in chapter four.

The Regenerate project investigated reductive digital manufacturing as a process for the fabrication of 3D objects to represent climate change research. The same climate change research material and data was used as for the Garden of Earthly Delight. Computer numeric control (CNC) routing was selected, as it is an industrial process that cuts into different materials using a range of commercially available end effectors - primarily drill bits of different sizes. The end effector is attached to a gantry that moves up and down above large vacuum bed or work platform. The material to be cut is secured by vacuum to the base to ensure no movement occurs during the cutting process. The advantages of the process are that it is possible to repeat complex shapes exactly and much quicker than cutting or carving materials by hand. The data dictating the form and lines to be cut was input as an STL or OBJ file. This file was then read by the CNC router’s software and converted to G-code which dictates the toolpath.

The material used for Regenerate project was 16 mm marine plywood fabricated of laminated layers of pine glued with Phenol Formaldehyde - a toxic glue that does not break down in the

262 Image sourced: Kate Dunn 2012.
environment. Each of the twelve plywood sheets was laid on the bed of the router and cut out over a period of 3 days. The accuracy of the digital file and the cutting process ensured that each piece was identical and fitted into a circular frame at the top of the seed forms.

The reductive process, when combined with the open forms of the design, resulted in considerable waste ply that cannot be reused. The qualities of the timber were also obscured by the addition of bright acrylic paint to preserve the object for outdoor display. While the project tested digital reductive processes for visualising climate change, it did not embody principles of sustainability in its processes or materials. The following project resumed experiments with clay as a more sustainable material.
Process and Material Investigation Three: Powder printed earthenware clay

This process and material was used in Case Study three, *3D printed Data Models* at Research Visions, University of Sydney, (2014). This case study is discussed in chapter four.

![Figure 3.14 Zcorp 310 printer with clay powder mix during printed part removal.](image)

Building on existing research by Gantor and Stori, the *3D Printed Data* project tested and adapted powder printing processes and materials to suit Australian conditions using a Zcorp 310 3D printer. The base materials selected were clay, sugar, maltodextrin, water and alcohol. These materials can all be sourced ethically, are non-toxic, can be recycled in the case of clay maltodextrin and sugar, and evaporate, in the case of the water and alcohol.

The process of developing materials to suit Australian conditions involved considerable research and testing because materials such as clay have different compositions depending on where they are mined and how they are mixed. Variables in clays can include kaolin, iron, silica and water. The other influential variable is the moisture content in the air in which the printer is operating and where the material is stored. This last factor influences the speed at which the materials bond. If the moisture content in the air is high, the materials will stick to the surrounding powder and not dry out enough

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263 Image sourced: Kate Dunn 2015.
265 Maltodextrin is a by-product of starch production – it is used in food and in the construction industry as a filler.
266 Sample test results are included in Appendix B.
to solidify into the form determined by the STL file.

Initial powder tests used a mixture of two-thirds clay, with one-sixth sugar and one-sixth maltodextrin powder. The clay powder used was a Keane Ceramics product\(^\text{267}\) designed to be used for slip casting; the sugar was Australian brand CSR grown in Queensland; and the maltodextrin was bought as Benefibre - a commercially available food additive designed to aid human digestion.

The powders were mixed and then sieved to ensure consistent texture, particle size and mixture. The powder was then loaded into the feed bed or platform of the Zcorp 310 printer. Another smaller amount was put into the raised bed of the build platform or bed in preparation for printing. To ensure an even printing sequence a series of layers of powder from the feed platform are swept to the build platform using a gantry, this must be done to level the powder. As each layer is added a piston lowers the build bed incrementally to make room for the next layer of powder. Each layer is 0.1016mm thick and can thus achieve very fine detail in the printed object. The print heads, which are attached to the same gantry that sweeps the powder, apply the binder in the pattern determined by Z print slicing software. The Zprint software is used to slice the object intended for printing into layers along the Z axis. The wet section caused by the binder then bonds to the previous layer.

Multiple prints can be done at once in powder printers. Unlike other types of printers, objects can be stacked on top of each other because the loose powder not sprayed with binder surrounds and supports the printed objects. All of the unused material is reusable making this a sustainable process. When combined with sustainable materials such as those outlined in this thesis the process has great potential to change negative environmental impacts in the 3D printing industry.

Initial test results with the clay mix described above yielded small, shrunken prints with distorted forms and coarse textures. This was in stark contrast to Zcorp’s commercially available material that is capable of sharp, precise forms. However as noted earlier the Zcorp’s powder cannot be recycled once printed and the binders must be professionally disposed of by a chemical specialist. Hence the Zcorp powder did not comply with the sustainability objectives of this thesis.

The clay mix was selected for the sustainable properties of the material, its ability to absorb water and thus respond to a non-toxic binder, its flexibility in being able to control the drying times in that it can be slowed or accelerated with heat and air and it can be watered down and recycled.

A series of 3D prints were made using this process and these were exhibited as part of the Research Visions exhibition at the University of Sydney described in chapter four. The pieces addressed the

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criteria of sustainability in their material composition and fabrication process; however, the objects remained fragile and crumbled when touched. A series of tests was undertaken to try and stabilise the material so that selected objects could be preserved.

After considerable testing to resolve the texture, scale and accuracy of the prints, one of the remaining issues was the limited stability of the printed objects due to slumping or melting and congealing of sugar in the mixture. One of the ways to address this problem was to stabilize the moisture of the environment the prints are in until after they have dried.

Another way to address this problem was to fire the prints in a ceramic kiln to 1000 degrees Celsius (or bisque) - the temperature needed to vitrify ceramics. However, after firing, the objects tend to remain powdery rather than vitrifying to a solid ceramic form. This can be attributed to the burning out of sugar and maltodextrin, leaving the object overly porous. The usual way to overcome porosity and low vitrification in a ceramic object is to coat the object with a liquid glaze and then re-fire the object to 1100 degrees or higher. The high silica content in the glaze vitrifies to a glass finish.

A series of tests was done to glaze the bisque fired prints; however, the residual powdery surface acted as a resist to the application of the liquid glaze. The first involved dusting the object with compressed air to remove the powdery surface. Resultant damage occurred to the integrity of the structure and a softening of the sharp edges of the form, similar to the effect of sandblasting an object. The second involved dipping the entire object into the liquid glaze. This resulted in uneven thickness in parts, particularly on very complicated forms where the glaze can become trapped and pool. After reviewing the test results, the following research questions evolved to address the problems described:

1. If porcelain slip casting powder is substituted for the earthenware casting slip used in the previous mixture, will it result in a stronger 3D printed object?
2. Can the addition of fritt or powdered glaze to the ceramic powder mix solidify the print materials, facilitate glaze adhesion and fit, and facilitate vitrifying?
3. Could ceramic powder with a powdered glaze embedded in it achieve a nonporous vitrified object that could withstand human interaction?

Using these questions as a framework, the following material and process research was undertaken.

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269 Glaze fit describes the relationship of thermal expansion and contractions of the clay body and glaze. Ideally, they expand and contract at the same rate. Ibid., 166.
Process and Material Investigation Four Powder-printed porcelain clay with glaze

This process and material was used in case studies five and seven, Fabricating Futures, University of Sydney, Faculty of Architecture (2015) and Rapid Prototyping - Models of Climate Change the Macleay Museum, University of Sydney (2016). These case studies are discussed in chapter four.

Figure 3.15 3D powder printed, glazed porcelain.

Building on the 3D Printed Data project and using the same Zcorp 310 printer, processes and workflow as the powder-printed earthenware clay research, a subsequent series of material tests were undertaken.

The first test substituted porcelain slip casting powder\textsuperscript{270} for the earthenware casting slip mix. Porcelain slip mix was tested because porcelain when fired to stoneware temperature (1280-1300 degrees Celsius) is considerably denser than earthenware clays fired to earthenware temperature (1100 degrees Celsius). Porcelain clay is fired up to 200 degrees higher than earthenware clay, causing it to fuse during the firing process.\textsuperscript{271} The substitution of the porcelain powder made little difference during the printing process. However, when fired, the material shrunk considerably more than the earthenware mix and remained crumbly in composition, making it difficult to handle and the same powdery surface made it equally difficult to apply liquid glaze.


\textsuperscript{271} Porcelain is white, fires to 1300 degrees and vitrifies to a hard-translucent state. Hamer and Hamer, The potter’s dictionary, 273.
The second test material used Frit 4110\textsuperscript{272} embedded in first the earthenware powder mix and then the porcelain powder mix. Results proved unsatisfactory. The fritt particles were too large and did not blend with other materials in the printing process. The mixture separated causing the prints to disintegrate.

The third involved adding powdered glaze\textsuperscript{273} to earthenware and porcelain slip casting powder mixes. The earthenware powder mixture with powdered glaze successfully bonded enough to be handled and fired; however, the final objects remain crumbly to touch and porous.\textsuperscript{274}

The porcelain powder mix with powdered glaze also successfully bonded during the printing process and, once fired, produced a material that was stable and of superior finish to the earthenware mixture. The pieces shrunk up to 18\% during the firing, however this could be overcome by scaling the file prior to printing to compensate. The pieces could also be successfully surface glazed as demonstrated by figure 3.15.

**Summary of powder printed earthenware and powder printed porcelain used in process and material investigations, three and four**

The addition of a glaze within the powder is a new development and one that has the potential for further investigation and possible commercialisation with additional material and financial resources. This testing and the results described in this chapter are a significant contribution to new knowledge in the field of 3D printing. The materials used can all be recycled in their raw state and are nontoxic thereby advancing the research aim described in chapter one of developing sustainable materials for 3D printing for the purposes of creating 3D printed visualisations of climate change data.

The materials and processes tested and described here were first exhibited at the Fabricating Futures Exhibition and then used to create a series of data models that were displayed in the exhibition at the Macleay Museum *Rapid Prototyping - Models of Climate Change*.

\textsuperscript{272} A Fritt is part of a glaze recipe that has been melted and reground prior to inclusion in glaze mix. Fritt 4110 is a leadless high expansion, high alkali fritt. Ibid., 156.

\textsuperscript{273} A glaze is layer of glass fused onto the clay body through a firing process. The glaze is made up of 3 basic ingredients including a glass former - for example silica, a flux to promote fusion - examples include sodium, magnesium oxide, zinc oxide and lead - and finally a stabilizer – usually aluminium. Ibid., 163.

\textsuperscript{274} Test results in Appendix B.
Process and Material Investigation Five Robotically controlled slip-casting clay with waste aggregate

These processes and materials were used in case study used in Case Study Five, Fabricating Futures, University of Sydney, Faculty of Architecture, (2015). This project is described in chapter four.

Figure 3.16 3D printing using a KUKA robot with a clay slip base material.

The research undertaken in the powder printing research produced sustainable materials that could be used for small scale 3D printed models of climate change data. The scale of the models was determined primarily by the size of the build volume of the Zcorp 310 printer which is 203 x 254 x 203 mm.

This next project sought to build on the powder printing research by scaling up the size of the printed objects and further investigating the potential of sustainable materials. The research built on the

Research described here was discussed in the following book chapter, Kate Dunn, Dylan Wozniak O’Connor, Marjo Niemelä, and Gabriele Ulacco, “Free Form Clay Deposition in Custom Generated Molds,” in Robotic Fabrication in Architecture, Art and Design 2016, ed. Dagmar Reinhardt, Rob Saunders and Jane Burry (Springer International Publishing, 2016), 316-325.

Images sourced: Photo by Graham Clarkson.
ceramic material and powder printing process and supplemented Free Form Fabrication extrusion delivery methods and liquid clay in order to achieve large-scale 3D printing.

“Liquid clay was selected as the test material for large scale 3D printing due to the following properties and material specifications: ceramics or clay when it is raw is plastic and can change consistency and mimic other materials through the addition or reduction of water, defloculant, sodium silicate, alcohol and a range of up-cycled industry waste aggregates. Clay also dissolves in water, facilitating testing in a range of machinery where a material such as concrete can get blocked and set, destroying equipment.”

To scale up the size of the 3D printed objects a KUKA robot arm was used as the means of controlling where the print material was deposited. The use of a robotic arm means that the printed object’s form is not defined by the constraints of a build bed; its size is only limited by the reach of the robot arm.

To further investigate the potential of sustainable materials, mixes were developed to alter viscosity and a range of aggregates made of waste materials from different industries were tested “including unbleached recycled paper, sawdust, polystyrene and waste sand from casting processes. Aggregates were added to improve the structural integrity of the material both during the printing process and in the final printed object. Different bonding materials were added to the mixture - including sugar, maltodextrin and cellulose fibre. Alcohol in the form of methylated spirits was added to decrease setting times through the effects of evaporation.” Detailed test records can be found in the Appendix C.

Investigations were carried out to test the potential of 3D printing in clay to address the problem of viscosity, tool path and setting times. Most importantly, clay deposition on a robotic tooling path enables a continuous and sustainable adaptation process, since clay is reusable, can mimic other material in viscosity and is compatible with a range of sustainable aggregates through to firing stages.

A series of test objects was produced using “Free Form Fabrication (FFF) 3D printing processes which rely on the extrusion of a material in a pattern determined by an STL file. In Free Form Fabrication, the material is extruded successively onto a work bed or plate; whereas in 3D printed robotic processes only robotic reach and work bed dimensions limit the printable object size.”

278 Ibid., 323.
279 Ibid., 318.
280 Ibid.
Before running test series and to establish a framework for the practical experiments of this thesis, several technical elements for the setup were addressed - such as fine-tuning an appropriate pump setup, hoses and deposition bed; limitations of aggregate body of the clay material; and the development of a customised end-effector.

“Setup and work envelope for robot arm.

The 3D clay depositing process was prototyped on a KUKA KR10-R1100, working within an envelope of approximately one cubic meter.”281 This prototype was then scaled onto the larger KUKA KR60, which, with a 60kg payload, can work on an architectural scale. The processes used are highly extensible, and can involve one small robot working on modular elements or multiple large robots working together on a much larger scale. To scale an extrusion printing method was used combined with a KUKA robotic arm to control toolpath. One of many advantages here is that limits of scale are only constrained by the span of the arm, the stability and structural qualities of the material and the chosen method of extrusion.

![Figure 3.17 Left to right: robot with black PVC remote material chamber behind, blue pump on the ground and corrugated flexible input and output hose; deposit bed with a first layer of material applied. Robotic work envelope dependent on work bed, material storage accessibility, work table for deposit of material into mould.282](image)

“The printing set up is designed with a remote pump, drawing material from a reservoir attached to the robot arm with a six metre hose that affords extruded material the full reach

281 Ibid., 321.
282 Images sourced: Photos by Photo by Graham Clarkson.
and range of the robot’s arm and axes of movement. The extrusion system has been intentionally configured in this way to achieve larger forms not limited by the size or weight of an end effector attached to a robot but, by drawing material from a remote reservoir, by working with a volume of material vastly beyond traditional robotic payload.”

“The KUKA KR10-R1100 was stationed at a standard workbench height of 900 mm on a portable, custom fabricated steel base.” From this, position experiments were conducted with various materials and aggregates of interest to develop two dimensional and three-dimensional extrusion toolpath ways through parametric robot control in KUKA|PRC. This began as a series of intuitive movements using the teaching pendant controller in manual mode to test appropriate speed and height for toolpaths. The clay material used demanded fast movement close to the work surface, or close formed mould walls, to deliver the most appropriate consistency of deposition width.

The pump powering extrusion was a “Moineau or Progressive cavity pump with a marine grade stainless steel core or driver” - specifically a MONO SK172IF-80LH4 model with a drive gear box and motor, inverter, variable frequency drive and a forced cooling fan. The pump draws from a 200L plastic reservoir connected by a flexible 40 mm diameter hose. The hose feeds the printing material into the chamber of the pump, and this material is then drawn through the pump and extruded into a 25mm diameter and 6-metre-long hose attached to the robot end effector, (figure 3.17).

The extruder setup utilizes an aluminum coupling which holds several commercially available irrigation components to act as extrusion nozzles during material testing. A later step reconfigured the extrusion end effector to incorporate an air powered piston valve capable of being synchronized with remote control of pump velocity within a parametric control environment. The current configuration enabled experimentation with a range of materials of different viscosities as well as aggregates in an accurate, repeatable and documentable way.” In addition, a series of control valves ensured safety of operation, maintenance and cleaning of the equipment. The first was located at the reservoir output, the second in the pump cavity and the third attached to the nozzle or end effector.

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284 Ibid.
285 Ibid.
286 Ibid., 324.
287 Ibid., 322.
288 Ibid., 324.
Limitations of aggregate body of the clay material - scaling up

“The material viscosity and aggregate are customized to suit the pump and depositing processes. Material tests used white earthenware casting slip as a base to build the layers of the object. The casting slip is composed of clay particles suspended in a liquid body. Typical ingredients include kaolinite, crystalline silica, water, sodium silicate and polyacrylate dispersant (dispex).”\(^{289}\)

Initial tests using prototype extrusion systems yielded successful results on a horizontal plane as well as tracing patterns on the interior of a closed form mould. Tests demonstrated potential for robotic applications that were inherently adaptable and responsive to different conditions such as humidity, motor speed and deposition rate and material viscosity.

![Figure 3.18](image)

*Figure 3.18 Development and testing of relationships between fluid material body, material aggregate conditions, voids between lines of deposit, shrinkage of material.\(^{290}\)*

Development of a customised end effector

“Several iterations of end effectors were produced to explore different approaches to clay deposition at each experimental stage.” Taking two-dimensional drawing as a starting point, a bullet point marker encased in a 3D printed coupling was used to draw on sensitive surfaces such

\(^{289}\) Ibid., 323.

\(^{290}\) Image sourced: Photos by Dylan Wozniack O’Connor.
as glass windows to trial a system with built-in flexibility that could work with inherently fragile objects such as plaster.

“Next, an electrically triggered solenoid valve with a roll plate coupling was trialed. This showed some of the limitations of working with multiple viscosities. Maintaining a consistent pressure with semi-liquid materials such as the clay slip to correctly operate the valve during movement did not prove feasible.” 291

The pressure built up in the tubes due to the pump meant that the valve was not strong enough to stop flow as required. Consequently, the process was adjusted so as to focus on continuous toolpaths as a starting point.

“A third proto-type coupling was devised to clamp various ‘off-the-shelf’ irrigation fittings as trial nozzles of varying diameter. This led to the end effector being modular in application so that individual components could be swapped for different material experiments, programs, and easily cleaned or replaced in the event of passages becoming clogged or damaged. Once experiments moved from two dimensional toolpaths that either spiraled or stepped up in the Z direction, to depositions within three dimensional forms, a nozzle 150 mm in length was added to enable placement of material necessitating less movement of the robotic arm to avoid collision with the work-piece. Additionally, this enabled increased velocity of movement and more options in the angle of material deposition.”292

292 Ibid.
Process and Material Investigation Five: Summary and reflection

These investigations of the potential of robotic 3D printing with clay “enabled a better understanding of ideal relationships between material viscosity, tool path and multiple time parameters such as depositing times, liquid run times and setting times.” Waste substances from industry as components of the deposition material were tested to address sustainability in large-scale 3D printing. An ongoing process of printing and fine-tuning material mixtures is envisaged to further invest tangible interfaces or objects that describe the material mixtures, the tooling process, and the resulting objects.

While test results demonstrate significant potential, the setting times remained relatively long and the materials were complicated to produce. The following additional research questions were developed to address these issues:

1. Can the process of deposition in large scale FFF be improved by using a ram press model of extrusion attached to a robot arm?
2. Using robotic means of deposition, can 3D print material viscosity be improved by starting from a solid clay body containing grog?

These questions were then addressed in a subsequent research project conducted in preparation for an interactive 3D printing workshop at the 2016 ROB|ARCH conference.

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293 Image sourced: Photos by Dylan Wozniak O’Connor.
295 Ibid., 325.
Process and Material Investigation Six: Robotically controlled modelling clay with waste aggregate

This process and material was used in case study five, *Robotic Fabrication in Architecture, Art and Design*, (ROB|ARCH) Conference Workshop & Exhibition, Pier 2/3 Walsh Bay, Sydney (2016). This case study is discussed in chapter four.

