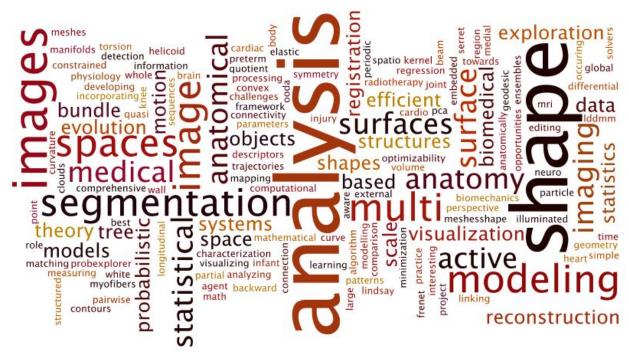# BIRS Workshop Report: Geometry for Anatomy (11w5018)

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Wordle produced based on the workshop talk titles (www.wordle.net)

Workshop Objectives

The primary objectives of the proposed workshop include the following:

- Provide a venue for discussion among researchers, whose interests overlap in the area of developing mathematical/computational techniques to study the geometry of anatomical structures, with the long term goal of advancing health care by maximizing the benefit from the wealth of data provided by different medical imaging modalities.
- Establishing links, identifying commonalities, and highlighting differences between closely related mathematical and computational approaches for shape modeling, analysis, processing, visualization, and interpretation developed in the different communities; promote cross fertilization and exchange of ideas between participants in these communities leading to the initiation of new collaborations.

- Create links between Canadian universities (researchers and students) and leading international research groups and provide a selected group of students with the opportunity to be immersed in a world-class, research-discussion intensive environment.
- Establishing communications between the computational scientists, clinicians, and industrial representatives, to identifying primary foci for accelerating technology transfer into the health care sector.
- Identify key future research challenges and directions from different perspectives: scientific / theoretical (computational / mathematical), industrial / translational, academic / pedagogical, as well as clinical and societal (health-related).

We believe that this meeting of minds under the common theme of "geometry for anatomy" will promote cross-fertilization between the different fields of computer science and mathematics, which are otherwise rather separate from each other. Currently, there is no other conference or workshop that brings these researchers in one forum or venue. We envision the proposed workshop can change this situation and set the stage for the development of a regular bi-annual or annual meeting to best serve the different communities. The medical imaging and clinical applications will not only bring these different communities together to discuss common and overlapping research issues, but will also expose new challenges to these communities from different perspectives in order to help direct research agendas for scientific advancements as well as the translation of research into clinical practice. The workshop will bring scientists from pure/applied mathematics, medical image analysis, computational anatomy, computer vision, computer graphics and visualization under one roof. The different backgrounds yet common goals and interests of the invited participants will naturally result in stimulating discussions, excellent mutual-learning opportunities, and advancements to both theoretical research areas in the mathematics of shape and to practical clinical applications focused on anatomical structures. With an aging population and increasing cost of health care, we believe the outcomes from such a meeting will offer great social and economical benefits to Canada.

Workshop Overview

This workshop was a five-day scientific retreat held at the Banff International Research Station for Mathematical Innovation and Discovery (BIRS). The workshop attracted many world-renowned researchers in the areas of medical image analysis, shape statistics, 3D visualization, computer graphics, geometry processing, and biomedical applications, who represented top universities and industries.

The workshop provided a forum for in-depth discussions and stimulating interactions among high caliber researchers working on the acquisition, processing, analysis and visualization of geometrical objects in various medical applications. The workshop helped foster multidisciplinary research by bringing together mathematicians, computer scientists, engineers, physicists and clinicians.

Workshop Themes

The workshop discussions and talks revolved around the following five themes:

Theme 1: Clinical Applications and Translational/Industrial Perspective for anatomy

Theme 2: Shape Modeling, Representations, and Synthesis for Anatomy

Theme 3: Shape Extraction from 2D and Volumetric Medical Image Data

Theme 4: Geometry Processing, Analysis, and Recognition

Theme 5: Shape Rendering, Visualization and Interaction

Overview of the Field

The title of the workshop is "Geometry for Anatomy". According to the Merriam-Webster dictionary, geometry is "a branch of mathematics that deals with the measurement, properties, and relationships of points, lines, angles, surfaces, and solids; broadly: the study of properties of given elements that remain invariant under specified transformations", or "surface shape". The origin of the word comes from the Latin word *geometria,* which means to measure the earth. Anatomy, on the other hand focuses on the study of the different parts of an organism, such as the human body, with a Latin origin, *anatomia*, meaning dissection. Hence this workshop focuses on the application of methods from the field of geometry applied to studying anatomy. In other words, this area is concerned with studying the shapes of body parts. The ultimate goal of such studies is improving human health and quality of life, which in turn relates to better understanding ailments or diseases, and attempting to answer questions such as how does a disease affect the geometry of anatomy, how can we predict a disease or disease progression by examining the shape of underlying anatomy, how does shape or form influence function and how function affects shape, etc. We wish to understand how anatomical shapes change with time or age, with disease state, and between individuals, in an effort to better understand, prevent diagnose, and treat diseases. As indicated by the workshop themes, this field deals with a variety of topics, including the different clinical applications, modeling or representing anatomical shapes, fitting such shape models to real data, manipulating the shapes, forming an understanding of such shapes (e.g. recognition), as well as displaying and interacting with such shapes using different input/output devices. It is important to emphasize the importance of medical imaging technologies (e.g. magnetic resonance imaging or computed tomography) when discussing this workshop, as medical images are the primary source for acquiring shapes of anatomical structures.

