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Mechanobiology of the root hair cell

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Plant growth is controlled by genetic circuits but also by mechanical cues as the plants need to adapt to their mechanical environment. The plant roots are good systems to study such an adaptation since they grow in soils with many mechanical heterogeneities. Our aim is to understand the mecanotransduction from the cell wall to the nucleus in growing plant roots. In particular, we study the growth of the root hair cell, a single cell, exhibiting tip growth. Combining microfluidics and optical microscopy, we quantitatively characterized the growth of single root hairs by measuring, in different mechanical environments, their growth speed and the concomitant nuclear dynamics. In particular, using growth media of increasing young moduli leads to root hairs with decreasing growth speed and length, whereas growth duration is unaffected. Interestingly, the growth medium stiffness also affects nuclear dynamics, suggesting mechanotransduction from the root hair cell surface to the nucleus.

Keywords: Mechanosensing, rigidity, microfluidics, Arabidopsis thaliana, nucleus, live, imaging, mechanotransduction

*Speaker

Bark biomechanical function: smart tissue organization enables extreme mechanical performance in the secondary phloem of Malvaceae

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In some botanical families, the secondary phloem is the main motor of postural control. The mechanism underlying this function is based on the conversion of wood radial growth into longitudinal stress in bark. Here we specifically studied how the microstructure of the secondary phloem may be optimized for this function, through its ability to redirect stress from the tangential to the longitudinal direction. We measured the longitudinal-tangential Poisson's ratio of secondary phloem in various tree species, and found extremely high values in species belonging to Malvaceae familly. We modelled the microstructure of the secondary phloem using finite-elements, and showed that the structure of Malvaceae secondary phloem is close to optimal for converting the radial pressure of the growing cambium into a functional longitudinal stress.

Keywords: bark, phloem, tension wood, postural control, Poisson's ratio, Malvaceae

*Speaker

Hydraulic stress at the meristem-organ boundaries

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Beyond biochemical factors, plant development is also shaped by physical variables and notably growth-derived mechanical conflicts. Such conflicts can involve hydraulic components, and thus water stress, too. In shoot apical meristems (SAM), the fast growth of new organs creates a local hydraulic conflict at the meristem-organ boundaries. In order to understand the morphological deformations in boundary cells, we performed an automated 4D image segmentation analysis over the whole SAM and measure cell volumetric changes. This suggests water flux out of the boundary domain, which correlated with a bias in water-stress gene expression. Through artificially compressing meristems and modifying osmotic conditions, we further show that tissue hydraulics can influence transcriptional activity. Taken together, our integratory analysis suggests that SAM boundaries are defined by mechanical as well as hydraulic stress. Interestingly, boundaries are also largely determining plant architecture, thus potentially relating plant branching to force-derived water stress.

Keywords: shoot meristem hydraulics mechanotransduction

*Speaker

Unlock the walnut: Shell development of Juglans regia visualized in 3D

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The mature walnut shell is a rigid tissue, made entirely out of one cell type; 3D puzzle cells. These cells have multiple lobes interlocking with their neighboring cells forming a tough structure. To understand shell formation, we followed the walnut development with 3D methods including serial block face-SEM and CT. During early morphogenesis, cell walls start to buckle causing the formation of cellulose reinforcements at sites with higher stresses. There, the thickening acts like a belt, which restricts expansion and causes the cell to form multiple lobes. When sclerification starts, the interlocked cells form secondary cell walls and incorporate lignin. This process is supported by an extensive pit channel network connecting the whole shell tissue. After sclerification of the shell, the inner tissue dries via the intercellular space to prevent the seed from moulding. Finally, the shell is ready to fulfill its task as a tough protective envelope.

Keywords: serial block face, SEM, CT, sclerification, interlocking, nutshell

*Speaker

Soft artillery: biomimetic cannon inspired by infectious spore dispersal

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Many fungal species rely on airborne spore dispersal for reproduction. The house fly-pathogenic fungus *Entomophthora muscae* employ a plethora of micrometric stalks, each using a liquid-based turgor pressure build-up to eject an initially attached single spore. However, the biophysical processes that regulate the optimization for dispersal are only superficially described. The physics of ejection is elucidated by designing a biomimetic soft walled consisting of a millimetric elastomeric barrel filled with fluid and plugged with a projectile. The build-up of pressure is experimentally controlled, and the cannon efficiency and ejection velocity are determined as a function of cannon geometry and wall elasticity. The cannon characteristics and flight trajectory models are used to predict an optimum size for dispersal that is consistent with the natural size of *E. muscae* spores.

Keywords: Fungal spore ejection, biomimetic soft cannon, force balance model, high speed videography, dispersal range

*Speaker

Excess growth combined with reduced cell wall stiffness in Arabidopsis triggers flowering stem breakag

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Flowering stems of herbaceous plants are pressurized cylinders, with the outermost epidermis under tension and the remaining inner tissues under compression. We reported that *clavata3 deetiolated3* (*clv3 det3*) mutants of Arabidopsis exhibited deep cracks within their flowering stems, reduced epidermal cell wall stiffness, distorted pith cells, and demonstrated that stem integrity requires a load-bearing epidermis (Asaoka et al., 2021). Because *clv3 det3* plant gross morphology was drastically affected, we wondered whether the unbalanced growth of inner and outer tissues ultimately leads to cracks, or plant dwarfism itself is a prerequisite for the cracking phenotype. In this study, to formally test this hypothesis, we selected mutants with morphological properties reminiscent of *clv3 det3*, generated higher order mutants with the aim to reproduce stem cracking genetically. Morphological and mechanical properties will be presented, and the role of cell wall integrity sensing and cell growth regulation in organ integrity will be discussed

Keywords: stem development, stem cracking, organ integrity

*Speaker

Quantifying cell-cell adhesion strength in plants

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Plant cell-cell adhesion is mediated by the cell wall which constantly undergoing remodeling to allow cell expansion. Simultaneously, the mechanical tensions in plant tissues generated by turgor pressure and differential growth threaten cell-cell adhesion. We study the mechanical basis of cell-cell adhesion quantifying the force needed to separate adjacent cells, to understand how cells maintain their adhesion under chemical and mechanical stress mediated stimuli. We use an interdisciplinary approach integrating genetics, biophysics, and live imaging to better understand both the physics and the biology of the phenomena. We use a Micro Scale Extensometer (MSE) system that allows a very precise force application to the sample combined with high-resolution live imaging with confocal microscope. Using MSE we pull the samples (wild-type and adhesion defective mutants like qua1-1, qua2-1, arp2) till the cells separate. Our approach aims to get a deeper understanding of the mechanical implications of cell-cell adhesion in plants.

Keywords: Cell, cell adhesion, Arabidopsis thaliana, Adhesion Strength, Adhesion defect, Extensometer.

*Speaker

The primary eATP receptor P2K1 mediates responses to the physical strength of medium in Arabidopsis roots

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Numerous studies have shown that extracellular ATP (eATP) is involved in a variety of plant processes, including thigmotropism and response to wound. P2K1, a lectin receptor-like kinase has been identified as the primary eATP receptor in Arabidopsis and is known to trigger a calcium signaling pathway. We have shown that the penetration ability of the root in response to a rise of medium growth strength is impaired in *P2K1* mutants primary roots compared to wild-type roots. To determine the possible implication of P2K1 in the calcium signaling pathway triggered by the meeting of the root with an obstacle, we use the ratiometric (Ca2+)cyt sensor RGECO1-mTurquoise to monitor the (Ca2+)cyt dynamics. Therefore we are currently developing a serie of experiments using a vertical stage fluorescent microscope in order to correlate in vivo the spatiotemporal characterization of the root apex reorientation and the cytosolic calcium distribution in P2K1 mutants and wild-type roots.

Keywords: root, obstacle, calcium

*Speaker

Pathogen-derived mechanical cues regulate the spatio-temporal implementation of plant defense

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Mechanoperception is essential for the plant to adapt to its physical environment. However, the plant environment is not only limited to its abiotic component since plants are also under permanent attacks from pathogens. However, whether mechanoperception is also essential to adaption to the biotic environment by regulating plant defense during pathogen attacks remains elusive. We found that mechanoperception of pathogen-derived mechanical cues regulates plant immunity through cortical microtubules (CMTs) anisotropic patterning. During infection, we observed the reorganization of mechanosensitive CMTs in the direction of pathogen-derived stress fluctuations. Interestingly CMTs anisotropic patterning also occurred in healthy cells distant from the pathogenic colony. In distant and healthy cells, mechanoperception of pathogen-derived stress instructed the expression of several immunity-related genes through the CMT anisotropic patterning. This mechanism contributed at least 40% of the plant resistance phenotype. We propose that the mechano-signaling layer potentiates the molecular signals involved in pattern and effector-triggered immunity.

Keywords: mechanoperception, microtubules, plant defense, pathogens, Sclerotinia sclerotiorum, Arabidopsis thaliana

*Speaker

Paving the way for understanding of secondary cell wall integrity sensing in aspen and Arabidopsis

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Defects in cell walls are perceived by cell wall integrity sensing (CWI), but the role of this mechanism in case of secondary cell wall (SCW) has been questioned. We generated lines with altered xylan structure in SCW in aspen and Arabidopsis. In several lines, cambial growth was stimulated. Using various omics approaches in the cambium and in developing xylem cells, we anticipate to reveal molecular players in CWI at the site of SCW damage perception and the site of response and expand understanding of mechanisms that contribute to SCW development. CrRLK1L-related proteins expressed during SCW formation in aspen will be knocked-out in Arabidopsis lines with a weakened SCW to decipher their putative role in the sensing of SCW defect. Since CWI might operate via mechanosensing, we also study a cross-talk between CWI and mechanostimulation by applying touch treatment to transgenic lines and by comparing alterations in transgenic and mechanostimulated plants.

Keywords: secondary cell wall, cell wall integrity, CrRLK1L, mechanical stimuli, fungal enzyme, priming effect, Arabidopsis, hybrid aspen

*Speaker

Mechanical properties of miscanthus rind : relation to tissue structure and composition

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Understanding the mechanical properties of lignocellulosic biomass is of great interest to improve their deconstruction (eg in the pre-grinding operation unit), and their functionality for different applications (eg biomaterials). Ten highly contrasted *Miscanthus sinensis* genotypes were selected based on their overall cell wall composition to cover the variability available within this species, and were harvested in two consecutive years. The rinds from the fifth internode were prepared and the shear force required to cut them was obtained using a dedicated prototype device. Based on the measured mechanical properties a subsample of rinds or associated internode were selected and characterized for histology (by light microscopy after FASGA staining or scanning electron microscopy) and cell wall biochemistry (neutral sugars, Klason lignin, hydroxycinnamid acids). A large variability was revealed for composition and structure (rind thickness and density) allowing to explain differences in the observed mechanical properties.

Keywords: histology, lignocellulose, cell wall composition

*Speaker

Mechanical control of seed shape in Arabidopsis

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Plant morphogenesis is thought to be controlled by a combination of biochemical and mechanical cues. Although mechanical signals have been shown to regulate a variety of cellular processes such as gene expression, growth and division, to which extent they contribute to the shaping of plant organs is still unclear. Using the developing seed of Arabidopsis as a model system, we are investigating the mechanical control of plant organ shape. We show that microtubule response to mechanical forces in the two layers of the outer-integument of the seed coat, the set of maternal tissues that surrounds the seed, drives an initial phase of anisotropic growth by guiding the oriented deposition of cellulose fibers in the wall. However, we further show that there is a subsequent transition from anisotropic to isotropic growth that may be linked to the thickening and stiffening of a specific wall of the outer-integument.

Keywords: Plant organ shape, Microtubules, Mechanical Forces, Seed Development

*Speaker

Validation of a Device to Measure High-Throughput Crop Strength

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Several staple crops experience significant levels of stem lodging (breakage of stems in windstorms prior to harvest). Rapid development of new lodging resistant crop varieties is vital to global food and energy security. To enable high-throughput measurements of bending stiffness the AgMEQ lab at the University of Idaho has developed the SOCEM device (Strength of Crops Extrapolation Machine). The device is operated by a single user and acquires force, position, and deflection data on an entire experimental field plot of wheat in under a minute. This data is fed into an advanced engineering model which approximates the crop canopy as a collection of partially interacting cantilever beams undergoing large displacements. The model enables calculation of bending stiffness measurements which have been validated against laboratory-based three-point bending tests. The device has also been used to successfully predict the lodging resistance of wheat varieties as determined by multiyear, historical lodging rate counts.

Keywords: phenotyping, bending, stalk, stiffness, strength, lodging

*Speaker

Combinatorial mechanoprobe screen for epitope specific micromechanical imaging of plant cell walls

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Mechanical patterns in the cell wall are crucial in a variety of plant biology phenomena, yet remain difficult to characterize and quantify in-situ and in-vivo. Recently, our group developed a class of molecular mechanoprobes that enable the non-invasive mapping of mechanical patterns in living plant tissues with fluorescence microscopy. However, to date, we lacked control over the cell wall epitopes that are targeted. Here we set up a chemical combinatorial screen to identify a suite of new cell wall targeting mechanoprobes with epitope specificity and identify the chemical design rules of cell wall targeting.

Keywords: mechanoprobes, cell wall, epitope targeting, chemical design, fluorescence

*Speaker

How do cell mechanical properties and response to forces affect plant organ growth?

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Plant organ growth depends on mechanical interactions between cells and tissues. Accordingly, seed growth in *Arabidopsis* is promoted by the pressure of the inner endosperm but is restricted by a specific layer of the surrounding seed coat, whose cells can perceive the tension generated by endosperm expansion and stiffen their cell wall accordingly. To get insights into the molecular mechanisms controlling seed coat properties, we are studying mutants for APETALA2 (AP2), a gene involved in the control of seed coat identity. We show that *ap2* mutants exhibit defects in cell response to mechanical forces and in wall differentiation that correlate with strong alterations of seed coat mechanical properties and of seed growth. These observations support that *ap2* mutant seeds are promising tools to study the molecular mechanisms controlling cell mechanical properties and response to forces in plants.