*Figure 3.20 (left) Press style 3D printer attached to a KUKA robot. Figure 3.21 (right) terracotta clay being printed.*

The research described in this material and process investigation contributed to a collaboratively run *Interactive 3D Printing* workshop at ROB|ARCH 2016.297 The workshop was a collaboration between Alexandre Dubor from the Institute for Advanced Architecture of Catalonia. Martin Bechthold, Kevin Hinz from the Harvard Graduate School of Design Dagmar Reinhardt, Kate Dunn, Samantha Horlyck, Susana Alarcon-Licona, Marjo Niemelä, Dyan Wozniak O’Connor and Rod Watt from the University of Sydney’s Faculty of Architecture.298

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296 Images sourced: Photos by Dylan Wozniak O’Connor and right, Kate Dunn.
The research undertaken during the previous material and process investigation focused on 3D printing with a monious pump and slip based clay. This project built on that research in order to design a clay body and extrusion system suitable for robotic 3D printing in the constrained context of the workshop. The constraints included limited time and the need for optimum functionality, so that the focus could be on the interactivity of the 3D print process rather than material composition and delivery system. To address these parameters, this research contribution to the workshop sought to answer two research questions that arose during evaluation of the robotically controlled slip-casting of clay with waste aggregate project.

1. **Can the process of deposition in large scale FFF be improved by using a ram press model of extrusion attached to a robot arm?**
2. **Using robotic means of deposition, can 3D print material viscosity be improved by starting from a solid clay body containing grog?**

**Workshop setup and process of deposition**
The workshop set up included two KUKA KR10-1100 robots and a range of different sensors. To address the research questions a new delivery 3D print material delivery system was developed. A ram press model of printer was attached to one of the robots while the second robot was used for a range of experimental end effectors that engraved, punched and carved the clay, in response to data input from the sensors.

The printer delivery system on the first robot utilised components of a Deltabot printer removed from its gantry frame. The printer consisted of a perspex tube with a threaded rod system controlled by a motor, pushing the clay through a small nozzle. The robot, which determined the position of deposition of the print material was controlled using KUKAPRC software. The toolpath for the robot was determined using Grasshopper software, a plug in for Rhino software. The sensors were controlled using Arduino software.

A negative outcome of this delivery system was the considerably reduced volume of print material capacity. The full weight of the extruder and the clay for printing had to be accounted for in the payload of the robot, thereby limiting the volume of material able to be printed continuously, to four litres.

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Material Viscosity and Sustainability
A different approach to the clay used for printing was also necessary to address the research questions, improve setting times and resolve structural issues in the printed objects. The clay was changed from a slip based clay and replaced with a solid terracotta clay body with grog as base material. This printing material relied on viscosity, volume and density to maintain its structure during printing and adhere to the previous layer, thereby ensuring a smooth printing process that directed the focus of the workshop to potential interactivity. To address the goal of sustainability in the printing process, waste aggregates were added using a manual process of wedging and a mechanical process of mixing in a pug mill. The printing process and materials described addressed also the criteria of sustainability because all the materials could be recycled and reused by the addition of water to the dried parts.

Process and Material Investigation Six: Summary and reflection.
The objects made using this system had considerably more structural integrity than in the slip-casting clay project. The process and materials yielded successful small-scale 3D printed objects using robotics. These tests were developed and used at the 2016 ROB|ARCH Interactive 3D printed workshop. There is potential to build upon this research to expand capacity and apply the process in different contexts, including the fabrication of 3D models of climate change data. This will be elaborated in chapter four of the thesis.
3.5 Scientific Research Data

This section outlines selected sources and formats of scientific research and data that are visualised in the case studies described in chapter four. This is done in order to demonstrate how climate change research and data can be visualised three dimensionally using a range of processes, materials and design strategies. The information is organised according to the case studies that referenced the data.

Scientific Research and Data on endangered plant species from the Cumberland Plain Informing Case Study One: The Garden of Earthly Delights and Case Study Two: Regenerate, described in chapter four.

The types and sources of scientific data and research referenced in the first two case studies, *The Garden of Earthly Delights* and *Regenerate* included plant specimens, government policy documents, maps, lists, diagrams and flow charts.

The specific sources for these first two case studies included discussions and collaborations with Dr. Caroline Lehmann, the key collaborating climate scientist referred to in chapter one and in chapter four in the review of the first case study. Dr. Lehmann shared climate change research in the form of graphs and charts, particularly about how fire impacts on the regeneration of species; and in the form of discussion while on field trips to habitats and observing specific species. Dr. Lehmann’s research links different sources of data in order to understand “savanna vegetation dynamics and extent related to climate and fire, the evolution and assembly of C4 grasslands and tropical biomes, and plant-fire coevolution.”

Another source of relevant data is the book *Seldom Seen-Rare Plants of Sydney* by botanist Alan Fairley. The book lists plant species from the Sydney region that are endangered or close to extinction. Each page is dedicated to a different species and includes the Latin name, a photo or drawing of the plant, a description, their location and their relative status in terms of being endangered using three different rating systems. The first rating system is the New South Wales legislative framework known as the *Threatened Species Conservation Act* (TSC Act). This first Act categories plant species and plant populations as either Schedule 1, *Endangered* or Schedule 2, *Vulnerable*. The second rating system is the Rare or Threatened Australian Plants (ROTAP). This system comes from a CSIRO publication and rates species using a code that indicates their distribution category and conservation status. The third system is the *Environment Protection and Biodiversity Conservation Act* (EPBC Act) which is the Commonwealth system for protecting amongst

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other things, threatened plant species and threatened ecological communities. The species are categorised as critically endangered, endangered, vulnerable, conservation dependent and extinct.

**Figure 3.22** Example of one of Alan Fairley’s listings of an endangered plant species in his book Seldom Seen. This particular page shows the Nielson Park She-Oak.  
**Figure 3.23** Flowchart to help with diagnosis of threatened species and communities.

Another source of data for the first two design research case studies described in chapter four, is the Australian government department for the Environment, Water, Heritage and the Arts, policy statement; The Cumberland Plain Shale Woodlands and Shale-Gravel Transition Forest-A guide to identifying and protecting the nationally threatened ecological community.

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The policy document outlines why the woodlands are important and what the endangered species are, the policy document states “The ecological community was previously listed as nationally endangered under the name Cumberland Plain Woodlands. The listing was re-assessed by the Threatened Species Scientific Committee, which recommended that the conservation status of the ecological community be revised to critically endangered.”

The policy also includes links to other relevant government resources and includes photos of some of the plant species, descriptions, maps and a flowchart. The document also outlines the target audience of land managers, environmental assessment officers and the general public and lists how to help with species protection, and recovery.

Physical specimens of plant species were sourced from the Cumberland State forest, a state-run arboretum and nursery specializing in native plant species and the Downing Herbarium, a collection of dried plant specimens, including marine algae, mosses and liverworts, lichens, ferns, conifers and flowering plants at Macquarie University.

**Research on Natural Catastrophes between 1980 – 2010 informing Case Study Three: 3D Printed Data Models**

The scientific research informing Case Study Three is sourced from Munich Re the reinsurance. The data is presented as line graphs. A comparative line graph showing different types of catastrophic events caused by climate change over the same period is pictured in Figure 3.25. The graph shows the volume and frequency of the events.

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308 Ibid.


Scientific Research on the effects of Rising Temperatures caused by Climate Change on the environment and Human Health - Informing Case Study Six: Rapid Prototyping Models of Climate Change.

The scientific research informing case study six was sourced from two scientists. The first was Dr. Dan Metcalfe, an environmental scientist from the Commonwealth Scientific and Industrial Research Organisation (CSIRO). The second was Dr. Sarah Perkins Kirkpatrick a climate research from the Climate Change Research Centre at UNSW.

Dr. Metcalfe’s research focuses on the sustainable use and management of Australia’s natural resources. The specific research being modeled in the Design Research Case Study was from a project which modelled predictive scenarios in response to temperature rises in the wet tropics of North Queensland. A series of four climate change scenarios were developed that anticipated plant species distribution in changing response to increases in temperature. Climate change scenarios were developed using existing environmental conditions as well as historical data in order to characterise future potential distribution of fifteen vegetation types. These vegetation types are found in mangroves, bushland, rainforest, agriculture such as banana and sugarcane farming as well as pasture land for livestock. Changes in the distribution of these plant species effects ecosystems, agriculture, human health.

![Figure 3.25 Examples Dr. Metcalfe’s Predictive models of plant species distribution under the effects of climate change.](image)

Dr. Metcalfe supplied data in a range of modes including maps in GIS software files, spreadsheets and graphs\(^{312}\). The data sets were quite large because each of the scenarios involved fifteen different species. The maps shown in figure 3.25 demonstrate the potential areas of species distribution under different temperature scenarios. The first map is the current distribution, the second is with current temperature plus 1°C with 90% of current rainfall. The third map shows the anticipated species distribution with the current temperature plus 5°C with 77% of current rainfall. The scenarios predict declines in cool wet rainforest, tea-tree swamps and medium woodlands, there would be less water

\(^{312}\) The expanded data can be seen in Appendix E.
and greater temperatures. Dr. Metcalfe and his team also surmise that restoration efforts will need to adapt to the new conditions—there is no point in replanting what was there because it won’t survive.

Figure 3.26 Examples of the different styles of data supplied by Dr. Metcalfe.

Dr. Sarah Perkins Kirkpatrick

The other source of climate change data was Dr. Perkins Kirkpatrick who works with the University of New South Wales ARC Centre of Excellence for Climate System Science. Dr. Perkins-Kirkpatrick’s research focuses on heatwaves in Australia and their effects on human health and the environment. “A heatwave is defined as at least three consecutive days where the daily maximum temperature is in the top 10% of warmest of warmest temperatures for that calendar date.” The increased frequency and intensity of heatwaves due to manmade climate change is impacting and causing livestock loss, crop failure, destruction of biodiversity and causing change in human behavior and health. Sarah takes records from a large number of weather recording stations around Australia.

Dr. Perkins Kirkpatrick supplied data in the form of linear graphs that show heatwaves over a three-month period. The temperature records are sourced from the Australian Bureau of Meteorology’s

weather stations which are located all around Australia. Dr. Perkins Kirkpatrick and her team have created a website called Scorcher\textsuperscript{314} which disseminates the history of these weather recordings in graph from for every weather station since 1910. The graphs show three month periods with the heatwaves clearly delineated in red as seen in figure 3.27.

![Figure 3.27 Page from the Scorcher website showing the heatwave and temperature records 2015.](image)

The research described in chapter four in Case Study Six; Rapid Prototyping Models of Climate Change, used the data from Sydney for the months of October November and December in 1910, 1960, 2015 The graph lines were used to create a vertical profile for three 3D prints made from wood filament. The 3D prints shared a footprint of the waterways from Sydney harbour and Parramatta river as a reminder of the effects of heatwaves on water supply and ocean levels.

\textsuperscript{314} Ibid.
3.6 Summary and Conclusion

Chapter three has described the approaches, process and material investigations and scientific data used to inform and fabricate the work described in the case studies in chapter four. The chapter was framed around addressing the research question;

*What kinds of processes and materials might be used or developed beyond a purely aesthetic dimension that makes a connection between the materials and the data being communicated and in particular, how can the issue of sustainability be cast within the selection and development of new materials in this enterprise?*

In order to contextualise the process and materials investigated as part of the design research described in section 3.4, this chapter initially outlined the current context of 3D print processes and materials at the time of writing. The chapter has then gone on the describe the process and material investigations undertaken as part of the design research. These included hand modelling porcelain clay, a process which developed material knowledge and informed some of the later material investigations. The second process and material investigated was CNC routed marine ply. This process investigated the potential of using digitally controlled machinery to achieve accurate repetition in order to create a creative work. The process however results in considerable waste being generated and involved several environmentally destructive chemicals; making it an unsuitable solution to the research question above.

The third process and material experiment built on the ceramic knowledge developed in the first project and investigated how it could be used to address the sustainability aspect of the research question. This project used raw clay mixed with sugar and maltodextrin as a powder printing material in a Zcorp 310 printer. The material outcomes successfully addressed the goal of sustainability because they could be recycled, were nontoxic. This was a significant development in the research and laid the material foundations for the remaining projects.

The subsequent project used the same printer but changed the base clay from an earthenware casting slip mix to porcelain casting slip mix in order to improve the texture and stability of the printed objects. After considerable testing a powdered glaze was added to the mix, resulting in a stable 3D printed artefact that could be vitrified for the purposes of conservation.

In order to scale up the 3D printing process and investigate alternative ways to address the research aim of creating a sustainable material Project Five was established. Using a KUKA industrial robot as the means of controlling deposition, a pump and hose system was established in order to 3D print on a large scale. The 3D print material was a mix of liquid casting slip with waste materials from industry.
added as aggregate. The setting times for this process were long, making the print process very slow. In order to speed up the process a second stage of the project was developed, Process and Material Investigation Six.

This project used a solid clay body extruded through a press style print reservoir. This material could also have waste material added as aggregate. The print mechanism was attached to a KUKA robot as a means of controlling the deposition. This process and material was subsequently used at the ROB|ARCH Interactive 3D printing workshop in 2016.

These investigations into robotic 3D printing with clay in order to address sustainability in large scale 3D printing, determined that there is significant potential to build upon this research past the PhD. This is evidenced by the interest from significant organizations such as James Gardiner from Laing O’Rourke construction and the other universities represented at the ROB|ARCH interactive 3D printing workshop.

This chapter also included all of the scientific research used to inform the Design Research Case Studies described in chapter four. The sources, types and the case studies they informed are described in section 3.5, Scientific research data.

Each experimental test described in this chapter explored discrete aspects, components or steps within a larger sustainable three-dimensional fabrication process. The tests investigated different ways to create a connection between the materials and the climate change data being communicated. This occurred by using form, material and process to connect back to the scientific research. The forms referenced the graphs of climate change and the majority of the materials linked back to the climate change data by ensuring that they did not contribute to climate change through their sourcing or processing.

To address the research aim of creating sustainability, considerable research into 3D printing materials and processes was undertaken. This happened successfully on a small scale by using a clay based material in a powder printer. The materials used can all be recycled in their raw state and are nontoxic, making the process eminently sustainable. Sustainability was also achieved on larger scale in the robotic 3D printing projects by upcycling waste in the deposit material. Thereby reducing the waste materials from industry going into landfill and also reducing the use of new materials in the build process. This testing and the results described in this chapter are a significant contribution to new knowledge in the field of 3D printing.
CHAPTER 4
Design Research: Case Studies of the Creative Works Produced
Chapter 4 Structure

4.1 Introduction
This section introduces the design research case studies produced as an integral part of this thesis.

4.2 Framework: Design Research, Criteria and Methodology
This section gives a theoretical framework and descriptive categories for each case study.

4.3 Case Studies: A series of Design Research Investigations
This section documents and discusses the six creative projects and exhibitions produced as part of the thesis that address different aspects of the research aims and questions.

The case studies are:
1. *The Garden of Earthly Delights* at Metalab Gallery (2012);
2. *Regenerate* at Sculpture by the Sea, Cottesloe Western Australia and Royal Botanic Gardens, Sydney (2012-13);
3. *3D printed Data Models* at Research Visions, University of Sydney (2014);
4. *Fabricating Futures*, University of Sydney, Faculty of Architecture (2015);
5. *Robotic Fabrication in Architecture, Art and Design*, Conference Workshop & Exhibition (2016);

4.4 Discussion and conclusion
In this section, the previously discussed research projects are summarised according to the following three key research areas:

- 3D printed 3 dimensional artworks and visualisations that communicate climate change research;
- models of collaboration in creative interdisciplinary projects;
- environmentally sustainable materials for 3D printing.
Preamble

Design Research Case Study Three: 3D Printed Data Models (2014) below contains material published in the following journal article of which I was the solo author.
“3D printing Ceramics and the advantages of Collaboration”. In the Journal of Australian Ceramics 15 Nov 2016.
Kate Dunn

Design Research Case Study Four: Free Form Clay Deposition, Robotic 6 axis 3D printing, producing sustainable fabrication processes. Fabricating Futures (2015) contains some material published in the following journal article of which I was the lead author.
Kate Dunn, Dylan Wozniak O’Connor, Marjo Niemelä, and Gabriele Ulacco.

Design research case study five; Robotic Fabrication in Architecture, Art and Design, Conference Workshop & Exhibition Pier 2/3 Walsh Bay, Sydney (2016) contains limited material published in the following book chapter of which I was a contributing author.
Alexandre Dubor, Gabriel Bello Diaz, Guillem Camprodon, Dagmar Reinhardt, Rob Saunders, Kate Dunn, Marjo Niemelä, Samantha Horlyck, Susana Alarcon-Licona, Dylan Wozniak-O’Connor, and Rod Watt, 2016
4.1 Introduction

Chapter Four documents and critically reflects on the suite of related case studies undertaken during the design research component of the thesis over a four-year period from 2012-2016. These case studies took the form of creative projects and exhibitions, through which the research questions and aims could be investigated using an iterative and reflective design process. The purpose of the case studies was to build on the theoretical and practical research described in Chapters Two and Three and investigate in a tangible, sequential way, the three research questions outlines in Chapter One:

1) Communication and Collaboration: In the current context of climate change, which tools for communication and collaborations between the disciplines of sciences and the creative practices could be mobilised to facilitate or enable innovative modes of communicating climate change?

2) Artefacts and Visualisation: What is the capacity of created (3D printed) artefacts to engage with climate change data to produce accessible forms of climate change information and visualise the effects of climate change?

3) Innovation with Processes and Materials: What kinds of processes and materials might be used or developed beyond a purely aesthetic dimension that make a connection between the materials and the data being communicated; and, how can the issue of sustainability be cast within the selection and development of new materials in this enterprise?

Each of the case studies was designed to investigate different aspects of the three focus areas of the research, namely; three-dimensional creative visualisations that communicate and represent climate change research; models of collaboration; and environmentally sustainable processes materials for 3D printing. This was done in order to create a vocabulary of three-dimensional visual communication techniques for communicating climate science in collaboration with climate scientists. An additional purpose was to refine and define collaboration models using boundary object theory to facilitate effective collaboration between relevant stakeholders in the projects and develop novel sustainable materials and 3D printing processes that engage with and communicate the fundamental research questions put by the project.

The case studies incorporate the research described in Chapter Two into collaborations between scientists and creative practitioners. Most of the case studies described in this chapter involved a collaboration with either a climate scientist or with other creative practitioners. The new categories of boundary object that were developed in Chapter Two are deployed here as a means of analysing and categorising the communication and collaborations and that occurred. The case studies also incorporated the material and process research described in Chapter Three to investigate innovative forms and sustainable means of creating artefacts that are designed to represent climate change.
research.

Each case study investigated different but related aspects of the three foci. Some projects focused on investigating models of collaboration between creative practitioners and scientists, and the boundary objects employed to facilitate collaboration. Others focused on investigating potential 3D visualisation models using data sourced through the collaboration. Others again focussed on investigating the material and fabrication methods employed to make the three-dimensional models. Most projects combined two or more of these focus areas, while some combined all three research areas. All projects were interdisciplinary and resulted in creative outcomes. The emphasis of the research undertaken in each case study is visualised using variations of the diagram in Figure 4.1.