Recent Developments

The recent developments in the area of Geometry for Anatomy are quite challenging to summarize, since the majority of such recent developments has been a result of efforts by a number of different scientific communities and researchers with disparate foci. These foci included: mathematics, statistics of shape, image analysis and computer vision, graphics and geometry processing, shape visualization and user-interaction, as well as the end-user perspective through clinical or industrial implications. We believe this is the first workshop that brings world-renowned researchers from all these different areas together in an effort to form a scientific community that works together on solving relevant problems and achieve the aforementioned goals. Most related research developments can be reviewed by examining scientific papers published at a variety of conferences, such as the following few examples: Medical Image Computing and Computer Assisted Intervention, Information Processing in Medical Imaging, SPIE Medical Imaging, the International Symposium on Biomedical Imaging, Shape Modeling International, SIGGRAPH, Symposium on Geometry Processing, Eurographics, and IEEE Visualization, as well as many journals such as these few examples: Medical Image Analysis, IEEE Transactions on Medical Imaging, IEEE transactions on Pattern Analysis and Machine Intelligence, IEEE Transactions on Visualization and Computer Graphics, ACM Transactions on Graphics, and Computer graphics forum. Relevant research has been published in other venues focused on mathematics, statistics, imaging sciences (e.g. computer vision), as well as many clinically-focused meetings and journals.

Workshop Website

The following website is devoted for the workshop:

http://www.birs.ca/events/2011/5-day-workshops/11w5018

The website contains additional details about the workshop, e.g. schedule, videos, and image gallery.

Participants

The workshop attracted 43 participants from top research labs and universities (e.g. Johns Hopkins University, GeorgiaTech, INRIA) and industries (Siemens and Philips) from North America, Europe and Asia. Below is a complete list of participants along with their affiliations.

Abugharbieh, Rafeef	University of British Columbia
Amenta, Nina	University of California
Andrews, Shawn	Simon Fraser University
Booth, Brian	Simon Fraser University
Damon, James	University of North Carolina
Deng, Zhigang	University of Houston
Dryden, Ian	University of South Carolina
Fletcher, Tom	University of Utah
Florack, Luc	Eindhoven University of Technology
Giblin, Peter	University Of Liverpool
Grady, Leo	Siemens Corporate Research
Grimm, Cindy	Washington University
Groeller, M. Eduard	Vienna University of Technology
Hamarneh, Ghassan	Simon Fraser University
Huckemann, Stephan	University of Goettingen
Jacob, Christian	University of Calgary
Joshi, Sarang	University of Utah
Jung, Sungkyu	University of Pittsburgh
Kazhdan, Michael	Johns Hopkins University
Kim, Peter	University of Guelph
Kindlmann, Gordon	University of Chicago
Kurtek, Sebastian	Florida State University
Marron, J. S.	University of North Carolina
Moeller, Torsten	Simon Fraser University
Nielsen, Mads	University of Copenhagen
Pennec, Xavier	INRIA-France
Pierrynowski, Michael	McMaster University
Pizer, Stephen	University of North Carolina, Chapel Hill
Pottmann, Helmut	King Abdullah University of Science and Technology
Saad, Ahmed	Simon Fraser University
Sheffer, Alla	University of British Columba
Siddiqi, Kaleem	McGill University
Sommer, Stefan	University of Copenhagen
Srivastava, Anuj	Florida State University
Sundaramoorthi, Ganesh (observer)	King Abdullah University of Science and Technology
Tagliasacchi, Andrea	Simon Fraser University
Taylor, Chris	University of Manchester
van Kaick, Oliver	Simon Fraser University
Whitaker, Ross T.	University of Utah
Yezzi, Anthony	Georgia Tech
Zhang, Hao (Richard)	Simon Fraser University
Zhou, Kevin	Siemens Corporate Research

Sessions and Presentations

The workshop included 15 scientific sessions (each included 2-4 short presentations) and several sessions devoted to extended discussions. Please refer to the workshop website for the detailed workshop schedule.

Outstanding Challenges and Open Questions

Extended discussions focused around outstanding challenges and open questions and can be summarized under the following topics (sub-topics, keywords, comments or key questions follow each topic):

- **Shape Manifolds:** shape spaces; manifold structure, shape parameterization; shape correspondence; shapes distances; choice of metric; quotient out parameterization (or not); shape transport in Riemannian geometry; diffeomorphisms (or not); differentiating signal from noise in shapes;

- **Shape Evolution:** statistics of cyclic or stochastically repetitive data; decomposition of amplitude and phase variation, e.g. registration and growth curve analysis; differential geometric setting for evolving shapes; real-time modeling and simulation of dynamic anatomic structures from multimodal medical imaging; the evolution of medial or skeletal shape models; biological evidence, growth only vs. creation of matter (not just deformation); spatio-temporal data objects, geodesics between spatio-temporal objects, practical solutions; will singularities appear in real data; neighborhood of singularities.

- **Method Evaluation:** benchmark datasets for comparing different shape analysis methods, especially in classifying healthy versus normal; reproducibility/external-validation: how to encourage/facilitate more sharing of software implementations, and results on interesting real-world datasets; requirement of for reward/motivation for sharing software; publication venues where there is value in performing validations and comparisons on real data; the Insight Journal (ITK-specific); Websites and organizations: NITRC.ORG , NIBIB, NCIGT, NAMIC, ADNI, OASIS, eurobioimaging.eu; agreement on how to evaluate (besides sharing data); Ground truth?; competitions (e.g. MICCAI Challenges); contrast with computer vision databases for object recognition; high dimensionality small sample size; need for large population; error measures; the problems with the popular Dice similarity coefficient (DSC) for evaluating segmentation: extremely shape sensitive, gives much credit for easy part, no localization; DSC and overlap measures agree with human evaluation?; evaluation of clinical outcome; web services (vs. data / software); bring data to software or vice versa.

