On Growth and Form 100
13-15 October 2017

Programme:

Friday 13 October (D'Arcy Thompson Lecture Theatre, Tower Building, University of Dundee)

08.45-09.15 Registration

09.15-09.30 Welcome

09.30-11.10 Session 1

09.30-09.50 Matthew Jarron (University of Dundee)
D'Arcy Thompson and the Mystery of Life – On Growth and Form in Context

This introductory talk aims to set the scene for the conference. It will describe the origins of *On Growth and Form* - its wider scientific context, D'Arcy's specific influences and the support he got from colleagues at University College Dundee. D'Arcy's early work on mathematical biology will be discussed as well as the publication of and response to the book.

09.50-10.10 Sarah Bonnemaison (Dalhousie University, Halifax)
D'Arcy Thompson and Organicism

In *On Growth and Form,* D'Arcy Thompson freely navigates between organic and inorganic nature, using one to shed light on the behaviour of the other. The insight, that organic and inorganic share certain patterns of behaviour inspired architect Frei Otto and his research team at the IL to develop modern lightweight structures. Frei Otto studied, among other things, the behaviour of soap film as a modelling technique to find optimum minimal surfaces for tensile roofs and to discover the rules for efficient packing.

In this paper, I show the influence of D'Arcy Thompson's approach to deformation as the result of forces and the influence it had on Otto's conception of lightweight structures. To put these issues in their proper intellectual context, I reach into the philosophy of aesthetics of *Organicism* and focus on the dynamics of invention and interpretation. Invention, in the context of lightweight structures, is aimed to create the most efficient forms using the minimum amount of materials. Interpretation on the other hand, focuses on nature and is aimed at uncovering patterns of behaviour that can inform, in a fundamental way, the design of lightweight structures.

I close with an analysis of one of my tensile architecture projects to scrutinize these two aspects of form making and reflect on a lineage of D'Arcy Thompson in relation to *Organicism*.

10.10-10.20 Mason Dean (Max Planck Institute, Potsdam)
To Build a Shark – 3D tiling laws of the tessellated cartilage of sharks and rays

Sharks and rays have skeletons made of peculiar type of cartilage that has characterized the group for hundreds of millions of years: the majority of the skeleton is unmineralised, but the surface of nearly every skeletal element is covered with a surface rind of geometric, mineralised tiles called tesserae. The top element in the attached picture shows a piece of the skeleton in microCT, with the tessellation network visible. Although this 'armoured' cartilage has been recognized for over a century, quantifying this diagnostic feature of shark and ray skeletons is challenging, given the small size of tesserae and their complex, 3D arrangements. We have, however, developed a

technique for isolating and quantifying morphology and relationships of tesserae. By applying this to a developmental series of stingray skeletal elements, we are determining the structural and geometric laws that govern the organization and development of the skeleton. In this way, the work is relevant to developmental, organismal and evolutionary biologists, but also engineers and materials scientists interested in tiled composites, particularly those with interesting hybrid mechanical properties (eg flexibility and stiffness). Our work is in keeping with D'Arcy Thompson's legacy of illuminating natural geometries, constructional morphology and scaling laws.

10.20-10.30 Madeleine Shepherd (Textile Artist, Edinburgh)
Botanica Mathematica

In this talk I'll give an overview of Botanica Mathematica - a mass-participation textile installation that explores the botanical forms which arise from simple mathematical rules applied to textile construction. In 2013, mathematician Julia Collins and I began work on generative instructions and textile techniques which would result in small sculptural objects resembling trees, flowers and algae. These instructions can be seen as an analogue of a genetic code with the makers' choices, additions and mistakes representing mutations and environmental pressures on growth.

Crafters around the world were invited to explore the patterns and send their work back to me to form part of the "woolly herbarium". The collection now stands at around 75 specimens of "Binary Bonsai" from the UK, Europe and the USA, showing great diversity and imagination. To make sense of the collection some analysis was needed. Taxonomist Jo Macrae visited my studio to examine the trees. We looked at common features and significant differences until each specimen was identified and a phylogeny emerged.

Over the last four years the installation (whole or in part) has been exhibited in Baltimore, Berlin, Dundee, Edinburgh and Kirkwall. The centenary of *On Growth and Form* seemed a fitting year for a final exhibition of the complete collection in the D'Arcy Thompson Zoology Museum, where it could be displayed in the context of the original ideas which inspired the project.

10.30-10.40 Mark Field (University of Dundee)
How to Build a Eukaryotic Cell – Lego bricks and bent membranes

All of life is divided into two domains - cells with or without a nucleus. The transition between these two forms represents one of the major events in evolution, and in keeping with Thompson, is an excellent example of how form is a vital aspect of biology and evolution. Nucleated, or eukaryotic, cells are significantly more sophisticated than non-nucleated, prokaryotic, forms, and the transition between the two occurred over one billion years ago. In this brief overview, I will summarise recent advances in 'eukaryogenesis', and how molecular lego has shaped the form of our cells and provided new functions that have allowed the building of animals, plants and much of the biological world we see around us.

10.40-11.05 Questions

11.05-11.35 Break

11.35-13.00 Session 2

11.35-11.55 Fordyce Davidson (University of Dundee)
From Bacteria to Birds: Understanding Space and Time in Biology

D'Arcy famously used mathematics to try to explain the shape of living things and how they had evolved through time to become that shape. 100 years on, we will discuss some breathtaking examples of how mathematics is being developed at Dundee to helping us understand coordination in space and time in biological systems.

11.55-12.15 Kelly Freeman (University College London)
Growing Bones – D'Arcy Thompson and the formation of the skeleton concept

In 1917 the polymath D'Arcy Wentworth Thompson published his compendious monograph *On Growth and Form*, a comprehensive and influential contribution to the study of twentieth-century zoological morphology. In his eighth chapter titled 'On Form and Mechanical Efficiency', a curious series of illustrations appear: the schematics for several iron bridges flanked by the skeletons of a fossilised bison and a stegosaurus. Taken together, these images invite a comparison between the materials of iron and bone with regards to their 'form' and 'mechanical efficiency', as addressed in the chapter's title. The grouping visually aligns the two materials, an association that is supported by the chapter's accompanying text and the numerous analogies made between the various architectural skeletons of bone and iron.
The mechanical correlation between 'skeleton' and 'bridge' is continued in the subsequent ten illustrations, presented in abridged levels of abstracted detail, which lead the reader from a bone-*like*-iron simile to a bone-*as*-iron perspective. These illustrations are an attempt at converging morphology, with its descriptive approach to the visual appearance of organic entities, with a more mathematical and mechanical method. In light of D'Arcy Thompson's metaphorical and material skeletons, and his reduction of the morphological into the diagrammatical, this paper presents the skeleton as a conceptual model of thought from which new abstract forms were generated. Through the transformation of material skeletons into an abstracted framework, D'Arcy Thompson laid the foundations for a 'skeleton concept' that would permeate the fields of art, architecture and digital-image processing for the next one hundred years.