![Diagram of the three research focus areas. Kate Dunn 2016.](image)

Case study reviews introduce the project and the specific questions being addressed through the design process. They also describe the climate change research or data source being investigated in the projects and exhibitions; the participants involved in any collaborations and the types of boundary objects used; the design strategy for transforming the data or research to three-dimensional objects; the material used and relationship to the subject matter as well as the fabrication methods and technology used and, where relevant, the site of display. Each description concludes with a reflection and lists the design research questions generated by the discrete project. These questions then led to new research parameters for the subsequent projects. The table below (Figure 4.2) describes the research emphasis of each of the projects.
<table>
<thead>
<tr>
<th>Design Research Case Studies</th>
<th>Models of 3D visualisation Focused Investigations</th>
<th>Collaboration Focused Investigations</th>
<th>Sustainable Material Focused Investigations</th>
</tr>
</thead>
<tbody>
<tr>
<td>The Garden of Earthly Delights-</td>
<td></td>
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<tr>
<td>Regenerate</td>
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<tr>
<td>3D Printed Data Models</td>
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<td>Fabricating Futures</td>
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<tr>
<td>ROB</td>
<td>ARCH 2016 Conference and Workshop</td>
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<tr>
<td>Rapid Prototypes: Models of Climate Change and Related Events</td>
<td></td>
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</tr>
</tbody>
</table>

*Figure 4.2 Table of Case Studies showing the different areas of focus in addressing the three research questions, Kate Dunn 2016.*
4.2 Design research, criteria and methodology

Each of the design research case studies investigated different and overlapping aspects of the research questions, but they all followed the same process of design. The reiterative approach to the research is informed by the rationale outlined in Chapter One in section 1.5. and demonstrated in Figure 4.3. The design methodology used in the case studies began by identifying research problems and questions, followed by undertaking research in the field. The next stage was a process of ideation and prototype design, followed by physical prototyping, whereby test artefacts were generated. These artefacts were then tested against the criteria determined for each project and evaluated using a process of review and reflection. From the review and reflection, the next research questions were generated. These questions then informed the subsequent case study.

![Diagram of the design research process](image)

*Figure 4.3 Diagram of the design research process, Kate Dunn 2016.*

**The framework for the design research case study evaluation, review and analysis is listed below:**
Each category will be explained in detail in the following section:

- *Introduction and research questions;*
- *The research or data source being investigated;*
- *Models of collaboration, participants and boundary objects used;*
- *Design strategy for transforming the data or research to three-dimensional objects;*
- *The material used and relationship to the subject matter;*
- *The fabrication methods and technology used;*
- *The site of display or interaction;*
- *Discussion and analysis and the resulting further research questions for the subsequent case study.*
Case study introduction and research questions, the primary concerns that drive each project

Each of the case studies investigated different aspects of the research focus, aims and questions outlined in Chapter One. The three different foci include: ways to three-dimensionally model or represent scientific data; the models of collaboration involved and the boundary objects used to facilitate this; and the development of sustainable materials for 3D printing that reflect the climate change research informing the artefacts created as part of the design research. The introduction to each case study review will outline the primary concerns of the project and the area of research focus. The introduction also defines the specific questions being addressed through the design research process of each case study. The collaborations, objectives, frameworks and outcomes of the case studies changed in response to the different cross disciplinary collaborations being conducted and the success or lack thereof of the collaboration. The initial Cumberland Plain plant species research was selected due to personal knowledge of the region over a thirty-year period. Over this period, the effects of climate change became apparent, triggering curiosity as to the cause and scope of the changes in the species – thus a collaboration with a climate scientist (Dr. Lehmann), who specializes in the effects of climate change on plants, was established.

The first two collaborations ended because Dr. Lehmann and Dr. Metcalfe moved overseas and interstate respectively. The subsequent collaboration with Dr. Perkins Kirkpatrick was established to continue this aspect of the research, continued until submission of the thesis. With different collaborations came different types and quantities of data. For example, some of the data sets had only three variables, such as in Case Study Three: 3D Printed Data Models (2014); whereas Case Study Six included data from Dr. Metcalfe and Dr. Perkins Kirkpatrick, supplied data in a range of modes including maps in GIS software files, spreadsheets and graphs. The data sets were large because each of the five scenarios (described in Chapter Three of this thesis) involved fifteen different species, while Dr. Perkins Kirkpatrick’s data covered temperature variations for multiple sites in Australia over a 110-year period.

The type and volume of data would in turn have effects on the design strategy for transforming the data or research to three-dimensional objects. Some of the data was chosen because of its suitability for 3D printing; for example, the data supplied by Dr. Perkins Kirkpatrick on heatwaves had obvious physical variation when 3D printed, rendering it an accessible boundary object for communicating the effects of climate change to a non-expert audience. By contrast, datasets with large volumes of data with little variation do not lend themselves to being represented with 3D printing. This is because the resulting physical forms have limited texture and therefore do not engage the haptic and visual attention of an audience.

Another factor influencing the design strategy for transforming the data or research to three-dimensional objects was the iterative nature of the design research methodology. Through the process of iteration and material research, numerous materials and processes were tested in order to get closer to sustainable solutions for three-dimensional objects that represent scientific research. This

315 Dr. Lehmann moved to Scotland in the first year of the PhD and Dr. Metcalfe moved to Queensland to take up a very demanding position for the CSIRO.

316 The expanded data can be seen in Appendix E.
would in turn affect the design of the objects, as certain sustainable materials could not be adapted to the fabrication processes. This is particularly evident in case study three, where the research moved forward from case study two – which used materials that would distract from the communication of the data being represented (by contributing to increased climate change in their sourcing and fabrication) – to using sustainable materials such as unfired clay.

**The research or data source being investigated**

Each case study review will describe the type and source of data used to inform the research. The projects primarily focus on scientific research data about the effects of climate change. The first projects undertaken focused on Australian plant species threatened by climate change. The sources of data included books written by specialists in the field and specimens of selected plants viewed in situ during field trips with climate scientist, Dr. Caroline Lehmann. Subsequent sources of climate change data included climate and ecology scientists from the CSIRO, Macquarie University and the Australian Research Council's Centre of Excellence for Climate System Science. The data and research were supplied in a range of modes including guided field trips, images and specimens. Numerical data was supplied as Excel spreadsheets, graphs and Geographic Information System (GIS) computer files. Most of the data supplied included summary text that explained the data and drew conclusions and implications, such as predictions of temperature increases, from the data. Detailed information about the scientific data is in Chapter Three in section 3.5, while the different data files are in the appendices.

**Collaboration and the boundary object – the model of collaboration deployed, the participants involved and types of boundary objects used**

The research conducted in Chapter Two into models of collaboration and multidisciplinary approaches has demonstrated that in order to address wicked problems such as climate change, it is essential to approach the problem in a multilateral manner. Solutions are possible if multiple disciplines collaborate to build on existing disciplinary knowledge and innovate new approaches and outcomes.

Different types of collaborations took place during the development and execution of projects. Some of the collaborations were focused on interdisciplinary knowledge exchange between artists and scientists, or artists and scientific organisations such as the CSIRO. While other collaborations were focused on the design and fabrication of the models, these collaborations were between artists, designers, engineers, and architects. The collaborations undertaken during the design research crossed numerous disciplinary and knowledge boundaries. The boundary object categories developed and outlined in Chapter Two will be used to evaluate and discuss the collaborations. These are:

- **Didactic boundary objects;**
- **Creative boundary objects;**
- **Reciprocal boundary objects.**

Boundary objects used included field trips, diagrams, specimens, prototypes, artworks and the physical spaces the works were displayed in. Descriptions of projects detail how collaborations evolved and operated, and the boundary objects used, as well as their successes and failures.
Design strategy for transforming the data or research to three-dimensional objects

The descriptions of each project outline the design parameters, their significance in relation to the concepts informing the works and the frameworks developed for each project to determine their physical forms and materials. There was a systematic focus on three-dimensional objects rather than digital or two-dimensional files since these better enable haptic, material and embodied experiential engagement. Innovations in 3D printing also permit very rapid prototyping, and the potential to print multiple models cheaply, hence allowing for quick testing during design as well as dissemination across multiple sites.

Design parameters for transforming the data to the three-dimensional objects that were developed and displayed were determined in response to a range of factors. These included consultations with the scientists who provided the data and their preferences and concerns about how their data is represented. For example, when working with Dr. Perkins Kirkpatrick, it was important to her that the 3D printed models displayed at the Macleay Museum accurately reflected the numeric information she provided. In discussion with Dr. Perkins Kirkpatrick she stated, “There needs to be accurate scale, otherwise it is not true to the underpinning science. I would have serious reservations if accuracy was not upheld”.

Another factor influencing the form of the models was the size and type of data or research being visualised. Making data comprehensible is a developing problem as the volume of data that can be collected and stored increases constantly. Known as big data, this problem is arising due to innovations in data mapping techniques and the enhanced capacity of super computers used by science organizations such as the CSIRO and elsewhere. However, the capacity of humans to read and understand this data is not increasing at the same rate, and therefore innovative ways to communicate it must be developed. The projects described in this chapter work with different types and volumes of data which are described in each case study review. The reviews also describe how the different types and size of data informed the three-dimensional form of the models.

A third element informing the way the data was transformed to three dimensions was the intended site of display. When displaying models in a museum such as the Macleay Museum, the small physical space allocated for the model dictated the possible scale of the objects. The cabinets the models were displayed in were designed to view displays from above. The dimensions were 190 mm high, 1800 mm wide by 1000 mm deep, necessitating that any objects displayed be relatively flat. In this case study, the models were small and designed and displayed with the intention of being viewed from above rather than the side.

A fourth consideration was the way potential audiences might interact with the models. Variables included: Would the models be touched? Would they be behind glass? Would the display setting allow the viewer to see all sides of the model?

317 Sarah Perkins Kirkpatrick, in conversation about how the collaboration could work. Select conversations are in Appendix A.
318 “Big data is a term describing the storage and analysis of large and or complex data sets using a series of techniques including, but not limited to: NoSQL, MapReduce and machine learning”. Jonathan Stuart Ward and Adam Barker, "Undefined by data: a survey of big data definitions." arXiv preprint arXiv:1309.5821 (2013)
The final consideration was the relationship of the design of the three-dimensional form to the fabrication techniques and materials used. For example, the Regenerate works intended for display at Sculpture by the Sea required a design that would convey the ideas informing the work as well as use fabrication methods and materials that were suitable and appropriate for an outdoor site. The specific material qualities also influenced the shape of the models because certain materials and processes are suitable for some forms whereas others are not. Powder printed clay, as was used in the 3D printed data models, could not be used to make the sculptures in the Regenerate project, as the printer was itself not big enough to make an object of a size sufficient to have any impact in that context.

Devices that were harnessed to transform the data to creative three-dimensional visualisations included design elements and principles such as shape, form, texture, colour, material, degrees of abstraction, display context, repetition and physical scale.

**The material used and relationship to the subject matter**

Making objects that foreground and communicate the implications of climate change prompts an unavoidable question about integrity – how does one negotiate those objects’ potential contribution to climate change through the materials used, the energy expended and the waste produced in manufacture? To address this question, the research pursued methods and materials for rapid prototyping that are inherently environmentally sustainable. Initially, there was a focus on ceramic over standard commercial rapid prototype products due to its low cost, safety for human interaction, environmental sustainability and recyclability. Subsequent investigations tested recycled timber filament, coffee filament and waste brick filament.

**The fabrication methods and technology used**

Projects investigated a range of analogue and digital methods of material manipulation and fabrication. Processes included hand-modelled porcelain, 3D printing and CNC Routing. Digital fabrication was the primary focus of the fabrication methods, and was selected for its potential to deliver accurate, repetitive, machine fabricated processes and objects. Different types of digital fabrication methodologies were tested, including large-scale CNC-routed forms and 3D printed models in a range of sustainable materials.

**Site of display and Interaction**

One of the aims of the projects was to investigate different ways to model climate change data three-dimensionally. To do this, different ways of representing the information in three dimensions as well as different sites of display and interaction were trialled. The specific characteristics of the site of display and the conditions under which an audience member might interact with the work were considered, and adjustments in the designs were implemented.

A crucial objective for the case studies was to investigate the different ways creative objects might represent the science informing the works. To achieve this, different environments for display of the models and different ancillary communication devices were investigated. Each of these different environments has different audiences, agency and affiliated disciplines. The cross-disciplinary focus of the research was pursued by juxtaposing different types of research output with traditional display contexts – for example, a fine art gallery (such as Metalab Gallery described in the first design research
case study of this chapter) is an integral element of the fine arts industry’s means of disseminating research, critique and collegial exchange. The gallery primarily shows art objects; however, by displaying climate change data at this venue, the case study can potentially reach new audiences who may not previously have been exposed to climate change research.

Other venues described in subsequent case studies were attended by different audiences and perceived in different ways. The Macleay Museum described in case study six is a natural history museum which attracts audiences interested in scientific research. This case study displayed art objects in what is traditionally a science discipline context. This was done in order to pursue the cross-disciplinary focus of the research and attract arts audiences to scientific research.

Other display locations included university forums, conference exhibitions and workshops. The diverse display contexts and the juxtaposition of the different disciplines of science and art were designed to communicate the ideas informing the work and explore ways to cross disciplinary boundaries in order to foster collaborative means of visualising and communicating climate change.

Some of the three-dimensional visualisations created were inherently tactile, inviting physical handling, and so had to be observed and experienced in close proximity. These were displayed in exhibitions at galleries such as Research Visions at the University of Sydney. Other models investigated the potential of large-scale works displayed in outdoor settings such as Sculpture by the Sea in Western Australia and Artisans in the Gardens in the Sydney Royal Botanic Gardens.

This research project is not intended to be a mouthpiece for scientific data. Rather, it is designed to test different ways that the science can be modelled three-dimensionally and to create portals to and sites of engagement with scientific data. To enable this, different ancillary devices were attached to the exhibitions and displays, including printed catalogues and videos that detailed the conceptual framework of the works and the science informing them.

Another ancillary communication strategy employed was a series of talks and panel discussions delivered by artists, designers, climate scientists and science communicators, held at the different exhibition sites. Discussions covered the science informing the work and the process of communicating it. Exhibitions functioned as event spaces for these discussions. An example was the talk by climate scientist Dr. Sarah Perkins Kirkpatrick with Kate Dunn and Dr. Liz Carter at the Macleay Museum on the 20th of April 2016 about the use of technology in responding to climate change.

Discussion and analysis and the resulting further research questions for the subsequent case study
Each project description concludes with an evaluation of its successes and failures in addressing the different strategic goals – including the model of collaboration, fabrication processes, effectiveness of the models in representing the scientific data and the context of display. Successes and failures were gauged in relation to the research questions and aims established at the outset and systematically refined during the design execution and evaluation phases.
4.3 Design Research Case Studies

Section 4.3 introduces the design research case studies. Each of these will be discussed using the criteria outlined above.

Design Research, Case Study One: The Garden of Earthly Delights, Metalab Gallery (2012)

![Image 4.4 The Garden of Earthly Delights, Metalab Gallery, 2012.](image)

**Case Study One Introduction**

The first case study, *Garden of Earthly Delights*, was exhibited at Metalab Gallery in Sydney in 2012. The exhibition consisted of thirty-five small hand-modelled white porcelain artworks representing the endangered plant species from the Cumberland Plain region. This project was the starting point for the series of case studies discussed in this chapter. The exhibition, and the models in it,

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319 Image sourced: Kate Dunn 2012.
investigated ways to three-dimensionally represent plant species in the Cumberland Plain region of Sydney that are under threat due to urban expansion and climate change.

At the time of European settlement in the late eighteenth century the Cumberland Plain contained over one thousand square kilometres of woodlands and forests. The westward expansion of Sydney due to population growth placed enormous pressure on the woodlands and other ecological communities. According to government estimates, only 10% of woodlands remain intact and only in small fragments of less than five hectares, creating issues with connectivity between the remaining vegetation, impacting native animal habitats and migration pathways. The dispersed fragments of woodland also make species pollination and propagation more difficult. Most of the ecological communities that originally flourished on the plain are now considered critically endangered due to the effects of climate change and urban expansion.

The title Garden of Earthly Delights was taken from a triptych painted by Hieronymus Bosch (c.1450–1516). Bosch’s painting (Figure 4.6) shows human figures in various states of pleasure and pain in fantastical environments. Progressing from the left, a utopian garden scene with three figures portrays God, Adam and Eve in peaceful harmony. The central panel shows a garden, substantially more populated, with figures engaged in a range of bacchanalian pursuits. The right panel transcends into a disturbing, dark and hellish environment, as if mankind has laid waste to nature and consequently themselves. The title of the triptych was employed in this case study to act as a metaphor for the destruction caused by human interaction with the environment.

![Garden of Earthly Delights by Hieronymus Bosch](image-url)

Figure 4.5 Garden of Earthly Delights by Hieronymus Bosch (c.1450–1516).

**Case Study One Research questions**

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This first case study, the Garden of Earthly Delights, was primarily focused on the following research question:

*How can three-dimensional creative works represent climate change research through a process of collaboration with a climate scientist and using a range of data sources?*

To address the question, the Garden of Earthly Delights investigated two of the focus areas of the design research, three-dimensional visualisations that communicate climate change research, and models of collaboration. The two fields of investigation overlap and inform each other, as demonstrated in the diagram below. The discussions that took place during the collaborations and the types of boundary objects used to facilitate the collaboration and knowledge exchange all informed the design of the creative works. For example, one of the boundary objects used during discussions with Dr. Lehmann were plant specimens in a national park. These specimens directly informed the shape of the final porcelain models. At the same time the prototyping stage of the production of the creative works helped the communication of ideas between creative practitioner and the scientist. This would involve showing the prototypes to Dr. Lehmann and discussing both the form of the objects and how they might be displayed to better communicate the ideas informing the works.

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**Figure 4.6 Case Study One, Garden of Earthly Delights investigated two areas of the research, three-dimensional visualisations of climate change and models of collaboration, diagram, Kate Dunn 2016.**

**Case Study One The research or data source being investigated**

Relevant scientific research was drawn from multiple sources. Some data came from government records and resources such as statistical publications about the Cumberland Plain region.\(^\text{322}\) This data was in the form of graphs, flowcharts and text (examples can be seen in section 3.5 of Chapter Three). Other sources included text books such as Alan Fairley’s *Seldom Seen*, a detailed guide with images, maps, the names and genesis of rare and endangered plant species in the Cumberland Plain region.\(^\text{323}\)

Primary sources of scientific data came from collaboration with Dr. Lehmann. This involved a series of field trips to habitats of endangered plant species. Lehmann explained the different

\(^{322}\text{Australian Government Department of Environment and Energy, policy statement- A guide to identifying and protecting the nationally threatened community of the Cumberland Plain Shale Woodlands and Shale-Gravel Transition Forest.}\)

\(^{323}\)Alan Fairley, *Seldom seen: rare plants of greater Sydney* (Frenchs Forest, NSW: Reed New Holland Publ., 2004).
species we encountered and their context in the environment. This information was then creatively interpreted by transforming it into a series of art works and exhibitions. Each artwork used the collaborations with Lehmann, data from Alan Fairley, government records and inspiration from plant specimens as a foundation for the experiments, for new collaborations and for ways of visualising scientific research.

**Case Study One Models of collaboration, participants and boundary objects used**

The types of collaborations and boundary objects employed during this project fall into different categories. When referencing the research of botanist Alan Fairley, his printed guide to endangered plant species operated as a didactic boundary object and a repository of information with no opportunity for exchange or reciprocity. The collaboration with Dr. Lehmann used a series of boundary objects to facilitate knowledge exchange. The primary boundary object used was the process of creative practitioner and scientist bushwalking together. These walks took place in various parts of the Cumberland Plain region and provided a neutral place outside of either person’s workplace in which to exchange knowledge. The walks could be considered reciprocal boundary objects, whereby both parties benefit from exchange and develop plans to further their own research based on the field trip experience. Another boundary object used during the collaboration were the plants themselves, found during the walks. These could be used to demonstrate points and illustrate differences between species.

The plants are didactic boundary objects in that they are repositories of information. The artworks generated from the collaboration became creative boundary objects, whereby an artist interprets and creatively responds to the scientific research findings of a scientist. Once displayed, these artworks crossed boundaries between the creative practices, science and the public domain. The final boundary object used to facilitate knowledge exchange was the process of discussing the problems of communicating climate science and the best means by which to do this. These discussions became reciprocal boundary objects, helping to articulate areas of difference and commonality.