- **Machine Learning:** machine learning of objects in images; uses of large amounts of training data; generative vs. discriminative (regression); machine learning for the segmentation initialization problem; machine learning for the data term / for feature detection; generative models for explaining data; machine learning for interactive systems; for biomarker discovery; explaining the "features" or what the ML system does; "classifiers" in clinical practice (rules that clinicians follow); explainable (to doctors) classifiers; facilitating the flow: research lab → drug company → FDA; mixing generative and discriminative models; visualization and interaction to understand the "black box"; semi-supervised methods.

- **Dimensionality Reduction:** dimension reduction for shape data; finding the right dimension; uncertainty in the manifold; development of (generic?) robust higher dimensional descriptors of geometric data and a nonparametric asymptotic statistic thereof; comparison of approaches for the analysis of non-Euclidian data.

- **Other topics** (proposed panel discussion topics) that were discussed briefly include:
  - Visualization that uses mathematics of or statistically defined spaces of object geometry
  - Learning methods and their generalizability
  - Free parameters: avoiding many free parameters (making variables commensurate); understanding the meaning of parameters
  - Weighting terms and forming the distributions; distribution on parameters

- Statistically-based actions on anatomy, e.g., hypothesis testing, classification, posterior optimization
- Statistics on the non-linear shape spaces to which objects of computational anatomy often naturally belongs
- Statistically meaningful shape analysis for biological research.
- Statistical models of shape recognizing (local) interactions
- Location specific hypothesis testing
- Scales; multi-scale shape analysis
- Object oriented data analysis
- Mathematics of object shape
- Applications for deformable models in medical applications
- The unique challenges, the commonalities and differences between the different groups (disciplines)
- Cross-divisional collaboration across the full chain of physical science, life science, and clinic
- The role of non-clinical or pre-clinical image analysis work

Scientific Progress and Meeting Outcomes

The workshop was successful in bringing together leading researchers from different disciplines under the common theme of geometry of anatomy. Presentations by the participants were successful in showcasing state of the art research and, more importantly, exposing how the topic of 'geometry for anatomy' is viewed and treated by researchers from different disciplines. The workshop provided a stimulating environment for investigating and discussing the latest in mathematical and computational methods for the study of geometry for anatomy, as well as present different clinical and industrial perspectives. Discussions between participants resulted in forming new collaborations between researchers with complementary expertise. Open questions and outstanding challenges were identified The organizers received very positive feedback from the participants highlighting their appreciation of the scientific atmosphere, the excellent group of researchers, and the ample opportunities for discussing various challenges in the field.

Presentation Highlights

1. **Peter Kim** (presented jointly with Michael Pierrynowski)
   Frenet-Serret and the Estimation of Curvature and Torsion

   (Joint with Kwang-Rae Kim, Ja-Yong Koo, and Michael Pierrynowski)

   In this talk we approach the problem of analyzing space-time curves from a functional data analytic point of view. In terms of classical geometry, the characterization of space-curves can be summarized in terms of a differential equation involving functional parameters curvature and torsion whose origins are from the Frenet-Serret framework. In particular, curvature measures the rate of change of the angle which nearby tangents make with the tangent at some point. In the situation of a straight line, curvature is zero. Torsion on the other hand measures the twisting of a curve, and the vanishing of torsion describes a curve whose three dimensional range is restricted to a plane. By using splines, we provide consistent estimators of curves and in turn, this provides consistent estimators of curvature and torsion. We illustrate the usefulness of this approach to a problem in understanding bone movement in biomechanics.

2. **Michael Pierrynowski**
   See No. 1 above.

3. **Stephan Huckemann**
On the statistical modelling of quasi periodic motion trajectories occuring in the biomechanics of the knee joint

(Joint work with Peter T. Kim (Guelph Univ.) Ja-Yong Koo (Korea Univ.) and Micheal Pierrynowski (Mc. Master Univ.)).

This research is motivated by the need to improve the statistical evaluation of human knee motion for clinical investigation. The relative motion of the knee joint can be described by a quasi-periodic space curve. For clinical relevance, the analysis of the relative rigid body motion of the underlying bone structure is of interest, which is given by a quasi-periodic curve in the space of Euclidean motions. As a first to date not satisfactorily solved problem in this context arises the problem of the decomposition into rotational, folding, twisting and relative translational parts of the motion. Moreover, as is the case with the spatial curve, in the space of 3D rotations, motion consists of ``straight'' parts and heavily curved (restricted) parts both of which are highly dependent on each other. Here we model a ``straight behavior'' in terms of geodesics on SO(3). In this formulation, motion diversity maps to a distribution of data points on the non-Euclidean space of geodesics. In particular this allows for nonparametric asymptotic statistics. Furthermore individual motion patterns can be related to a diffusion process. Likewise in order to model the heavily curved parts, torsion can be singled out as an appropriate descriptor also allowing for consistent estimation.

4. **Ian Dryden**
Curve modeling in shape spaces

In many biomedical applications the data lie naturally in a non-Euclidean space. Examples include shapes of landmarks, directional data, diffusion tensors and covariance matrices. The concept of a mean can be defined in such spaces, and also we can work with minimal geodesics as being analogous to straight lines. However, it is not immediately clear how we define more general curves in non-Euclidean spaces, for example in describing the expected shape change in a rat skull as the animal grows.

A family of shape curves is introduced which is useful for modeling the changes in shape in a series of landmark shapes. The relationship between the pre-shape sphere and the shape space is used to define a general family of curves based on horizontal geodesics on the pre-shape sphere. Likelihood based inference for curves in the non-Euclidean shape space of point sets is discussed. We illustrate the ideas by carrying out statistical analysis of various biomedical applications.