Keywords: Organ growth, Seed Development, Cell wall properties, Response to forces

*Speaker

Imaging the dynamics of symbiotic network architecture reveals a traveling-wave foraging strategy for trade

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Arbuscular Mycorrhizal Fungi (AMF) are widespread symbiotic fungi colonizing more than 60% of plant species. Using plant carbon, they grow away from the root and form a network of hyphae called the Extra Radical Mycellium (ERM). AMF acquire plant inaccessible phosphorous through the ERM and transport it back to the root. ERM growth is the main use of plant carbon, and its final form is reminiscent of the acquisition of phosphorous. Its morphogenesis is particularly informative of the dynamic of trade. ERM characterization has been up to date limited by the difficulty of obtaining time resolved data of its growth. Using an unprecedented, automated imaging set-up and image analysis pipeline, we show that the growth of the ERM colony follow a morphogenetic program that leads to a travelling wave dynamic. This dynamic is essentially described by two parameters: the speed of the wave and the final density reached.

Keywords: Morphogenesis, fungi, symbiosis

*Speaker

Falling behaviour of leaves

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The falling leaves of the autumn months annually punctuate the year with colour, and the sudden dispersal of these leaves after this event affects the entire local ecosystem. These leaves still hold significant nutrition, provide a source of shelter or ground cover, and sustenance for certain neighbouring organisms. The initial deposition of these leaves depends heavily on the falling behaviour from the tree, which we attempt to understand more thoroughly here. To elucidate the link between falling behaviour and shape, we use a laser cutter to carve delicate leaves from paper with complete geometric freedom. We visually track their behaviour as they fall and compare the performance of leaves from a variety of plant families with idealized shapes. Evolutionary implications and biomimetic applications are discussed.

Keywords: leaves, autumn, sedimentation, fluid dynamics

*Speaker

Pavement cells of Arabidopsis thaliana dwarf mutant – growth analysis

Dorota Borowska-Wykręt * [1], Wiktoria Wodniok *

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A model cell type for studies of growth and complex shape formation is jigsaw puzzle-shaped pavement cells of Arabidopsis thaliana. Morphogenesis of such cell comprises the formation of interdigitating lobes by anticlinal (perpendicular to the leaf surface) walls of adjacent pavement cells. Mutation in the gene (DWF4-102), responsible for the biosynthesis of a key enzyme in the brassinosteroid pathway, leads to reduced growth and cell divisions, and plant dwarfism. We investigate the mutation effect on pavement cell morphogenesis using two combined protocols for growth analysis of outer periclinal walls of abaxial leaf epidermis. Fluorescent microbeads applied on the wall surface serve as artificial landmarks for growth tracing at the subcellular scale, which is combined with in vivo long-term time-lapse imaging in a confocal microscope. This method enables detailed quantification of pavement cell growth (both anticlinal and periclinal walls) and lobe/neck development.

Keywords: pavement cell morphogenesis, Arabidopsis thaliana

*Speaker

Mechano-biology of cambium: influence of mechanical interactions between wood and bark on wood formation

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Diameter growth in trees is the result of cell divisions in the cambium, a secondary meristem located between the stiffer layers of wood and bark. Because of this confined position, the extension of secondary tissues must face the resistance of bark. This work aims at studying these mechanical interactions between growing wood and bark. To do so, we first need to quantify (*i*) the driving force of cell growth, i.e. turgor pressure and (*ii*) the resisting force that inhibits growth, i.e. bark's tangential stiffness. We also follow the response of cambial growth to an artificially applied radial pressure in order to record the maximal pressure under which growth is possible, and to quantify the consequences on the cell division and enlargement processes.

Keywords: cambium, secondary growth, xylem, phloem, water potential, mechanical properties, mechano biology

*Speaker

Multi-physics modelling of freeze-thaw cycles effects on tree branches

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Frost hardiness is the main factor affecting plant species distribution at high latitudes and altitudes. The main effects of freeze-thaw cycles on trees are damages to living cells, as well as the formation of gas embolism in xylem vessels. Frost effect on trees is also quantified through changes in branch diameter. In order to resorb embolism, some species (walnut, maple, birch, etc.) exhibit an increase in xylem sap pressure during successive freeze-thaw cycles. The modelling of such phenomenon is very challenging due to its multi-physics and multi-scale nature. In this work, we present a numerical model coupling heat transfer, phase change, water and osmotic fluxes, taking into consideration different cell types within walnut branch tissues. We show how diameter and pressure variations are inter-related, and we validate the model against experimental results from the literature. We eventually show how this work can be adapted in order to explore inter-species differences.

Keywords: Embolism recovery, modelling, freeze, thaw cycles

*Speaker

Where the only constant is change: balancing biophysical and physiological constraints on wave-swept shores

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A core challenge in ecology and evolution is understanding the causes and consequences of phenotypic diversity in relevant environmental contexts (PxE interactions). Increasingly, ecomechanical and other mechanistic modelling approaches have been used to link functional traits to the performance of organisms in their environment. An ecomechanical approach is ideal for wave-swept intertidal communities, where sessile macroalgae and animals alternately experience aquatic and aerial conditions twice daily. I describe a coupled biophysical and energetic modelling approach that estimates the growth and survival of intertidal seaweeds (red algal turfs, rockweeds, kelps) common to the NE Pacific. Specifically, heat, water and energy budgets are used to quantify performance tradeoffs and to identify hard versus soft constraints for thalli with different morphological and physiological characteristics. The model is also used to evaluate PXE interactions over a range of spatial (shoreline elevation, longitude) and temporal scales (tidal, seasonal, decadal).

Keywords: ecomechanics, macroalgae, heat budget, energy budget, morphology

*Speaker

Mechanisms underlying gravitropic and autotropic recovery in poplar

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[1] UMR Integrative physics and physiology of tree in a fluctuating environment (PIAF) – Institut National de Recherche pour l'Agriculture, l'Alimentation et l'Environnement : UMRA547, Université Clermont Auvergne : UMRA547 – France

Lodging is a serious hazard for herbaceous crops and young woody plants, causing significant yield losses. Resilience to lodging involves active postural control involving gravitropism and autotropism (related to proprioception). Using a novel method combining i) spherical growth cabinets with isotropic lighting with 2D clinostat to suspend graviperception, ii) a specifically-developed tracking software called Interekt 2.0, we investigate the graviperceptive and proprioceptive sensitivities, and the motors of the movements in the woody part of poplar stems . We also test the relevance of a universal model of postural control called the AC model (Moulia et al. 2021), that has not been assessed in details in woody stems. The first results show that the method used to monitor the movements is accurate. The AC model is validated for the woody part. Moreover, the tension wood seems to be the motor tissue involved in gravitropism but also in autotropism.

Keywords: Autotropism, Postural Control, Gravitropism, Proprioception

*Speaker

Diffusion and flow across shape-perturbed plasmodesmata nanopores in plants

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Plasmodesmata are slender nanochannels that link neighboring plant cells and enable the exchange of nutrients and signaling molecules. Nicolas et al. (2017) have demonstrated significant variability in the concentric pore shape, and Mai and Holbrook (2021) proposed that the central desmotubule can be displaced. However, the impact of these geometric fluctuations on transport capacity is unknown. Here, we consider the effects on diffusion and advection of two ideal shape-perturbations: a radial displacement of the entire central desmotubule and a harmonic variation in the cytoplasmic sleeve width along the length of the pore, using Fick's law and the lubrication approximation. Our results indicate that an off-center desmotubule always increases the pressure-driven flow rate. However, the diffusive current is only enhanced for particles comparable in size to the channel width. In contrast, harmonic variations in the cytoplasmic sleeve width reduce both the diffusive current and the pressure-driven flow.

Keywords: Plasmodesmata, diffusion, pressure driven flow

*Speaker

An Automated, Parameterized Model of Maize Stalk Strength via Machine Learning

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A fully parameterized model of the maize stalk morphology was created using machine learning techniques. A database 1000 CT scans of maize stalks served as the training data. The model consists of over 50 geometric parameters and 14 physical material properties. The parameterization scheme allows independent control of each physical feature of the stalk. This was accomplished by linking key landmarks with empirical eigenfunctions to capture morphological patterns in the transverse and axial directions. The parameterized model was validated by comparing results of models based on actual maize stalk shapes with parameterized counterparts in multiple loading scenarios: axial, torsion, bending, transverse compression, flexural stiffness, and ultimate bending strength. The resulting model accurately captures behavior of actual stalks, can be "fit" to any specimen, and can be used to perform sensitivity and optimization studies. The model creation, validation, and preliminary sensitivity results will be presented.

Keywords: modeling, sensitivity, uncertainty, parameterize, machine learning

*Speaker

Mechanosensitive ion channel MSL8 is required for pulsatile growth and normal pectin deposition in A. thaliana pollen tubes

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In flowering plants, pollen is the male gametophyte that not only performs the critical role of fertilization but also represents a unique and accessible system for interrogating plant cell mechanics. Pollen endures rapid rehydration upon contact with the stigma, and germinates the fastest growing cell in the plant kingdom. A key component in this robust mechanical system is MscS-Like 8 (MSL8), a mechanosensitive ion channel. Our previous work has suggested that MSL8 serves as an "osmotic safety valve", regulating pressure in the germinating pollen grain by releasing anions when the plasma membrane experiences tension and preventing pollen rupture. However, we have recently identified defects in the cell walls of *msl8* mutant pollen, suggesting a role independent of osmoregulation. MSL8 channel function appears to be required for pulsatile growth dynamics and typical pectin deposition, suggesting a mechanism where ion release into the apoplast regulates wall dynamics in a mechanosensitive manner.

Keywords: Pollen, cell wall, pectin, mechanosensitive ion channel

*Speaker

Minimizing the elastic energy by conformal growth: the case of Monstera deliciosa

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Recently, many attempts have been made to determine the stress-free deformation triggered by two-dimensional growth. We show that stress free configurations are simply given by the time evolution of a conformal mapping which concerns not only the boundary but arbitrary displacement inside the sample. For the general cases, natural fresh leaves almost in planar shape and their shape can be easily represented by holomorphic functions. By adjusting the mathematical shape function, their different morphologies of three main characteristics, tip, undulating borders and veins, can been mathematically recovered with consistency with observations. It is worth mentioning that this flexible method allows to study complex morphologies of growing leaves such as the fenestration process in Monstera deliciosa and can shed light on many other 2D biological patterns.

Keywords: Stress, free growth, Leaf patterns, Comformal mapping

*Speaker

The multiple mechanosensitive responses of wood formation to bending: a matter of sign of the strains, dose, and sensitivity adjustments

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When submitted to recurrent mechanical stimulations such as wind-related stem bending, trees modify their stature thanks to a syndrome of growth and developmental responses called thigmomorphogenesis. Wood formation is one such key process modulated by bending.
We hypothesized that different local strains may generate specific growth and wood differentiation responses, and that the perceived number of stimulations could be a driver of wood formation. This work lead us to propose new terminologies to distinguish wood produced under transient tensile strain (tensile flexure wood; TFW) or under transient compressive strain (compressive flexure wood; CFW). By highlighting similarities and differences between tension wood and TFW, by demonstrating that plants could have the ability to discriminate positive from negative strains, and by demonstrating that poplars adjust wood formation according to the number of bending stimulations, this work provides new insight into the mechanisms of mechanosensitivity in plants.

Keywords: flexure wood, strain perception, dose, effect, secondary growth, cell wall, G, layer, thigmomorphogenesis

*Speaker

DARLING – Device for Accessing Resistance to Lodging IN Grains

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5% - 25% of corn, wheat and rice yields are destroyed by wind each year. These losses are the result of stalk lodging, which occurs when wind forces break the plant stem prior to harvest. To reduce these losses, it is crucial to develop new crop varieties with increased bending strength. To this end we developed a field deploying measurement device known as the DARLING which is capable of accurately measuring the bending stiffness and bending strength of plant stems. We have worked with agronomist and plant scientist from industry and academia to implement more than 30 of these devices in numerous scientific studies. However, parts of the device are patented, and manufacturing the device costs approximately $5,000. We have now developed and will present a reliable, low-cost alternative to the DARLING for the academic research community.

Keywords: Keywords: phenotyping, bending, stalk, stiffness, strength, lodging, DARLING – Device for Accessing Resistance to Lodging IN Grains

*Speaker

Keeping in touch – Hechtian strands connect the plasma membrane to the cell wall

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The cell wall is the major load-baring structure of the plant. It is deposited by the cells and feedbacks onto them. Therefore, the connection between the cell wall and the plasma membrane is important for correct deposition of the cell wall, but also for correct read-out of the mechanical status of the cell wall from within the cell. The cell wall adheres to the plasma membrane at discrete connection points. Indeed, in plasmolysis conditions, membranous structures, so called Hechtian strands, anchor the plasma membrane to the cell wall at these sides. In this project, we aim to characterise the composition and dynamics of the Hechtian strands as well as their physiological role during drought and cooling.

Keywords: cell wall plasma membrane contacts, Hechtian strands, cell wall sensing

*Speaker

Mechanosensing tailors the inside tree biomass allocation in beech poles

Jana Dlouha * [1], Thiéry Constant [1], Bruno Moulia [2], François Ningre [1], Vivien Bonnesoeur [1,3], Marin Chaumet [1,4], Joël Hans Dongmo [1], Etienne Farré [1], Pauline Défossez [5], Meriem Fournier [1]

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Mechanosensitive control of sapling's growth in controlled condition is now rather well documented (Moulia et al., 2015; Niez et al., 2019). Recently, the ecological significance of mechanosensing as an important growth factor for forest trees was reported for young pine and beech trees (Bonnesoeur et al., 2016; Constant et al., 2020; Defossez et al., 2022). Beyond this primary effect observed at the breast height, we analysed in more details the biomass allocation inside the tree on forty beech poles during four years after thinning and/or guying. Results show that biomass allocation along the tree height is under strong biomechanical control. Further, the biomass is preferentially allocated to the stem compared to roots likely to increase the stem resistance, as roots do not present the main mechanical weakness at the pole stage due to limited tree size. Importance of these results for forest growth and risk modelling is discussed.