**Case Study One Design strategy for transforming the data or research to three dimensional objects**

The data was supplied in a range of formats including numerical data, graphs, physical samples and written descriptions. The process of converting the data or samples to three-dimensional creative works involved an iterative approach to model making.

Initial steps in the design research process involved drawing specimens from national parks in a range of mediums including lead pencil, fine line marker pens, inks and watercolour paints. The intention of this process was to understand the structure and details of the plants, through using drawing techniques such as single line drawing and blind contour drawing, where the focus is on the process of observation rather than producing accurate records of the objects. This process then progressed to accurate drawings of sprigs of the plant species followed by test models of these sprigs in soft porcelain clay. After testing the works through to firing stages, a final suite of thirty-five different fired porcelain works that attempted to accurately represent sprigs of thirty-five different plant species was produced. Despite the literal and figurative style of the forms, the materiality of the porcelain would in no way lead the viewer to believe that the porcelain models could be actual plant specimens.
The design strategy and aesthetic choices for these works were influenced by research conducted into collaborations between artists and scientists from the eighteenth and nineteenth century, as described in Chapter Two of the thesis. A particularly relevant example was the Mintorn family who worked with botanists at Kew Gardens in London making wax and plaster models of plant specimens. The porcelain works produced in this case study are decorative in appearance and reference botanical drawing in their composition, in that they illustrate a sprig of a plant species rather than an entire plant. The pieces can be best described as three-dimensional drawings of specimens. This is reiterated by their absence of colour, relying instead on the tonal variation caused by light and shade – as with a lead pencil drawing – to define their form for the viewer.

![Fig 4.7 Garden of Earthly Delights](image)

The installation format of the exhibition at Metalab Gallery in 2012 referenced the nineteenth-century post-Darwinian penchant for collecting, drawing and displaying the natural world. Mounted like taxidermy trophies, the pieces protruded horizontally from the wall in rows that allowed comparisons between the models and cast long lacy shadows onto the white wall. The bone-like material invites touch, and yet the spikes of some of the works may scratch or snap off. Like pinning down butterflies or beetles, there is a macabre quality to our desire to touch and consume the fragile. Jacqueline Millner’s theory of Conceptual Beauty could be applied to describe the aesthetic devices used to engage audiences with the scientific information informing the work. Millner describes how “in the late 1990s and early 2000s ... the discourse along with the practice began to re-evaluate the power of positive affect-delight, wonder, beauty”. The pieces are deliberately delicate and make use of the fragile quality of the porcelain to draw the viewer’s attention. The works are small in scale, requiring intimate

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325 Image sourced: Left Kate Dunn and right Greg Piper.
327 Ibid., 13.
viewing to comprehend the detail. The lighting plan of the exhibition is designed to focus solely on the works and leave the viewer in relative darkness, so that as they approach the works they come into the light. These design elements worked together to give a sense of preciousness to the objects and give viewers visual and material cues to understand their relationship to the objects. The exhibition was the first investigation into modes of display and forms of three-dimensional visualisation of the same data set.

**Case Study One**

**The material used and relationship to the subject matter**

The thirty-five works were made of Southern Ice porcelain, chosen for its historical and contemporary links to the notion of preciousness.\(^{328}\) Porcelain is notoriously difficult to manipulate for the following reasons: it dries out quickly at room temperature, causing it to crack and break during construction; during the firing process, porcelain slumps and cannot maintain its own weight in the final 100 degrees of the 1290 degrees firing. To prevent the works slumping, supporting scaffolds must be built from an alternate material such as a highly grogged stoneware clay that is placed in the kiln to support individual pieces during the firing. This is time consuming and labour intensive. Each piece took approximately four hours to make, thirty minutes to prepare for firing and thirteen hours to fire. Once fired, porcelain is hard as bone, translucent and pure white. When modelled into the forms of plant specimens and mounted on a wall, the objects appear as if they are skeletons of extinct species.

**The fabrication methods and technology used**

The porcelain works are small in scale and modelled by hand with fine tools such as tweezers and dental tools. The intimate process of modelling each specimen over a four-hour period necessitated a detailed understanding of each plant’s form and structure. The act of making became a meditation on the significance of each piece and its place in the total installation – much like the place of each plant species in an ecosystem. The process of hand forming rather than digital fabrication mean that each piece is unique and impossible to repeat identically. Once broken or lost, pieces cannot be replaced. These qualities produced a metaphorical register in the works – one that enables them to speak about the threat of species extinction implicit in the science.

**Site of Display and Interaction**

The audience interaction with porcelain objects in the installation at Metalab Gallery in 2012 entailed viewing the porcelain works and reading the wall plaques describing the science informing the works. The audience was not able to touch the work due to its fragility; however, their three-dimensionality allowed the works to be viewed from multiple sides, allowing audiences to understand the details of the forms and their physical spatial relationship to each other and to their own bodies. The descriptions of the works as well as photos were shared by the gallery administration through their website and on social media sites such as Facebook and Instagram. Dr. Lehmann supported this stage of the collaboration, commenting:

> Communication and dissemination of information about climate change is an increasingly... 

\(^{328}\) A rarity in late sixteenth-century England, porcelain arrived there through gift, trade and plunder. Porcelain was initially a rarity that would be gifted to royalty. As the Dutch East India Company expanded the importation of porcelain in the early seventeenth century, it became a luxury good that indicated a family’s status and wealth. L.L. Peck, *Consuming Splendour: society and culture in seventeenth-century England* (Cambridge: Cambridge University Press, 2005), 47.
mainstream goal of scientific research, but one that many scientists struggle with. Hence, work that aims at meaningful cross-disciplinary collaboration is urgent both from a communication standpoint but also to act as a model.329

The exhibition was promoted on event guide websites330 and reported by the ABC,331 and was retrospectively discussed by Altair Roelants in her article “Material thinking and sustainability in contemporary ceramics” in Artlink.332 While it is not possible to measure the readership of these websites and articles, or otherwise demonstrate audience responses to these works, it could be argued that the critical impact of the creative work is the stimulus of discourse between disciplines. This first case study also became a benchmark to measure research outcomes against in the following case studies.

Case Study One Discussion and analysis and the resulting further research questions for the subsequent case study
The Garden of Earthly Delights sought to answer the research question:
How can three-dimensional creative works represent climate change research through a process of collaboration with a climate scientist and using a range of data sources?

The project successfully achieved the research aims of creatively visualising climate change information, drawn from multiple sources, in three-dimensional form. In order to achieve this, a successful reciprocal cross-disciplinary collaboration with climate scientist Dr. Caroline Lehmann was established. This first case study became a catalyst for the subsequent five case studies, each of which referred back to this initial one in its own way. Some expanded on ceramic materials, some on models of collaboration, others on modes of three-dimensional visualisation of scientific information. This initial project set the aims and goals for the creative research practice, and its outcomes framed subsequent evaluations.

Challenges encountered during this project included the limited audience due to the small size of the gallery space; compared to this, the potential audience at large outdoor public exhibitions such as the subsequent case study staged at Sculpture by the Sea333 can reach up to five hundred thousand people. The works were small and delicate and took a long time to fabricate. They could not be handled by viewers and had to be observed at close proximity, thus reducing the number of people who could see them at any one time.

As research results from this first case study were analysed, limitations due to the scale of both the artefacts and the display context of the gallery became apparent. Consequently, the research set as aims for the next case study the following questions:

1) How can audience numbers for creative works designed to communicate climate science be expanded?

329 Dr. Lehmann in conversation with the author, 2012.
331 http://www.abc.net.au/local/stories/2012/09/08/3262755.html
2) In which other ways can the scientific data informing The Garden of Earthly Delights be three-dimensionally visualised so that there is increased potential for audience interaction and awareness of climate change research?

These questions were addressed and further expanded, as will be discussed in the following case study: The Regenerate project.
Design Research Case Study Two Regenerate (2013)

![Image of Regenerate sculptures]

Figure 4.8 Regenerate, 2012-2013 (exhibition Sculpture by the Sea, Cottesloe Western Australia, and Artisans in the Garden, Royal Botanic Gardens Sydney Australia).

Case Study Two: Introduction

The thesis discusses here the installation *Regenerate*, exhibited at *Sculpture by the Sea* and *Artisans in the Gardens* (2012-2013). The *Regenerate* installation consisted of three large wooden sculptures whose structure referenced plant seed pods that are native to the Cumberland Plain region. These seed pods are from banksia trees, eucalypts and melaleuca trees. All of these species were visualised in *The Garden of Earthly Delights* exhibition however, these three dimensional visualisations are much larger in scale, ranging from 1.2 metres high to 1.8 metres high. The works were also brightly coloured in order to attract attention in the large outdoor environments where they were exhibited. The large scale and bright colours increased the potential of attracting audience attention and thereby encouraging engagement with the science informing the work, triggering reflection on and transformation in attitudes to climate change.

The project is a continuation of the previous case study, *The Garden of Earthly Delights*, which primarily focused on ways to visualise climate change data three-dimensionally in collaboration with a climate scientist. *The Garden of Earthly Delights* also referenced didactic boundary objects such as text books and plant specimens.

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334 Image sourced: Keith McInnes 2012.
The Regenerate project builds on this design research and investigates two new research questions triggered by The Garden of Earthly Delights.

Case Study Two: Research questions
1) How can audience numbers for creative works designed to communicate climate science be expanded?
2) In which other ways can the scientific data informing The Garden of Earthly Delights be three-dimensionally visualised so that there is increased potential for audience interaction and awareness of climate change research?

The Regenerate project does not introduce new climate change research; rather, it builds on this same data source as The Garden of Earthly Delights and investigates ways to increase audience numbers for creative works designed to communicate climate science. It also investigates other possible ways the same scientific research can be three-dimensionally visualised to increase potential audience interaction and awareness of climate change research.

The diagram in Figure 4.9 represents the primary focus of this case study, which was an investigation of ways to model and communicate climate change research. The other two research foci – collaboration and sustainable materials – are not addressed in this case study. These research areas are addressed in detail in subsequent case studies.

Case Study Two: The research or data source being investigated
The Regenerate project continued the scientific research focus on plant species that are threatened or close to extinction in the Cumberland Plain region of Sydney, with a particular focus on the seed pods of these plants. Many of these species are iconic Australian plants such as Eucalypts and Banksias, threatened because of factors such as erosion, drought conditions caused by climate change and urban expansion. Another factor threatening the regeneration of these species is that several of these rely on fire to cause the seed pods to open.\textsuperscript{335} The fire systems that prevailed prior to British colonisation in the Cumberland Plain region have been mitigated because of the obvious threat to human life and homes. Without the fires, the seed pods cannot open and allow the process of regeneration of the species to

take place.

**Case Study Two Design strategy for transforming the data or research to three-dimensional objects**

The design strategies for the forms of the sculptures used the previous case study’s delicate and literal mode of representation as a counterpoint in order to address the second design research question: *In which other ways can the scientific data informing The Garden of Earthly Delights be three-dimensionally visualised so that there is increased potential for audience interaction and awareness of climate change research?*

This case study instead investigated large robust structures that could withstand audiences touching and even climbing on them. The model of representation, in contrast to the first case study, was greatly simplified and abstracted in order to investigate the spectrum of ways to model the scientific research on plant species from the Cumberland Plain.

The design process of converting the research into endangered plant species to large scale outdoor sculptures began during field trips with Dr Lehmann. During these trips plant samples were observed, photographed and drawn, particular attention being paid to the different stages of development of seed pods during metamorphosis. As the seed pod opens, the delicate storage of the seeds and organic design becomes apparent. Using these shapes, patterns and textures as inspiration, the design for the *Regenerate* objects was developed.

The process of designing the forms for the sculptures involved sequential drawing techniques to abstract shapes and develop biomorphic patterns. The mode of representation was deliberately abstracted and simplified in order to test other ways the scientific research could be visualised. The form of the sculptures demonstrates a funnelling of focus in ways to creatively represent the science; rather than try and model thirty-five different species, the project focused on the seed pods of three different species. The process of reiteratively drawing the seeds’ internal structure in order to create the skeleton frame of the sculptures seen in Figure 4.10 is reminiscent of viewing specimens through a microscope; the detailed scrutiny on the structure highlighted intriguing aspects that became design elements in the objects.

*Figure 4.10 Seed pods and sketches of potential forms of the models.*
This second case study also investigated the potential of different scales of models of scientific research and how this could offer audiences alternate ways to interact with the objects and in turn the data informing the works. The porcelain works in the Metalab Gallery in Case Study One were small, approximately the size of a person’s hand. They required close inspection to understand the detail, because of their size and the fact that they were white on a white background. The information about the scientific research was easily accessible on a wall plaque beside the works. The *Regenerate* works on the other hand had a large, commanding physical presence, being wider and taller than most people and painted in bright blues and reds that contrasted with each other and with the natural hues of the outdoor parklands in which they were displayed. The information about the scientific research was in a catalogue that audiences were encouraged by the event organisers to carry with them and read as they viewed different works.

![Figure 4.11 Cover of the Sculpture by the Sea Catalogue.](http://sculpturebythesea.com/cottesloe/)

**Case Study Two The material used and relationship to the subject matter**

These works are fabricated from marine ply and sealed with long-life paint. Marine ply was chosen for durability in wet environments and structural strength to withstand freight, handling, wind and human interaction. There was no relationship between the material used and the concept of the work, or to the data being modelled.

**Case Study Two The fabrication methods and technology used**

The drawings of the internal structures of the seedpods that were produced during the design phase of the fabrication became a discrete sectional drawing through a seedpod. These sections were repeated like sections of an orange. The drawings were scanned into a computer and, using Illustrator and Rhino

software programs, modelled in preparation for laser cutting. They were then scaled up to be cut on a CNC router. After prototyping at 300 mm high, modifications were made to the design to ensure the work would have structural integrity to withstand being outdoors and in the public domain. Considerations included water resistance, high winds, people potentially climbing on the pieces and ensuring no body parts could be trapped in any part of the work. Other design considerations included the relationship of the works to each other and to the site. The process of CNC-routing timber allows for the fabrication of large-scale objects in a relatively short time frame. This process was selected for its ability to accurately and repeatedly cut the segments of the sculptures at a scale that would be visible in a large outdoor setting. The fabrication process in turn influenced the design of the segments as the CNC router is three-axis, and therefore the cutting tool can only be deployed at ninety degrees to the material. In this way, in order to accurately and repeatedly cut the segments of the sculpture, the fabrication process determined that the segments be created from flat sheet that was then assembled to form three-dimensional shapes.

Case Study Two Site of Display and Interaction
To address the first research goal of expanding audiences, the Regenerate works were displayed in large outdoor public art events. The artworks are brightly painted to stand out in a large public space. They could be viewed from all sides and touched by the audience. The paint was selected for its physical properties of weather resistance and stability over time. Colours were chosen to relate to the ocean and earth environments of the sites where the works were to be displayed.

The display context had no admission fee and exhibitions were open to the public. Regenerate was exhibited publicly as part of two Australian public art festivals: Sculpture by the Sea at Bondi NSW and Cottesloe WA in 2012-2013; and Artisans in the Gardens at the Royal Botanic Gardens, Sydney in 2013. The combined audience for these events was more than 750,000 people. The significant audience numbers indicate the potential to devise large public outreach platforms for community education about, and engagement with, climate science. The exhibitions were accompanied by a published catalogue that explained the nature of the collaboration and the climate change issues informing the design, thus providing a pathway for audience engagement with the science informing the artworks.

Case Study Two Discussion and analysis and the resulting further research questions for the subsequent case study
The Regenerate Project sought to answer the research questions:
1) How can audience numbers for creative works designed to communicate climate science be expanded?

337“Staged on the spectacular Bondi to Tamarama coastal walk, Sculpture by the Sea, Bondi is one of Sydney’s most popular events, with 520,000 visitors viewing over 100 sculptures by artists from around the world. Held since 1997, this free to the public exhibition captures the imagination of Sydney and its visitors for three weeks each spring and is the largest annual sculpture exhibition in the world”. “Staged since 2005 the Cottesloe exhibition features over 70 sculptures and is enjoyed by 260,000 visitors”. http://sculpturebythesea.com/about/ accessed 11/05/2016.
2) In which other ways can the scientific data informing The Garden of Earthly Delights be three-dimensionally visualised so that there is increased potential for audience interaction and awareness of climate change research?

The works successfully expanded audience numbers and created new audiences for the models and in turn, for the research informing the works. This is evidenced by the records kept of audience numbers at both events and the catalogues distributed at the events informing audiences of the science behind the works. The pieces also successfully investigated new ways of three-dimensionally visualising the same data set as The Garden of Earthly Delights so as to create increased opportunities for interaction and awareness of climate change research.

Challenges to successfully addressing all of the research aims of the thesis included the ideological clash between the purported concept of the works and the materials used to fabricate and finish them. The design and concept for the works were informed by an intention to communicate climate change research, but the materials used to make the works actually contribute to climate change in their sourcing and fabrication processes. Marine Ply is a laminate wood product bonded with Phenol Formaldehyde, a highly toxic resin that does not break down in the environment. The sourcing of the wood is not disclosed; however, a great deal of timber for plywood is sourced from rainforest timber that is home to many endangered species of plants and animals.

The paint used on the surface is a type of plastic coating that, while not toxic to use, does not break down over time and therefore stays in the environment for many decades. The process of CNC routing results in considerable waste material, as each section is cut out and leaves approximately 50% of the of the original material as waste. The integrity of the work is compromised by the use of materials and processes that contribute to the problem the works are drawing attention to – thus the message regarding effects of climate change may become confused. An audience member, while having their consciousness raised about the problem of climate change, is not being shown an exemplary way of addressing it.

In order to ensure that the material outcomes of the research align with the research aims of the thesis, new research questions and trajectories were developed to investigate how this might be achieved and to inform the next case study. The research questions generated were:

1) How can the materials and processes used to make 3D models designed to communicate climate science reflect the ideas embodied in the works?

2) How can three-dimensional models accurately convey scientific research?

3) How can changes which occur over a long time, as is the case with climate change, be three-dimensionally visualised?

Using these questions, the 3D Printed Data Models project was initiated.
Design Research Case Study Three 3D Printed Data Models (2014)

Figure 4.12 Three-Dimensional Models of Data at the Research Visions Exhibition with the working 3D Printer creating the models during the exhibition, 2014.

Case Study Three Introduction

The thesis discusses here the design research project and installation 3D Printed Data Models (2014), exhibited at the Research Visions exhibition at the University of Sydney in the Faculty of Architecture Design and Planning in 2014.

As a continuation of the previous research study Regenerate, which mainly focused on different ways to model climate change research about the Cumberland Plain, the 3D Printed Data Models project aimed to convey climate science research outcomes accurately in three-dimensional form; to use materials and processes that are environmentally sustainable and reflect the ideas embodied in the works; and to visualise change that occurs over a period of time.

This last aim was an important driver in this particular case study because the graphs that the visualisations were based on reflected over thirty years of climate change data; as Lesley Duxbury notes, “One of the difficulties of communicating climate change is that it is taking place over a span of time too great for us to comprehend, having only our own short lifetimes to measure it by.” This is an even greater challenge when using static objects to communicate this thirty-year time frame. The objects do not change, but they do provide a tangible haptic object through which audiences may engage with the data. This third case study overview will describe the different ways the research investigated communicating the passage of time, including multiple objects, accompanying text and the process of the models’ production to demonstrate change.

338 Image sourced: Kate Dunn 2014.
339 Lesley Duxbury, “Breath-taking”.

Kate Dunn, Prototyping Models of Climate Change, Chapter Four, PHD 2017  Page 196 of 243
Case Study Three Research questions

1) How can the materials and processes used to make 3D models designed to communicate climate science reflect the ideas embodied in the works?
2) How can three-dimensional models accurately convey scientific research?
3) How can changes which occur over a long time, as is the case with climate change, be three-dimensionally visualised?