12.15-12.25 Caroline Erolin (University of Dundee)
Zoology 3D – Creating a Digital Collection of Specimens from the D'Arcy Thompson Zoology Museum

The D'Arcy Thompson Zoology Museum houses many fascinating specimens from around the world, most of which were originally acquired by D'Arcy himself. During 2016 a project to digitise key specimens from the collection was undertaken as part of the centenary celebrations. Smaller specimens were scanned using a Nikon XT H 225ST micro CT scanner, while larger specimens were captured using hand-held structured light scanners (Artec Eva and Artec Space Spider). The resulting 3D models were further processed using the 3D modelling software ZBrush before being hosted online via Sketchfab (https://skfb.ly/PpUo), where they were made available for viewing and downloading worldwide under a creative commons licence. They were subsequently embedded on a new webpage (https://www.dundee.ac.uk/museum/collections/zoology/zoology3d/) as an extension of the existing University Museum website. In addition to the methodology described above, this presentation will briefly discuss the resulting collaborations and benefits of sharing museum collections online.

12.25-12.55 Questions

12.55-14.00 Lunch (including visit to the D'Arcy Thompson Zoology Museum)

14.00-15.35 Session 3

14.00-14.30 Wallace Arthur (National University of Ireland, Galway)
D'Arcy Thompson's influence on Evo-devo and Astrobiology

Evolutionary developmental biology, or evo-devo, emerged as a distinct field of study in the years around 1980. Although the biggest single factor in its origin was probably the discovery of the homeobox in 1984 and the consequent mushrooming of knowledge on developmental genes, another major factor was Stephen Jay Gould's book *Ontogeny and Phylogeny*, first published in 1977 by Harvard University Press, with its famous frontispiece dedication to D'Arcy Thompson. An issue of major importance in evo-devo is the origin of evolutionary novelties. One view of these is that they delimit different zones of morphospace within each of which Thompsonian transformations work but between which they do not work.

Astrobiology is, arguably, an even younger science than evo-devo; though exactly when astrobiology started is an open question. Indeed, we could argue that it doesn't yet exist – at least in the form of actual study of extra-terrestrial life-forms, since none of these have yet been discovered. However, that has not stopped astronomers and biologists from hypothesising about, and discussing, their possible nature. At one side of this discussion is the "don't be a carbon chauvinist" camp, focusing on the possibility that alien life could be very different from is terrestrial counterpart. At the other side is the 'convergent evolution' approach, focusing on the possibility that alien life might in fact be rather similar to life here on Earth. The rapid pace of exoplanet discovery (with about 4000 known as of mid-2017) brings the first finding of alien life ever-closer. But what can we say about D'Arcy's theory of transformations in an extra-terrestrial context? This question leads to an interesting way of exploring the possible nature of evolution on other planets. Biology may not, after all, be a one-planet science.

14.30-14.50 Kim Dale & Philip Murray (University of Dundee)
Working out what makes the segmentation clock tick

A segmented body axis is a conserved feature of all vertebrate species, most overtly seen in the skeleton. Segmentation, which arises early during vertebrate body plan formation, generates repeated segments/somites that later give rise to the vertebral column, most skeletal musculature and dermis. Interference leads to severe segmentation and skeletal defects. During somitogenesis segments bud off the rostral end of the unsegmented paraxial mesoderm (PSM). The periodicity of segment formation is regulated by a molecular oscillator known as the somitogenesis clock which acts in the cells of the unsegmented PSM from which segments are formed. A wealth of knowledge about the molecular players has been acquired through classical embryology experiments that involve the culture of PSM tissue explants from the most posterior, immature part of the embryo.

We use genetic and pharmacological tools to perturb the role of candidate signalling pathways as a means to determine their contribution to the molecular regulation of the oscillatory gene expression. In parallel we design a computational work flow to precisely quantify the effects that the perturbations elicit on oscillatory gene expression using live imaging of real time reporters of dynamic gene expression in PSM tissue. We will discuss our recent findings from this multidisciplinary approach to investigate the molecular mechanism regulating somitogenesis.

14.50-15.05 Peter Burt (University of Greenwich)
D'Arcy Thompson knew my (Grand)fathers

Setting some of D'Arcy Thompson's work in a broader historical context, this presentation will discuss aspects of the careers of two individuals who interacted with D'Arcy through what we would now recognise as D'Arcy's widening participation and outreach activities, as well his abilities as a teacher and a scientist. Coincidentally, despite a mutual professional knowledge of D'Arcy there is no evidence that these two people ever met, but they have a common descendent.

Captain Sir William Adams, from Dundee, was a whaler and navigator of the Arctic and Antarctic. Although D'Arcy's collaboration with the Dundee whalers is well documented, no correspondence between him and William Adams has been found. However, Adams provided material for D'Arcy's teaching collection in University College, and it is highly likely they would have discussed their shared interests in aspects of the whale fishery and meteorology, elements which emerge in D'Arcy's work.

Dr David Burt was a student of Zoology from the time of D'Arcy's move to St Andrews in 1917, and then his Assistant from 1921-1924, before taking up a position as Lecturer in, and later Professor of, Zoology at the (then) Ceylon University College, Colombo. The two remained in contact during the rest of D'Arcy's life and Burt returned from Ceylon in 1946 to take over running the Department of Natural History during D'Arcy's last illness. He also spent the first seven years of his retirement refurbishing the Bell Pettigrew Museum in St Andrews as a labour of love for his friend and teacher.