Keywords: tree, thigmomorphogenesis, sylviculture, biomass allocation, biomecanics

*Speaker

A Search for New Water Harvesting Technologies in the Driest Desert on Earth

Jacques Dumais * [1]

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Evolution has provided plants with unique structures to acquire water from their environment but few match the structural sophistication of the chilean airplant *Tillandsia landbeckii*. *T. landbeckii* thrives in the Atacama Desert, relying almost exclusively on microscopic leaf trichomes to capture water from fog. In this talk, I will discuss the physical origin of the trichome's valve action, leading to a 5800-fold asymmetry in the water conductance. The conductance asymmetry results from a clever juxtaposition of a thick hygroscopic wall and a semipermeable membrane. While fog absorption is achieved by capillary flow of liquid water, reversal of the flow under dry external conditions shifts the liquid-gas interface deep into the trichome thus forcing water to move through the thick trichome wall in the vapor phase. *Tillandsia* and other desert plants are inspiring new technologies to acquire water from non-traditional sources.

Keywords: cell hydraulics, drought

*Speaker

Coordinated Bacterial Migration During Root Colonisation

Ilonka Engelhardt [2,1], Yangminghao Liu [3], Daniel Patko [1,2], Mimault Matthias [4], Timothy George [4], Nicola Stanley-Wall [5], Nicola Holden [6], Mariya Ptashnyk [7], Macdonald Michael P [3], Tim J Daniell [8], Lionel Dupuy * [9,1]

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The establishment of microbes in the rhizosphere requires a complex sequence of mobility, proliferation, and attachment/detachment from the root as well as soil surfaces. Most research has focused on proliferation and biofilm formation while the mobility and attachment of microbes in soil has remained mysterious and hidden. We developed novel live light sheet microscopy technologies and mathematical models and were able to capture and characterise the dynamic movement of *Bacillus subtilis* through soil during the early stages of root colonisation. The study revealed how bacteria behave as a flock to exploit the pore space and move towards plant roots where they collectively interact with the root tip before forming biofilms on more mature root zones. Results in this study add significantly to our understanding of the biophysical mechanisms enabling microbial colonisation dynamics in soil.

Keywords: root, microbe interaction, active fluids, live system imaging, light sheet microscopy

*Speaker

Shape Shifting Stomata: Mechanical Interactions of Grass Stomata

Clinton H. Durney * [1], Matthew J. Wilson [2], Jodie V. Armand [2], Richard S. Smith [1], Richard J. Morris [1], Julie E. Gray [2], Andrew J. Fleming [2]

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Stomata are tiny adjustable pores in the leaf epidermis that balance gas exchange for photosynthesis with water loss. The mechanical interactions of a pair of guard cells are responsible for the reversible opening and closing of each pore, reliably regulating this dynamic process. Grasses, which inhabit dry environments, have evolved specialised stomatal complexes. Grass stomata consist of dumbbell shaped guard cells plus a pair of subsidiary cells, and this enables them to open and close more rapidly. Using a Finite Element Method (FEM) model, we have investigated the mechanical interactions of the guard cells with the subsidiary cells and elucidated the role that geometry, cell wall properties and cell-cell interactions play in the rapid opening and closing process of grass stomata. Our results are contrasted with a FEM of a two-cell kidney shaped stomata, underscoring the unique properties present in grass stomata that enhance their performance.

Keywords: Stomata, guard cells, subsidiary cells, mechanics, computational modelling

*Speaker

Wind safety of rubber trees in plantations: comparison of the resistance to breakage of two clones

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Rubber trees (Hevea brasiliensis) are grown on about 15 million hectares of plantations in tropical plantations, producing 13 million tons of rubber per year of industry (IRSG statistics 2020). However, during their economic life on the plantation, rubber trees appear to be very susceptible to wind damages in general and trunk breakage in particular. The main hypothesis is that bleeding could affect the capacity of the tree to increase its trunk diameter and thus, its mechanical rigidity. Here, we focus on two rubber tree clones well-known to show contrasted sensitivity to wind breakage; one being considered as "weak" and the other as "resistant". Standing tree bending tests were carried out to the trunk breaking point in two plantation plots (Ivory Coast) to assess the resistance to breakage of each clone.

Keywords: Rubber tree, Clone, Resistance, Trunk breaking, Tree bending

*Speaker

Multifunctional Banksia Seed Pods

Michaela Eder * [1]

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Mechanisms of plants to cope with harsh environments are manifold and some of the most fascinating examples are found in fire-prone regions. For example Australian *Banksias* retain their seeds on the plant for several years before they release them after experiencing the double triggers of fire and water. The functionality of the seed pods, including opening at site-specific temperatures, arises through the structure and composition of the seed pods. This talk aims to illustrate the underlying mechanisms for long-term seed storage, temperature-triggered opening, seed protection during fire as well as water-fuelled further opening for seed release. The potential of basic research of seed pods will be discussed with respect to land management, knowledge transfer to other plant-based or bio-inspired materials.

Keywords: Banksia seed pods, opening mechanism, water, fire

*Speaker

Ultra Structural Characterization of Cell Adhesion in Plants

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Cell-cell adhesion is a fundamental feature of multicellular organisms. In plants, cell-cell adhesion is mediated by the cell wall surrounding the cell. In other words, when we scale down to the cellular level, adjacent cell walls are linked to each other through a middle lamella which is believed to be very important for cell adhesion. However, it is still not clear what structural role the middle lamella is playing in this process and whether other structures of the cell wall are involved. A precise characterization of cell-cell adhesion in plants is still lacking. Here, I will present our recent observations obtained using different types of electron microscopy techniques (i.e SEM and TEM). I will also show how we combine different microscopy techniques such as fluorescence microscopy, Atomic Force Microscopy and SEM in order to gain further insight into plant cell adhesion.

Keywords: cell wall, cell, cell adhesion

*Speaker

Molecular connections between the cell wall and outer membrane are the key determinants of the mechanical integrity of the bacterial cell envelope.

Dylan Fitzmaurice * [1], Anthony Amador [1], Glen Hocky [2], Enrique Rojas [1]

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The outer membrane is the defining characteristic of Gram-negative bacteria. We recently demonstrated that it is critical for the mechanical integrity of the entire bacterial cell. To determine the key molecules and moieties within the outer membrane that underlie its mechanical role, we used molecular techniques to systematically alter its charge density, sugar content, and protein concentration. In addition, we developed novel microscopy and microfluidics-based tools to precisely measure outer membrane stiffness. We found that altering charge density had little impact on outer membrane stiffness. Conversely, altering sugar content and protein concentration had dramatic effects. Specifically, outer membrane stiffness was correlated with core oligosaccharide length, while proteins that link the outer membrane to the cell wall function as key mechanical lynchpins of overall cell envelope integrity. This latter result revises our understanding of the bacterial cell envelope from a multi-layered structure to an integral composite material.

Keywords: Outer membrane, Gram, negative, bacteria, cell wall, mechanics, stiffness, microfluidics

*Speaker

Leaf squeeze-flow rheometry: measuring plant water status via static uniaxial compression of the leaf lamina

Tomás Fuenzalida * [1], Oliver Binks [1], Callum Bryant [1], Joe Wolfe [2], Marilyn Ball [1]

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Turgor pressure has been quantified by indentation of cells or tissues, but a simple method to perform these measurements is lacking. We hypothesized that leaf turgor pressure can be monitored by uniaxially compressing the leaf lamina and measuring the stress under a constrained thickness (stress relaxation); and that leaf water content can be monitored by measuring the thickness of the leaf lamina compressed under a constant force (creep). We performed compression tests on leaves from thirteen plant species. The stress measured during stress relaxation was correlated with leaf turgor pressure (R2 > 0.95) and with leaf water potential (R2 > 0.94); the leaf thickness measured during creep was correlated with relative water content (R2 > 0.74). An average-cell model suggests that the cell stiffness during compression is largely determined by the leaf osmotic pressure. Our study presents an inexpensive and automatable method to monitor leaf water status.

Keywords: turgor, rheometry, water content, water potential, drought

*Speaker

Exploring the role of cell-type specific expansin overexpression in the control of cell wall biomechanical properties and root growth of Arabidopsis

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Expansins (EXPAs) are cell wall-loosening proteins. EXPAs are known to disrupt non-covalent bonds between cell wall (CW) polysaccharides and facilitate the CW loosening. Their molecular action enabling CW expansion remains elusive. Our results suggested that spatial-specific distribution of expansins, disruption of fine-tuned pH, and strain-stress optimum lead to growth arrest of roots. We propose that tightly controlled spatiotemporal specificity of expansin expression and hormonal-mediated pH distribution within the root apoplast plays an important regulatory role controlling the root growth and development in Arabidopsis. We induced ectopic expression of α-expansin 1, in each individual layer of the root apical meristem (RAM) using cell type-specific activators of the inducible system pOp6/LhGR. We measured the size of root and RAM but interestingly found no significant differences. We plan to follow more closely the growth after applied hormonal treatment and pH changes using confocal microscopy and 4D imaging.

Keywords: expansins, cell wall

*Speaker

Good vibrations. Some analytical advances on leaf vibration analysis

Florent Gril [1], Mathieu Secail-Geraud [1], Frédéric Ablitzer [1], Sylvain Raffaele [2], Vincent Tournat [1], Adelin Barbacci [2], Aroune Duclos [1], Frédérick Garcia * [3]

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A significant part of the mechanical stimulation from the environment involves vibrations in plant tissues such as leaves. However, little is known about the mechanoperception of these vibrations because of experimental difficulties in quantifying tissue motions. Here we report experimental and analytical advances developed to explore plant leaf vibrations from Hz to kHz. We developed a finite element model describing leaf vibrations of Arabidopsis thaliana. The model has been validated by 3D laser measurement. Since 3D laser measurement systems are not easily accessible, we also developed an alternative advanced image analysis method exploiting high speed cameras allowing the spatio-temporal quantification of vibrations. These experimental and conceptual tools are valuable aids to find morphological parameters favoring mechanoperception at specific frequencies and allow us to investigate spatially molecular mechanisms involved in mechanoperception of vibrations at sub leaf scale.

Keywords: leaf vibration, finite element model, laser measurement, high speed camera

*Speaker

Integrating Jasmonate-mediated defense with plant osmotic potential

Debora Gasperini * [1]

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Throughout the life cycle of flowering plants, the jasmonate (JA) pathway via its biologically active conjugate JA-Ile, is essential to protect plants against herbivorous insects, necrotrophic pathogens, mechanical wounding and to regulate growth. Yet, the cellular signalling events leading to the initiation of its biosynthesis in plastids remain poorly understood. By analysing Arabidopsis cell wall mutants compromised in cellulose production, we have found that JA-Ile levels are constitutively high in inner tissues of the root early differentiation zone. This ectopic hormone production could be restored to WT conditions by remodelling cell wall properties via genetic means and by increasing the water potential in cellulose mutants through osmotic treatments, suggesting that turgor-driven mechanical stress may govern the initiation of JA biosynthesis. Consistently, osmotic treatments dramatically impact the capacity to produce JA in WT plants, highlighting broader implications of turgor pressure and water potential on hormone elicitation and plant resilience.

Keywords: jasmonate, osmotic treatments, mechanical stress, Arabidopsis root

*Speaker

A multi-scale suite of cell wall architectural features powers plant organ actuation

David Sleboda [1], Reza Sharif Naeini [1], Anja Geitmann * [1]

[1] McGill University – Canada

Pulvini are joint-like motor organs that power active leaf folding in many plants. To generate a mechanistic hypothesis about the underlying mechanical principles, we built a soft hydraulic actuator that mimics pulvinus bending mechanics. Circumferential hoop reinforcements dramatically improved the bending performance of the actuator, and we hypothesized that biological pulvinus organs may contain analogous reinforcements that guide tissue swelling during rapid turgor changes. To validate this in vivo, we monitored the osmotic swelling behavior of live, isolated pulvinus organs and tissues from *Mimosa pudica*. At all hierarchical scales studied excised pulvinus organs displayed strongly anisotropic swelling behavior, indicating that structural specializations control turgor-induced shape changes at multiple spatial scales. Specialized cell wall structure and epidermis morphologies revealed by electron microscopy support this interpretation. Our findings provide underscore the hierarchical, emergent nature of biomechanical systems, and highlight design principles that can inform the development of biologically inspired soft actuators.

Keywords: thigmonasty, actuation, pulvinus, cell wall, mimosa

*Speaker

The temporal modification of histone marks plays a significant role in gene regulation in poplar after once or repeated mechanostimulation.

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Plants can attenuate their response to repetitive mechanical stimulation as a function of their mechanical history, known as the accommodation phenomenon. The role of epigenetic memory in modulating plant response to other abiotic signals is well known. However, such information is still lacking to explain the accommodated expression pattern of mechanoresponsive genes in plants. Necessitated by this, using poplar as a model plant, we studied the histone modifications at mechano-responsive loci upon recurrent mechanostimulation at varying intervals. The result shows that a single mild bending of stem for 6 seconds is sufficient for rapid modification of histone marks, highlighting the fact that plants are extremely sensitive to mechanical signals. It also indicates that acetylation of histone H3 on lysine 9/14 (H3K9/14ac) and trimethylation of histone H3 on lysine 4 (H3K4me3) at the regulatory regions of accommodated genes contribute to their expression pattern upon recurrent mechanostimulation.

Keywords: Mechanoperception, Thigmomorphogenesis, Time series, Acclimation, Accommodation, Epigenetics, Histone modification

*Speaker

A new 2D Model for studying spatial and temporal biomass allocations along searcher shoots in climbing plants and better understand their self-support against gravity

Vecchiato Giacomo * [1], Tom Hattermann [2], Michele Palladino [1,3], Fabio Tedone [1], Patrick Heuret [4], Nicholas Rowe [2], Pierangelo Marcati [1]

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There is an increasing interest in developing models to describe the growth of searcher shoots, which are the climbing plant systems adapted to support-foraging and attachment. Our model considers the processes of extension, rigidification and sensing of the external stimuli, taking particular account of the variability of the mass within the shoot. In this framework, all the parameters of the model are calibrated from experimental data, collected on two twining climbing species: Trachelospermum jasminoides (Lindl.) Lem. and Condylocarpon guianense Desf.. The resulting simulations resemble the shapes of the real plants and suggest that the inclusion of the variable mass distribution along the shoot in a model is fundamental to predict the postural development and self-supporting growth phase of shoots in climbing plants.