3D Printed Data Models was an installation of a series of powder printed models exhibited on plinths. The models were three-dimensional visualisations of graphs sourced from reinsurance company Munich Re showing increases in natural catastrophes caused by climate change over a thirty-year period.340

The installation had over ten different models displayed, as well as a working 3D powder printer making more models during the exhibition. The powder printer was printing in experimental ceramic powder developed as part of the material research described in Chapter Three of this thesis. Audience members were invited to handle the models during the exhibition. The installation included a catalogue and wall plaque describing the science behind the works. The aim of the exhibition was to bring the different aims and streams of the research together and provide a space to reflect on the progress of the research to date.

As noted in the previous Regenerate case study, there was a disconnect between the ideas informing the works and the materiality of the models. This case study sought to use materials that were conceptually linked to the ideas informing the work, so as not to dilute or distract from the viewers’ experience of the works when viewing and handling them. The sustainable powder mix ingredients of clay, sugar and maltodextrin were clearly displayed on a sign next to the objects on display.

Figure 4.13 Diagram of the research focus of the 3D printed data models project. Kate Dunn 2016.

The diagram in Figure 4.13 demonstrates the two focus areas of the research. The first is three-
dimensional visualisations that communicate climate change research. In this case study, the form of the models is determined by investigations into ways to accurately represent the data. This is taken to mean that the percentage of increases in a graph (the vertical increases) over a particular time frame (the horizontal increases), are the same percentage increases in the three-dimensional model of the graph. In this initial test case, the third dimension of the 3D printed graphs were simple extrusions of the cross section of the graph. While this may appear to be a straightforward process, converting a two-dimensional graph to a three-dimensional printed model using experimental materials has a range of obstacles to success. These include inaccuracies in the tracing of the graph and warping of the print material during processing.

The second research focus demonstrated in Figure 4.13 was on developing sustainable materials for 3D printing so as to ensure that the materiality of the objects did not conflict with the conceptual intent of the works. This aim led to ongoing material research and was a substantial element in the research’s contribution to new knowledge.

Case Study Three The research or data source being investigated

Numeric Data in the form of graphs for this project was sourced from reinsurance company Munich Re’s record of increases in natural catastrophes over a thirty-year period. One of the largest reinsurance companies in the world, Munich Re’s primary business is insuring smaller insurance companies for severe disasters that they are unable to cover. Munich Re’s corporate website details the research they conduct into climate change events, such as natural disasters including floods, cyclones and droughts, and their considerable effects on business, politics, technology and security.341

The graph in Figure 4.14 details geophysical events such as earthquakes, storms, flooding, drought and fire. Munich Re drew the conclusion in consultation with climate scientists that the increase in such events is caused by climate change.342 The graphs from Munich Re accurately mapped multiple factors and variables over the same period, providing a useful and comprehensive data set to frame and inform the 3D Printed Data Project.

Case Study Three Models of collaboration, participants and boundary objects used

Munich Re archive and publish their research findings on their website for open access. It might be argued that the website is a didactic boundary object, since no exchange of information takes place within it and there is no ongoing relationship with people who view and reference the published material. While the data has different implications, and uses across different research constituencies, it remains static, and this is what defines it as a didactic boundary object. The data has been widely used for different purposes – the Munich Insurance company, for example, has used it to analyse risk and set insurance premiums. For the 3D Printed Data Project however, the data was used to source

342 Climate change influences physical parameters in the biosphere (atmosphere and oceans). This phenomenon can be clearly measured through changes in weather factors such as temperature, precipitation and air pressure. For Munich Re, the long-term changes in weather extremes are just as relevant as the current developments in weather.
information on the increased frequency of natural disasters caused by climate change over the last thirty years.

**Case Study Three Design strategy for transforming the data or research to three dimensional objects**

The design strategy for *3D Printed Data Models* was framed around answering the research questions developed at the evaluation stage of the *Regenerate* Project. One of the research questions developed during *Regenerate* was: *How can changes which occur over time, as is the case with climate change, be three-dimensionally visualised?*

Representing change through a static object is inherently challenging, as there is no capacity to dynamically represent the dimension of time. Object-based designs are obliged to spatialise and “fix” those factors related to duration and temporality. Potential solutions to this dilemma were developed in the past, including creating a series of objects that appear to evolve over time, such as those used in museums to demonstrate development in plants and animals. An example is the models of the development of a frog in twenty-five stages, shown in Figure 4.14. Similar to the process of stop motion animation, this process involves a series of static objects or images placed or displayed in sequence to indicate to the viewer the transition that occurs over time.

The volume of data and the long period of time (thirty years) covered by the Munich Re graphs meant that a series of sequential models, such as the frog models pictured, would not be viable. Instead the design strategy adopted was to accurately represent the data in three dimensions. To further convey a sense of urgency about climate change, a working 3D printer was included in the exhibition. The printer was programmed to fabricate the items during the exhibition. The urgent, insistent movement of the printer physically demonstrated the increased rate of catastrophes as it built the graphs. The audience could see the objects being built and then experience them through the senses of touch and sight.

![Figure 4.14 Development of the frog, Ziegler Studio, Germany, after the work of Alexander Ecker; 25 models in series, late nineteenth century, photograph by Tim Harland, Macleay Museum.](image)

Another research question informing the design strategy of the case study was: *How can three-dimensional models accurately communicate scientific research?*

To address the question, and in response to conversations with scientists about the scientific imperative of complete accuracy in data representation, a series of models were derived on the basis of the numerical and visual data from the Munich Re graph shown in Figure 4.15. The tests sought to identify the most appropriate type of 3D printing that could deliver accuracy, and three-dimensionality, while addressing the goal of sustainability. Test CAD models were developed and tested on FDM makerbots and Zcorp powder printers. The process of 3D powder printing was selected as the most accurate means of representing numerical data generated by climate change research in three-dimensional forms.

Despite the goal of scientific accuracy in the visualisations, the process of translation from two
dimensions to three dimensions inevitably introduced a degree of authorship in the way the objects were resolved; for example, the creative practitioner selected the material the models were made of, the size of the models and the thickness of the printed extruded cross sections. These decisions determined the three-dimensional characteristics of the model, but it was still possible to retain the accuracy of the scientific research by ensuring that the numerical data and relative percentages are accurately translated and retained in the three-dimensional model. This third case study is a step in an iterative methodology of investigation into ways to accurately translate climate change research from two dimensions to three dimensions. The use of the form of the graph as the dominate visual motif was a first stage of the investigations. Subsequent case studies built on this approach and investigated other ways of accurately modelling data.

Figure 4.15, (Left) Graphs of Natural Catastrophes World Wide 1980-2010, sourced from Munich Re’s website;\textsuperscript{343} and (Right), showing the separation of the graph lines and transformation to an Illustrator file.

The technical procedure of translating the two-dimensional data to a three-dimensional form began by using Adobe Illustrator software to accurately import, separate and copy the graph shown in Figure 4.15 into the 3D modelling software Rhino.\textsuperscript{344} Once in Rhino, a three millimetre thickness was added to selected graph lines to ensure the final 3D printed physical model would have the structural integrity and volume to support itself.

Figure 4.16 Sample of test forms of the Munich Re graphs modelled in Rhino in preparation for 3D printing.


\textsuperscript{344} https://www.rhino3d.com/.
To further improve the structural integrity of the physical model and give the graph line three-dimensional volume, different ways to extrude the line were tested. The first test extruded the three millimetre graph line forty-five degrees in two different directions for a total of fifty millimetres. The Rhino models of this test are shown in Figure 4.16. Subsequent test models involved extruding the graph at a ninety-degree angle. However, the increase shown in the two-dimensional line graph, once actualised in three dimensions and affected by gravity, ceased to accurately represent the rise in events over the thirty-year period because the form was not self-supporting and so dropped to the table surface. Other experiments included capping the end of the graph at ninety degrees and closing the form by including a base and capping the end of the model, as seen in Figure 4.17. These closed models were the most successful in that they accurately represented the data and were strong enough to withstand people touching them without breaking. The models are initial interpretations of scientific data on climate change; some are representations of land and sea temperature increases over a 130-year period. Others are extrusions of graphs of climate change-related natural disasters.

![Figure 4.17 3D Printed Data Models, made using recyclable ceramic powder.](image)

**Case Study Three The material used and relationship to the subject matter and the fabrication methods and technology used**

The primary criteria for selection of the materials and processes were determined by the research question: *How can the materials and processes used to make 3D models designed to communicate climate science reflect the ideas embodied in the works?*

In order to address this question, it was imperative that the project used sustainable materials and processes that would not contribute to climate change and therefore would embody the ideas informing the objects. Having selected 3D printing as the process capable of accurately representing the numeric data generated by scientific research, potential sustainable processes and materials available were then evaluated. At the time of writing the only types of printers that could use multiple materials and maintain optimum functionality were 3D powder printers and fused-deposition 3D

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345 Image sourced: on the left by Phillip Gough and on the right by Kate Dunn.
printers. This made these two processes the best options for experimenting with different types of sustainable materials. Commercially available materials for powder printing are currently limited to one gypsum-based product that cannot be recycled and uses a toxic binder that must be professionally disposed of. 346 Materials currently available for fusion deposition 3D printing include PLA and plastic. Some experimental filaments such as recycled wood filament, coffee filament and brick filament have been developed; however, at the time of this research (2014) these could not be sourced.

As a consequence, the process of developing a sustainable material involved considerable research and testing, which is detailed in Chapter Three. The materials eventually selected were clay, sugar, water and alcohol. These can all be sourced ethically, are non-toxic, can be recycled in the case of clay and sugar, and evaporate in the case of water and alcohol. Building on research conducted by Professors Mark Ganter and Duane Stori from the Solheim Rapid Manufacturing Laboratory at the University of Washington, 347 3D Printed Data sought to adapt processes and materials to suit locally sourced Australian materials. Using a Zcorp 310 3D powder printer and the materials developed by the research, a series of 3D models of the Munich Re graphs were made and exhibited. These models were displayed in a gallery context and were accessible for audience interaction.

**Case Study Three Site of display and interaction**

3D Printed Data Models was displayed at Sydney University in the Faculty of Architecture, Design and Planning, in September 2014 during the Research Visions conference – an annual postgraduate student event that showcases current research. The space of the exhibition was informal and removed from usual gallery protocols. Audience members were free to touch and experience the 3D data models interactively as well as view the working 3D printer up close. Audiences were drawn to touch the models because of the novelty of the material and the unusual sight of a working powder printer in an exhibition space.

**Case Study Three Discussion and analysis and the resulting further research questions for the subsequent case study**

The first research question arising from Regenerate was: How can the materials and processes used to make 3D models designed to communicate climate science reflect the ideas embodied in the works? – The question was addressed by fabricating the three-dimensional models from recyclable materials and processes, thereby making them sustainable.

However, through the manufacture and exhibition stages other material issues became apparent. Some of the materials, such as sugar, were perfectly stable under certain conditions; however, once exposed to a humid environment they started to distort, alter their tactile qualities and impact on audience participation.

In their unfired state, some objects remained crumbly and aerated in texture – a result of 3D printing whereby dry materials are mixed but not compressed. These material attributes proved challenging for works designed to be touched. In some cases, this could be overcome by environmental control such as air-conditioning; however, not all exhibition contexts have access to this kind of infrastructure. The 3D

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346 Powder print materials that are commercially available are detailed in Chapter Three.

printing machine itself also responded poorly to the sugar mixture in humid environments – with small parts becoming easily dislodged, clogging the printer and demanding frequent cleaning.

The second research question – *How can 3 dimensional models accurately convey scientific research?* – was addressed by literally and directly translating data sourced from Munich Re into three-dimensional form. A negative outcome was the lack of interaction with the climate scientists conducting the research. There was no opportunity for consultation on issues such as identifying the most important data from the scientists’ point of view; the features of their research considered most important to communicate; and how they might best like to see the data modelled.

The third research question – *How can changes which occur over time be three-dimensionally visualised?* – was addressed by the inclusion of the working 3D printer in the exhibition and the accompanying textual explanation of the models, rather than generating many small models that demonstrated incremental change.

During the process of answering these questions and reflecting on the outcomes, two new research questions arose: firstly, to investigate the relationship of the materials to the ideas informing the works; and secondly, developing materials and processes that produce tangible artefacts

1) *How can the material research be developed further, to produce stable three-dimensional models that reflect the principles of sustainability and recycling in both the materials and process?*
2) *How can material research already undertaken be applied and further developed to investigate large-scale models that might contribute to other areas of sustainability and recycling?*

Using these questions as design parameters, Case Study Four was established: *Robotic 6 axis 3D printing of data Free Form Clay Deposition, Producing sustainable fabrication processes (2015).*

Case Study Four focused on investigating aspects of the research in depth, rather than incorporating multiple areas of research in one project. Case Studies Four and Five involved a deeper investigation into the potential of the processes and materials discussed in Case Study Three, and culminated in a display of test results at the Fabrication Futures Exhibition at Sydney University in 2015 (Case Study Four) and then at the ROB|ARCH Conference in 2016 (Case Study Five). Consultation with climate scientists resumed in Case Study Six – *Rapid Prototyping Models of Climate Change, Macleay Museum (2016)*
Design Research Case Study Four Free Form Clay Deposition, Robotic 6 axis 3D printing, producing sustainable fabrication processes. Fabricating Futures (2015)\textsuperscript{348}

![Figure 4.18 Installation shot, Fabricating Futures (2015).](image)

**Case Study Four Introduction and research questions**

*Free Form Clay Deposition* was exhibited at the Fabricating Futures Exhibition in 2015 at the University of Sydney. This project was an in-depth investigation into the potential of 3D print materials and processes to reflect the principles of sustainability on a larger scale than the previous projects described in this chapter. The technical aspects of this project are discussed in Chapter three, Process and Material Investigation Five, *Robotically controlled slip-casting clay with waste aggregate.*

\textsuperscript{348} Research discussed in this Case Study has contributed to the following published book chapter: Kate Dunn, Dylan Wozniak O’Connor, Marjo Niemelä, and Gabriele Ulacco, “Free Form Clay Deposition in Custom Generated Molds,” in *Robotic Fabrication in Architecture, Art and Design 2016*, ed. Dagmar Reinhardt, Rob Saunders and Jane Burry (Springer International Publishing, 2016), 316-325.
A series of test 3D printed objects was produced using a KUKA Kr 60 robot with an extruder attached. The objects were printed onto a plaster slab work bed using Free Form Fabrication (FFF) processes that rely on the extrusion of material in a pattern determined by an STL file. The focus of the Free Form Clay Deposition project was determined by the two research questions raised during the analysis of the 3D Printed Data Models project:

1) How can material research be developed to produce models that reflect principles of sustainability and recycling?
2) How can material research already undertaken be applied and further developed to investigate large-scale models that might contribute to other areas of sustainability and recycling?

Figure 4.19 demonstrates the research focus of Case Study Four.

Case Study Four Scientific research and data
To answer the research questions above, a detailed focus on materials and processes was necessary. There was no attempt to visualise scientific data; rather, the goal was to embody research on climate change and enact principles of sustainability in the work by incorporating recycled materials and reducing waste in the fabrication process.

Case Study Four Model of collaboration, participants and types of boundary object
The collaborations in the Free Form Clay Deposition project were not with scientists, but with colleagues at the University of Sydney. The colleagues working on this project included, Dylan Wozniak O’Connor, Marjo Niemelä, and Gabriele Ulacco. Each of these colleagues collaborated to explore the potential of collaboration in robotic and material research to achieve innovation. The project sought to research and develop a functional material delivery system for sustainable clay 3D printing, and the collaborations that occurred in this project traversed the disciplines of design, engineering, advanced manufacturing, material science and computational design.
The multi-disciplinary nature and scale of the project necessitated ongoing collaborations with a range of people. The 3D printing pump system trialled was a new innovation and consequently there were no precedent records to build upon. In order to achieve successful outcomes, the process of communication and collaboration was critically important. These collaborations used a series of reciprocal boundary objects such as sketches, technical drawings, collaboration through computational design software environments, live demonstrations and prototyping. One of the most important boundary objects used to facilitate communication was the records of the experiments conducted.

These records included instructions on the use of equipment, videos of the printing process, still photography of the printing tests, and spreadsheets of the material mixes trialled. Like the systematic records of collected samples and species data kept by Joseph Grinnell, the director of the Museum of Vertebrate Zoology at the University of California, described in chapter two, the keeping of records of the process and material experiments meant that any one of the collaborating team could understand the process, contribute to the outcomes and apply the information and research to a range of contexts. Figure 4.20 shows a sample of the records of material experiments. The full records of the tests are in the appendix.

![Figure 4.20 sample of the records of tests kept during Case Study Four.](image)

**Case Study Four Design strategy for transforming the data or research to three-dimensional objects**

The design strategy of the forms in the *Free Form Clay project* was determined by the need to compare types of material mixes with each other. Simple shapes that could be measured and tested were required, thus the form determined by the tool path was a series of simple overlapping grids that demonstrated the following: material shrinkage, structural integrity, drying times, layer adherence and material consistency when printed. Figure 4.21 illustrates the grid pattern used for the tests.

**Case Study Four The material used and relationship to the subject matter**

*Free Form Clay Deposition* built on material developments in the *3D Printed Data Models*, where clay based materials were mixed with other sustainable materials to create a hybrid substance for 3D printing. The selection of the materials in this project was determined by the research aim of

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349 Star and Griesemer, “Institutional ecology, translations’ and boundary objects”, 387.
using waste material as aggregate in the printing material. *Free Form Clay Deposition* used the same base clay mix but added a range of other materials for adaptation to large-scale 3D printing. These materials included water, recycled paper, sawdust, waste polystyrene, bentonite, industrial grade maltodextrin, cellulose fibres and alcohol. The material selection was determined by site and context specific parameters for the material research.

The research took place in the DMAF\(^{350}\) labs of the University of Sydney’s Faculty of Architecture Design and Planning. The labs include a wood workshop, a metal workshop, a material casting lab and an expansive digital fabrication lab. The labs are used by over a thousand students and staff to produce architectural models and three-dimensional propositions that visualise and communicate ideas, enable discussion and physically investigate concepts. These activities, while critically important to the process of design research, generate large amounts of material waste, particularly from the wood workshop and the CNC router in the digital fabrication lab. This project sought to recycle the waste from the fabrication labs to contribute to the 3D print material tested. This was done in order to investigate site-specific recycling as a way of improving the environmental sustainability of the 3D print material.

![Image](image_url)

*Figure 4.21 shows the different waste materials being used as aggregate and the process of 3D printing them in a test pattern.*

In order to develop a viable 3D print material that could work with the pump system, a semi-liquid consistency was necessary. Water was added to the clay to generate a base mix and then a range of additives were tested. The waste sawdust, paper and polystyrene were used in a liquid clay slip base as an aggregate. The intention of the aggregate tests was to give the material structural integrity –

as with gravel in concrete. The other test materials added to the clay slip 3D print material included bentonite, industrial grade maltodextrin and alcohol. These materials were added specifically to test ways to change viscosity and setting times of the clay slip. Bentonite absorbs water and swells, causing the clay slip to thicken and adhere to the previous layer when laid down. Maltodextrin (a byproduct of wheat processing) is a starch-based product that becomes glue-like once exposed to the moisture in the slip, while alcohol evaporates, causing the slip to dry and solidify more quickly than just water in the slip. The materials were systematically tested using the same pattern repeatedly in order to allow comparisons.

**Case Study Four**

**The fabrication methods and technology used**
There is a detailed description of the technical aspects of this project in Chapter Three in section 3.4, Process and Material Investigation five. Thus, the fabrication methods and technology used will not be addressed again here.

**Case Study Four**

**Site of display and Interaction**
The results of the tests were displayed in the studios of the University of Sydney’s Faculty of Architecture Design and Planning. The studio context of the display created an informal environment that encouraged people to touch the works and interact with the processes of fabrication as well as the artefacts of the research. This was an important way to draw attention to the link between the design research being displayed and the underlying goal of embodying the research concerns of sustainability. Viewers could see the waste materials being incorporated into the material and process research, in the same context in which they are generated through the activities in the studio.