15.05-15.30 Questions

15.30-16.05 Break

16.05-17.20 Session 4

16.05-16.25 Polly Gould (Newcastle University)
"But things have turned out otherwise…" – feminist critique of parametricism in architectural design

In the 1942 edition of *On Growth and Form*, Thompson expresses the disappointed hopes relating to his discussion of Darwin's *Origin of Species* and the very "curious thing" of "the failure to solve the cardinal problem of evolutionary biology". I employ the feminist philosopher Rosi Braidotti's thinking on transposition as a way to rethink Thompson's transposition, critique visual analogy and the search for resemblance, and avoid the associated foreclosure of future possibility that may occur in its application in architectural design.

By bringing Braidotti's thinking on transpositions to bear upon Thompson's transpositional method, I suggest that despite the fact that Thompson was attending to the patterns of variety and difference in evolution, which are produced through genetic recombinations, his mathematical and formalist method of transposition fails to identify the spontaneous, mutant leaps that evolution generates because his method is one based upon reflection and reversibility. Yet I also want to give account of another context in which Thompson spoke against symmetry; that is Antarctica. Before its discovery, Antarctica had been hypothesised on the basis of symmetry. The idea that the Arctic and Antarctica were analogous and symmetrical in climatic and other matters had also manifested in theories that speculated as to whether the Arctic and Antarctic would prove host to similar species. With regard to this search for resemblance, contributing to the Zoology section in the *Antarctic Manual 1901*, Thompson, specialist in the Arctic and its life forms, did not expect to find

straightforward symmetry with Antarctic life.

My aim is to show how a shift from a movement figured as reversibility partnered with an optic of reflection to an alternative movement figured as Braidotti's transposition partnered with the optic that I have termed as 'refraction', can usefully expose some shortfalls in the application of parametricism in architectural design.

16.25-16.35 Caroline Brown (University of Dundee)
D'Arcy in Dundee

D'Arcy Wentworth Thompson spent 32 years at University College Dundee having been appointed UCD's Professor of Biology at the age of 24. He joined a group of forward-thinking, socially-minded professors who were to have a profound influence on his thinking. This brief talk looks at D'Arcy's Dundee career and the educational and social context in which he wrote *On Growth and Form*, which was published shortly before he left Dundee for St Andrews in 1917.

16.35-16.45 Tracy Mackenna & Edwin Janssen (University of Dundee) (video presentation)
Between Clocks and Clouds – Life, Death & Beauty

The influence of D'Arcy Thompson will be presented through a number of key artworks including *Growth, Form and the Inevitability of Herself* (Tracy Mackenna & Edwin Janssen, 2004) and *On Growth, and Forms of Meaning* (Tracy Mackenna & Edwin Janssen with Marco Stout, 2011). This will be contextualised within the current project *The Museum of Loss and Renewal*. The curators of this autarchic museum, Tracy Mackenna & Edwin Janssen, develop in collaboration with others art projects that address issues of societal concern such as wellbeing, end of life and sustainability.

In *Growth, Form and the Inevitability of Herself*, the growth cycle of a garden is shown in relation to the human process of ageing, focussed through images of Tracy's mother. The video work questions accepted notions of beauty as extreme close-ups of decaying matter become images of striking beauty. The progressive stages of ageing in one woman's life are juxtaposed with detail of plant matter and art historical references. The work is a contemporary still life, nature morte informed by the 17th century Dutch tradition. Eighteen images move hypnotically and independently of each other in a grid pattern across a large scale.

The curated exhibition and event space *On Growth, and Forms of Meaning* played host to a series of multidisciplinary discussions that took D'Arcy's work as the starting point for informal 'experimental' natural conversations exploring ideas around visual thinking, both orally and visually. Content was captured by Tracy Mackenna through 'writing in situ' and conveyed to designer Marco Stout, active in the same space developing a publication through image and text. Through processes of staging, performing and translating, the combined presentation of artefacts from the University of Dundee's D'Arcy Thompson Zoology Museum and on-site generation of artwork in an environment for the interrogation and analysis of a subject positioned the artists' research and practice within a multidisciplinary framework.

16.45-16.55 Rita Hardiman & John Clement (University of Melbourne)
D'Arcy Thompson, the Human Femur, and Melbourne, Australia – growth, form and human function

Since D'Arcy Thompson's definitive work *On Growth and Form*, advances in imaging technologies now make it possible for quantitative anatomists to investigate and quantify dimensional and morphological changes in three dimensions, rather than two. Using non-invasive digital imaging technologies such as computed tomography (micro-, synchrotron and clinical) quantification of

variations in form becomes possible. Acquisition of large amounts of morphological data enables the production of an archetype of form, which we can then manipulate to test the changes produced by external variables. Non-invasive, high resolution imaging of mineralised tissues allows the study of external and internal morphologies, how they relate to each other, and how they relate to mechanical influence which can be physically tested in the same specimen. In this way, Thompson's "adaptations to outward circumstance" can be related to quantified morphology of a biological specimen.

The Melbourne Femur Research Collection (MFRC) is an internationally significant research collection curated at the Melbourne Dental School. It comprises over 600 samples, biometric data, and 5TB of research data including high resolution 3D scans. Because we can quantify bone morphology at various scales of resolution, it opens up possibilities of mathematical modelling to describe and predict tissue adaptations to a variety of external factors. Since Thompson's time, leaps the scientific field of genetics have also been made. Applying genetic studies to the vast amount of quantitative morphological data acquired from the MFRC over the years will enable us to tease out the external environmental effects and those from a genetic source, ultimately leading to a determination of risk factors for mineralised tissue disease. This presentation discusses the history of quantitative anatomical studies on the MFRC, which have advanced the knowledge of three-dimensional growth, form and age-changes in mineralised tissues. This is all possible by following the growth and form lead provided by D'Arcy Thompson a century ago.

16.55-17.20 Questions

17.20-18.30 Reception in Lamb Gallery and opening of On Growth and Form 100 exhibition

18.30-19.30 Keynote – Stephen Wolfram (Wolfram Research)
D'Arcy Thompson and the Growth of Computational Form

Stephen Wolfram is an internationally renowned computer scientists and physicist. Best known as the creator of Mathematica and the Wolfram Language, he is the author of *A New Kind of Science* and the founder and CEO of Wolfram Research. Over the course of nearly four decades, he has been a pioneer in the development and application of computational thinking. His early work on complexity in nature led him to study the behaviour of simple computer programs known as cellular automata. These studies laid the groundwork for the emerging field that Wolfram called complex systems research. He went on to discover fundamental connections between computation and nature, and his work led to a wide range of applications, providing scientific foundations for such initiatives as complexity theory and artificial life. Wolfram himself used his ideas to develop a new randomness generation system and a new approach to computational fluid dynamics, both of which are now in widespread use. In this special keynote lecture, he will discuss the importance of D'Arcy Thompson to his ideas and the development of computational form.