Keywords: mathematical model, elastic rod, variable density, climbing plants, searcher shoot, liana

*Speaker

Modeling intertwining in growing shoots

Ourania Giannopoulou * [1]

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Climbing plants exhibit diverse behaviours depending on their surrounding environment. In some cases plants {intertwine} two or more stems to form braid-like structures to bridge gaps between supports. In this study we regard intertwining by considering three fundamental mechanisms: circumnutation, a circular periodic motion; gravitropism, the reaction to the perception of gravity; proprioception, a straightening mechanism. We investigate intertwining in the framework of morphoelasticity (Goriely, 2017), therefore considering the effect of elastic deformations on the plant's evolution. This approach allows us to include ageing effects such as lignification, and forces such as gravity or contact. As demonstrated in (Vecchiato et al., 2022), when elastic mechanisms are considered, a variable mass distribution directly impacts on the final reach a growing shoot can attain. In that regard this study aims to investigate how intertwining improves the material and mass properties of shoots and subsequently favours plants' evolution.

Keywords: plant bio, mechanics, morphoelasticity, intertwining modeling

*Speaker

Upward transport in a canopy assisted by raindrop impacts on plant leaves

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Plant leaves are regularly infected by pathogenic fungi, with disastrous consequences on crops. The fungal spores are often dispersed during rainfalls. Surprisingly, the observed dispersal is not only downward (wash off / dripping) or outward (splash), but also upward, which may considerably speed up the fungus propagation. Other nutrients and microorganisms might also benefit from upward transport. In this work, we unravel an efficient and universal mechanism of upward dispersal: after a raindrop splashed on a plant leaf, the residual water on the leaf can be shot upward as the leaf springs back. We illustrate this phenomenon with several plant leaves. Then we present results obtained from systematic experiments with artificial leaves, thanks to which both the mechanics of rain-induced leaf motion and the fluid dynamics of leaf-induced droplet ejections are elucidated. In particular, we identify the range of mechanical properties of the leaf that makes upward shooting fully effective.

Keywords: Fluid, structure interaction, plants and rainfalls, leaf biomechanics

*Speaker

Why are the stems of fiber crops so slender?

Tatyana Gorshkova * [1], Anna Petrova [1], Mikhail Zakharov [1], Liudmila Kozlova [1]

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Fibers with a thick tertiary cell wall may perform as an active element in plant biomechanical systems. To check that, an assessment was made of the presence and amount of tension in flax stem at different stages of bast fiber development. The mechanical properties of various tissues of the flax stem and their cell walls were characterized at the macro- and nano- levels. To elucidate the possible ways of stress compensation in the flax stem, the dynamics of development and the partial areas of different tissues in the flax stem were characterized. The results obtained suggest that slender stems of fiber crops having the developed rings of fibers with pronounced tertiary cell walls are actually organized in a manner similar to tall towers, like Ostankino TV tower, with high-tension cables at the periphery of the construction that make it flexible and help to withstand various mechanical stresses. This work was partially supported by the RSF grant #19-14-00361.

Keywords: plant fibers, tension, tertiary cell wall, flax

*Speaker

A Multiscale Micro-Biomechanical Analysis of the Tangential Cell Wall of the Coniferous Tracheid - Biomimetic Application

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A detailed multi-scale micro-biomechanical analysis of the coniferous tracheid tangential cell wall was conducted to assess the possible mechanical significance of the transition ply architectures of the S1 and S3 sublaminates. The Finite Element Method (FEM) was used for all analyses. A global model of xylem tissue was analyzed for nine combined loading conditions (body, applied mechanical and vascular). FEA submodels of the tangential cell walls used point-wise micromechanical de-homogenization to obtain the combined constitutive material strain tenors for all nodes within each individual ply. All ply and CML properties were derived with Molecular Dynamics and transverse isotropy considerations. Nine laminate layups were included in the study. Results indicate the presences of the transition plies reduce the maximum deformational response with the S2 sublaminate, the most vulnerable sublaminate with respect to matrix damage. A biomimetic design principle was extracted from the study and applied to a typical aerospace problem.

Keywords: biomechanics, biomimetics, micromechanical de, homogenization, finite element analysis, multiscale

*Speaker

Regulation of Cell Size of Vessel Elements, and Related Effects on Water Transport and Drought Response in Populus

F. Daniela Rodriguez-Zaccaro [1], Isabelle M. Henry [2], Andrew Groover * [1,3]

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[3] US Forest Service – United States

The regulation of cell size is a fundamental but still poorly understood process underlying plant development. Angiosperm trees transport water through specialized vessel element cells. Vessel element differentiation is initiated by a dramatic increase in cell diameter, followed by synthesis of a lignified secondary cell wall and programmed cell death. The remaining cell corpse is joined end to end with other vessel elements to make longer structures, vessels, whose size have major effects on water transport capacity and cavitation under water stress. We used a population of *Populus* hybrids carrying genomically defined chromosomal insertions and deletions to dissect vessel element morphological traits. Individual QTL were identified for vessel traits, and together with heritability estimates are consistent with classical quantitative traits controlled by many genes with modest effects. Gene expression data was used in a systems genetics approach to summarize mechanisms and identify individual candidate genes underlying traits.

Keywords: Forest trees, water transport, cell size

*Speaker

How repeated acoustic stimuli increase Arabidopsis resistance to the necrotrophic fungus Sclerotinia sclerotiorum?

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The repetition of acoustic stimuli (RAS) is particularly effective in priming plant resistance to pathogens. Arabidopsis plants exposed to 3h of sound per day (1KHz, 100dB) exhibited a 12% gain in resistance compared to c.a. 1% gain obtained by genetic engineering. Intriguingly, the resistance gain only occurs after a specific RAS number and remains stable thereafter. The molecular bases associated with this resistance gain remain unknown.
We studied the effect of repeated acoustic stimuli on gene expression. In healthy plants, RAS triggered the expression of c.a. 50% of Arabidopsis resistance-associated genes (> 4000 genes). Plants exhibited extensive transcriptomic reprogramming over increasing RAS involving dominant memory mechanisms. To explore this irreversible dynamic molecular mechanism, we developed dynamic gene network inference methods tailored for very short-time series. The inferred network exhibited hierarchical and robust topology. The inferred network revealed the active role played by the mechanosensitive channel AtMSL10 in RAS priming dynamic implementation.

Keywords: Acoustic, defense priming, Arabidopsis thaliana, Sclerotinia sclerotiorum, plant immunity, dynamic network inference, MSL10

*Speaker

Engineering Biological Complexity: Auxin-Driven Pattern Formation and Emergence in Yeast

Oliver Hernández Fernández * [1], Vahid Shahrezaei [1], Tom Ellis [1], Naomi Nakayama [1]

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Cells undergo pattern formation to achieve spatiotemporal organisation. Synthetic pattern formation aims to develop design principles of multicellular development through the bottom-up engineering of spatiotemporal differentiation. We **aim to use auxin as an orthogonal pattern generator to engineer synthetic development in *Saccharomyces cerevisiae***. In plants, auxin controls many morphogenic processes. The membrane-bound efflux carriers PIN-formed (PINs) dynamically regulate the auxin accumulation pattern. PINs have been functionally expressed in yeast, and tools for auxin-regulated gene expression are being developed. We will conduct experimental and theoretical work iteratively to engineer auxin intercellular dynamics, auxin signalling and downstream gene expression in yeast. For this, we are attempting PIN polarisation in yeast, and building auxin-based synthetic gene circuits through chimeric Auxin/Indole-3-acetic acid (AUX/IAA) protein fusions. We envision this work will help make sense of auxin-driven morphogenesis in plants, and improve the prospects of budding yeast as a synthetic biology chassis.

Keywords: Auxin, Synthetic Biology, Pattern formation, Morphogenesis, Yeast

*Speaker

The vascular system of monocot nodes: structural limitations and plasticity

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[3] Citizen scientist, Hofheim – Germany

The structural design of monocotelydons is based on a highly pronounced fiber-reinforced bauplan at multiple levels of hierarchy, ranging from fibrous biomolecules (nm-scale) to tissues (mm-scale). At the tissue level, a rigid fibrous vascular network is embedded within a viscoelastic parenchymal matrix and is established and constrained by primary vascular growth. Only few monocot genera, mainly belonging to the Asparagales, are able to modify their stem tissue via secondary thickening growth. The vascular bundles are multifunctional as they mechanically support and supply the plant as conductive and mechanically rigid tissue. Both functions are especially important within the interconnecting elements between internodes and laterals, the nodes. I will present how 3D imaging using μCT and MRI techniques help to unravel structural design patterns and structural plasticity in nodes of monocots on the tissue level.

Keywords: Monocots, vascular bundles, 3D imaging, nodes

*Speaker

A Parametric Process for Root System Architecture Analysis: Case Study Analyzing Topology and Morphological Traits Across Tree Species Imaged in the Field

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Current root analysis is based on (semi)-manual measuring techniques. These tedious, expensive, scale-limited, and/or error prone techniques limit the breadth of root research, and comparison between studies. In this regard, we combine photogrammetry, 3D skeletonization algorithms, and parametric analysis to extract topology and morphological traits from root systems imaged in the field. These traits are compared across individuals and species to understand principles of root adaptation. As a proof-of-concept case study, we will present morphological trends observed in 9 hydrologically excavated root systems of 3 species. Beyond its use in biological research, the knowledge gathered is also transferred to other disciplines, including civil and coastal engineering through biomimicry. The accessibility and replicability of our proposed approach, as well as the automated nature of the root traits algorithm, facilitate its deployment for biological research on root adaptation of various species across environments through citizen science.

Keywords: Root system architecture, root research, biomimicry, biomimetics, parametric algorithm, photogrammetry, civil engineering, coastal infrastructure

*Speaker

Mechanics of the 3D puzzle cells in nutshells

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The encapsulation of seeds in hard coats and fruit walls fulfils protective and dispersal functions in many plant families. In nutshells, packaging tissues possess a remarkable range of different morphologies and functionalities. Key to these different functionalities are characteristic structural arrangements and chemical modifications of the underlying sclerenchymatous tissues. Despite the abundance of hard plant shells, particularly nutshells, it remains unclear which fundamental properties drive their mechanical stability. In this talk, we will clarify the role of cell shape and shell geometry for the mechanical behaviour of nutshells. The significance of 3D puzzle sclereids will be discussed in detail.

Keywords: diaspore adaptations, hard plant shells, sclerenchyma, seed storage and protection, tissue mechanics

*Speaker

Radial growth and stress patterning of the plant stem

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The morphogenesis of plant tissue is a reliably stable and efficient process, yet individual cell shape and growth underlies a high variance. Theory and experiment show that there is a mechanical and biochemical feedback loop for plant tissue development and morphogenesis. In fact, mechanical forces in plants have a pronounced effect on microtubule orientation in cells, thereby changing the mechanical properties, leading to anisotropic growth. Here we study the effect of cell mechanics on the bidirectional, radial growth of plant stem tissue and the arising morphological patterns, the emergence of which is yet unclear. We investigate feedback mechanisms, stress patterns and how these affect tissue and early organ shape and development. We seek to unveil the minimal biophysical requirements and relevant forces to achieve the experimentally observed morphology. First results show that already pure growth generates stress patterns that hint the connection of observed morphologies and anisotropy of mechanical forces.

Keywords: radial stem growth, stress patterns, stress anisotropy, mechanical feedback

*Speaker

Role of Rapid Alkalinisation Factor signaling in the control of cell expansion

Herman Höfte * [1]

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Pectin de-methylesterification plays a critical role in the control of cell expansion. Here we investigated the feedback mechanisms that coordinate pectin methylesterase activity, apoplastic pH and cell expansion.
We focused on the role of Rapid Alkalinisation Factor (RALF) signaling. Many RALFs are poly-cationic peptides, and hence prone to bind to poly-anionic pectin. We investigated the interaction of RALF peptides with pectin layers using a Quartz Crystal Microbalance with Dissipation monitoring (QCM-D). We show for several RALF peptides that they form polyelectrolyte complexes with pectin in a charge dependent way causing the expulsion of water from the pectin layer. We also provide evidence that RALF peptides can bind and condense intact cell walls.
We propose a scenario in which cell wall pH, PME activity and growth rate are controlled by a feedback mechanism in which pectins compete with receptor complexes for RALF binding in a charge and pH- dependent way.

Keywords: plant cell wall, pectin, cell wall integrity, root hairs, apoplastic pH control

*Speaker

MCAs are land plant-specific, inherently mechanosensitive Ca2+-permeable channels

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[2] Royal Botanic Garden Edinburgh – United Kingdom
[3] Kanagawa University – Japan
[4] Shibaura Institute of Technology – Japan

Mechanical stimuli, such as touch, gravity, and osmotic stress, influence the size and shape of cells and tissues in plants. Mechanosensing is, thus, crucial for plant growth and development. Mechanosensitive ion channels are key systems that mediate ion fluxes in response to mechanical stimuli and convert them into intracellular signals, including Ca2+ signals. Arabidopsis MCA1 and the highly homologous paralog MCA2 were characterized as candidates for Ca2+-permeable mechanosensitive channels. Here, we provide fluorometric and electrophysiological evidences demonstrating MCAs being inherently mechanosensitive channels permeable to Ca2+ and show with molecular phylogenetic analyses that MCAorthologs are found exclusively in land plants. This finding suggests that MCAs have land plant-specific functions in addition to those likely to be common to all organisms, including osmosensing. Indeed, MCAs are involved in sensing soil hardness and gravity. We discuss the structure, function, and evolution of the MCA family.

Keywords: MCA, mechanosensitive channel, protein purification, liposome, patch, clamp, molecular evolution, Arabidopsis

*Speaker

Mechanical stresses and long-distance signaling in poplar

Erwan Tinturier [1], Nathalie Fournier-Leblanc [1], Eric Badel [2], Jean-Louis Julien * [3]

[1] UMR 547 PIAF – Université Clermont Auvergne – France
[2] UMR 547 PIAF – INRAE – France
[3] UMR 547 PIAF – Université Clermont Auvergne – France

Under natural conditions, plants are subjected to mechanical stresses and potentially show a response at a distance from the site of stimulation suggesting the transfer of information. The nature of the information vector remains unknown to date. The propagation of an electrical signal following the bending of the poplar stem was studied by extracellular electrophysiology measurements. This study revealed the propagation of a graded potential (GP), an electrical response with original characteristics that differentiate it from an action potential (AP) and its electrotonic propagation, leading to the idea of another mode of propagation and to the hypothesis of a hydroelectric coupling. In order to determine whether the PG is likely to trigger a biological response, various RNA seq experiments were undertaken. The results revealed a significant transcriptional response at a distance from the solicited area, dependent on the passage of a PG.