5. **Anthony Yezzi**
Incorporating Global information into Active Contours and Active Surfaces

Active Contours (2D) and Active Surfaces (3D) have become widely popular for medical image analysis applications primarily for their flexibility to represent arbitrarily complex geometric shapes (sometimes even arbitrary topologies). However, this high degree of flexibility (and potential fine-scale accuracy) typically comes at the price of a highly localized fitting processes which makes active contours more sensitive to noise, background structure, and coarse scale texture or other intensity inhomogeneities within the region of interest, compared to lower dimensional shape representations which typically exhibit more robustness to these types of interference. In this talk we present various ways to make the localized deformations of active contours respond to more global information in order to increase their robustness for

segmentation applications without overly constraining or reducing their infinite-dimensional flexibility in representing a wide class of arbitrarily complex shapes.

6. **Misha Kazhdan**
   Efficient Multigrid Solvers for Poisson Systems on Meshes

   This talk will focus on a recently proposed method for using an octree-based finite-elements system for defining and solving Poisson-like systems on meshes. We will discuss how hierarchical structure of the octree supports both streaming and parallel computations and will consider applications in real-time surface editing and surface evolution.

7. **Helmut Pottmann**
   Shape Space Exploration of Constrained Meshes

   (Joint work with Yongliang Yang, Yijun Yang and Niloy Mitra.)

   We present a general computational framework to locally characterize any shape space of meshes implicitly prescribed by a collection of non-linear constraints. We computationally access such manifolds, typically of high dimension and co- dimension, through first and second order approximants, namely tangent spaces and quadratically parameterized osculant surfaces. Exploration and navigation of desirable subspaces of the shape space with regard to application specific quality measures are enabled using approximants that are intrinsic to the underlying manifold and directly computable in the parameter space of the osculant surface. We demonstrate our framework on shape spaces of various types of meshes which are important in freeform architecture and indicate directions for future research beyond this specific application.

8. **Sungkyu Jung**
   Analysis of population of shapes via a backward generalization of PCA

   A generalized Principal Component Analysis (PCA) for manifold-valued shapes is introduced. We discuss two viewpoints of classical PCA, forward and backward stepwise views, pointing out that a backward approach leads to a much more natural and accessible extension of PCA for dimension reduction on non-linear manifolds. In particular, a general framework of composite Principal Nested Spheres is proposed that generalizes PCA in a backward manner and composes one or more such non-linear analyses with Euclidean data. The method works for a variety of application areas, including landmark shapes, point distribution models and skeletal representations. In examples from a lung motion study and from a population of hippocampi, composite PNS is shown to give a more succinct representation of shape data than alternative methods in the literature.

9. **Tom Fletcher**
   Geodesic Regression on Shape Manifolds

   In this talk I present a regression method, called geodesic regression, for modeling the relationship between a manifold-valued random variable and a real-valued independent parameter. The principle is to fit a geodesic curve, parameterized by the independent parameter, that best fits the data. Error in the model is evaluated as the sum-of-squared geodesic distances from the model to the data, and this provides an intrinsic least squares criterion. Geodesic regression is, in some sense, the simplest parametric model that one could choose, and it provides a direct generalization of linear regression to the manifold setting. I will also present a hypothesis test for determining the significance of the estimated trend. While the method can be generally

applied to any form of manifold data, I will show a specific example of analyzing shape changes in the corpus callosum due to age.

10. Xavier Pennec
Measuring and modeling the (differential) longitudinal evolution from sequences of images

Follow-up imaging studies require the evaluation of the anatomical changes over time for specific clinical groups. The longitudinal morphological changes for a specific subject can be evaluated through the non-rigid registration. However, to perform a longitudinal group-wise analysis, the subject-specific longitudinal trajectories need to be transported in a common reference.

One of the main problem is that the (relatively) small longitudinal deformations typical of growth, remodeling or aging often get drawn into the large and highly variable inter-subject deformations. Moreover, in many cases, only scalar measurements, such as the local volume change (e.g. Jacobian of the longitudinal deformation), are transported (using resampling) because there are very few grounded methods to parallel transport other quantities, such as the full longitudinal deformation parameters.

I will discuss different longitudinal models and different parallel transport method proposed recently. A particularly interesting algorithm is the Schild's Ladder procedure, which is a discrete algorithm valid for any Riemannian metric and even valid in the more general setting of connections. For instance, it can be very implemented extremely efficiently with great stability in the framework of stationary velocity fields (SVF). This paves the way for the comparison of different metrics in computational anatomy.

11. Anuj Srivastava
Role of Quotient Spaces in Registration, Comparison and Statistics of Shapes and Images

(Joint with Eric Klassen, Sebastian Kurtek, Wei Wu, Ian Jermyn, and many others.)

In this talk I will discuss the central role played by quotient spaces of the type M/G, where M is a manifold and G is a group acting on M, in many interesting problems associated with medical image analysis. Here are some examples:

(1) Shapes of Curves: If M is the manifold of parameterized curves (open or closed) and G is the product group of rigid motions and re-parameterizations, then M/G is the shape space of elastic curves (open or closed). I will show examples from shape-based analysis of DT-MRI fiber tracts and sulcal curves.

(2) Shapes of Surfaces: If M is the manifold of embeddings of the 2-sphere in R3 and G is the product group of rigid motions and re-parameterizations, then M/G is the shape space of closed surfaces. I will demonstrate applications of this idea in detecting ADHD disorder and Math disability amongst subjects using shapes of their subcortical structures.

(3) Multiple Image Registration: If M is a set of signals/images/surfaces and G is the diffeomorphism group acting on an appropriate background space, then one is interested in jointly registering multiple (more than two) images. One solution comes from aligning given images to the Karcher mean of given images in the quotient space M/G

An important component of this framework is to find a Riemannian metric on M such that the

actions of G are by isometries. I will describe the use of Fisher-Rao Riemannian metric, adopted to these different scenarios, in defining G-invariant comparisons and statistical analysis of shapes and images

12. Gordon Kindlmann
Particle systems for visualizing the connection between math and anatomy

Dynamic particle systems have been used in graphics and visualization for implicit surface sampling, but particles have a largely unexplored role in extracting mathematical features of unsegmented image data. Particle systems can sample features with diverse dimension and co-dimension, in three-dimensional image domains or four-dimensional scale-space domains. These features include height-field crease lines and crease surfaces, as well as a variety of other extremal surfaces involving gradients and curvatures. In diffusion tensor fields, the connections between tensor invariants and tensor eigenvectors are especially interesting. In all cases, only simple rules are needed to define the particle system behavior, so that the range of possible mathematical features can be sampled and visualized, to assess their anatomic significance.