20.00-22.00 Dinner at D'Arcy Thompson Restaurant

Saturday 14 October (Parliament Hall, University of St Andrews)

09.00-09.30 Registration

09.30-11.05 Session 5

09.30-10.00 Tim Ingold (University of Aberdeen)
Making, Growing and the Genesis of Form

In the histories of archaeology and anthropology, a recurrent question has been how to distinguish organisms from artefacts, things made from things grown. Much of the debate has hinged on a dichotomy, going back to Aristotle, between form (*morphe*) and material (*hyle*). According to what has come to be known as the hylomorphic model, things are created through the unification of material and form. The difference between making and growing came to depend upon whether the form, or design, unfolds from within or is imposed from without. To put it crudely, in the making of artefacts, a design that pre-exists in the mind of the maker is imposed upon initially formless raw material; in the growth of organisms, the design is implanted at the point of inauguration of a new life cycle, encoded in the materials of heredity, whence it is manifested in the phenotype. However, setting the boundary of interiority and exteriority is itself problematic, as is evident from examples of the architecture of non-human animals which are supposed to lack cultural tradition, and the patterning of many human artefacts – as in weaving, looping and knitting – that is not imposed but arises from the iteration of an underlying generative schema. As I shall show in this paper, these examples point to the fundamental circularity of the hylomorphic model itself, insofar as it posits form prior to the processes that give rise to it. Drawing inspiration primarily from D'Arcy Thompson's *On Growth and Form*, I shall show how, in both making and growing, the forms of things are generated within fields of force and fluxes of material that cross-cut their emergent surfaces. Thus the distinction between organisms and artefacts is not as hard and fast as we are inclined to think. With both, form arises ontogenetically, in processes of growth.

10.00-10.20 Joseph Klein (University of North Texas College of Music)
Practical Applications of D'Arcy Thompson's On Growth and Form on Musical Materials and Structures

Within the art world, D'Arcy Wentworth Thompson's seminal work, *On Growth and Form*, has had arguably the most significant influence on the fields of architecture and the plastic arts. While Thompson's influence is most obvious in forms that exist in physical space, potential applications of his research as expressed in the temporal realm through the sonic arts, though not nearly as common, are no less striking in their effect or relevance. In particular, the domains of pitch, rhythm, and musical structure are fertile areas for applying models and concepts presented in *On Growth and Form*. Thompson's explorations of the rate of growth in organisms (Chapter 3), the logarithmic spiral (Chapter 11), and transformations and related forms (Chapter 17) provide ample resources that may be fruitfully applied as schemata for musical development.

Examples from my own compositions will be used to illustrate specific principles explored in *On Growth and Form*, as manifested in sound: *the road in its unfoldings* for wind symphony (1996) is a work directly inspired by Thompson's book, and addresses a number of concepts discussed therein; *Occam's Razor* - seven studies for ten players (1999) is another composition that uses models drawn from this book, perhaps even more overtly than the previous work; a third and more recent composition, *Interstices* for flute, saxophone, and percussion (2014) provides further examples of Thompson's influence on micro- and

macro-structural elements. Additional compositions by Edgard Varèse (1883-1965) and Olivier Messiaen (1908-1992) will also be referenced in order to illustrate musical structures and processes that are similar to those explored in D'Arcy Thompson's work. The presentation will include diagrams and musical examples illustrating the influence of Thompson's principles on rhythm, pitch, and musical form, accompanied by audio excerpts of the aforementioned compositions.

10.20-10.40 Meic Pierce Owen (University of Dundee / Fife Council)
D'Arcy – his polymath pursuits, life and times as revealed through his correspondence

D'Arcy Wentworth Thompson's career spanned seven decades. It saw him make significant contributions across a range and breadth of disciplines that would perhaps be impossible today. It spanned a period of not only huge advances in science but also the journey from High Victorian horse-drawn Britain to the dawning of the jet age. D'Arcy saw scientific thought transformed, he saw two world wars and he saw old worlds end and new worlds develop.

Not only did D'Arcy live through these tumultuous times, he also observed them- describing, discussing and commenting on them in his correspondence. He corresponded a lot- his prolific production of letters looking akin to email in their volume to modern eyes- and, being the systematic collector and cataloguer that he was, he kept it all- both incoming and type-copy out-going. He kept it all for the whole of his career- from his time as a student at Trinity College Cambridge in the early 1880s to his death in St Andrews in 1948. He also archived the extant correspondence from his childhood that his father, D'Arcy Thompson the Elder, had likewise kept. He kept it all, the professional and the personal, in filing cabinets in his office. On his death, the whole collection, which extends to well over 35,000 items, was, along with all his papers, transferred to the University of St Andrews Library.

This paper offers a headline walk through the breadth of this collection - shedding light on D'Arcy's thought processes and extensive personal networks as he both developed his own ideas and assisted others in the development of theirs across all his academia - from Marine Biology to Egyptology - and so much more besides! It also headlines D'Arcy's commentary on his life and times - from the great themes of the day to the domestic realities of living through two world wars.

10.40-11.05 Questions

11.05-11.35 Break

11.35-13.00 Session 6

11.35-11.55 Marie-Claire Beaulieu & Jennifer Burton (Tufts University)
Exploring the Intersection of Classics and Biology in D'Arcy Thompson's Glossary of Greek Birds

In the *Glossary of Greek Birds*, D'Arcy Thompson combines his interests in Classics and ornithology to create a reference work which bridges between ancient and modern science. Our team is investigating ways to take advantage of new technology and social media to make this treasure trove of information available to a broad audience while at the same time exploring and exposing Thompson's scholarly and scientific method.