Keywords: Poplar, stem bending, electrical signal, hydraulic pressure wave, RNA seq

*Speaker

Getting old is hard: biomechanical changes during the maturation of stomatal guard cells

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Stomatal conductance varies as plant leaves develop, but insights into the functional relationships between stomatal maturation, the biomechanics of guard cell walls, and stomatal dynamics are lacking. We used time-lapse imaging to track geometric changes in stomatal complexes after pore initiation, finding that a pore length:junctional length ratio of 1 represents a transition point between young and mature stomatal complexes in cotyledons of *Arabidopsis thaliana* seedlings. Mature stomata have thicker cell walls than young stomata but attain a higher dynamic range between closed and open states. Using incipient plasmolysis and microscopy analyses, we tested turgor pressure and cell wall structure as potential mechanisms underlying this difference in dynamic range, concluding that guard cell length primarily determines the dynamic range of stomata. Together, these data highlight how changes in the geometry and biomechanics of guard cells during maturation underlie changes in stomatal function.

Keywords: Stomata, Guard cells, Cell wall

*Speaker

Fluid-structure interactions in plant vascular flows

Kaare Jensen * [1]

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Vascular cells in plants are soft enough to deform in response to stresses from the fluid flows they carry. Yet fluid stresses are, in turn, affected by the altered geometry. This leads to interesting coupled elasto-viscous phenomena. This talk explores recent progress in understanding how fluid-structure interactions in plant cells impact transport across scales: We consider the link between tissue deformation and cellular pressure, flow in soft conduits under tension, the effects of elasticity in intercellular flows, and the energetics of cytoplasmic streaming. Finally, biological implications and biomimetics applications are discussed.

Keywords: Fluids, Elasticity, Fluids, structure interactions

*Speaker

Differential growth dynamics controls aerial organ geometry

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How genes and biomechanics together direct organ shapes is poorly understood. Plant leaf and flower develop from highly similar initial structures, yet they exhibit drastically different mature shapes - flat and bilateral leaves, and radially symmetric floral primordia, respectively. We analyzed cellular growth patterns and gene expression in young leaves and flowers of *A. thaliana*, and found significant differences in cell growth rates, which correlate with convergence sites of auxin. In leaf, the *PRS* -expressing middle domain grows faster than adjacent domains and show higher auxin retention. In contrast, the *LFY*-expressing adaxial domain in flower shows both accelerated growth rates and elevated auxin levels. This distinct cell growth dynamics between leaf and flower requires changes in levels of cell wall pectin demethyl-esterification and mechanical properties of the wall. Data-driven simulations at organ and cellular levels demonstrate that growth differences are central to obtain distinct organ shape, corroborating *in planta* observations.

Keywords: cell growth, computational modelling, gene expression, growth and patterning, live, imaging, morphogenesis, organ shape

*Speaker

Comparative biomechanics of energy storage and release across seed-shooting witch hazels

Justin Jorge * [1], Sheila Patek [1]

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The seed-shooting fruits of three confamilial species shoot their seeds at similar speeds despite their seeds spanning an order of magnitude in mass. The fruits of *Fortunearia sinensis*, *Hamamelis virginiana*, and *Loropetalum chinense* use the same pinch-based mechanism: a spring-like structure surrounding each seed pinches on the seed to eject it. As a spring-actuated system, fruits shooting more massive seeds are expected to have significantly lower seed ejection speeds if the other seed-shooting components are held constant. Given that this is not the case, we investigate how the fruits of these species adjust to launch larger seeds. We collected measurements of seed mass, spring mass, energy storage, and energy release. We found remarkable variance in compensation strategies across species that use seemingly similar seed-shooting components. We conclude that fruits can compensate for larger seeds by storing more energy or by more efficiently converting stored energy to kinetic energy.

Keywords: biomechanics Hamamelidaceae ballistochory dispersal

*Speaker

Fluttering leaves to determine water stress in plants

Jisoo Yuk [1], Joseph Lee [1], Caroline Graves [1], Sunghwan Jung * [1]

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Water stress directly affects crop growth, so it is used as a key indicator in evaluating crop yield. In terms of technology, there are non-destructive approaches to utilize the relationship between water stress and leaf vibration frequency, but the tendency of the frequency due to the dryness was controversial. Here, we proposed a new perspective of leaf surface curvature affecting vibration frequency in order to understand this discrepancy. To this end, the changes in surface curvature during the drying process were monitored with a 3D camera. In addition, bending and flexural rigidity tests were conducted with soybean leaves. From video-recordings, we found that leaves had varied curvatures as they grew, from flat to curling up. Therefore, the frequency of fluttering leaves can show contrasting results standing on the surface deformation. These results indicate that the morphological feature of the leaves is the key to the vibration frequency.

Keywords: Water stress, Fluttering leaves

*Speaker

Regulation of Charra Corallina growth by turgor pressure

Weiyuan Kong * [1], Etienne Couturier [1]

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In plants, turgor pressure is the hydrostatic pressure exerted by an inward osmotic flow which presses the cell membrane against the cell wall. The action of turgor pressure on extensible cell walls is known to drive plant growth. While turgor pressure is isotropic, plant growth often requires anisotropic cell wall expansion. The cell growth anisotropy is strongly correlated with cell wall strain anisotropy. However, the way these observations combine with Lockhart's law to describe the regulation of anisotropic growth by turgor remains quite fuzzy. By combining confocal microscopy and pressure probe, we aim to complete this lack by tracking the growth of *Chara corallina* in 3D while alternating its turgor pressure. Preliminary results suggest that when pressure is varied, the growth rate varies in both directions. This difference in rate seems to be more significant in the transverse direction, especially for very young cells.

Keywords: Turgo pressure, Cell wall, anisotropic growth

*Speaker

Nano-mechanical response in stressed living root tissues

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It has been observed that in low phosphate condition, presence of excess Iron (Fe) leads to root growth arrest phenotype. Our project aims to study the relationship between root growth arrest and CW stiffness using nano-indentation experiments on live Arabidopsis roots with atomic Force microscopy (AFM). To characterize the cell wall stiffness we have developed a robust protocol. Results indicate that CW stiffening is proportional to added Iron concentration. The addition of Aluminium (Al) further increases the CW stiffness. However, when Al3+ ions are added without Iron, no change in CW stiffness is observed.These results suggest a co-operative effect of Fe and Al in CW stiffening and root growth arrest. Organic acids such as Malate are the anticipated mediator of the boost effect of Al by over accumulation of iron in the apoplast region, which likely induces Reactive Oxygen Species response that catalyzes changes in CW organization.

Keywords: Arabidopsis, Cell Wall stiffness, Atomic force microscopy.

*Speaker

Edge-based growth control in Arabidopsis involves two cell wall-associated Receptor-Like Proteins

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Morphogenesis of multicellular organs requires coordination of cellular growth. In plants, 3D growth is driven by undirected turgor pressure, whereas growth directionality is controlled by cell wall mechanical properties at 2D cell faces. The cell wall also fixes cells in their position, and plants thus have to integrate tissue-scale mechanical stresses arising due to growth in a fixed tissue topology. This implies a need to monitor cell wall mechanical and biochemical status and to adapt growth accordingly. Here, we propose that plant cells use their 1D cell edges to monitor their cell wall status. We describe two edge-localised Receptor-Like Proteins, RLP4 and RLP4-L1, that can associate with the cell wall and participate in directional growth control in *Arabidopsis*. We also uncover that establishment of the RLP4s polar edge domain at the plasma membrane requires edge-directed secretory transport mediated by the small GTPase RAB-A5c, while endocytosis and recycling play subordinate roles.

Keywords: cell edges, morphogenesis, receptor, like protein, cell wall

*Speaker

Multiscale modelling and analysis of growth of plant tissues

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[3] Heriot-Watt University – United Kingdom

How morphogenesis depends on cell properties is an active direction of research. Here, we are interested in mechanical models of growing plant tissues, where microscopic cellular structure or even subcellular structure is taken into account. In order to establish links between microscopic and macroscopic tissue properties, we perform a multiscale analysis of a model of growing plant tissue with subcellular resolution. We use homogeneisation to rigorously deduce the corresponding tissue scale continuous model. Tissue scale mechanical properties are computed from all microscopic structural and material properties, taking into account advection by the growth field. We then consider case studies and numerically compare the detailed microscopic model and the tissue-scale model, both implemented using finite element method. We find that the macroscopic model can be used to efficiently make predictions about several configurations of interest. Our work will help making links between microscopic measurements and macroscopic observations in growing tissues.

Keywords: homogenization, multiscale modelling, plant tissue growth, linear elasticity, finite elements, FreeFem

*Speaker

Force generation in coiling tendrils of the climbing passion flower Passiflora caerulea

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Instead of building a self-supporting stem, climbing plants attach to external supports to hoist themselves upwards. Tendril bearing climbing plants, such as e.g. most species of the genus *Passiflora*, attach to a support by coiling their tendril's tips around the support or by forming attachment pads. After the tendrils attached to a support, they coil along their axis and thereby form a spring-like dampening element in the attachment system. The coiling shortens the tendril and draws the plant stem closer to the host. With a newly developed experimental setup, we are able to measure continuously the contractile force generated by the coiling movement of climbing plant tendrils at high resolution. In combination with a close control and monitoring of environmental conditions and the use of time-lapse photography, we show how the force generated by the tendrils of *Passiflora caerulea* changes during the coiling process.

Keywords: Climbing plant, tendril, coiling, Passiflora

*Speaker

Uncovering roles of cell walls in protoplast regeneration

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Plant cell wall instructs fundamental cellular processes such as growth, division, communication and differentiation. When cell wall is enzymatically removed (protoplasted), fully differentiated plant cells can regain a stem-cell-like state. Under appropriate conditions, protoplasts can regenerate whole plants. Although protoplasting is an established protocol, the role of cell wall in regeneration isn't well understood. Therefore, we are modifying cell wall remodelling in protoplasts to observe effects on cell de- and re-differentiation. To monitor the progress of protoplast regeneration, physiological and genetic markers are developed for quantitative microscopy, and we investigate the effects of different cell wall degrading enzymes. To aid cell wall and protoplast engineering, we are creating a suite of synthetic biology tools. They include stage-specific promoters and coding sequences for cell wall modifying proteins, as well as highly sensitive fluorescent reporters and multi-inducible systems. These new tools will help elucidate cell wall's role in regulating plant development.

Keywords: Cell wall, regeneration, protoplasts, synthetic biology

*Speaker

Geometry reconstruction of 3D vascular patterns from confocal microscopy imagery.

Andrzej Kokosza * [1], Wojciech Pałubicki [1], Agata Burian [2]

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[2] University of Silesia in Katowice – Poland

The investigation of plant biomechanics requires accurate methods of plant geometry reconstruction, for example, to measure a strain of vascular bundles. We present a method for semi-automatic reconstruction of filament patterns, e.g. vascular bundles in various tissues of the plant body. User annotates starting position inside the pattern. The method generates accurate 3D skeleton graphs indicating filament patterns. It is formulated as an agent model. The agent is placed in the starting position and moves alongside the pattern based on the agent's cone of vision which the user can adjust. In comparison morphological skeletonization requires post and pre-processing, making it time expensive, whereas our method works almost in real-time, thus allowing for iterative tuning. We demonstrate the results of our model by tracing paths formed by auxin marker in confocal stacks. We discuss advantages, potential shortcomings and show how the method's parameters can be predicted using a neural network.

Keywords: confocal microscopy, vein patterning, Arabidopsis thaliana, machine learning, computer vision

*Speaker

In search of growth-limiting tissue in monocotyledonous and dicotyledonous roots

Anna Petrova [1], Tatyana Gorshkova [1], Liudmila Kozlova * [1]

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To test the hypothesis that a particular tissue can control root growth, we analysed the mechanical properties of cell walls belonging to different tissues of growing roots of monocotyledonous and dicotyledonous plants using atomic force microscopy. The dynamics of the properties during elongation growth were characterized in four consecutive zones of roots of each species. Both tissue- and zone-specific differences of cell wall elasticity were observed. Extensive immunochemical characterization was used to establish the polysaccharide motif(s) associated with changes in cell wall mechanics in type I and type II primary cell walls. When measured values of elastic moduli and turgor pressure were used in the computational simulation, this resulted in an elastic response of the modelled root and the distribution of stress and strain similar to those observed *in vivo*. Root growth is limited by the inner cortex. This work was partially supported by the Russian Science Foundation 18-14-00168

Keywords: primary cell walls, atomic force microscopy, root, elongation growth, immunochemistry

*Speaker

Formation of gas spaces in pimpernel (Anagallis grandiflora) petal epidermis – interplay between growth, geometry and cell wall mechanics

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We study differential growth at subcellular scale. Epidermal cell of pimpernel petal represents an extreme case of such growth variation. During its ontogeny, apart from undulation of both anticlinal and periclinal walls, numerous intercalary gas spaces are formed, i.e. spaces at contacts of only two adjacent cell walls. The space is initiated as a small invagination of one of the anticlinal walls. The invagination subsequently expands toward the cell lumen, and "opens" forming a drop-like gas space. Finally, after further wall expansion and opening, a crescent-shaped space is formed by walls of two adjacent cells, concave from one cell side and convex from the other. Such wall expansion is reminiscent of puzzle-shaped pavement cells only the undulation is formed by a single wall rather than adherent walls of two cells. We quantify wall growth, geometry, and analyse wall composition and structure, aiming to understand what drives such subcellular growth heterogeneity.

Keywords: Cell wall, intercalary gas space, growth heterogeneity, subcellular scale

*Speaker

Parallelized plant morphogenesis in a controllable microfluidic environment.

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We developed a microfluidic system capable of following several plant individuals in parallel under the same controllable experimental conditions. Our plant model is Marchantia polymorpha, a bryophyte capable of growing in aqueous media and whose asexual reproductive cycle produces numerous, genetically identical gemmae. They are flat and millimetric in size. This makes them ideally suited for observation in a microfluidic chip. This chip has traps to isolate individuals and maintain them in place for observation during 36h. With several inputs for flow and computer-controlled syringe pumps, the environment inside the chip can be tightly controlled and rapid changes can be applied to perform osmotic chocs. This allows for measurements of hydromechanics properties by analyzing the deformation response to osmotic stress. In our current experiments, we are combining growth observation and hydromechanical measurement on the same samples to draw correlations between growth characteristic time and mechanics at the organism level.