13. Peter Giblin
Views of illuminated surfaces

(Joint work with James Damon)

This work investigates the interactions between shades, cast shadow, apparent contour, surface markings, surfaces creases and corners on illuminated surfaces in 3-space. The object is to list all the transitions which occur during a 'flypast' of the surface, that is when the view direction moves in a generic a 1-parameter family.

14. Steve   Pizer
3D multi-source visualization for external beam radiotherapy

Abstract: After explaining the needs of radiation oncology for simultaneous, interactive display of image and object information from multiple sources, I will describe a skeletal representation that provides an object-based coordinate system that can mediate such display. Applications of this coordinate system to bring sources together, to texturing surfaces to allow painting of radiation dose, to interactively revealing relevant parts of objects of interest, and to presenting temporal changes of the anatomy will be presented. The uses of a system built with these capabilities for improving radiation therapy will be described.

15. Alla Sheffer
Space-Time Reconstruction - Understanding Motion

As research on space-time reconstruction matures, we should ask ourselves what information we use to correctly leverage the temporal or motion component of the data. In my talk I will discuss several possible motion priors and their impact on the reconstruction. Specifically, I will address the observation that most changes in shape are gradual, in both intrinsic and Euclidean sense. I will discuss the impact of this observation on the interpretation of shape over time and present a reconstruction method that uses this observation to correctly reconstruct shape and motion in the presence of self-contacts.

16. Andrea Tagliasacchi (trainee with Richard Zhang)

Volume-Aware Surface Evolution for Surface Reconstruction from Incomplete Point Clouds

(Joint with Matt Olson, Hao Zhang, Ghassan Hamarneh, Daniel Cohen-Or)

Objects with many concavities are difficult to acquire using laser scanners. The highly concave areas are hard to access by a scanner due to occlusions by other components of the object. The resulting point scan typically suffers from large amounts of missing data. Methods that use surface-based priors rely on local surface estimates and perform well only when filling small holes. When the holes become large, the reconstruction problem becomes severely under-constrained, which necessitates the use of additional reconstruction priors. In this paper, we introduce weak volumetric priors which assume that the volume of a shape varies smoothly and that each point cloud sample is visible from outside the shape. Specifically, the union of view-rays given by the scanner implicitly carves the exterior volume, while volumetric smoothness regularizes the internal volume. We incorporate these priors into a surface evolution framework where a new energy term defined by volumetric smoothness is introduced to handle large amount of missing data. We demonstrate the effectiveness of our method on objects exhibiting deep concavities, and show its general applicability over a broader spectrum of geometric scenario.

17. **Chris Taylor**
Building Anatomical Models Automatically – Theory to Practice

(Joint work with Tim Cootes and Carole Twining)

Methods for building optimal statistical models of anatomy automatically, and fitting them to unseen images have existed for a decade or more. There is, however, no clear methodological consensus, with contention around such issues as whether truly correspondence-free methods exist. At the same time, there has been significant progress in applying the methods to real clinical problems, solving significant engineering challenges in the process. We will provide a Manchester perspective spanning theory through to practical applications.

18. **Sebastian Kurtek** (trainee with Anuj Srivastava)
Statistical Shape Analysis of Elastic Anatomical Surfaces

In this talk, we will discuss some recent advances in elastic shape analysis of anatomical surfaces. This requires a Riemannian framework, which allows re-parameterizations of surfaces by isometries as well as computations of geodesic paths between surfaces. These tasks are difficult because they require the definition of a non-standard metric on the space of parameterized surfaces, which is infinite dimensional. In this presentation, we will present one example of such a metric and we will use it to define geodesics, and parameterization-invariant statistics of anatomical shapes. Removing the parameterization variability provides more natural geodesic paths between surfaces and more parsimonious models, which can be used for disease diagnostics or monitoring disease progression.

19. **Ross Whitaker**
Shape-Based Analysis of Large Image Ensembles

In medical image analysis, large clinical studies and large collections of associated images are become quite common. These large databases present some important new opportunities for modeling and analyzing biological shapes, but they also present some new challenges. This talk describes a body of work that addresses some the challenges associated with building statistical

models of ensembles of shapes. This work includes parameterizations and metrics that explicitly account for variability in populations, as well as data-driven, nonlinear statistical models of large sets of images. The applicability of these technologies depends on the ability quickly quantify differences in biological shapes, and thus we also present a new framework for quickly making large numbers of comparisons.

20. Eduard Gröller
Comprehensive Visualization of Cardiac MRI Data

Coronary artery disease is one of the leading causes of death in the western world. The continuous improvements in magnetic resonance imaging (MRI) technology facilitate more accurate diagnoses by providing increasingly more detailed information on the viability, functioning, perfusion, and anatomy of a patient's heart. The talk covers several techniques that realize multi-modal visualizations of a patient's heart to assist in the diagnosis of coronary artery disease . A volumetric bull's eye offers a more comprehensive view on the viability of a patient's heart by providing detailed information on the transmurality of scar while not suffering from discontinuities. Anatomical context is often lost due to abstract representations of data, or may be scarce due to the nature of the scanning protocol. Several techniques to restore the relation to anatomy are presented. The primary coronary arteries are segmented in a whole heart scan and mapped onto a volumetric bull's eye plot, adding anatomical context to an abstract representation. Similarly, segmented late enhancement data are rendered along with a three-dimensional segmentation of the patient-specific myocardial and coronary anatomy. Additionally, coronary supply territories are computed from patient-specific data as an improvement over models based on population averages. Information on the perfusion of the myocardium provided by MRI is typically of fairly low resolution. Using high-resolution anatomical data, an approach to visualize simulated myocardial perfusion is presented, taking full advantage of the detailed information on perfusion. Finally, a truly comprehensive visualization of a cardiac MRI exam is explored by combining whole heart, late enhancement, functional, and perfusion scans in a single visualization.