Each entry in the *Glossary* seeks to elucidate an ancient Greek bird name by associating it with a bird species in modern scientific terms. Thompson collects an extensive list of ancient authorities, ranging from mythography and poetry to Aristotle, his preferred informant. These authorities provide the basis for the bird identification, taking into account its appearance, nesting habits,

migrations, etc. Thompson then evaluates the identification proposals of other biologists and makes an identification decision.

There are many different possible ways to represent the rich data of the *Glossary*. An interesting challenge lies in identifying classes of data and the relationships between those classes in a manner that will allow us to use semantic technologies to represent and explore Thompson's reasoning in reaching his bird identification decisions. This process also gives us insight into Thompson's use and understanding of myths. Throughout the *Glossary*, he favours astronomical interpretations of myths which he uses to support his identifications by correlating them with bird behaviors such as nesting and migrations. We will examine the level of consistency among the mythological narratives used to support a bird identification. For instance, the two myths about the bird *aithyia* associate it to women who throw themselves into the sea and become helpful deities for sailors. Collecting data on the mythological assertions throughout the glossary will help us gain an understanding of the bird names from a cultural perspective, as we decode the symbolism associated with each bird, something Thompson was highly interested in.

11.55-12.15 Stephen Marsland (Massey University)
Thompson's Theory of Transformations and Multi-Registration of Images

In the chapter of *On Growth and Form* entitled 'On the Theory of Transformations, or the Comparison of Related Forms' Thompson sets out the hypothesis that the effects of evolution can be seen in global transformations of the appearance of species. He demonstrates this by drawing the outlines of parts or whole animals, super-imposing a regular grid, and then deforming the grid, carrying the outline along with it. Thus, the appearance of one species within a genus can be transformed to another through relatively simple warps that align the gross features of the images. While this chapter has occasioned great admiration, there has been relatively little study of it explicitly; rather it has been used as motivation for a variety of field, most notably morphometrics, and pattern theory (which has led to the diffeomorphic registration of medical images).

One key point that is often missed in modern consideration of Thompson's ideas is that the deformations between closely related species should be simple, which in modern mathematical parlance could be interpreted as based on low-dimensional groups. This is markedly different to the thin-plate splines of morphometrics and the infinite dimensional diffeomorphism group of medical image registration. The second part of Thompson's hypothesis is that species that lie on the evolutionary path between two species should lie along the curve that joins the two points (he posits that his transformation from the human skull to each of the chimpanzee and baboon "differs only in an increased intensity of degree of transformation".

In this talk I will provide an overview of our work to provide a mathematical framework to investigate and utilise Thompson's ideas, through the use of Lie groups, ie mathematical groups that are also smooth differentiable manifolds and hence can be endowed with a metric. I will describe how images (for example, of the various species studied by Thompson) can be registered in a series of different Lie groups, and methods of comparing them through model selection. This approach also enables the various species to be fitted to a curve of development, thus testing Thompson's hypothesis. I will also talk about *multi-registration*, where images are registered using a sequence of progressively larger groups, thus providing more information than standard registration, for example about the significance or insignificance of each group of transformations.

12.15-12.25 Maia Sheridan (University of St Andrews)
D'Arcy on Paper – an introduction to the archives of DWT held at St Andrews University Special Collections

This collection of over 30,000 items was left to the University by D'Arcy's daughter Molly. It can be used to chart the genesis of *On Growth and Form*, to re-create the global networks that D'Arcy was involved in, to follow him on trips to the Bering Straits, Japan and India, as well as documenting his teaching in Dundee and St Andrews, and family matters. It also contains drafts and annotated versions of his publications, where his habit of dropping in multiple languages is a challenge to non-linguists. There will be a chance to view some of the archive during the lunch break.

12.25-12.35 Marija Matejcic (Max Planck Institute, Dresden)
Deconstructing tissue growth and its limits in the developing retinal neuroepithelium

Tissues and organs need to grow to their correct size during development to give rise to an optimally functioning organism. Despite knowing many factors that affect tissue growth, we still know little about what maintains tissue shape and stops it from overgrowing. To shed light onto this, I am studying growth of the pseudostratified epithelium (PSE), a specific tissue type that exists in many different organisms and gives rise to diverse tissues including the liver, gut and brain. Because of this universality, studying the PSE can let us understand very general mechanisms. The novelty of my approach is in following growth, using the developing zebrafish retina as a model, in a quantitative, 3D manner, while these questions were previously addressed mainly in cell culture and/or in 2D.

Retinal PSE cells proliferate, to eventually acquire more specific features and become neurons. I find that this differentiation event ensures the conservation of tissue shape. Without some cells differentiating others cannot elongate to follow tissue growth, thus leading to an aberrant retinal shape. We propose a model in which this inability of cells to elongate results from the amount of 'usable' space being reduced in the tissue by an accumulation of a molecular component, actomyosin. As the number of cells continues to increase during development, the pressure in the tissue increases and to relax it, the blocked space has to be freed. This relaxation would then ensure uniform growth and maintenance of a correct shape of the retina.

Altogether, I show how a particular tissue maintains its shape during growth by controlling subcellular organization in a tissue-cell crosstalk. Our study, with many others, gives detailed insight into the underlying principles of growth that D'Arcy Thompson proposed a hundred years ago - that all biological matter forms and changes only while obeying the laws of physics.

12.35-13.00 Questions

13.00-14.00 Lunch (including visit to On Growth and Form display curated by University of St Andrews Library Special Collections)

14.00-15.35 Session 7

14.00-14.30 Alan Werritty (University of Dundee)
Shaping Geographic Enquiry – D'Arcy Thompson's On Growth and Form

D'Arcy Thompson's seminal monograph O*n Growth and Form* is widely acknowledged by biologists as the first successful biophysical explanation of the size and shape of organisms. In explaining how the shape of plants and animals is determined, Thompson gave mathematical rigour

to the concept that forms follows function. Two of his fundamental ideas – the concept of allometric growth and the theory of transformations – not only radically influenced the development of biology but also stimulated cutting edge advances in geography. In the 1950s and 1960s Thompson's ideas played a significant role in the development of spatial analysis, most notably in influential monographs by Haggett and Bunge and Tobler's liberation of map projections from the constraints of Euclidean geometry. A century after the publication of O*n Growth and Form* Thompson's ideas continue to inform geographical scholarship in Batty's studies on the size, shape and scale of cities, Dorling's World Mapper project and fractal-based analyses of the morphology of river basins. This paper re-assesses Thompson's contribution to geographic enquiry from the 1950s through to the present time.