Keywords: Growth, biomechanics, microfluidics

*Speaker

A front propagation model for leaf morphogenesis

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Leaves are photosynthetic organs with a diversity of shapes and complex vascular networks. During morphogenesis, two types of growth modes can be distinguished, peripheral and global. In order to explain the peripheral development, we propose a numerical model of growth by interface propagation describing the dynamics of the vein network as a function of the initial shape of the front and the spacing of the veins. In the case of a single lobe growth, we find an unstable central vein, whose position oscillates in the middle of the lobe. Its dynamics can be modelled by an iterated function whose geometry explains the instability. We modify this model and introduce a feedback loop. In a second model where the growth of the front is dependent on the position of the veins, we find two lobes by edge effect and an oscillation of the growth front, similar to an optical mode.

Keywords: Leaf, morphogenesis, front propagation model

*Speaker

The mechano-hydraulic regulation of plant cell growth variability.

Yuchen Long * [1]

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In plant cells, cell wall mechanics and turgor pressure play key roles of growth regulation. Whereas cell wall has been the focus of biomechanical studies, the precise role of turgor pressure is largely underdeveloped. By combining atomic force microscopy (AFM), confocal live imaging and physical modelling, we determined cell-specific turgor pressure noninvasively in the shoot apical meristem (SAM) of *Arabidopsis thaliana*, and demonstrated that turgor pressure is highly heterogeneous *in planta*. Pressure heterogeneity, intriguingly, also does not directly correlate to growth rate, and their relation is controlled by:
- mechano-hydraulic balance
- cell size and topology
- cell shape
which may change during growth and create feedback to autoregulate cell expansion rate. Together, our results reveal cell turgor pressure as a source of patterned heterogeneity and illustrate links between local topology and geometry, cell mechanical state, and cell growth, with potential roles in tissue homeostasis.

Keywords: mechanical hydraulic balance, cell size, growth regulation, geometry and topology, atomic force microscopy.

*Speaker

The mechanics of seed size control in Arabidopsis

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How cells stop their growth once an organ has reached a certain size is a key question in developmental Biology. In animals, mechanical signals act with biochemical factors to control organ growth and size. In plants, mechanical signals regulate a variety of processes such as growth, division or gene expression; but their contribution to organ size control remains to be demonstrated. By combining experimental approaches with modelling, we propose that Arabidopsis seed growth is regulated through an incoherent mechanosensitive feedforward loop where the turgor pressure of the inner tissues (endosperm) induces growth directly but represses it indirectly by promoting the stiffening of the cell walls of the outer tissues (seed coat) in a tension-dependent manner. Our work sheds new light on the mechanisms of organ size control in plants and allows us to redefine the contribution of turgor pressure to plant organ growth.

Keywords: Organ size, Hydrostatic pressure, Mechanical forces, Pectins, Seed development

*Speaker

How mechanical signals contribute to plant resilience after drastic pruning: the case of pollard trees

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The resilience shown by tree species where all upper and lateral branches are pruned highlights the adaptation to shoot loss. Such pruned trees, called pollards, share a characteristic phenotype of massive branching and increased thickening of the trunk. We hypothesize that, as part of the wounding response, pruning also changes the mechanical status of meristems and their activity. To test this, emergence of new shoots and covering bulge after pruning will be described in poplars. We will focus on the mechanical and hormonal interplays after pruning by bending poplar stems. In parallel, the contribution of hormonal signals and mechanical forces to the activity of meristems after pruning will be investigated in a perennial arabidopsis mutant sharing anatomical features with woody stems. In other words, we will investigate the long-term consequences of pruning on meristems and what makes trees robust to repeated traumatic events.

Keywords: pollard trees, pruning, meristematic activity, bending

*Speaker

Cell-type-specific behaviour underlies cellular growth variability in plants

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In plants, cell growth is controlled by positional information. Yet the behavior of individual cells in an expanding tissue is often highly heterogeneous. The origin of this variability is still unclear. Using quantitative time-lapse imaging, we determined the source and relevance of cellular growth variability in developing organs of *Arabidopsis thaliana*. We showed that the cell-autonomous behavior of specialized cells is the main source of local growth variability in otherwise homogeneously growing tissue. Growth differences are mechanically buffered by the immediate neighbors of specialized cells to achieve robust organ development.

Keywords: Leaf, floral organs, live, imaging, local growth variability, growth tracking, mechanical feedback, plant organogenesis, stomata, trichomes, Arabidopsis thaliana

*Speaker

Phosphoinositide phosphates dependent regulation of Microtubules dynamic by MDP25 in A. thaliana pavement cells

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The plasma membrane (PM) is at the interface between cell wall and microtubule (MT) arrays which makes it a key compartment to understand how cells transduce external stimuli. It has been proposed such transduction to involve cytoskeleton through a direct link with the PM. To decipher this interplay, we combined phosphoinositide phosphates (PIPs) alteration, mechanical stress and analysis of pavement cells microtubules. We identified the tubulin- and PIPs-binding protein MICROTUBULE DESTABILIZING PROTEIN 25 (MDP25), as a key component of this interplay. We showed PIPs perturbation to strongly impact microtubules dynamic. We could show MDP25 is a regulator of the MT response during PIPs alteration. Furthermore, we found MDP25 as a positive regulator of MT reorganization during mechanical stress. We showed MDP25 associates with MT and actin cytoskeletons at specific regions. Altogether, our data demonstrate MDP25 mediates fine microtubule regulation at the interface between PM and cytoskeleton during mechanical stress.

Keywords: Microtubules, Phosphoinositide Phosphates, Mechanical Stress, Pavement Cells

*Speaker

Sepal morphogenesis and cellulose synthase guidance

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Plant cell growth is driven by turgor pressure deforming the cell wall. Plant cell wall load-bearing elements, cellulose microfibrils, are thought to direct growth perpendicularly to their orientation and are synthesized by cellulose synthases (CESAs). CESAs are primarily guided along microtubules via a protein called CELLULOSE SYNTHASE INTERACTIVE 1 (CSI1). Here, we focus on the sepal of the plant Arabidopsis thaliana to investigate how the guidance of CESAs by microtubules contributes to organ morphogenesis. We observed that sepal shape was less elongated in csi1 mutant, which originates from lower elongation in csi1. Surprisingly, cell anisotropy was similar in csi1 and wild-type plants. We propose that the discrepancies between organ and cellular scale are due to an absence of spatial coordination in csi1 in which cells grow in more variable directions. This is revealed in particular by the shape of giant cells : straight in wild-type and snakey in csi1.

Keywords: cellulose, csi1, morphogenesis, cell growth, sepal

*Speaker

A novel kinematic method for quantifying gravitropic and proprioceptive sensitivities illustrated on Arabidopsis wild type and XI myosin mutants.

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Gravitropic movements, which are essential in controlling plant shape and function, are driven by the sensing of organ inclination and organ curvature (proprioception (1)). Although crucial for understanding the growth dynamics and the final phenotype, disentangling these two sensitivities is challenging. In our two-step method, based on (2), the plant is first tilted to the horizontal to trigger tropic bending. Then, a clinostatic rotation around the horizontal axis is set to suspend graviception, and the stem straightens under pure proprioceptive driving. We implemented this method together with time-lapse image analysis using a novel version of the Interekt software (3). We illustrate this automated pipeline on *Arabidopsis* WT and proprioception-deficient *XI myosin* mutants.

(1) Moulia *et al.* 2021, doi:10.1126/science.abc6868
(2) Okamoto *et al.* 2015, doi:10.1038/nplants.2015.31
(3) Hartmann *et al.* 2022, doi:10.1007/978-1-0716-1677-2_9

Keywords: gravitropism proprioception quantitative_phenotyping kinematics

*Speaker

Plant puzzle cell shape is an adaptation to a developmental constraint based on mechanical stress and isotropic growth

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The puzzle-shaped cells that appear in the epidermis of many plant species are a striking example of a complex cell shape. Since shape in an organism is often thought to be closely related to its function, it suggests that these unusual shapes must have some functional benefit to the plant. We propose that the creation of these complex shapes is an effective strategy to reduce mechanical stress in the cell wall. Although the formation of these shapes requires highly anisotropic and non-uniform growth at the sub-cellular level, it appears to be triggered by isotropic growth at the organ level. Analysis of cell shape over multiple species is consistent with the idea that the puzzle is in response to a developmental constraint, and that the mechanism is like to be conserved among higher plants.

Keywords: mechanical stress, growth, cell shape, pavement cells, puzzle cells

*Speaker

Why plant cells do not pop like soap bubbles?

Alice Malivert * [1], Özer Erguvan [1,2], Antoine Chevallier [1], Antoine Dehem [1], Rodrigue Friaud [1], Mengying Liu [1], Marjolaine Martin [1], Théophile Peyraud [1], Olivier Hamant [1], Stéphane Verger [1,2]

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To survive, plant cells must constantly resist mechanical stress caused by turgor pressure. This involve the perception of cell wall tension, the reinforcement of cell walls and the regulation of the osmotic pressure to maintain mechanical integrity. Here, we show that the receptor-like kinase FERONIA, a candidate wall mechanosensor, is necessary for the mechanical integrity of plant cells. The *feronia* mutant exhibits burst cells and small cotyledons, two phenotypes that can be partially rescued by reducing water potential and tensile stress levels. We also showed that FERONIA and cortical microtubules independently contribute to wall reinforcement. If FER perceives cell wall tension and/or turgor pressure, it could integrate mechanical signals linked to water availability in a mechanotransduction pathway and play a broader role in the perception of the environment (mechano-eco-sensing), explaining its pleiotropy.

Keywords: FERONIA, mechanosensing, mechanical intergity, cell wall tension, turgor pressure

*Speaker

Jumpy dynamics of air embolism in biomimetic leaves

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In case of drought, the water in the xylem hydraulic circuits of trees falls down to very negative pressures. Cavitation bubbles can nucleate, initiating an air embolism that propagates, a process called air-seeding, leading to the failure of the water circulation. Observations on real lives showed that the embolism advances by a succession of long stops and sudden jumps.
To understand the nature of jumps, we propose an experimental model using biomimetic leaves in silicone (PDMS), made of a thin water-permeable membranes. The veins of these artificial leaves are channels filled with water, and we have introduced constrictions to mimic the pit in between real leaf channels.
We observed that the jumpy dynamics of the air embolism front is due to an elasto-capillary coupling between the interface and the deformable channel structure. Fast camera experiments reveal the speed of those events, to make the link with biological observations.

Keywords: cavitation, embolism, air, seeding, surface tension, biomimetic, leaves, elasticity

*Speaker

Measuring the axial variation in flexural stiffnesses of septated plant stems

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Flexural three-point bending tests are useful for characterizing the mechanical properties of plant stems. The best practice involves long spans with supports and load placed at nodes. A new method pairs physical test data with analytic models to obtain values of flexural stiffness for individual stalk segments. Uncertainty in flexural stiffness values were found to be strongly dependent upon measurement errors. Row-wise scaling of the system of equations reduced the influence of measurement error. Relationships between measurement uncertainty and solution uncertainty were provided for two different testing methods. The methods presented in this study can be used to measure the axial variation in flexural stiffness of plant stem segments. However, care must be taken to account for the influence of measurement error as the individual segment method amplifies measurement error. An alternative method involving aggregate flexural stiffness values does not amplify measurement error, but provides lower spatial resolution.

Keywords: flexural stiffness, axial variation, model

*Speaker

Leaf unfolding: concepts for biomechanical analyses

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Leaf unfolding can serve as a promising functional model for bio-inspired packing and unpacking systems (Kobayashi et al. 1998). Previous biological studies focus on underlying mechanisms and mathematical modelling of bud and leaf opening rather than on mechanical properties (van Doorn & van Meeteren 2003, Lin et al. 2021). So far, no reliable and reproducible criteria for biomechanical tests of unfolding leaves are set (Poppinga et al. 2013). Biomechanical analyses will help for characterising the unfolding process. A comparison of various leaf species shall enable to find various fundamental principles of unfolding in leaves which may be used for a broad range of technical implementations. Amongst other methods, leaf biomechanics shall be analysed by (1) tensile experiments on isolated leaf areas of different ontogenetic stages and by (2) measuring the forces during the natural unfolding process. *Syngonium podophyllum* will serve as a first model species for establishing these methodological approaches.

Keywords: leaf unfolding, leaf biomechanics, tensile experiments

*Speaker

Dynamic of growth and tension in explosive fruits

Gabriella Mosca * [1,2], Ryan Eng [1], Mila Adibi [1,3], Angela Hay [1]

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Cardamine hirsuta uses an explosive mechanism to disperse its seeds which contributed to its ecology as an invasive weed. Explosive dispersal is made possible by the rapid coiling of each valve as it detaches from the fruit. The core mechanics and cellular innovation underlying this trait have been analyzed in Hofhuis et al. (2016). One key innovation is the generation of contractile tension in C. hirsuta valves. The outer cell layer of the valve, while always pressurized, grows into a state of tension which would, if isolated, make it shrink in length. In this work we combined live-imaging of cell growth, cortical microtubule and cellulose synthase dynamics, with mechanical modeling, to explain how these cells can grow and at the same time efficiently develop and increase contractile tension. We furthermore show how cellulose microfibrils dispersion is not mere noise, but plays a role in optimizing the contractile tension up.

Keywords: biomechanics, FEM, modeling, imaging, cytoskeleton, microfibrils, grow

*Speaker

Mechanics of transition from dormancy to growth in Marchantia

Elise Muller * [1], Stephanie Drevensek [1], Arezki Boudaoud [1]

[1] Laboratoire d'hydrodynamique – Polytechnique - X – France

Several plants switch between a resting phase, called dormancy, and a growing phase. Dormancy allows organisms, notably at seed stage, to better cope with unfavorable environmental conditions as cold or drought. To what extent is cell mechanics involved in the transition between dormancy and growth? Vegetative propagules, known as gemmae, of the bryophyte *Marchantia polymorpha* provide an ideal model to tackle this question. Indeed, the transition of gemmae between dormancy and growth can be imaged live. Gemmae are clones, which enables the investigation of large numbers of genetically identical individuals. Moreover, the study of gene functions is facilitated by *Marchantia*'s genome low redundancy. Using osmotic treatments and mechanical modeling, we could measure differences of elastic modulus and hydraulic conductivity between dormancy and the growing phase, and we characterized growth of gemmae. We started exploring underlying molecular mechanisms. Altogether, our work sheds light on the mechanical control of growth.