21. Kaleem Siddiqi
Heart Wall Myofibers Bundle into a Generalized Helicoid

We report a novel higher order structural organization of heart wall muscle fibers which provides excellent fits to diffusion MRI data from three mammalian species: the fibers lie on a special type of minimal surface. This discovery has direct implications for heart wall muscle function and heart tissue engineering.

22. Brian Booth (trainee with Ghassan Hamarneh)
Spatio-temporal Analysis of Connectivity Patterns for White Matter Injury Detection in the Preterm Infant Brain

(Joint with Ghassan Hamarneh and Steven Miller)

Preterm infants have a high incidence rate of neurodevelopmental disability. It is believed that these disabilities stem from early white matter injuries. We desire the ability to assess these white matter injuries early through the use of diffusion tensor MRI (DT-MRI) analysis. In particular, we examine whether brain connectivity patterns, obtained via tractography, can be used to differentiate between normal and abnormal development. As a first step, we generate a spatio-temporal DT-MRI atlas that captures normal development for the 28-45 week gestational age range. This atlas is used as a control to which we compare subject scans. Second, we examine

brain connectivity through the use of graph-based random walks. This tractography approach required us to develop the ability to encode the DT-MRI connectivity information into a graph-based format without introducing additional forms of error. From this encoding, we are able to examine brain connectivity in a multi-region approach that spatially localizes connectivity patterns to a greater extent through the use of competition. Finally, we introduce information content estimation for full DT-MRI data, allowing us the ability to generate a mutual information metric for longitudinal registration of preterm DT-MRI. This longitudinal registration will provide us with the ability to track how brain connectivity develops through this crucial period of growth.

23. **Leo Grady**
Shape Characterization with Network Analysis

Radiologists and pathologists use geometrical information to make diagnostic and prognostic decisions about the anatomy they observe. As segmentation algorithms improve and datasets become larger, it becomes possible to characterize image-based biomarkers with a precise and complete set of measurements. Traditional methods of quantifying shape emphasize classical measures of geometry, such as volume, surface area and curvature. However, by modeling shapes as a network of pixels, it becomes possible to employ an arsenal of powerful network characterization tools to capture structural and topological properties of shapes. Furthermore, these tools can be employed beyond shape analysis to characterize the structure of neurological networks, protein-protein networks and biological systems.

24. **Richard Zhang**
Symmetry analysis for shape processing

Symmetry is ubiquitous in both organic shapes and man-made artifacts. Symmetry detection and symmetry-driven shape analysis have been receiving much attention lately. Most existing works have focused on low-level, extrinsic symmetry detections that apply to input shapes as a whole. In this talk, I will present two recent works on partial intrinsic symmetry detection and symmetry hierarchy construction and discuss various applications including shape segmentation and manipulation. I will also go over our on-going works to follow up these efforts. Finally, I will briefly talk about why despite of the beauty and ubiquity of symmetry, it may not always be what we want and we should move away from it.

25. **Oliver van Kaick** (trainee with Ghassan Hamarneh and Richard Zhang)
Pairwise Shape Descriptors for Partial Matching

(Joint with Ghassan Hamarneh and Richard Zhang)

Shape descriptors are an important component in the solution of shape analysis tasks such as correspondence or retrieval of anatomical datasets. One effective way of constructing shape descriptors is to first define a region of interest around a given point, and then lay out a grid over this region to sum the curvature of the points that fall within each bin of the grid. This provides a powerful contextual representation of the point, however, properly setting the extent of coverage for the region of interest is a difficult problem, especially to enable partial matching. We propose pairwise shape descriptors to circumvent these problems. The scale and shape of the region of interest is defined by a pair of feature points, so that the region only captures the portions of the shape that are common to the two points. This provides a contextual representation suited for partial matching tasks, since potentially extraneous regions of the models are ignored in the

matching if the correct point correspondence is selected. We demonstrate the effectiveness of the shape descriptors for partial matching through correspondence and retrieval experiments.

26. Kevin Zhou
Whole Body Image Parsing

In this talk, I will present research challenges in parsing whole body image scans. How to robustly detect the presence of hundreds of anatomical landmarks and, if present, their locations? How to accurately segment a cohort of major organs (e.g., heart, lung, liver, kidney, etc.)? I will also present novel machine learning approaches and software platform that enable whole body parsing and illustrate the efficiency and effectiveness of these approaches using real examples.

27. James Damon
Analyzing Configurations of Objects in Images via Medial/Skeletal Linking Structures

For a configuration of objects in a 2D or 3D space, there are a number of questions involving their interaction and how their shapes and relative positions allow for improved information for various imaging questions. This includes analyzing the contributions of both the shapes of the objects and their relative position to the properties of the configuration. Such configurations model collections of physiological features such as organs, bones, glands, arteries, etc, in medical images which motivate a number of questions. We will explain how to do this by extending the medial/skeletal representations of the individual objects to a medial/skeletal linking structure for the collection of objects   This structure for individual objects allows for the introduction of mathematical operations which capture the geometric and shape properties of individual objects from an underlying skeleton. Discrete versions for objects, called "m-reps" and "s-reps", have been successfully used by the MIDAG group at UNC for segmentation of regions, statistical comparison of individual objects in a population of patients, and time series for individual patients.