14.30-14.50 Valerie Bentivegna (University of Dundee)
The Physics of Cancer

Quite recently, a new field has emerged that takes an interdisciplinary approach to biomedical research: the physics of cancer. It is now increasingly clear that as cancer progresses, mechanical changes occur both on multiple length scales: ranging from subcellular, over cellular, to tissue scale. On the other hand, it has also emerged that physical forces can cause change in the behaviour of cells, and that this process could play a part in cancer progression. This is just one example of how D'Arcy's view on science (*"the fertile field of discovery lies for the most part on those borderlands where one science meets another…"*) is being applied to cutting-edge, translational research, specifically by linking physics to biology.

Relying on techniques that were initially developed for material science, new insights have led to a better understanding of cancer development that could lead to better diagnosis, prognosis and treatment. For example, experiments using atomic force microscopy, which allows mechanical measurements at sub-micrometre length-scales, have shown that tumour cells are softer than healthy cells. This is especially true for metastatic cancers, suggesting that mechanical properties can give an indication of cancer aggressiveness.

Other research has shown that physical forces on cells influence their behaviour. For example, cells that were subjected to mechanical pressure, whether this was due to the pressure of a tumour growing in their near vicinity or due to artificially induced pressure, activated regulating pathways that are commonly associated to cancer. This suggests that a tumorigenic pathway can be activated by a number of different means; not only biological but also physical activation is possible.

14.50-15.10 Brandon Taylor (University of Southampton)
D'Arcy Thompson and Surrealism

Thompson's *On Growth and Form* and other publications give rise in some quarters to grave misgivings about the apparent gulf between quantitative and qualitative descriptions of the world. The present contribution surveys the gaps, both methodological and cultural, between Thompson's ambitious physics of the natural world and some contemporaneous philosophies of perception, notably those of art. By what contrasting means did bio-mathematics and art address the distinction between nature measured and nature apprehended? There is evidence that the dissident Surrealists of the *Documents* group had *On Growth and Form* in mind – and other expositions like it – in their rage against mathematics, taxonomy, and natural law. Further, how did Thompson try to accommodate nature's discrepancies (so-called monsters and other exceptional cases) in comparison to painters of the order of Picasso, Miró and Dalí? What part did anamorphosis, the geometry of projection systems discovered in the Renaissance and taken up again in Surrealism, play in Thompson's so-called method of coordinates? How did Thompson's claim that "the harmony of the world is made manifest in Form and Number" stand with those for whom the inter-war period was

anything but ‘harmonious’; for whom ‘form’ must always be unstable, always beyond generalisation and the rule of law?

15.10-15.35 Questions

15.35-16.05 Break

16.05-17.20 Session 8

16.05-16.25 Artemis Yagou (Deutsches Museum, Munich)
Where Biology Meets Construction and Play – D’Arcy Thompson and the Continuum of Knowledge

D’Arcy Thompson was interested in play. In 1933 he published a paper in which he discussed the games and playthings of ancient Greek children (demonstrating at the same time his deep knowledge of the ancient Greek language). This is not the only case where my work on play and toys has encountered the work of D’Arcy Thompson; focusing specifically on building blocks and other construction toys elicits various relevant associations. D’Arcy’s work developed around ideas of structure and construction in nature, with a special interest in birds’ wings and in flying. *On Growth and Form* includes references to the flight pioneer Otto Lilienthal, whose experiments led to his untimely death. Interestingly, Otto Lilienthal and his brother Gustav were instrumental in developing building blocks for children: the stone bricks they invented became successful internationally under the Anker – Richter brand. *On Growth and Form* is connected with building blocks and similar playthings through the shared ideas of construction, ideas which were central to industrializing societies.

Other late 19th century toys such as wooden cubes with animal images cut in an orthogonal grid remind us of D’Arcy’s transformations. He was also deeply interested in the design and structure of bridges, a regular feature of late 19th and early 20th century construction toys. D’Arcy states: “[…] things are *interesting* only in so far as they relate themselves to other things; only then you can put two and two together and tell stories about them.” This is praise for interdisciplinarity as well as a declaration on the continuum of knowledge; the latter emanates from observation and study of even mundane things. In his best known work, whose centenary we celebrate, he states: “We learn and learn, but never know all, about the smallest, humblest thing.”

16.25-16.35 Doug McKenna (Mathemaesthetics Inc)
Evidence of a Combinatorial Basis for Spiral Tendril Growth

Spiralling structures occur in nature at all scales, from atomic particle collision traces to sea shells to galaxy forms. This ubiquity implies high simplicity to the physical and mathematical constraints out of which spirals are emergent phenomena. Based on recent research on the fundamental forms of space-filling curves that perhaps model very long polymers compacted into a small space (such as DNA), there is preliminary mathematical evidence that even in the domain of the very simple 2-dimensional square grid graph, certain very general combinatorial constraints lead to spirals as the only solution. These constraints include self-similar replication of form, connected path self-avoidance, and an odd-width tendril growth structure that maximizes surface area.

16.35-16.45 William E N Austin (University of Edinburgh & Scottish Association for Marine Science)
Molecules and Morphology

For nearly 200 years the taxonomy of Foraminifera has been firmly based upon the traditions of the Linnaean roots of nomenclature and has relied upon their morphology for classification purposes.

Foraminiferal morphologies are intricate and complex, yet up to 25% of modern benthic Foraminifera names are thought to be synonyms. There is therefore a perception in some quarters that Foraminiferal taxonomy is in a state of extreme confusion. Here, I summarise work that illustrates the fusion of molecular and morphological systematics using type material in benthic Foraminifera (Roberts et al., 2016); this approach offers a new prospect for taxonomic stability.

My talk will be illustrated with reference to the above and will draw on some examples of a correspondence and sample collection donated to D'Arcy Wentworth Thompson by Arthur Earland; now in the collections of the University of St Andrews (Robinson & Austin, 2001).