**Case Study Four Discussion and analysis and the resulting further research questions for the subsequent case study**

*Free Form Clay Deposition*¹³⁵¹ foregrounded an understanding of robotically controlled clay deposition in three-dimensional space using a robotic tool path. The process successfully incorporated sustainable materials into the clay mix and began a process of scaling up the capacity of the work envelope. “The use of waste substances from industry as a component of the deposition material was tested and successfully addressed questions of sustainability within the context of 3D printing. As a future research trajectory, the process could be adapted to other specific site conditions by the including locally sourced materials as aggregates, and furthermore be up-scaled towards architecture applications.”

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¹³⁵¹ Ibid., Dunn et al., 325.

¹³⁵² Ibid.
Significant challenges remained, however, including resolving the setting times of the clay; determining the optimum materials; and developing more efficient means of interacting with the robotic 3D printing process and materials in order to input design criteria. The process revealed considerable potential for further research and experimentation, particularly in terms of experimental robotically controlled clay deposition. Two subsequent research questions were collaboratively developed, focusing on robotics and material deposition as part of the Interactive 3D printing workshop held at the 2016 ROB|ARCH conference.

“1) How do robots and humans work together to explore material agency?
2) How does the application of robotics expand design affordances or intuition?”

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Case Study Five Introduction and research questions

The ROB|ARCH conference workshops featured participants from around the world testing out the limits of robotic fabrication with materials as diverse as paint, timber, polystyrene and clay. The questions raised by the *Free Form Clay Deposition* project were directed at resolving the technical and material means of delivering sustainable, 3D printing materials and investigating the potential for interactivity in large-scale FFF Fabrication processes.

The research undertaken during the workshop sought to answer the following research questions:

“1) How do robots and humans work together to explore material agency?

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355 Image sourced: Photo by Kate Dunn.
2) How does the application of robotics expand design affordances or intuition? \textsuperscript{356}

Figure 4.23 demonstrates the research focus of Case Study Five.

Case Study Five The research or data being investigated

The primary focus of the research conducted during the workshop was experimental material and fabrication processes.

Public interest in digital fabrication and the rising availability of 3D printers has allowed an increasing number of non-specialists to understand and adapt the logic and mechanisms behind the process. It is now becoming common for users to change parameters of a digital fabrication process including feed-rates and nozzle temperatures, to adapt it to their specific requirements. In addition, the spread of open source hardware and software has empowered hobbyists, artists and designers to build their own machines, permitting the rise to new types of machines and fabrication processes. In architecture, industrial robots have proven to be a robust and flexible research platform, allowing the precise placement of many types of tool within a large working envelope. \textsuperscript{357}

Robotic fabrication processes enable designers and architects to explore the boundaries between digital and material worlds. Beyond optimisation criteria or parametric design, new design strategies such as generative design and collaborative design are enabling new ways of approaching material exploration through robotics. Open source software and hardware enable new forms of design, yet these new tools also demand design frameworks dealing with robots, data, sensor technologies and material contingencies. \textsuperscript{358}

\textsuperscript{356} Dubor et al., “Sensors and Workflow Evolutions”, 412.
\textsuperscript{357} Ibid., 413.
\textsuperscript{358} Ibid., 412.
Case Study Five: Model of collaboration, participants and types of boundary objects used

The workshop was a collaboration between different areas of expertise to the process as a triangulation between experts in robotics and sensors, design and architecture, 3D printing, and ceramics. Collaborators included Susana Alarcon Licona, Kate Dunn, Dylan Wozniak O’Connor and Dagmar Reinhardt from the University of Sydney; Martin Bechthold and Kevin Hinze from the Harvard Graduate School of Design; and Alex Dubor from the Institute for Advanced Architecture of Catalonia.

The collaboration took place through a series of Skype planning sessions followed by face-to-face meetings and discussions on site. The model of collaboration was reciprocal, whereby each participant contributed and benefited through the process of the research. The reciprocal boundary objects employed included data, scripts, sketch drawings, shared documents and the time and space of a collaborative three-day workshop with participants. Figure 4.24 shows the collaborating team discussing design strategies.

Figure 4.24, Interactive 3D printing workshop with the collaborating team and workshop participants.

Case Study Five Design strategy for transforming the data or research to three-dimensional objects

As well as addressing issues of material sustainability in large-scale 3D printing, the workshop also sought to address the relationship of maker to materials and processes used in digital fabrication. A common criticism of 3D printing and digital fabrication is that it disconnects maker from material and final product. The process of digital printing or cutting generally involves a program or script being written, then input into a 3D printer, robot or laser cutter. The machine executes the script without
any input from the maker or designer from this point, until the object is complete. The creative practitioner creates the work on a screen, imagining how it might be imbued in three dimensions with the qualities of the material it is made from. There is currently no opportunity to interact with the material as it is being formed or carved. This is for two reasons. The first is safety: most digital fabrication equipment currently does not have movement sensors built in, making it quite dangerous to intervene mid-process. The second reason is that many 3D printing processes rely on heating materials such as plastic to melt and adhere. In the case of clay, the material shrinks as it dries and needs moisture to adhere. It can be difficult to restart a print once it has stopped. This is a different experience from the intuitive one of shaping and forming materials by hand, as part of which mid-process design decisions can be made and implemented easily and successfully.

One of the goals of the workshop was to explore how this problem of the maker’s detachment from the process and end product can be addressed. Using an inexpensive toolbox of sensors useful for digital fabrication, participants in the workshop constructed an integrated sensing apparatus into a 3D printing process to explore the role of changing conditions in an on-going design process. The sensors respond to factors such as light or sound variations and changed the pattern of the extrusion of clay onto the table surface.

![Figure 4.25 showing the process of transformation of the input data using Rhino and Grasshopper software to a script for printing a three-dimensional form.]

Groups of four participants worked collaboratively to design a series of modular 3D printed clay
components. These were printed using a robot with the clay extruder attached. This set-up is described in Chapter Three, in material and process investigation six. Each of the scripts for the modular components was then subjected to sensors that responded to environmental conditions such as sound or light to inform robotic deposition.

Case Study Five The material used and relationship to the subject matter and the fabrication methods and technology used
The workshop used two KUKA robots, one fitted with an altered clay extruder that relied on a ram press mode of material delivery and one with a series of tools to mark and manipulate clay. The clays used for 3D printing were selected for their capacity to address the goals of sustainability in large-scale 3D printing. Variations included terracotta clay with recycled paper and sand added and white earthenware clay with recycled paper added.

Figure 4.26 shows the process of printing and some of the test structures produced. The techniques explored have tremendous potential to create real-time three-dimensional models of a range of data using sustainable materials.

Case Study Five Site of Display and Interaction
The workshop took place at Sydney’s Walsh Bay as part of the Robots in Art, Architecture and Design conference and workshop. The workshop environment encouraged an experimental collaborative approach to the research that removed hierarchies of knowledge, thereby facilitating the development of innovative research and outcomes. There were twenty participants in the

359 Images sourced: Dylan Wozniak O’Connor.
workshop over a three-day period. This culminated in an exhibition of the artefacts generated during the workshop. The exhibition was open to the public.

**Case Study Five Discussion and analysis**

The workshop was designed to test the parameters of what is possible in interactive 3D printing. Robotic fabrication processes facilitate material and digital design research in the creative industries. New design strategies such as generative design and collaborative design are enabling new ways of approaching material exploration through robotics. “Typically, the outcomes of a fabrication process are predetermined, however, with the introduction of sensors, design and fabrication process may be interrupted by real-time feedback”.360 This workshop explored the potential for creative practitioners to adopt robotic fabrication processes augmented with the introduction of sensors. The workshop tested the following: applications of parametric modelling, robotics, and additive manufacturing for innovation of new construction techniques, in order to create a range of scalable 3D-printed objects using sustainable materials. This was done to employ environmental conditions (like sound/ light) to inform robotic deposition, focusing on dynamic processes where information continuously changes; and to test material response to gravity/ density/ texture/ structural integrity, and aesthetics.

The material investigations undertaken successfully addressed the research questions posed at the evaluation of the last project and built a framework for both small- and large-scale sustainable 3D printing solutions. The material and process research described here contributed to the research displayed in *Case Study Six: Rapid Prototyping Models of Climate Change*.

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360 Ibid, 411.
Design Research Case Study Six Rapid Prototyping Models of Climate Change, Macleay Museum (2016)

Figure 4.27 Exhibition Overview and Context, Interior of the Macleay Museum.  

Case Study Six Introduction and research questions

Rapid Prototyping Models of Climate Change was a summary exhibition, combining all three areas of research in one exhibition at the Macleay Museum, a natural history museum at the University of Sydney. On display was material generated throughout the course of this thesis over a three-year period, including: design research; artefacts and artworks; and three-dimensional visualisations generated from collaborations with climate scientists, artists, designers, engineers and architects. Consisting of four large glass-topped vitrines, the museum display documented the three research areas of the thesis:

- 3-dimensional data visual models and sites of engagement for communicating climate science in collaboration with climate scientists.
- Collaboration models using boundary object theory to facilitate effective collaboration between relevant stakeholders.
- Sustainable materials for 3D printing to embody the principles of sustainability in the models produced through the research.

The vitrines framed different groupings of objects and text, representing different research trajectories. Accompanying the exhibition were wall panels explaining the scientific and technical research informing the works. There was also a video documenting the processes used in the fabrication of the research. (This can be found in the appendices of this thesis.) A series of talks and workshops was delivered during the course of the exhibition by creative...

practitioners and scientists, to give audiences a chance to ask questions and learn to 3D print, using sustainable PLA printing filament. Audiences for the exhibition and talks ranged in age from 2 to 80 and were from diverse cultural backgrounds. Combining objects with images and text meant that everyone could access the exhibition and research in their own way.

Figure 4.28 demonstrates the research focus of Case Study Six.

**Case Study Six**

The research or data source being investigated

The research informing *Rapid Prototyping, Models of Climate Change* focused on climate change research and sustainable fabrication and materials for 3D printing. Climate change information was sourced through collaborations with two climate scientists, Dr. Dan Metcalfe from the CSIRO Land and Water Research Facility, and Dr. Sarah Perkins Kirkpatrick from the ARC Centre of Excellence for Climate System Science, UNSW.

Dr. Metcalfe’s research focused on threatened species and threatening processes in the Wet Tropics bioregion and past, current and predicted distribution of species and communities in Australian rainforests. The research by Dr. Metcalfe that was modelled and 3D-printed and displayed in the exhibition predicts what plant species will become dominant with increased temperatures and different levels of moisture, as a way of helping to facilitate habitat restoration.

Dr. Sarah Perkins Kirkpatrick’s research focus is primarily on heatwaves in Australia as described in Chapter Three. Her research collates records of temperatures from weather stations around Australia in order to map the increasing frequency and intensity of heatwaves in response to climate change. The research that was modelled and 3D printed and displayed in the exhibition was a comparison between the frequency and intensity of heatwaves in Sydney in 1910, 1960 and 2015.

The scientific data supplied by the two scientists was in the form of spreadsheets featuring numerical records of historical temperature changes, as well as predictive models of changes.

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to plant and animal species due to increased temperatures. Details of the different types of data are provided in Chapter Three in section 3.5.

The research informing sustainable fabrication and materials for 3D printing outcomes was developed during the previous projects - *3D Printed Data Models, Free Form Clay Deposition* and the *Robotic Fabrication in Architecture, Art and Design workshop*.

Case Study Six Models of collaboration, participants and boundary objects used

The primary collaborations were with the two climate scientists, Dr. Sarah Perkins-Kirkpatrick and Dr. Dan Metcalfe, introduced in the previous section. These collaborations evolved over a two-year period, initially with Dr. Metcalfe in 2014 and in 2015 with Dr. Perkins-Kirkpatrick. The collaborations used different types of boundary objects including records of data, websites, spreadsheets, prototypes and diagrams to facilitate communication and investigate possible material outcomes. Exchanges were by telephone, email, and meeting in person.

The first collaboration with Dr. Metcalfe

Dr. Metcalfe works for the CSIRO in a senior position as Research Director of Landscape Intensification, and as Program Manager of the Office of Indigenous Engagement. He has previous experience as a teacher and is interested in the process of communicating ideas and education.

The collaboration at times functioned as a creative boundary relationship, in that the research used data supplied by Metcalfe as a source of inspiration for creative projects. For example, in scanning Metcalfe’s numerical data, it was noted that one of the industries likely to be affected by climate change is the Queensland banana industry; so the research modelled and 3D printed a small crop of banana trees made from coffee filament as a test visualisation. Here, data contributed a formative, catalytic role in the conception and fabrication of the models shown in Figure 4.32.

At other times Dunn responded to data supplied by Metcalfe as a didactic boundary object in that it fulfilled the role of a repository of numerical data. The process of communication and collaboration was somewhat compromised by access and distance, as Dr. Metcalfe is based in Atherton in Far North Queensland and conducts regular field work. At no time was the collaboration a reciprocal one, as Dr. Metcalfe was always a supporting figure in the research project. In discussing the value and experience of collaborating with a creative practitioner in order to communicate his research, Dr. Metcalfe stated:

> My greatest regret is that I wasn’t located sufficiently close, nor suggested organising video conferencing, so that I would have been better able to understand the creative process as it developed, and fully collaborate in the project as it progressed.\(^{363}\)

\(^{363}\) Dr. Metcalfe in conversation about ways to develop collaborations between disciplines. Selected conversations are in Appendix A.
Despite the difficulties in the collaboration due to distance, the data that Dr. Metcalfe supplied was very relevant to the research focus on climate change and lent itself to modelling because of the different but related climate scenarios the research encompassed. In discussing potential ways to improve the collaboration, Dr. Metcalfe suggested:

**Early, ongoing, and regular engagement!** From my perspective, this is only a collaboration in a very limited sense, as I generated the numbers in isolation, we subsequently had some discussions and I provided the data to Kate, and then I was invited to visit and see Kate’s final objects in an exhibition setting. The numerical model is a prediction of what may happen in a very unpredictable world, and the objects are a re-interpretation of those numbers. I wonder if in a fuller collaboration, with Kate engaged, contributing and understanding the numerical modelling process, and me then engaged, contributing and understanding the 3D object development from those numbers, whether we could have arrived at outcomes which might have transcended the two disciplines and enhanced communication between them?

**The second collaboration with Dr. Perkins Kirkpatrick**

To attempt to overcome the challenges of establishing early, ongoing and regular engagement, and address the research goal of investigating all three different categories of boundary collaborations defined in Chapter Two of this thesis, another collaboration was established, with Dr. Sarah Perkins Kirkpatrick from the ARC Centre of Excellence for Climate System Science at UNSW.

The goal was to achieve a reciprocal collaboration across the disciplines of creative practice and science. The proximity of Dr. Perkins Kirkpatrick’s offices to the lab where the PhD research was being conducted meant that ongoing communication, exchange of ideas and analysis and review of the 3D printed models were possible, thereby contributing to increased understanding and constructive exchange. Dr. Perkins Kirkpatrick had a keen interest in communicating her research, and in conversation indicated that she saw benefit in communication across multiple channels, forms and constituencies in order to more effectively disseminate her research, make it more understandable and reach a larger audience. In response to the question “Do artists and designers contribute to communicating scientific research, and what is different about how they do that compared with other channels that you use to disseminate your research?”, Dr. Perkins Kirkpatrick responded:

**The general public seem to understand more. Science is all graphs and numbers, and not everyone thinks that way so it can be difficult communicating our results with these resources. Artists and designers have a different way of thinking and presenting to us, allowing us to reach a wider audience, often with using less words in the explanation. Artists and designers definitely contribute to communicating scientific research.**
The collaboration with Dr. Perkins Kirkpatrick continued through the research development of the artefacts, the launching of the exhibition and two public presentations that discussed multi-disciplinary ways to communicate scientific research.

**Case Study Six Design strategy for transforming the data or research to three-dimensional objects**

The artefacts generated by these collaborations were displayed at the Macleay Museum at the University of Sydney in four large Victorian glass vitrines. The design strategy for the design of the artefacts and the mode of display took significant influence from the museum context it was displayed in. The Museum, as described in Chapter Two, was built in 1887 to hold the large Macleay family natural history collection. The museum is in the style of many Victorian natural history museums, with an imposing stone facade, wooden and glass display cabinets and a vast array of taxidermy animals in glass cases.

During the museum’s long history, its floor space has been successively reduced to make way for teaching laboratories. Much of the Macleay collection had to be consolidated or stored, lending a crowded quality to the displays. The museum furniture is the original furniture from 1887 – there are dark wood cabinets arranged to guide the viewer around the space. At the back of the museum are four large glass vitrines, pictured in Figure 4.27, intended for displaying specimens. These were made available to the PhD project for the exhibition and influenced the way the research artefacts were displayed. This was done by referencing some of the visual tropes of historical museum displays of natural history, such as sequential classification of objects, scientific specimen display containers and a familiar, consistent and prominent labelling system. These display devices are influenced by the museological conventions deployed in Case Study One, *The Garden of Earthly Delights*; small objects are arranged in a grid like formation, thereby encouraging the viewer to note differences and similarities between the objects displayed. The use of these homogenising devices was intended to lead viewers to draw conclusions and see relationships in the objects displayed. For example, the use of specimen containers tells viewers that the contents are related and significant. The vitrines operate as frames, letting viewers know where to focus their attention in the display.

The cluttered dark Victorian museum environment, full of historical modes of communicating science, provided a vivid contrast to the implied modernity presented by the 3D printed objects. To reiterate this contrast, a 3D printer was included in the exhibition. This dichotomy was further pronounced through the lighting in the museum; while most of the display cabinets are quite dark in order to preserve the specimens, in contrast the four vitrines used to display the 3D printed models were brightly lit. The juxtaposition of historic scientific models around the walls with new technologies such as 3D printing was a new way to engage the curiosity of the public and see the lineage of three-dimensional science communication in one place.

**Case Study Six The material used and relationship to the subject matter and the fabrication methods and technology used**
Each vitrine displayed a different area of the PhD research and practice. The models displayed in the vitrines are the artefacts or models generated throughout the research. All of the artefacts are made from experimental sustainable 3D printed material such as coffee, waste wood, waste brick, clay, sugar and corn.

Some of the models investigate accurate ways to three-dimensionally model the same dataset in a range of different sustainable materials. This is evident in Vitrine One. Other models tested creative ways of modelling scientific data using emotive devices; these were displayed in Vitrine Two. Vitrine Three focused on portraying the material investigations that took place during the research, while Vitrine Four displayed a larger comparative study of heatwave models. The thesis will now describe the research exhibited in detail, according to the vitrines the artefacts were displayed in.
**Vitrine One**

The first cabinet displayed a range of different models of Dr. Perkins Kirkpatrick’s and Dr. Metcalfe’s research. The same large data sets were sourced and differently modelled using a range of experimental sustainable materials and potential forms of three-dimensional visualisations of climate change data. Figure 4.29 shows a plan view of the first glass cabinet. Each model is a design variation based on three data sets, recording of climate change and predictive models of the future effects of climate change on the environment, provided by Perkins-Kirkpatrick and Metcalfe.

Figure 4.29 shows three different ways Dr. Metcalfe’s research was modelled and printed. The models represent three different predictive climate change scenarios defined in his study of threatened species and threatening processes in the Wet Tropics bioregion. The models refer to past, current and predicted distribution of species and communities in Australian rainforests. The models shown are made from porcelain, sugar and maltodextrin, and PLA. Figure 4.31 shows a 3D printed data model of heat spikes from January 2015. The data was sourced from Sarah Perkins Kirkpatrick. The model is made from porcelain, sugar and maltodextrin.

![Figure 4.29 Vitrine One at the Macleay Museum Plan View.](image_source)

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Figure 4.30 Models of different climate change scenarios.

Figure 4.31 Experimental model of data from Cabinet One. 3D printed data model of heat spikes from January 2015.