The linking structure augments this in a minimal way, yet still allows for the introduction of mathematical entities which separate shape change from positional change, measure closeness and significance of portions of objects, associate a natural hierarchy among objects, and provide an approach to understand their deformations.

28. Benedikt Hallgrimsson (presented by Christian Jacob)
The Lindsay Project: A framework for anatomically embedded simulation for medical education

(Joint with Christian Jacob, Sebastian von Mammen, Heather Jamniczky, Bruce Wright)

LINDSAY—Virtual Human is a 3-dimensional, interactive model of male and female anatomy and physiology; the LINDSAY software suite is tailored to create illustrative scenarios and course contents for medical education. One key characteristic of LINDSAY is the integration of computational models across scales to simulate physiological processes from the body level to the level of organs, tissues, cells, and sub-cellular structures.

For in-classroom use we have developed LINDSAY Presenter, a visualization and exploration environment that presents different scenarios within the simulated human body. In order to create complex scenes for presentation and investigation, we implemented LINDSAY Composer, a graphical programming environment, which facilities the composition of complex educational scenarios around the human body. The computer simulations can be explored in real time and

allow instant feedback and navigational control. We will present examples of first prototypical simulations and discuss their embedding into anatomical structures in the form of mesh data and volumetric data sets.

LINDSAY is a collaborative project between the Faculties of Medicine (Undergraduate Medical Education) and Science (Computer Science) at the University of Calgary.

29. Christian Jacob
Multi-scale, Agent-based Modeling for Human Anatomy and Physiology: Challenges and Opportunities

Agent-based modeling is being considered as a complementary approach to traditional mathematical modeling techniques, where, primarily, differential equations are used to capture dynamical processes. For simulating biological processes, this works well if one is only interested in the average behaviour of very large quantities of individual entities (such as molecules) or in general changes of concentrations.

The picture is different, though, when relatively small numbers of individual units influence the outcome of a biological process (such as in gene regulation, for example). Then the interacting entities should be represented as identifiable, individual 'agents' that have specific physical, chemical, and other properties that influence their interactions.

I will present a number of examples of agent-based simulations developed in my Evolutionary & Swarm Design Lab, where we specialize in simulations of biological systems. Our recent focus is on building software development environments for dynamic models of human physiological processes embedded in 3D, anatomical structures that have to capture a wide range of scales: from systems and organs to tissues and cells.

30. Torsten Moeller
Tuner - finding the best parameters for your algorithm

We address the difficult problem of parameter-finding in image segmentation. We replace a tedious manual process that is often based on guess-work and luck by a principled approach that systematically explores the parameter space. Our core idea is the following two-stage technique: We start with a sparse sampling of the parameter space and apply a statistical model to estimate the response of the segmentation algorithm. The statistical model incorporates a model of uncertainty of the estimation which we use in conjunction with the actual estimate in (visually) guiding the user towards areas that need refinement by placing additional sample points. In the second stage the user navigates through the parameter space in order to determine areas where the response value (goodness of segmentation) is high. In our exploration we rely on existing ground-truth images in order to evaluate the "goodness" of an image segmentation technique.

31. Ahmed Saad (trainee with Ghassan Hamarneh and Torsten Möller)
ProbExplorer: Uncertainty-guided Exploration and Editing of Probabilistic Medical Image Segmentation

(Joint with Ghassan Hamarneh and Torsten Möller)

In this presentation, we will talk about ProbExplorer: an interactive analysis and visualization tool for probabilistic segmentation results in medical imaging. We provide a systematic approach to

analyze, interact, and highlight regions of segmentation uncertainty. We introduce a set of visual analysis widgets integrating different approaches to analyze multivariate probabilistic field data. Then, we introduce a set of multidimensional transfer function widgets that furnish the user with contextual information about conformance or deviation from the population statistics using shape and appearance prior information. We demonstrate the ability to identify suspicious regions (e.g. tumors) and to correct misclassification results.

32. Luc Florack
Cardio & Neuro Imaging from a Mathematical Perspective

The Imaging Science & Technology Eindhoven (IST/e) is a cross-divisional collaboration involving several image related research groups at Eindhoven University of Technology in The Netherlands. It is built on four pillars: image acquisition, biomedical image analysis, mathematical image analysis, and visualization, and covers two main themes: cardio imaging and neuro imaging. The aim of IST/e is to bridge the gap between methodological sciences, notably mathematics, physics, and computer science, on the one hand, and biomedical and clinical sciences on the other hand. IST/e has collaborations with various clinics and with industry. I will present mathematical models with the help of which we address challenges from both themes

33. Ghassan Hamarneh
The fidelity vs. optimizability trade-off in the analysis of medical images and geometry of anatomy

Many problems of geometry for anatomy (e.g. segmentation, registration, correspondence) are typically formulated in an optimization framework (energy-minimization). I will discuss two important recurring questions: What to optimize and how to optimize and expose the resulting tradeoffs between the fidelity (of the domain and range) of the objective function and its optimizability.

34. Nina Amenta
Surface Mapping and Registration

Finding surface correspondences of collections of biological shapes is a persistent and difficult problem in shape analysis. Optimization approaches often need to be augmented with regularization terms; without regularization, they produce obviously poor correspondences. I argue that this implies that the wrong function is being optimized, and propose some alternatives.

35. Cindy Grimm
Biomedical modeling: From 3D images to computational models

The last several years has seen a tremendous advance in both the quantity and quality of biomedical image data. This data provides an unprecedented opportunity for biologists to visualize and understand complex biological processes. Unfortunately, processing this data into useful computational forms is both challenging and time-consuming. I discuss two advances in this area: 1) Simplifying the contouring process (joint with colleagues in Radiology) and 2) Using strain to establish correspondences between changing surfaces (joint with colleagues in Neural studies, Heart development, and Mechanical engineering).