16.45-16.55 Tony Penington for Harry Matthews (Murdoch Children's Research Institute, Melbourne)
Studying Growth Using 3D Photographs for Surgical Assessment

Facial surgery is often aimed restoring normal appearance and growth potential. In some cases it is assumed that intervention will enhance growth potential resulting in catch up growth. As what is normal growth changes throughout childhood a comprehensive understanding of this is essential for proper assessment and planning of facial surgery. Medicine has traditionally used distances or angles between biologically 'privileged' points in order to describe typical and abnormal growth. However, such measurements fail to represent the complete geometry of the surface under study. Modern work with 3D photographs of faces uses a dense array of points on a template face (the descendants of the intersection points on the grids used by D'Arcy Thompson) to provide a standard representation of each face. Based on a sample of 441 boys and 446 girls we provide normative values for growth-rate and direction across the entire surface of the face throughout childhood. These can be used to test for 'catch-up' growth and related issues in surgical evaluation. We present an example assessment of a case of midline cervical cleft.

16.55-17.20 Questions

17.20-18.30 Reception in Bell Pettigrew Museum of Natural History

18.30-19.30 Keynote – Evelyn Fox Keller (Massachusetts Institute of Technology)
Mathematics in Biology – Has D'Arcy Thompson been vindicated?
(The Fauvel Lecture, supported by the British Society for the History of Mathematics)

Evelyn Fox Keller is one of the most internationally respected historians of science. A physicist, author and feminist, she is currently Professor Emerita of the History & Philosophy of Science at MIT. Beginning her career in theoretical physics, she moved on to work in molecular biology before becoming renowned for her work as a feminist critic of science. Over the years she has documented how the masculine-identified public sphere and the feminine-identified private sphere have structured thinking in two areas of evolutionary biology: population genetics and mathematical ecology. Her concern is to show how the selection process that occurs in the context of discovery limits what we come to know. Her books include *Keywords in Evolutionary Biology* (1998), *The Century of the Gene* (2000) and *Making Sense of Life: Explaining Biological Development with Models, Metaphors, and Machines* (2002). The latter has a particular focus on mathematical biology and in this lecture she will discuss the legacy of D'Arcy Thompson's work.

20.00-22.00 Dinner at the Byre Theatre

Sunday 15 October (Large Lecture Theatre, Carnelley Building, University of Dundee)

09.30-10.00 Registration

10.00-11.35 Session 9

10.00-10.30 Armand Leroi (Imperial College London)
D'Arcy Thompson and the School of Athens

In 1910 Oxford University Press published Thompson's translation of Aristotle's great zoological treatise, *Historia animalium*. It is a work in which his deep knowledge of classical literature, zoology and his beautiful prose style are perfectly combined. In the preface to his *HA* he proposed the novel – and now widely accepted – hypothesis that Aristotle had commenced his zoological work in middle age, when he was in the Eastern Aegean. Elsewhere he describes lyrically how the ancient philosopher contemplated the wealth of nature at his feet and so began the science of life.

For Thompson, then, Aristotle was something of a hero. But not in *On Growth and Form*. There Thompson rejects Aristotle's functionalism – and so Darwin's – in favour of an explanatory tradition that is, at once, older than Aristotle and newer than Darwin. Organismal form is not to be primarily explained as adaptation, but as the result of physical forces. Thompson's new champion is Democritus – and, perhaps, Plato with his maths.

In this talk I will outline how Thompson read the ancient natural philosophers, and embedded his own ideas in theirs. And I will try to resolve the conundrum of how a scholar who so loved Aristotle could reject the very foundations upon which his great predecessor's science was built.

10.30-10.50 Ann Warde (Composer and Independent Scholar, Ithaca, New York)
On Growth and Form in Experimental Music Composition and Analysis

Widely respected by both avant-garde and academic musicians, the American experimental composer and music theorist James Tenney (1934-2006), whose early pioneering research included work with psychoacoustics at Bell Labs, is increasingly recognized as one of the 20th century's most insightful musical thinkers. Tenney frames two sections of his 1961 book *Meta-/-Hodos* (reprinted in 2015 in *From Scratch*, a collection of his theoretical writings) with passages from D'Arcy Thompson's *On Growth and Form*. Echoing Thompson's biological notion of an object's dynamic form finding its source in the interaction of multiple forces, Tenney articulates a set of active, musical forces in play at the intersection of human aural perception and musical pattern. He also captures the shape, or form of specific musical entities in "parameter profile" plots, paralleling Thompson's idea that "the form of an object is a 'diagram of forces'."

Deeply influenced by Thompson's thought, Tenney's prescient book importantly encompasses crucial aspects of now well-established contemporary music analysis: use of scientific methodologies as underpinnings for the theoretical study of music (eg musical perception of sound and emotion), linking acoustic and physical concepts such as force, form, energy, and shape to music's unfolding patterns in time, and the notion of similarity among shapes arrived at through mathematical transformations. Tenney employs these concepts (among others) as a means for generalising theoretical discussions of music and thus is able to reach beyond the specifics of particular musical languages. And, in this way, he reaches toward sound itself— the basic material of music; Tenney's theoretical research finds its realisation in his prolific compositional activity.

This talk includes straightforward explications of the influence of D'Arcy Thompson's conceptualisations as far-reaching contributors to a theory of music in which multidimensional

pattern is intertwined with the patterning processes inherent in human aural perception.

10.50-11.10 Andy Hahn (Oregon State University) (video presentation)
The Botanical Work of D'Arcy Thompson and Its Appearance in On Growth and Form

Of the many and varied interests that occupied D'Arcy Thompson throughout his career, it is easy to overlook those relating to botany. Thompson's first major publication was a translation of Hermann Müller's *The Fertilisation of Flowers* in 1883, to which Charles Darwin contributed a preface. There, Thompson garnered the praise of many botanists, particularly for his thorough bibliographic work. Before he was considered for the Chair in Biology at University College Dundee, Thompson pursued overseas botanical posts by reaching out to William Thistleton Dyer at Kew Gardens, whom he would later correspond with over the translation of Greek plant names.