Vitrine Two Climate Change Graveyard
The second cabinet displayed creative models of research into the effects of heatwaves caused by climate change on Australian plants and animals. The collection of objects in the vitrine had *The Climate Change Graveyard* as a unifying title. The models in this cabinet investigated ways to incorporate emotive and narrative devices into the design of the physical forms. An example of this strategy are the models of black cockatoos shown in Figure 4.33 made from experimental wood filament. The material retains some of the original qualities of the wood structure, resulting in a fibrous texture. The cockatoo’s appearance references mummified bodies that have dried and shrivelled, as if preserving an extinct species. To amplify the effect, the models were piled on top of each other as if buried in a tomb.

Included in the cabinet was an 1851 taxidermy specimen of a black cockatoo from the Macleay collection. Historical models of communicating science, where actual specimens of the species are killed, stuffed, preserved and exhibited, are here contrasted with the future potential of digitally printed three-dimensional models of science. Both formats rely on the audience’s perceptions of sight, imagined touch and the ability to see the object from multiple angles to convey relevant information. The advantages of the 3D printed models over taxidermy models are that no animals have to die; the models can be repeated cheaply and endlessly; they can be made accessible to more people; and scientists can have input into their form and focus through a process of collaboration with a creative practitioner.

![Figure 4.32 Plan view of Vitrine Two at the Macleay Museum.](image1)

![Figure 4.33 3D printed wooden models of birds.](image2)
Vitrine Three

Vitrine Three displayed the material elements of the 3D printing undertaken during the design research of this thesis. Sustainable materials include coffee, corn, clay, sugar, recycled waste wood, clay and polystyrene. 3D printing processes include powder printing, fused deposition modelling and robotic 3D printing. As Michael Hohl has observed, the materiality of objects contributes to the communication of the information and the way a viewer interprets objects, hence the importance of displaying the breakdown of the sustainable and recyclable materials in the exhibition.366

![Figure 4.34 Plan view of Vitrine Three at the Macleay Museum.](image)

366 Hohl, "From Abstract to Actual”.
367 Image sourced: Photo by Greg Piper.
Vitrine Four

Figure 4.35 Plan view of Vitrine Four at the Macleay Museum.\(^{368}\)

Figure 4.36 3D printed models of temperature in Sydney 1960. Recycled wood filament.\(^{369}\)

The fourth vitrine displayed investigations into ways to model the effects of climate change in a specific location over a period of time. The three models in the cabinet reflect the recorded temperatures in Sydney from October to December in 1910, 1960 and 2015. Each of the 3D printed models shares the footprint of the Sydney waterways, indicating the potential impact of climate change on water supplies and levels. The models sit on transparent laser-etched maps of the greater Sydney region, enabling local residents to locate their home suburb on the map and imagine the effects of rising ocean levels caused by climate change. The models were printed in recycled wood filament so as not to further contribute to climate change. They were made using the same process as in the 3D Data Model project, where an Illustrator file of a graph is extruded using Rhino software to create volume – in this case, shaped in the form of Sydney’s river system. The models protrude vertically in direct correlation with temperature increases over the last century.

The mode of 3D visualisation selected was such that the models directly and accurately reflect the data supplied by the scientist, rather than interpreting it and using creative devices such as those in

\(^{368}\) Image sourced: Photo by Greg Piper 2016.

\(^{369}\) Image sourced: Photo by Greg Piper 2016.
the black cockatoo models in Vitrine Two. This eventuated in response to conversations with Perkins-Kirkpatrick who was keen to ensure that the accuracy of the data remain a priority in the display model. Building a relationship or collaboration requires incremental extensions of trust. For Perkins-Kirkpatrick to feel confident in having her research visualised, it was important to ensure that accuracy was privileged over interpretation. In a public forum attached to the exhibition, Perkins-Kirkpatrick declared that through the process of visualising her work it was the first time her husband felt that he understood what her research was about.

![Image](image.png)

**Figure 4.37 Detail of 3D printed models of temperature records in Sydney based on Dr. Perkins Kirkpatrick’s research.**

**Case Study Six Site of display or audience interaction**

Three ancillary devices were staged during the exhibition period to facilitate increased and diverse opportunities for audiences to interact with the work and learn about the science informing it. The first was a public talk, about the use of new technologies in combating climate change, held within the exhibition space. Speakers included Perkins-Kirkpatrick, Dunn and Dr. Liz Carter. The talk gave the public the opportunity to hear and ask questions about the exhibition and the science informing the works, as well as other ways that new technology is being deployed to address the effects of climate change. The talks and question period gave audiences multiple ways to understand both the work and the science informing it.

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371 Dr. Carter is a specialist in Vibrational Spectroscopy of Biological Materials. Vibrational spectroscopy is now commonly used to investigate a range of biological samples from the outermost layer of the body, the stratum corneum, into its inner depths such as: gallstones, blood, hemoglobin and even DNA. Infrared (IR) and Raman spectroscopy are non-destructive, non-invasive analytical techniques that provide information about the molecular composition, structure and interactions within a sample. Potentially, these techniques can detect the biochemical changes that accompany the manifestation of predisease. [http://sydney.edu.au/science/chemistry/spectroscopy/staff_and_students/elizabeth_carter/research.shtml](http://sydney.edu.au/science/chemistry/spectroscopy/staff_and_students/elizabeth_carter/research.shtml).
The second ancillary device was a workshop on sustainable 3D printing held at the museum. Targeted at children, the workshop facilitated haptic interaction and immersive experience as ways for audiences to engage with climate change data.

The third ancillary device was a panel discussion held at the UNSW Michael Crouch Innovation Centre. The panel included Perkins-Kirkpatrick, Dunn, journalist Paddy Manning and science communicator Alvin Stone. The discussion focused on the role that collaborations between artists and scientists can play in communicating climate change and how creative practitioners can help to create new audiences by visualising critical climate change research.

(Case Study Six Discussion and analysis)

The exhibition, the works in it and the affiliated events all contributed to providing multiple ways to visualise and communicate climate change data in collaboration with climate scientists. The exhibition successfully managed to combine all three research areas:

- Models of collaboration in creative interdisciplinary projects;
- 3D printed three-dimensional artworks and visualisations that communicate climate change research;
- Environmentally sustainable materials for 3D printing.

The process of collaboration with climate scientists facilitated ongoing exchange about the design of the objects and different ways to represent their research. The materials used were all sustainable and were primarily developed by the practical research which, in the event, tested over thirty different ways to model and represent climate change data. These different models formed boundary objects between scientists and creative practitioners and the public. The objects in the exhibition provided a space for knowledge exchange, curiosity, discussion and acted as catalysts for further research.

372 Image sourced: Photo by Kate Dunn.
4.4 Summary and conclusion

Collaborative approaches across disciplines are enabling new ways of approaching science communication. The six research projects described in this chapter conducted detailed investigations into collaborative practice, different ways to model climate change data and different types of sustainable materials and processes for 3D printing. The practical research was informed by the theoretical, precedent and technical inquiry described in Chapters Two and Three.

The form of the models was determined by climate change data interpreted in different ways and then 3D printed using a base material of clay with additions of different materials to address sustainability and function. The data was modelled in different ways, as one style of communication does not suit all audiences. Many of the models were based on the same data set and visualised in different ways to test the parameters of potential forms.

The different collaborations with climate scientists were analysed using boundary object theory with categories developed in the research and described in Chapter Two. Each collaboration provided new insight into the effects of climate change and offered challenges and solutions to communicate and address its effects. Artists and designers can make a valuable contribution to communicating global problems such as climate change in the way they choose to represent these issues and where they display their art works. Exhibitions of creative responses to climate change research can reach new audiences and provide a place for knowledge exchange and discussion.

The introduction of new technologies such as robotics and 3D printing provides an opportunity for creative practitioners to contribute to solutions to global problems such as climate change and sustainable fabrication. The contributions creative practitioners can make include complex understanding of materials and materiality; complex understanding of formal and spatial practices; working knowledge of communication and visualisation techniques; and the capacity to engage with wicked problems such as climate change through processes of iterative design, creativity and innovation.
Chapter Five
Conclusion
Chapter 5 Conclusion-Chapter Structure

Chapter 5 summarises the research draws conclusions and outlines future directions for the research.

5.1 Research summary
The research summary gives an overview of the research undertaken during the PhD candidature and discusses how the research questions have been answered.

5.2 Research dissemination
This section outlines the dissemination that has occurred during the candidature and demonstrates the significance of the research.

5.3 Future directions of the research
This section describes the future directions of the research.
5.1 Research Summary

The research conducted both theoretical and practical research in order to address the following research questions:

1) **Communication and Collaboration:** In the current context of climate change, which tools for communication and collaborations between the disciplines of sciences and the creative practices could be mobilised to facilitate or enable innovative modes of communicating climate change?

2) **Artefacts and Visualisation:** What is the capacity of created (3D printed) artefacts to engage with climate change data to produce accessible forms of climate change information and visualise the effects of climate change?

3) **Innovation with Processes and Materials:** What kinds of processes and materials might be used or developed beyond a purely aesthetic dimension that makes a connection between the materials and the data being communicated and in particular, how can the issue of sustainability be cast within the selection and development of new materials in this enterprise?

**Theoretical Research**

The theoretical research investigated theories of collaboration in order to situate an innovative model of collective practice between creative practitioners and scientists for the purposes of communicating climate change. The concept of boundary objects devised by Star and Greimser in 1989 and successively developed by Carlile in 2002, Lee in 2007 articulated the devices and methods used in and across different fields to facilitate collaboration. Building on this research the thesis developed three new categories of boundary objects, didactic, creative and reciprocal, that are appropriate for the context of collaborations between creative practitioners and scientists. These categories were used to frame precedent studies of collaboration models and subsequently analyse the exchanges and collaborations undertaken as part of the research.

**Historical and Precedent Research**

Historical research covered models of collaboration between creative practitioners and scientists used in the past to communicate scientific research. There was an initial focus on three dimensional models of communication from the Victorian era, including taxidermy sculptures, museum collections, and teaching models such as the Blashka glass models. Precedent studies analysed the way artists responded to scientific research in order to promote its communication to the public. Contemporary examples of collaborations between creative practitioners and scientists working together to communicate climate change research were investigated and used to frame the methodologies, practices and creative outcomes of the thesis.

**Design Research**

Practice-based creative outcomes were developed as a series of seven projects and associated exhibitions, each investigating and combining different aspects of the research. Some projects focused on developing sustainable materials for 3D printing, while others focused on models of
collaboration or different ways to model climate change data. Most projects combined two or three aspects to create new ways to visualise climate change research that could embody aspects of the science in material artefacts.

**Engagement with research questions**

The three research questions were addressed and answered through theoretical investigation and practice-based creative works.

*Communication and Collaboration:* In answer to question one the tools developed through the research to facilitate communication and collaborations between the disciplines of sciences to communicate climate change constitute new categories of boundary objects, described in chapter two - didactic, creative and reciprocal. These categories were applied and investigated through practice-based creative work, described in chapters three and four, through a series of collaborations with three different climate scientists. Each collaboration used different types of boundary objects to facilitate communication between the creative practitioner and the scientist and communication between these two parties and audiences.

Developing efficient ways to collaborate and communicate across and between disciplines is critically important in addressing global challenges such as climate change. Problems such as climate change are not being solved by any one discipline. Innovation requires concerted, collaborative and transdisciplinary effort to find solutions. The categories of boundary objects developed in the thesis provide new tools for analysis and communication.

*Artefacts and Visualisation.* 3D printing has the capacity to fabricate objects quickly, repeatedly and with extreme accuracy - rendering it an invaluable tool for making three-dimensional models of data. Previous means of communicating data have included graphs and charts or three-dimensional models made by creative practitioners interpreting the data. The introduction of new technologies such as robotics and 3D printing provide opportunities for creative practitioners working with scientists to develop novel ways to accurately communicate climate change research that engage haptic interactivity as well as visual experience.

*Innovation with Processes and Materials.* In answer to question three on process and material innovation, the thesis conducted extensive practical research and testing of materials for 3D printing in order to arrive at a sustainable solution for fabricating objects that not only communicate climate change research in their form, but also embody climate change research their material composition and perceived materiality.

The research conducted a series of practical investigations of the potential of sustainable 3D printing with a range of materials including clay, sugar, paper, wood and coffee. Material investigations focused on the use of clay as a sustainable base material in powder printing and large scale robotic 3D printing. Also explored were waste substances from industry as components of the deposition material to address sustainability. The results set a framework for further development in both small scale and large scale sustainable 3D printing.
5.2 Research Dissemination

The research led to significant measurable impact - largely through dissemination by publication in books and peer reviewed journals; as well as in well attended public exhibitions.

Outcomes of the research were disseminated nationally and internationally through publishing, in books, peer reviewed journals, conference presentations, workshops, well attended exhibitions in high profile venues and public speaking events. The research value is in the opportunity made available to future practitioners to develop and elaborate the theoretical, collaborative, exhibitioner and material outcomes of the thesis - building on the frameworks and techniques developed for collaborating and visualising climate change using sustainable materials and fabrication processes.

Dissemination during the conduct of the thesis included the following:

2016

• Dunn KM. 3D printing Ceramics and the advantages of Collaboration Journal of Australian Ceramics 55(3) 15 Nov 2016 (Journal article).

• Dunn, K.M, Perkins Kirkpatrick, S., Stone, A., Manning,P., Climate Change Panel Discussion/ Michael Crouch Innovation Centre, 16 Sep 2016 - 16 Sep 2016 (Panel Presentation).


• Dunn, K.M. Perkins Kirkpatrick, S. Carter, L., Art and Science: investigating Climate Change/ Panel Discussion at the Macleay Museum, Art and Science: investigating Climate Change, Macleay Museum, 20 Apr 2016 - 20 Nov 2016 (Conference Presentation).


• Dunn, K., Rapid Prototyping- Models of Climate Change 3D printed sustainable materials. Macleay Museum University of Sydney. 03 Mar 2016 - 17 Jun 2016 (Creative Work non-textual).

In Robotic Fabrication in Architecture, Art and Design 2016 (pp. 410-425). Springer International Publishing (Book Chapter).


2015

- *Sustainable Materials for 3D Printing* 07 Sep 2015 Fabricating Futures University of Sydney Faculty of Architecture Design and Planning (Creative Work (non-textual)).


2014


- Dunn K.M., Gough P.J., *Collaborative Mapping* hand drawn digitally animated projected illustrations. 07 Nov 2014 - 07 Nov 2014 (Creative Work (non-textual)).

2013

5.3 Future directions of the research

Further research and practice-based creative work are anticipated - specifically to investigate reciprocal collaborations with scientists for communicating climate change, its consequences and urgent adaptation strategies. Expanded research will focus on refining sustainable fabrication systems and materials that were provisionally tested in the thesis. Through an ongoing process of 3D printing and fine tuning of material mixtures, the research can further investigate tangible interfaces or objects that communicate their material constituents as part of the climate change narrative. The field of 3D printing is in its infancy, yet offers great potential to combine sustainable material with new technologies - and in doing so, to address global problems such as climate change through informative, engaging and persuasive outcomes at the interface of the creative practices and science.
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Appendices

Appendix A
Conversations with Dan Metcalfe and Sarah Perkins Kirkpatrick about collaboration.

Appendix B
Powder Printing Research
Samples of tests.

Appendix C
Robotic 3D Printing Material Tests Samples
Samples of tests.

Appendix D
Table of Ceramic Process and Material Terms.

Appendix E
Examples of Formats of Scientific Research informing the investigations into potential three-dimensional visualisations.

Research is compiled here from:

Dr. Caroline Lehmann
Dr. Dan Metcalfe
Dr. Sarah Perkins Kirkpatrick

Appendix F
Extended design research images.
Background: One of the hypothesis of my research is that objects allow viewers to understand information in different ways to images and graphs. I have chosen 3D printing because it allows you to accurately translate numerical data to 3D form. I have used sustainable materials for the 3D printing because I theorise that if you are making objects that reflect climate change research, the objects should not be contributing to climate change in their processing and disposal.

KD: Do artists and designers contribute to communicating scientific research, and what is different about how they do that compared with other channels that you use to disseminate your research?
DM: Yes, absolutely! Perhaps most commonly through developing pictographic ways of displaying concepts or information – so called ‘infographics’, but also through things like photo-montages or edited images to illustrate scenarios like land-use change or sea level rise (see below). Less commonly, but significantly, we have also used models ranging from laser-cut foam landscapes that we can project images and scenarios over, to papier mache topographies developed by communities in workshop situations to help us scientists understand their concept of landscape and its biophysical and cultural linkages.

KD: Can you describe your experience of collaborating with a creative practitioner (Kate) to communicate your research?
DM: I’ve never before worked with a creative practitioner like Kate to develop novel representations of data, but I really enjoyed the experience of investigating a completely valid but non-traditional way of presenting numerical data. I still haven’t completely got my mind around how to interpret numerical data presented in a physical form, but that suggests to me a comfortable familiarity with traditional ways or representing data, and I suspect that after longer exposure I would learn how to ‘read’ such models. I also valued the thought put into the modelling medium. My greatest regret is that I wasn’t located sufficiently close, nor suggested organising video conferencing, so that I would have been better able to understand the creative process as it developed, and fully collaborate in the project as it progressed.

KD: Does displaying scientific research in museums and art galleries change the audience for your research?
DM: I hope that it doesn’t change the audience, because I hope that we communicate our science in sufficient alternative ways that people interested in art galleries are also able to engage with scientific data, but I think that it fundamentally changes the way the audience interacts with it, and potentially understands it better. I also hope that in this tactile form, people have been able to engage with the
work rather than simply look at it. I’m also happy to see the data used to bring a dialogue about the future into spaces which largely deal with retrospective views of the world around us.

**KD:** Did you find the 3D printed models of your research gave you any new insights into your own research?

**DM:** Not really, in this instance, because I suspect that I’m too used to looking at presentations of data in traditional scientific modes. I suspect that I would have needed to be more engaged with the process of converting data into physical models to fully appreciate the assumptions and limitations imposed on converting numerical data to 3D models, and such engagement would have helped me read and understand them.

**KD:** It is important that the models are 3D instead of 2D (i.e. paper based or screen based models) and why?

**DM:** We typically represent numerical data in 2D figures, or if we are reporting data against three parameters we might use a 2D representation of a 3D figure, so most scientists (and probably most non-scientists who have had a secondary education) will be familiar with 2D representations of data, even if those data are currency fluctuations or fuel prices or unemployment figures. Actually, producing a 3D structure which faithfully scale to the data is unusual, and in my experience, I’ve only done it when trying to convey scientific data to people with very limited education. This project has caused me to reflect, though, that while as a teacher I’m concerned about presenting data to students in a variety of ways to accommodate preferred learning styles and thus increase the chance that my students will identify and understand my lectures, I’ve almost always defaulted to standard 2D presentations of data in communicating my research outcomes. It seems highly likely (and is eminently testable) that some people will, however, find physical 3D representations of data more accessible, and thus such an approach may actually widen public understanding of science.

**KD:** Is it important the objects accurately reflect the numerical data informing the objects?

**DM:** It really depends on what you mean by ‘accurately reflect’. The individual numbers are highly constrained simplistic representations of highly complex and dynamic systems at one point in time. As the numbers are the results of modelling, we have already made assumptions, held some changeable parameters constant, and ignored some complexity in order to achieve a surrogate for reality. Reproducing these numerical data in a 3D form might thus justifiably use non-linear scaling to produce objects which accurately reflect the numerical data in a defensible manner.

**KD:** It is important where the objects are displayed and why?

**DM:** Yes, which in turn depends on what the purpose of the objects is? Presumably as artistic representations they serve to stimulate conversation or debate, so where and how they are displayed will provide context for who sees them, what their reactions to the objects might be, and thus what conversation might be stimulated.
**KD:** Does it matter what the models are made of and why?

**DM:** Again, this is completely subjective – at face value it probably doesn’t matter what the models are made of if their purpose is to represent some aspect of the numerical data, but choice of medium can again add a context or help to promote a particular reaction. I’m personally very happy to see them made out of a medium which is not contributing to climate change, but suspect that if identical objects had been made out of coal taken from a shipment due for export they might have stimulated a slightly different reaction and discussion?