36. Rafeef Abugharbieh
Active Learning for Interactive 3D Image Segmentation

(Joint with Andrew Top and Ghassan Hamarneh)

I will describe a novel method for applying active learning strategies to interactive 3D image segmentation. Active learning has been recently introduced to the field of image segmentation. However, so far discussions have focused on 2D images only. Here, we frame interactive 3D image segmentation as a classification problem and incorporate active learning in order to alleviate the user from choosing where to provide interactive input. Specifically, we evaluate a given segmentation by constructing an "uncertainty field" over the image domain based on boundary, regional, smoothness and entropy terms. We then calculate and high- light the plane of maximal uncertainty in a batch query step. The user can proceed to guide the labeling of the data on the query plane, hence actively providing additional training data where the classifier has the least confidence.

37. Zhigang Deng
Efficient Segmentation of 3D Anatomical Structures from Biomedical Imaging

Automated and efficient algorithms to reconstruct and segment 3D anatomical structures has been a major challenge in the past decades due to the intrinsic complexity of human anatomical structures and relatively low quality of current medical image methods. In this talk, I will present two new algorithms to deal with such geometric problems in medical applications. The first is an efficient and interactive geometric technique to accurately segment the lower and upper teeth from CT images, and its accuracy and efficiency was experimentally validated via comparison with the ground truth as well as state of the art algorithms. The second work is inspired by current neurobiology research. Determining the relationship between the dendritic spine morphology and its functional properties is a fundamental challenge in neurobiology research. In particular, how to accurately and automatically analyze meaningful structural information from a large microscopy image dataset is far away from being resolved. We propose an automated approach to a novel approach to detect and segment neuronal spines, in particular, a breaking-down and stitching-up algorithm to accurately separate touching spines, based on various global and local geometric features of the dendrite structure.

38. Shawn Andrews (trainee with Ghassan Hamarneh)
Convex Energy Minimization Over Multi-Region, Probabilistic Segmentation Spaces

(Joint with Chris McIntosh and Ghassan Hamarneh)

Image segmentation is often performed via the minimization of an energy function over a domain of possible segmentations. Convexity in minimization problems allow the global optimum to be found, resulting in a more efficient and robust segmentation method. While convex energy functions incorporating a wide variety complex image information exist, the space of possible segmentations must also be convex. Constructing more descriptive, problem specific shape spaces often results in non-convexity. Here, we propose a method for constructing a principal component analysis based segmentation space that allows for multi-region, probabilistic segmentations while still enforcing adherence to a problem specific shape prior. Furthermore, since we map our probabilities to real vectors using the isometric log-ratio transformation, this space requires no constraints to ensure valid segmentations. We explore sample energy terms over our segmentation space and discuss their probabilistic interpretations. To our knowledge, these features (convexity, shape prior, multi-region, and probabilistic) do not exist together in any other segmentation method.

39. J. S. Marron
OODA of Tree-Structured Data Objects

The field of Object Oriented Data Analysis has made a lot of progress on the statistical analysis of the variation in populations of complex objects. A particularly challenging example of this type is populations of tree-structured objects. Deep challenges arise, which involve a marriage of ideas from statistics, geometry, and numerical analysis, because the space of trees is strongly non-Euclidean in nature. These challenges, together with three completely different approaches to addressing them, are illustrated using a real data example, where each data point is the tree of blood arteries in one person's brain.

40. Mads Nielsen
Towards a theory of statistical tree-shape analysis

In order to develop statistical methods for shapes with a tree-structure, we construct a shape space framework for tree-like shapes and study metrics on the shape space. This shape space has singularities, corresponding to topological transitions in the represented trees. We study two closely related metrics on the shape space, TED and QED. QED is a quotient Euclidean distance arising naturally from the shape space formulation, while TED is the classical tree edit distance. Using Gromov's metric geometry we gain new insight into the geometries defined by TED and QED. We show that the new metric QED has nice geometric properties which facilitate statistical analysis, such as existence and local uniqueness of geodesics and averages. TED, on the other hand, does not share the geometric advantages of QED, but has nice algorithmic properties. We provide a theoretical framework and experimental results on synthetic data trees as well as airway trees from pulmonary CT scans. This way, we effectively illustrate that our framework has both the theoretical and qualitative properties necessary to build a theory of statistical tree-shape analysis.

41. Stefan Sommer
A Multi-Scale Kernel Bundle for LDDMM

At the heart of the LDDMM image registration framework lies the notion of regularization kernel, and the choice of kernel greatly affects the results of registrations. The LDDKBM extension of LDDMM allows multiple kernels at multiple scales to be incorporated in each registration while preserving many of the mathematical properties of LDDMM. The new framework removes the need for classical scale selection, and, by decoupling the momentum across scales, it promises to provide better interpolation properties, to allow sparse descriptions of the total deformation, to remove the trade-off between match quality and regularity, and to allow for momentum based statistics using scale information. We will outline the construction of the framework and compare registration results between LDDKBM and LDDMM.

42. Sarang Joshi
Simple Statistics on Interesting Spaces for Developing Imaging Biomarkers Analysis

A primary goal of Computational Anatomy is the statistical analysis of anatomical variability. Large Deformation Diffeomorphic transformations have been shown to accommodate the geometric variability but performing statistics of Diffeomorphic transformations remains a challenge. I will start with the simple concept of defining the "Average Anatomy" and then extend this to the study of regression and co-variation of anatomical shape with independent variables. The motivation is to model the inherent relation between anatomical shape and clinical measures

and evaluate its statistical significance. We use Partial Least Squares for the multivariate statistical analysis of the deformation momenta under the Large Deformation Diffeomorphic framework. The statistical methodology extracts pertinent directions in the momenta space and the clinical response space in terms of latent variables. We report the results of this analysis on 313 subjects from the Mild Cognitive Impairment group in the Alzheimer's Disease Neuroimaging Initiative (ADNI)

43. **Ganesh Sundaramoorthi**
    observer