Thompson's botanical interests also made important appearances in both editions of *On Growth and Form*. Pollen grains and meristems appear among his many examples illustrating cell division and tissue formation. Meristems in particular illustrated the more complex cell divisions involved in continual growth, a process Thompson understood as driven by the resulting form. Thompson generated simple equations using radial coordinates to represent leaf forms and corolla arrangement in his discussion of morphology and mathematics. Phyllotaxis was an important enough topic for Thompson to occupy an entire chapter, difficult as it may have been for him. After his initial draft for the first edition, Thompson read further on the topic and decided to completely rewrite it. However Thompson still received some critiques on this chapter from botanists, but their overall response to *Growth and Form* was positive as many wrote to him expressing their gratitude. Still few botanists delved into the possibilities opened up by Thompson until the 1950s collaboration between Alan Turning and C W Wardlaw which resulted in Turing's 'The Chemical Basis of Morphogenesis' and Wardlaw's attempts to translate Turing's complex mathematical ideas into something more palatable for plant scientists.

11.10-11.35 Questions

11.35-12.05 Break

12.05-13.30 Session 10

12.05-12.25 Charissa Terranova (University of Texas, Dallas)
Space, Time, Visualisation – D'Arcy Wentworth Thompson, Joseph Plateau, and the History of Art-Sci Imaging

D'Arcy Wentworth Thompson was a visual thinker. This is not only evidenced by the 554 images in his seminal work, *On Growth and Form*, but by the prose of the text. Simply put, he made pictures using language. Words do the work of lines, brushstrokes, chemical substrates activated by light, filmic montage, and pixels. Passages devoted to an array of force-based causal relations – such as the magnitude of a flea's jump, comparisons of the spongey trabeculae of bones to the cantilevering of the Forth Bridge, and the temporal logic of the shapes and silken surfaces of a cell – crystallise as images in the mind's eye through Thompson's ability to limn with words.

This presentation focuses on the role of Thompson's *On Growth and Form* in the history of art-sci imaging, that is, visualisation between words and pictures. The phrase "art-sci imaging" refers to objects, experiences, and other exploratory and disinterested forms of knowledge made from the use of scientific data, experimentation, and imaging technology. Contemporary examples include living architecture [bioarchitecture], generative art that is both computational and biological [bioart], and moving-image art. After providing a brief overview of the role the book plays in the history of

contemporary art-sci imaging, the presentation focuses on the relationship between still and moving images in Chapter Five, titled 'The Forms of Cells.' Key here is Thompson's invocation of Belgian physicist-cum-artist Joseph Plateau's ideas. While Thompson focuses on Plateau's 3D models of surfaces of revolution (plane, sphere, cylinder, catenoid, unduloid, and nodoid), Plateau is better known as a pioneer of cinema, having invented the pre-cinematographic device, the phenakistoscope. This talk will foreground contemporary art-sci imaging in the aesthetic troika of space-time-visualisation in Thompson's and Plateau's work.

12.25-12.45 Marjorie Senechal (Smith College)
D'Arcy Thompson and Dorothy Wrinch

D'Arcy Thompson influenced a broad spectrum of scientists and artists he never met, but arguably none more deeply than one he knew well: the polymathic, polyhedral, poly-controversial Dorothy Wrinch. Dorothy was a student of Bertrand Russell when she met D'Arcy in 1918; their correspondence, in the St Andrews University Library, shows how D'Arcy nudged her from logic toward biology and fostered her career. He remained her steadfast supporter, through thick and thin and, in the aftermath of her bitter battle with Linus Pauling over the structures of protein molecules, helped get her a coveted fellowship. Conversely, her glowing review of the second edition of *Growth and Form* raised his bleak spirits at a time when "the days are growing shorter." Their affinities were many; I will discuss two that brought grief in the time when "interdisciplinary" was derogatory, not praise: they followed their interests onto no matter whose turf, and they dreamed of, and worked toward, a mathematical biology.

12.45-12.55 Fabian Rost (Technische Universität Dresden)
Cellular behaviours driving growth in the regenerating axolotl spinal cord

D'Arcy Thompson became interested in regeneration early on – in 1884 he published a paper in *Mind* on 'The regeneration of lost parts in animals'. Later, he became especially interested in the regenerative growth, which he perceived a particular case of the general phenomenon of growth. For him it remained to hope that a simple explanation for the curves of growth might be found. Our own current research focused on identifying the cellular behaviours that underlie the spinal cord regeneration of the axolotl, *A. Mexicanum*, after tail amputation.

For our study, we combined quantitative data, which we derived by image analysis, and mathematical modelling. In particular, we measured the time-course of the cell proliferation rate. This identified a high-proliferation zone in the regenerating spinal cord that shifts posteriorly over time. Furthermore, we quantified cell influx into the regenerate by tracking sparsely-labelled cells. Finally, we set up a mathematical model of regenerative growth that involves cell proliferation, neural stem cell activation and cell influx. With our model, we showed that, while cell influx and neural stem cell activation play minor roles, the acceleration of the cell cycle is the major driver of regenerative spinal cord growth in axolotls.

12.55-13.05 Andy Lomas (Digital Artist, London)
Constrained Forms – Influencing Morphogenesis

Inspired by the work of Alan Turing and D'Arcy Thompson, *Constrained Forms* is the latest stage of an artistic exploration into creating form through digital simulation of growth processes. Computational simulation of morphogenesis is used to create a system that generates complex emergent forms, which when combined with a number of additional constraints and influences can give rich and often unexpected behaviour.

In a manner analogous to D'Arcy Thompson's studies of how variations of the same growth

processes can create an enormous variety of resulting forms, in this work the author has taken the system that he previously used for a body of work called Cellular Forms, which uses a simplified model of morphogenesis at the level of cellular units, and explored the use of additional constraints and influences to try to create structures with desired properties such as limiting overhang angles to aid fabricability, or to give differentiation of structure in specified directions.

Various methods are explored including:

- Controlling the source of nutrient that allows cells to grow.
- Directionally biases to the diffusion of nutrient between cells.
- Biases to the plane of cleavage when cells split.
- Parameter selection using evolutionary and machine learning techniques.

The desire is to keep rich emergence, often resulting in complex alien but familiar combinations, influencing the results to achieve aesthetic goals through iterative experimentation rather than explicit directorial control.

13.05-13.30 Questions

13.30-14.30 Lunch

14.00-17.00 Visits (D'Arcy Thompson Zoology Museum, LifeSpace, CentreSpace and other locations – details provided on the day)

17.30-18.30 Dark Dundee walking tour
(please note – this event is bookable on https://www.darkdundee.co.uk/tours/dead-centre-sunday-15th-october-5-30pm/)