Keywords: Growth mechanical control, Elastic modulus, Osmotic treatments, Morphogenesis, Dormancy, Marchantia

*Speaker

Biomechanics and functional morphology of the European mistletoe and its connection to the host tree

Max D. Mylo * [1,2], Mara Hofmann [1,2], Samuel Beisel [3], Frank Balle [3], Thomas Speck [1,2], Olga Speck [1,2]

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Parasitic plants have evolved 12 times independently in Angiosperms. They all have in common the formation of a haustorium that structurally and physiologically connects them to their host plants. We analyzed the morphology, anatomy, and biomechanics of the connection between the European mistletoe (*Viscum album*) and its host tree, which in nature never mechanically fails despite the size ($>$ 2 m) and age ($>$ 20 years) of old mistletoes. Segmented μCT scans visualized the transition of anchoring structures (several small into one main sinker) during mistletoe growth. Histological analyses revealed a distinct separation line and cellular and biochemical gradients at the mistletoe-host interface. Tensile tests to failure on intact and sliced samples, combined with fracture area quantification, showed that as mistletoes age, maximum force of the interface increases, but its tensile strength remains constant. Digital image correlation revealed that local strains above 30% initiate fracture at the interface.

Keywords: mistletoe, parasite host connection, tensile testing, digital image correlation, fracture surface quantification

*Speaker

Dandelion 'decisions': to fly or not to fly – that is the question

Naomi Nakayama * [1]

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The common dandelion generates one of the most iconic flyers in nature. Their diaspores contain a pappus, a bundle of about 100 filamentous organs positioned above the seed. The pappus is dogmatically believed to act as a parachute to lift the seed, but with over 90% empty space, the fluid dynamic mechanism of the traditional parachute cannot apply to the pappus. We have uncovered a ring-shaped vortex that is physically separated from the pappus but stays at a constant distance downstream of the body, which helps the seed stay afloat. The pappus morphology is not fixed; it reversibly closes when wet. This morphing enables effective dispersal in tune with specific weather conditions. There is a hydrostatic actuator at the base of the pappus underlying this morphing. We have identified what structural features are critical drivers by deformation analysis combined with 2D finite element method modelling.

Keywords: Structural function, dispersal, morphing, diaspore, environmental response, actuation, mechanical ecology

*Speaker

Living on the edge - How to control cell growth at the organ surface

Zoe Nemec Venza * [1], Charlotte Kirchhelle [2]

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Robust organ shapes in plants require regulation of cell growth, and new mechanisms of cell growth regulation have recently emerged. For instance, cell edges (where two cell faces meet) have emerged as domains of growth control independently of cellulose organization. In epidermal cells, a vesicle trafficking route directs secretion specifically to cell edges, and its disruption perturbs cell growth in lateral roots. Our data suggests the need for edge-based growth control is limited to cells at the organ surface. In roots, the root cap covers part of the meristem, and edge-directed transport is limited to epidermal cells not covered by the root cap. Thus, we hypothesise that the mechanical niche of cells at the organ surface, which have to negotiate dramatic pressure differences, both explains the requirement for edge-based growth control and regulate its activity. We will explore this hypothesis combining quantitative imaging, mechanical and genetic manipulations, and transcriptomic approaches.

Keywords: Edges, Surface, Epidermis, Rootcap, Arabidopsis, Mechanical niche

*Speaker

Rapid Generation of Specimen Specific Finite Element Models of Plant Stems

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[2] Fairleigh Dickinson University – United States

Cross-sectional measurements including rind thickness and diameter are key determinants of bending stiffness and bending strength in plant stems. However, current methods of measuring cross-sectional morphology of plant stems are time consuming and often require specialized equipment and expertise. This is especially true of large grain crops like maize which plays a vital role in maintaining global food and energy security. This study presents a high-throughput, inexpensive, and user-friendly methodology that enables measurement of diameter, rind thickness and vascular bundle counts. These cross-sectional features are used to develop specimen-specific, finite element models of plants in a semi-automated fashion. Using this methodology finite element models can be generated in less than a day whereas other state of art methods typically require over a week. The rapid generation of in silico plant models has and will continue to enable detailed studies of plant biomechanics that cannot be accomplished through other means.

Keywords: cross, section, diameter, finite element, modeling, computational

*Speaker

Shifting from searching to twining in climbing beans

Amir Ohad * [1,2]

[1] Yasmine Meroz – Israel
[2] Amir Porat – Israel

Twining plants have been studied for many years, but the initialization of twining has not been understood to this day.
The movements of a green bean impacting a pendulum support rod are studied on several support masses.
We notice a minimal contact time with the support before twining is initiated, as well as a mechanical limitation of the stem elasticity which, combined with the position of impact along the stem can lead to the organ slipping off of the support structure.
The measured force trajectories fit well with simulations of a circumnutating organ impacting a stable support structure, using measured experimental parameters,hinting that the force may be sufficiently explained via the circumnutation movement.

Keywords: Twining, signal integration, biomechanics

*Speaker

A field theory for plant tropisms

Hadrien Oliveri * [1], Derek Moulton [2], Alain Goriely [3]

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Tropism refers to the directed movement of a plant in response to external stimuli. Typically, these stimuli induce hormone redistribution that triggers cell deformation. In turn, these local cellular changes create mechanical forces within the tissue that are balanced by an overall deformation of the plant, hence changing its orientation with respect to the stimuli. This feedback mechanism takes place in a three-dimensional plant with varying stimuli depending on the environment. In this talk, I present a multiscale mechanical modelling framework for tropism. For an arbitrary stimulus, the model links hormone transport to local tissue growth, that elicits curvature along the shoot and global deformation of the plant in three dimensions. I will show, as examples, that the gravitropic, phototropic, nutational, and thigmotropic dynamic responses can be naturally captured; and that integrating evolving or contradictory stimuli can lead to complex behaviour.

Keywords: Tropism, Morphoelasticity theory, Morphoelastic filaments

*Speaker

Automatic metabolite extraction using machine learning

Hansol Bae [1], Magnus Paludan * [1], Jan Knoblauch [1], Kaare Hartvig Jensen [1]

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Plant metabolites comprise valuable compounds, including spices, therapeutics, and natural rubber. However, extracting these compounds in a non-disruptive manner is not trivial. Conventional extraction methods rely on mechanically harvesting the entire plant and then separating the mixtures of interest. Interestingly, many plant metabolites are stored in small distinctive features, favouring a localised non-disruptive extraction method.
Inspired by aphids in nature which feed on plants using a long trunk, we identify three key components to automated non-disruptive harvesting: *1)* a means of identifying the local storage, *2)* a means of moving, and *3)*a means of piercing and pulling out the content.
We describe a recent experiment (Bae et al. 2021, Plant Physiology) combining *1)* a neural network for visual identification of target cells, *2)* a machine learning controlled robotic arm, and *3)* a microcapillary needle to extract plant metabolites.

Keywords: Metabolite extraction, Machine learning

*Speaker

Strength and failure mode of the junction between stem and aerial roots of Hylocereus undatus

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Hylocereus undatus is a branched, epiphytic root-climbing cactus. Shoots grow along supporting plants or rocks to which they attach themselves with adventitious roots. In the junction all root vascular bundles and fibers directly turn towards the plant base and merge with the shoot vascular tissue. Tensile and pull-out tests showed lower forces for failure within the root as compared to the pullout of the root out of the vascular cylinder of the shoot. The fracture surface in case of junction failure was ellipsoid with the long axis oriented parallel to the shoot axis. Fibers connecting the root towards the base of the shoot broke more distantly from the junction as those connecting the root towards the apex, due to differences in bending radius. Damage to the cortical tissue was limited to the diameter of the root. Failure of the root is preferred to failure of the junction.

Keywords: Cactus, Hylocereus undatus, Biomechanics, Anatomy, Adventitious roots

*Speaker

Life without support: survival of flax plants with impaired intrusive growth

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Fibers are important in creating plant architecture, as a mechanical support and as elements with contractile properties resembling muscles. In mutant flax plants with intrusive growth disorder, not only a significant fiber shortening, but also a number of other changes in stem anatomy have been noted. The mutants exhibited a traits characteristic of flax plants under gravitropic reaction. Curved stems, different morphology of phloem fibers on different sides of the stem, additional layers of thickened cell walls with high content of 1,4-galactan in xylem fibers, and eccentric growth of xylem resembling taut wood growth in overgrown trees. Disturbances in cambium development, deposition and transformation of the tertiary cell wall of phloem fibers, and significant reductions of mechanical properties at both macro- and nanoscale levels were also observed. The results obtained indicate large compensatory effects in the plant's attempt to survive impaired fiber growth. Work was supported by the RSF #21-74-10131.

Keywords: fiber, tertiary cell wall, intrusive growth, flax

*Speaker

On the mechanical origins of waving, coiling and skewing patterns in Arabidopsis thaliana roots

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We present novel simulations of the well-known waving, coiling and skewing patterns presented by roots of Arabidopsis thaliana when grown on stiff agar substrates that are tilted with respect to gravity. By creating a novel numerical solver based on a quasi-static integration scheme and a Cosserat rod integrator, we are able to investigate in-silico how growing rod-like organs mechanically interact with their environment for the first time. Our simulations confirm previous theories suggesting that waving and coiling result from the combination of active gravitropism and passive interactions between the root and the tilted plane, while skewing is related to an intrinsic twist profile (also known as cell file rotation) and may result from circumnutations. Furthermore, we develop analytic models and scaling laws descibring these patterns and compare our simulation results to quantitative data from a number of published experimental papers and find a good agreement.

Keywords: Roots, Waving, Coiling, Skewing, Modeling, Theory, Numerics

*Speaker

Effect of soil removal on the tree stability in confined space

Alena Klimesova [1], Luděk Praus * [1], Václav Sebera [1], Jan Tippner [1]

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Confined root space is one of key limiting factors for urban trees preservation. Underground structures and road constructions limit the spatial development of the root system, thus the morphology and spatial extent is compromised, affecting tree mechanical stability and vitality. To investigate an impact of soil renewal around trees, we examined four hackberry (*Celtis occidentalis*) trees using pulling test before and after replacement of 20 cm of highly compacted superficial soil, in Lužická street, Prague. The original size of pavement openings 80 x 160 cm or 160 x 200 cm was widened to 200 x 220 cm. Original soil was removed using AirSpade© device and replaced with structural soil (main portion: 85% gravel of fraction 32/64, 5% compost, 10% biochar). The results indicated that decrease of tree root system rotational stiffness before and after soil replacement are significant, repeated measurements after three months showed partial recovery and increase.

Keywords: root system, tree stability, pulling test, soil removal

*Speaker

Plant root growth against a mechanical obstacle : the early growth response of a maize root facing an axial resistance agrees with the Lockhart model

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In the current context of climate change and the ensuing hardening of the soil because of an increase in drought events, plant root growth is dramatically reduced in compacted soil and this in turn affects the growth of the whole plant. Through a model experiment coupling force and kinematics measurements, we established the force-growth relationship of a primary root contacting a stiff obstacle, mimicking the strongest soil impedance variation encountered by a growing root. How the force applied on the root modifies features of the growth distribution - such as the growth zone length, the maximal elongation rate, or the growth rate- during the first 10 minutes was predicted thanks to a parameter-free model based on the Lockhart law. These results suggest a strong similarity between the early growth responses caused by a directional stress (such as contact) and that caused by an isotropic perturbation (such as a hyperosmotic bath).

Keywords: root growth, mechanical impedance, growth rate, Lockhart model, force, growth relationship

*Speaker

Cell-cell adhesion and polarization are key to the self-organisation of regenerating shoot progenitors

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Tissue culture-mediated shoot organogenesis is driven by the stochastic initiation of shoot regeneration foci in pluripotent callus. Intriguingly, only a subset of the regenerating foci called progenitors converts into productive shoots while others terminate their development midway through the process. The factors regulating the divergent developmental fates of the productive and non-productive shoot progenitors remain unknown. We show that cell polarisation and cell-cell adhesion play key roles in instructing the fate of the progenitors. Distinct polarisation and compact arrangement of cells in the productive progenitors generate a low auxin level that is conducive to regeneration. Transcriptomic analysis of various genetic backgrounds defective either in the initiation or subsequent developmental stages of progenitors, identified that a shoot promoting factor activates the expression of cell wall-modulating-enzymatic genes. The resultant cellular landscape of differential cell wall mechanics regulates the regenerative potential of shoot progenitors in the absence of any pre-specified positional context.

Keywords: Cell wall, Shoot regeneration, Auxin

*Speaker

A universal growth trajectory of a 3D mechano-hydraulic model for plant cells

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Growth is fundamental to many biological processes. Recently, we showed that cellular turgor pressure is highly heterogeneous in the shoot apical meristem (SAM) of *Arabidopsis thaliana*, balanced by mechanical and hydraulic parameters. We developed a 3D physical model of a single plant cell with classical mechanical and hydraulic properties and recovered a typical, nonlinear growth trajectory. Depending on initial size, cells spontaneously go through consecutive phases of accelerating-then-decelerating growth separated by a critical cell size defined by the mechano-hydraulic balance and cell geometry. To test this model, we tracked long growth trajectories of *Arabidopsis* SAM cells treated with oryzalin, which blocks cell division but permeates continuous growth, and recovered the predicted growth trajectory using our 3D image analysis pipeline. Our theoretical and experimental analyses suggest that plant cells may follow a universal trajectory to autoregulate growth, which could potentially be applicable to other tissues and organisms.

Keywords: Growth, Cell wall Mechanics, Cellular hydraulics

*Speaker

Understanding the curvature of the Arabidopsis ovule

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A central aspect of biology is to understand the mechanical and molecular basis of tissue morphogenesis. We use the Arabidopsis ovule as a model to address how organs attain their species-specific 3D architecture. The mature ovule is characterized by an extreme curvature along the proximal-distal axis. We are particularly interested in the contribution of tissue conflict resolution, arising from differential growth between and within layers, to the final shape. To this end, we are using 3D and 2D digital ovules and FEM modeling integrating signaling and mechanical constraints to build experimentally testable predictions. With a 3D continuous tissue-based model we are addressing the contribution of differential growth-promoting gene expression and material properties of the outer integument to the overall curvature. The 2D tissue layer-based model explores the role of differential growth for different tissue layers in generating the ovule curvature. We will discuss the insights gained so far.