**KD:** Should the original data be displayed with the models?

**DM:** Yes, I think so. I would at least like to see a link to the data made available, such as a reference, so that any interested viewer could pursue the original data if appropriate, but to fully appreciate the objects I think that understanding their genesis requires that the underpinning data is important. As I comment below, I think earlier and more collaborative co-development of such a project could improve the dialogue between data and object, in which case co-presentation of the data and the object would be essential to understanding both.

**KD:** Can you recommend any ways to improve the process of collaboration between artists and scientists?

**DM:** Early, ongoing, and regular engagement! From my perspective, this is only a collaboration in a very limited sense, as I generated the numbers in isolation, we subsequently had some discussions and I provided the data to Kate, and then I was invited to visit and see Kate’s final objects in an exhibition setting. As explained above, the numerical model is a prediction of what may happen in a very unpredictable world, and the objects are a re-interpretation of those numbers. I wonder if in a fuller collaboration, with Kate engaged, contributing and understanding the numerical modelling process, and me then engaged, contributing and understanding the 3D object development from those numbers, whether we could have arrived at outcomes which might have transcended the two disciplines and enhanced communication between them?

**KD:** Do you anticipate that you will collaborate in the future with artists or designers to creatively communicate your research?

**DM:** I would jump at the chance, if the opportunity arose!
Interviews with collaborating scientist Dr. Sarah Perkins Kirkpatrick

Questions by Kate Dunn sent by email to Dr. Sarah Perkins Kirkpatrick on the 16th of March 2017. Dr. Perkins Kirkpatrick responded by email on the 19th of April 2017

Background: One of the hypothesis of my research is that objects allow viewers to understand information in different ways to images and graphs. I have chosen 3D printing because it allows you to accurately translate numerical data to 3D form. I have used sustainable materials for the 3D printing because I theorise that if you are making objects that reflect climate change research, the objects should not be contributing to climate change in their processing and disposal.

KD: Do artists and designers contribute to communicating scientific research, and what is different about how they do that compared with other channels that you use to disseminate your research?

SPK: The general public seem to understand more :) Science is all graphs and numbers, and not everyone thinks that way so it can be difficult communicating our results with these resources. Artists and designers have a different way of thinking and presenting to us, allowing us to reach a wider audience, often with using less words in the explanation. So, Artists and designers definitely contribute to communicating scientific research.

KD: Can you describe your experience of collaborating with a creative practitioner (Kate) to communicate your research?

SPK: At first I was skeptical because I couldn’t see how wart and science could work together. I thought it was a really weird linkage. But She has been very easy to work with. She showed me examples of how art could translate scientific knowledge and immediately I began to see what she could do with my data. It was a very educational and enjoyable experience, and has made me very open to working with other artists in the future.

KD: Does displaying scientific research in museums and art galleries change the audience for your research?

SPK: Definitely. It’s a wider audience, that may not have an immediate interest in my work but still might enjoy it or learn something all the same.

KD: Did you find the 3D printed models of your research gave you any new insights into your own research?

SPK: I wouldn’t say new insights. Just a different way of showing it. I knew heatwaves have increased, but it was a different, more striking way of expressing this change. To me it was more cementing what I already knew.

KD: It is important that the models are 3D instead of 2D (i.e. paper based or screen based models) and why?

SPK: Yes, they look real and tangible, almost more interactive. It gives more presence to the data, why use a 2D model when you can just plot a graph?

KD: Is it important the objects accurately reflect the numerical data informing the objects?
SPK: Yes. There needs to be accurate scale, otherwise it is not true to the underpinning science. I would have serious reservations if accuracy was not upheld.

KD: *It is important where the objects are displayed and why?*
SPK: No, so long as they reach a wide audience, with a good explanation, that’s targeted to that audience. They could be shown anywhere!

KD: *Does it matter what the models are made of and why?*
SPK: Yes. I really appreciated Kate’s philosophy in using recyclable materials. I would be hypocritical to print out heatwaves on plastic. We need to reduce landfill and reduce our addiction to fossil fuels and the arts are no exception to this.

KD: *Should the original data be displayed with the models?*
SPK: Depends on the audience. It might help with the interpretation of the model. It might also give the audience extra material for them to look up, and also give validity to the model (i.e. that it’s backed up from a credible source). I don’t think it hurts, but it would depend where it’s displayed and why.

KD: *Can you recommend any ways to improve the process of collaboration between artists and scientists?*
SPK: It’s going to be difficult to convince scientists, we’re a skeptical bunch! What did it for me was a one-on-one conversation with Kate. If Artists are happy to individually approach scientists and look past the skepticism, then there might be more success.

KD: *Do you anticipate that you will collaborate in the future with artists or designers to creatively communicate your research?*
SPK: Definitely! Though I can’t necessarily see the “art” in my work, this needs to come from them.
Appendix B
Powder Printing Research

Samples of tests
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### Preparation Process
- Mix and sieve through 80micron mesh

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Mix and sieve through 120micron mesh using a vibratory sieve
mix
mix using a commercial
mix
Appendix C
Robotic 3D Printing Material Tests Samples
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<td>Earthenware</td>
<td>Casting slip: Kaolinite, Crystalline Silica, Water, Sodium Silicate, Polyacrylate Dispersant</td>
<td>Cellulose fibre</td>
<td></td>
<td>The cellulose fibre stayed in suspension in the material however tended to clump during extrusion and upon deposition. Due to the absence of porosity in the cellulose fibres, the slip drying and setting time was unchanged from the base material.</td>
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<td>2</td>
<td>Earthenware</td>
<td>Casting slip</td>
<td>Unbleached Paper Pulp 30% by volume</td>
<td>Water</td>
<td>The paper pulp is aerated through its fabrication process and when added to the base creates an aerated even, lumpy texture. The tool path lines, once layered, tend to slump on corners as the tool path changes direction. The paper absorbs moisture quickly and also dries quite quickly, facilitating a quicker drying and building time once exposed to air on the fabrication bed. The paper also gives some structural integrity to the lines deposited.</td>
<td></td>
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<tr>
<td>3</td>
<td>Earthenware</td>
<td>Casting slip</td>
<td>Unbleached Paper Pulp 30% by volume</td>
<td>Maltodextrin &amp; fine sugar dry weight added to base mix before water. 16% each</td>
<td>The texture is very similar to mix 2 however the sugar and maltodextrin make the mix quite sticky, facilitating the layered toolpath deposits adhering each other and deposition bed. The material bonds to itself better and thickens on contact with air however can still only deposit 3 layers at a time before resting the material and allowing it to set.</td>
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<tr>
<td>4</td>
<td>Earthenware</td>
<td>Casting slip</td>
<td>Unbleached Paper Pulp 30% by volume</td>
<td>Maltodextrin &amp; fine sugar dry weight added to base mix before water. 16% each</td>
<td>Methylated spirits 3% added to liquid by volume</td>
<td>The texture is quite different with the addition of the methylated spirits. The mixture becomes thicker and holds its shape a little better. Once set, the material goes hard and is reasonably strong even in an unfired state. Methylated spirits is added to facilitate evaporation. As the material is deposited the alcohol evaporates in the air. The sugar and maltodextrin solidify with the water content in the slip. This allows the layers to double to 6 at a time before resting.</td>
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<td>5</td>
<td>Earthenware</td>
<td>Softwood Particles 20% by volume</td>
<td>Bentonite 5%</td>
<td>Quite Textured with some particles being up to 4mm long and 2mm wide. The bentonite absorbs moisture and acts to hold the materials in suspension. Because the bentonite is a type of clay, it shrinks as it dries at a different rate to the Kaolinite in the casting slip. This causes some problems in the deposition in that as the material dries, it becomes quite lumpy and wants to separate. The softwood particles act as a lattice or structure and help hold the materials in place.</td>
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This test series marks the beginning of an alternative to slip casting whereby a mould is filled to the edge or top of the mould and a hollow shell is formed from the outer wall inward through the plaster absorbing the clay slip material. The excess in this process is then emptied. This method causes overspill and wastage of time and materials through the need to trim excess material and the loss due to spillage and mistimed absorption. The multiple axis rendering of a material wall straight on to the surface of the inside of a closed mould potentially eliminates wastage in the trimming process and by selective delivery of material.
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<td>PW + poly</td>
<td>1 round</td>
<td>4</td>
<td>#0</td>
<td>56mm off the plaster</td>
<td>heat gun 100°</td>
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<td>17-Jul</td>
<td>3</td>
<td>PW + poly</td>
<td>1 round</td>
<td>4</td>
<td>#0</td>
<td>56mm off the plaster</td>
<td>heat gun 100°</td>
<td>Plaster</td>
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**NOTES**

1 Data notes generated as part of robotic clay extrusion, Kate Dunn University of Sydney 2015
### Appendix D

**Table of Ceramic Process and Material Terms.**

<table>
<thead>
<tr>
<th>Term</th>
<th>Definition</th>
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<tbody>
<tr>
<td>Clay</td>
<td>The pure form is hydrated silicate of aluminium, or kaolinite. In a workable form it is a plastic material or clay body that sets upon drying.</td>
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<tr>
<td>Clay Body</td>
<td>Clay body describes a clay mixture, designed for specific functions. Ingredients are added give the body particular qualities. For example, to lower or raise the firing temperature, increase plasticity, or change the fired colour.</td>
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<tr>
<td>Casting Slip</td>
<td>A clay and water mixture, held in suspension, commonly used for slip casting.</td>
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<tr>
<td>Clay Paste</td>
<td>A clay body containing below 40% of clay materials as well as feldspathic materials and silica. Examples include Porcelain and Bone China.</td>
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<tr>
<td>Aggregate</td>
<td>In the context of construction or clay it refers to crushed materials added to a body to add different properties of strength, moisture absorption and refractory properties.</td>
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<tr>
<td>Grog</td>
<td>Grog is ground, fired clay added to clay bodies to give refractory qualities, helps the clay to dry uniformly, cut down shrinkage, warping and cracking during the drying process. Grog can also mean filler such as sand or quartz. As with aggregate it is graded by a series of mesh screens of different width holes. (Hamer 2004)</td>
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<tr>
<td>Plasticity</td>
<td>The unique property held by clays that combines the strength of a solid with the fluidity of a liquid. 1) Plasticity can be determined in terms of slide or ‘shear’ (the initial response to pressure.) 2) Strength is attained by a mix of particle sizes and thixotropy, which holds fine particles in a strong network. (Hamer 2004)</td>
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<tr>
<td>Thixotropy</td>
<td>The properties of slips to change fluidity when left undisturbed; the slip at rest becomes more viscous. This is the result of the establishment of mutual attraction bonds between the particles. (Hamer 2004)</td>
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<tr>
<td>Viscosity</td>
<td>The stiffness of a liquid created by the friction amongst its particles and molecules. Viscous slips are thick and pour with difficulty. Viscosity is measured in units called poise. (Hamer 2004)</td>
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<tr>
<td>Fluidity</td>
<td>The property of flowing or moving freely without friction. The friction is between adjacent molecules or particles such as clay particles. Fluidity is measured in rhe. (recast values of viscosity) rhe= 1/poise. A thick or stiff casting slip might have a rating of 0.002 rhe. Water has a fluidity rating of 100 rhe. (Hamer 2004)</td>
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<tr>
<td>Flow rate</td>
<td>The volume of fluid that flows past a given cross sectional area per second. Volume Flow Rate (SI:m³/s)</td>
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<tr>
<td>Flocculant</td>
<td>A soluble material added to a suspension to increase the viscosity. The material is generally an acid, for example vinegar or calcium chloride. (Hamer 2004)</td>
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<tr>
<td>Deflocculation</td>
<td>Dispersing the fine clay particles in a slip so that the slip becomes more fluid. This allows for a higher density of clay while remaining fluid enough to be poured. The deflocculant is a soluble material added to clay suspensions (slips). The deflocculant creates fluidity by increasing the electrostatic forces of repulsion. The clay particles slide past each other rather than clumping in the suspension. Common deflocculants include sodium carbonate, potassium carbonate and sodium silicate. (Hamer 2004)</td>
</tr>
<tr>
<td>Refractory</td>
<td>This term refers to the material attribute of experiencing high temperatures as well as frequently changing temperatures without deforming.</td>
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<tr>
<td>Firing</td>
<td>Generally done in kilns, the clay objects are heated to a minimum of 800 degrees, causing the clay particles to vitrify or harden.</td>
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<tr>
<td>Vitreous</td>
<td>Clay particles are bonded to a glass like material with very low porosity.</td>
</tr>
<tr>
<td>Porcelainous</td>
<td>Generally white clay with high kaolin content and little or no grog.</td>
</tr>
</tbody>
</table>
Appendix E
Examples of Formats of Scientific Research informing the investigations
into potential three dimensional visualisations

Research is compiled here from:

Dr. Caroline Lehmann

Dr Dan Metcalfe

Dr. Sarah Perkins Kirkpatrick
Defining global units of fire
Quantifying the dimensions of fire on Earth today

C. Lehmann, S. Archibald, J. Gomez-Dans and R. A. Bradstock

1. Department of Biological Sciences, Macquarie University, Australia
2. Natural Resources and the Environment, CSIR, South Africa
3. Department of Geography, University College of London, UK
4. Institute for Conservation Biology and Environmental Management, University of Wollongong, Australia

Current understanding of controls on fire

- Fuel and weather are dominant constraints on burned area
- Fuel & weather show opposite trends along productivity gradients – fuel is too wet or there is not enough...
- Energetic considerations should constrain multiple dimensions of fire – e.g., frequency & seasonality should relate to the probability of flammable conditions
- Trade-offs among fire characteristics should help us identify potential “fire regimes”

The “fire regime”

- Repeated pattern of fire at a location
- Alternate suites of plants traits relate to alternate fire types
- Alternate fire types imply defined relationships among fire characteristics forming those fire types/regimes
- E.g., where fire is frequent, fuel loads capable of producing intense fire would not have time to accumulate.
- Fire return times and intensity should be very related
- Hence, regimes with frequent, high intensity fires should not exist (today)

Fire is a product of vegetation and climate; vegetation is strongly controlled by both climate and fire

Research Summary Dr. Lehmann
Introduction
Habitat restoration can increase landscape resilience by increasing landscape linkages, buffering fragile habitat or protecting ecosystem services
• Revegetation and restoration are attempted for various reasons
• Species compositions of plantings depend on cost, availability of stock, landscape context, purpose of planting, etc.
• Typically, restoration aims to produce an analogue of the former natural vegetation type on that site
• Current vegetation distribution is largely determined by climatic factors
• Climate change will alter rainfall patterns, temperatures, humidity, etc.
• Existing environmental envelopes for current plant communities are going to change

Methods
Whole of catchment vegetation for the Tully and Murray catchments in the Wet Tropics of Queensland was modeled, and climate change scenarios were applied to compare vegetation responses at a whole catchment scale, looking specifically at riparian forests, and looking at cleared riparian areas in the lowlands which are targets of revegetation works.
Climate change scenarios were developed using a feed forward artificial neural network (Hilbert, Ostendorf & Hopkins 2001) using climate, soil parent material and terrain variables to characterise future potential distribution of 15 vegetation types
Difference in vegetation types between three climate scenarios (pre-European settlement, current and two 2080 warmer, drier scenarios) were analysed using GIS.

Results
• At whole of catchment scale, significant increases in climate suitability for mesophyll vine forest and low shrubland as wetter communities dry out under both climate change scenarios (Fig. 1)
• Declines in cool wet rainforest, tea tree swamps, medium woodlands & coastal complexes (Fig. 2)
• When only considering riparian rainforest, obtain broadly similar results to whole catchment, with transition of inundated communities to drier rainforest types, and of open woodlands to drier scrub types
• Replanting riparian zones with pre-clearance species assemblages could mean 50% of plantings would mature in sub-optimal environmental conditions
• Planting lists containing mesophyll vine forest species may need to be prioritised if current planting conditions permit

Conclusion
This study shows that restoring riparian ecosystems using species assemblages determined from some historic condition or past climate may not encompass the climatic envelope predicted to exist in the future, and thus will result in failed attempts at restoration and waste valuable resources. It also shows the value of climate modelling when deciding on suites of species to be used in restoration.

Reference

Acknowledgements
We thank David Hilbert and Cameron Fletcher for help with modeling climate scenarios, and the Australian Government’s Marine & Tropical Research Facility for funding.

Further Information
Contact: Dr. Daniel Metcalfe
Phone: (07) 4091 8838
Email: dan.metcalfe@csiro.au
www.csiro.au
Sample of Dr. Metcalfe's Climate Change research data informing the models in Case Study Six.
Informing the models
Sample of Dr. Metcalfe's Climate Change research data informing the models in Case Study Six.
Sample of Dr. Perkins Kirkpatrick's Climate Change Data, informing the models on Case Study Six.
MEET THE TEAM

Dr Sarah Perkins

Dr Sarah Perkins is a climate scientist at the ARC Centre of Excellence for Climate System Science, UNSW. She actively researches past, present, and future changes in heatwaves, both globally and Australia. Her most recent work seeks to constrain the large number of metrics used to measure heatwaves and investigating how well climate models can simulate historical events. Sarah is also interested in what drives heatwaves, and how these mechanisms may change over time. This is important since the impacts of heatwaves are very broad and damaging, affecting human health, infrastructure, agriculture, and natural systems. For more information, see www.sarahinscience.com.

The ARC Centre of Excellence for Climate System Science

The ARC Centre of Excellence for Climate System Science is a major initiative funded by the Australian Research Council. The Centre was established in 2011 with extensive investment from the Australian Research Council, the University of New South Wales, the Department of Climate Change and Energy Efficiency, New South Wales Government, Monash University, the Australian National University, the University of Melbourne, and the University of Tasmania. The Centre’s focus, Climate System Science, is the quantitative study of the climate system designed to enable modelling of the future of the climate system. It is built on a core of the sciences of the atmosphere, ocean, cryosphere and land research enabled by the Centre will provide for the enhancement of climate modeling and future climate projections.

2 Screenshots from Climate “Scorcher” Change Awareness Website developed by Dr. Sara Perkins accessed 20/6/2017
On Scorcher, we define heatwaves based on peer-reviewed and published scientific research, conducted at the ARC Centre of Excellence for Climate System Science.

A heatwave is defined as at least three consecutive days where the daily maximum temperature is in the top 10 percent of warmest temperatures for that calendar year.

The website uses daily temperature records that extend back to 1910. See the FAQ below for more information.

**1910**

The Hottest Day was in Eucla on 04-01-1910: 46.7°C

The Longest Heatwave in Cape Leeuwin lasted from 07-04-1910 to 14-04-1910: 7 days
On Scorcher, we define heatwaves based on peer-reviewed and published scientific research, conducted at the ARC Centre of Excellence for Climate System Science.

A heatwave is defined as at least three consecutive days where the daily maximum temperature is in the top 10 percent of warmest temperatures for that calendar year.

The website uses daily temperature records that extend back to 1910. See the FAQ page for more information.

1960

The Hottest Day was in Oodnadatta on 02-01-1960 at 50.7°C.

The Hottest Heatwave in Wilsons Promontory Averaged from 15-01-1960 to 17-01-1960 (2 days) at 37.2°C.
On Scorcher, we define heatwaves based on peer-reviewed and published scientific research, conducted at the ARC Centre of Excellence for Climate System Science.

A heatwave is defined as at least three consecutive days where the daily maximum temperature is in the top 10 percent of warmest temperatures for that calendar year.

The website uses daily temperature records that extend back to 1910. See the FAQ page for more details.

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2010

- The Hottest Day was in Learmonth on 02-01-2010
  - 48.9°C

- The Hottest Heatwave in Wandering Averaged and lasted from 17-01-2010 to 19-01-2010 (2 days)
  - 41.9°C

- The Longest Heatwave in Horn Island lasted from 15-07-2010 to 13-09-2010
  - 60 days
SYDNEY (33.86S, 151.21E)

The solid red line on the graph is the heatwave threshold for this particular station. When temperature exceeds this threshold for 3 or more days, a heatwave occurs.
SYDNEY (33.86S, 151.21E)

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