Keywords: ovule, curvature, morphogenesis, FEM modeling, differential growth

*Speaker

Understanding how flowering plants build communication devices on their petals

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Colourful patterns on the petal epidermis are key signals to attract pollinators. *Hibiscus trionum* flowers display a striking bullseye pattern, made of a basal purple spot (flat, elongated, striated cells) and a white distal region (conical, smooth cells), separated by a boundary positioned at 1/3rd from the petal base. How is this boundary specified is unknown. We developed a quantitative imaging pipeline to decipher the mechanisms specifying the distinct regions of the bullseye in developing petals. We captured early cellular behaviour in *H. trionum* petal epidermis and showed that growth and division are not uniform, following a pre-pattern long before the bullseye become visible. To probe the mechanisms accounting for a change in bullseye dimensions, we characterised natural variants/transgenic lines that differ in bullseye size and tested whether bumblebees can distinguish and/or prefer specific proportions. We are now building a computational model to simulate petal growth/patterning mechanisms.

Keywords: Petal, pattern, growth, division, pollinators

*Speaker

Temporal integration in shoot gravitropism

Mathieu Rivière * [1], Yasmine Meroz [1]

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Tropisms are growth-driven motions via which plants re-orient themselves in response to directional stimuli. Tropisms follow a dose-response relationship i.e. plants respond to an integrated history of stimuli. Recent studies have proposed an updated model of plant tropisms where this temporal integration behaviour is accounted for by a memory function.
Here, we aim to extract the memory function underlying shoot gravitropism, and understand its role.
We conduct several kinds of transient gravistimulation experiments on wheat coleoptiles, and numerically extract the form of the memory function.
Our approach reveals the complex shape of the response function. It displays a positive and a negative lobe, suggesting the ability to sum and subtract signals over time respectively. We further show that this specific shape leads to previously unobserved regimes of tropic responses. Our results provide a quantitative framework for the future investigation of behavioral processes involving memory, such as decision-making and navigation.

Keywords: gravitropism, plant behaviour, memory, computational process

*Speaker

Anatomy and biomechanics of peltate Begonia leaves

Annabell Rjosk * [1], Christoph Neinhuis [1], Thea Lautenschläger [1]

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Plant leaves are exposed to various external stresses. Shape, geometry and size affect the impact of these stresses on the leaf. Peltate leaves are not very common and so far, only few studies focused on their properties. Four *Begonia* species with different leaf shapes and sizes were studied regarding their leaf morphology, anatomy and biomechanics. Anatomical characteristics, low leaf dry mass and low amount of lignified tissue in the petiole point towards turgor pressure as crucial for leaf stability. While non-peltate leaves exhibit simple fiber branching in the petiole-lamina junction, peltate leaves show more complex net-like structures. Tensile testing revealed similar structural Young's moduli in all species for intercostal areas and venation, but differences in the petiole. While in individual species correlations between different parameters can be found, these correlations do not apply to all species similarly. The detailed analysis highlights the connection between leaf anatomy and biomechanical properties.

Keywords: anatomy, biomechanics, peltate leaves, Begonia

*Speaker

Using Mechanistic, Multiscale Knowledge of Plant Biomechanics to Improve Genome to Phenome Modeling Efforts

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Current genomic prediction methods are almost exclusively empirical in nature and are generally based upon linear statistical models which relate genomic information to observed phenotypes. These Blackbox models are fairly accurate when used in similar environments as the training dataset, but their accuracy quickly degrades when their predictions are extrapolated to other genetic or environmental conditions. Our group is developing a novel "white box" genome to phenome model that combines domain specific, mechanistic knowledge with advanced Bayesian statistics and finite element methods. To this end we have developed a multiscale mechanistic framework for maize stalk bending stiffness and strength. To date we have individually tested and characterized over 40,000 plants for numerous biomechanical phenotypes at several length scales. We are combining this data with current genome to phenome methodologies to determine the genetic underpinnings of plant strength.

Keywords: Bending, Strength, Stiffness, Maize, Lodging, Genome, Phenome, Modeling

*Speaker

How does cell division alter the mechanical properties of growing tissues?

Sarah Robinson * [1]

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The Robinson lab is interested in the relationship between cell division and cell expansion from a mechanical point of view. We are using time-lapse atomic force microscopy (AFM) with confocal imaging to follow cell walls through successive rounds of cell division to understand how cell division alters the local mechanical properties of the tissue. We have observed that the mechanical properties of the newly formed walls are different to that of the parental walls in both Arabidopsis and Marchantia. In both species, there is a strong correlation between the properties of the walls and their growth rate. This data opens the possibility that cell division alters the rate of tissue expansion by allowing new material with different properties to be incorporated into the tissue. Using mechanical models of plant cells we are investigating the impact of altered cell wall stiffness on the mechanical stress in the tissue.

Keywords: cell division, Marchantia, AFM, growth, development, mechanics

*Speaker

The actuation of wood – influence of wood anatomy on predictability and performance

Markus Rueggeberg * [1], Philippe Grönquist [2], Falk Wittel [2]

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The swelling and shrinking of wood is commonly regarded as a challenge and limiting factor in the utilization of wood. However, this disadvantage can also be seen as a material inherent capacity for generating shape changes when used in a smart way. By manufacturing wooden bilayers with differential fibre orientation in the two layers, one obtains humidity driven actuators as well as curved elements by an innovative self-forming process rather than with heavy machinery and large external forces. Our simulation procedures for predicting the shape-change perform well for beech wood, but are less precise in case of spruce wood. The influence of wood anatomy and species-specific mechanical properties on the self-shaping process and its implications for further research on non-linear mechanical behaviour and modelling of wood will be discussed.

Keywords: wood, bilayer, computational mechanics, actuation, anatomy

*Speaker

Quantifying Sources of Experimental Error in Bending Strength and Stiffness Measurements.

Pearl Rwauya * [1], Clayton Bennett *

[1], Daniel Robertson *

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The mechanical failure of cereal crops before harvest causes significant yield losses. Accurately phenotyping stalk strength can help to solve this problem. In this study, a field-based stalk bending strength measurement device know as DARLING was used to collect force and rotation measurements. Stalk flexural rigidity and bending strength were calculated from these measurements. Testing conditions, device malfunctions, and user-to-user variability during testing and post-processing of data were considered as potential sources of error. It was found that user-to-user variability in the post-processing phase was minimal. Erroneous load and rotation readings could be identified from a stiffness and strength scatter plot. Differentiating between erroneous force readings that resulted from a human error from those that resulted from device malfunction was difficult to determine during postprocessing. However, these errors could readily be identified by the user when viewing the data immediately after completing a test.

Keywords: Bending, Strength, Stiffness, Error, Phenotyping

*Speaker

Expansins control cell wall stiffness and root growth via cell type-specific expression in Arabidopsis

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Changes in the cell wall (CW) mechanics are a driving force of plant growth and. Expansins facilitate cell expansion via mediating pH-dependent CW loosening. We determined specificity of expression and localization of selected expansins. We found EXPA1 localized dominantly in the epidermis of lateral root cap; EXPA10 and EXPA14 at the three-cell boundaries of epidermis/cortex in various root zones. Localization of EXPA15 overlapped with higher CW stiffness measured via Brillouin light scattering (BLS) microscopy. The ability of EXPA1 to increase the CW stiffness was confirmed in transgenic lines following dexamethasone-induced *EXPA1* overexpression by higher BFS as well as Young modulus measured via AFM. *In situ* measurement of the refraction index using a holotomographic microscope excluded the possibility that the observed increase of BFS is due to changes in the CW mass density. The *EXPA1* overexpression resulted in the root growth arrest phenotype, severity of which was enhanced by lower pH.

Keywords: expansins, Brillouin light scattering, atomic force microscopy

*Speaker

Actin mediated avoidance of tricellular junction influences global topology and phyllotactic robustness at the Arabidopsis shoot apical meristem

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Division plane orientation contributes to cell shape and topological organization, playing a key role in orchestrating morphogenetic events. Here, we show that perturbation of actin cytoskeleton results in more rectangular cell shapes and higher incidences of four-way junctions in Arabidopsis shoot apical meristem. Quantitative cellular level growth tracking revealed defects in mechanical maturation of the new cell wall in the actin mutant, affecting the evolution of internal angles at tricellular junctions. Visualization of microtubules in dividing cells showed increased width of the preprophase band in the actin mutant, contributing to the inaccuracy in placement of the new cell wall away from a tricellular junction. In addition, showed that changes in cell division plane orientation in response to micromechanical manipulation are also under the influence of actin. Our results further indicated that actin-mediated cell shape regulation impacts the global topology of cells, contributing to morphogenetic events at the shoot apical meristem.

Keywords: Actin, cell division, patterning, cell shape

*Speaker

Investigating the impact of cell wall dynamics on secondary growth regulation

Theresa Schlamp * [1], Klaus Brackmann [2], Dongbo Shi [3], Thomas Greb [1]

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Remodeling the plant cell wall is an essential aspect of plant growth and development. During developmental processes, cell wall adaptations take place but their crosstalk with cell identity changes is obscure. Here we take radial plant growth as showcase for induced trans-differentiation of cells and the re-establishment of stem cell attributes in a differentiated cellular context to investigate the role of cell wall remodeling. Strikingly, induction of auxin biosynthesis specifically in starch sheath cells was sufficient for provoking an endogenously induced cell fate change and provided an experimental switch to analyze the sequence of events during the *de novo* initiation of cambium identity. Interestingly, genome-wide transcriptional profiling upon auxin-induction revealed induction of both auxin signaling components and cell wall remodeling factors. Indeed, immunohistochemistry revealed changes in the chemical composition of starch sheath cells during cambium initiation arguing for cell wall remodeling as an important aspect of cellular trans-differentiation.

Keywords: stem cell, trans, differentiation, cell wall

*Speaker

Experimental and numerical assessment of soil-root interaction

Vaclav Sebera * [1], Lenka Ševelová [1], Jan Tippner [1], Luděk Praus [1], Klimešová Alena [1]

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The mechanical behavior of a tree is substantially dependent on a root system which represents complicated composite where roots and soil interact with each other, especially when a tree is loaded. Our work focused on the interaction between these two parts of root system with an emphasis on finite element analysis (FEA) of representative volume element (RVE). The RVE in FEA is represented by a single root surrounded by soil in a square layout. The analysis of RVE is to investigate how variable proportion of root in soil impacts the composite elastic response. Within the work, two kinds of FE models are built – noncontact and contact one where soil and root are not bonded. The FE models are compared with the basic analytical model (transversal Reuss model) and experiments employing cyclic California bearing ratio (CBR) test providing global stiffness and elasticity.

Keywords: root, soil, finite element analysis, California bearing ratio test, representative volume element

*Speaker

Divergent trade-offs associated to stem posture control in maritime pine

Rosario Sierra-De-Grado * [1,2], Valentín Pando [1,2], Jordi Voltas [3,4], Rafael Zas [5], Juan Majada [6], Gianluca Segalina [7,2], José Climent [2,8]

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The adaptive implications of the ability to straighten the stem of trees are far from fully understood. The straightening of the stem is key for the mechanical stability of the tree and the capture of light and implies costly processes in terms of energy and resources. Therefore, trade-offs with competitive processes such as growth, maintenance, and defense are expected. We set up a manipulative experiment on a common garden of nine-year-old Pinus pinaster, including provenances that typically displayed straight or crooked stem phenotypes. A bending up to 35○ was imposed and then released. Verticality recovery, shoot elongation, biomass partitioning, reaction wood, wood microdensity, xylem reserve carbohydrates, phloem secondary metabolites and bark thickness were evaluated. The straight and crooked type plants showed a markedly different combination of responses to treatment. This intraspecific divergence in reaction to mechanical stress may be related to different adaptive phenotypic plasticity in both types of plants.

Keywords: Adaptation, biomechanics, integrated phenotype, intraspecific variation, life history, provenances, stem straightness, trade offs.

*Speaker

Mechanical interactions between tissue layers underlie anther morphogenesis

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In plants, the differential growth between connected tissues generates mechanical conflicts which are thought to control organ shape. Using the male reproductive parts of flowers (anthers) as a model system, we assessed the role of external and internal tissues in the development of complex organ morphology. We focused on the formation of lobes in Arabidopsis anthers, e.g., tube-like structures containing the future pollen grains. Combining live-imaging, 3D image analysis, genetics, and computational modeling, we show which biological and physical parameters are essential for the rapid growth of internal cells driving lobe formation. We also demonstrate the emergence of specific division patterns leading to the formation of endothecium (subepidermal layer) restricting growth at later stages. Our data reveal how tissue mechanical interactions can influence morphogenesis.

Keywords: Arabidopsis, confocal microscopy, floral organs, growth analysis, stamen, timelapse imaging

*Speaker

Robustness in laminar sepal shape in Arabidopsis requires growth coordination between abaxial and adaxial surfaces

Avilash Singh Yadav * [1], Lilan Hong [2], Michelle Ming-Yu Heeney [1], Patrick Michael Klees [1], Richard Smith [3], Arezki Boudaoud [4], Adrienne H K Roeder [1]

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Organ size and shape robustness is a remarkable developmental feature that is not well understood. To address how reproducibility in shape is achieved, we screened for *variable organ size and shape* (*vos*) mutants. The *vos3* mutant exhibits random ectopic lumps and outgrowths on the outer sepal surface. We found that cells on the outer surface of *vos3* grow faster compared to those of the wild type (WT). We hypothesize that growth imbalance on the outer and inner surfaces of *vos3* sepals triggers buckling, leading to lump formation. We developed a novel technique to live-image both surfaces of young flowers simultaneously. Our initial results reveal that outer surface cells of *vos3* initially exhibit fast growth towards the edges that eventually spreads throughout the surface, whereas inner surface cells maintain a non–uniform growth distribution, which we are currently comparing to the WT to understand how flat sepal shape is achieved.

Keywords: Robustness, Arabidopsis, Growth co, ordination, genetics, morphogenesis

*Speaker

Analysis of growth of Arabidopsis sepal surface and cuticle pattern at subcellular scale

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Growth is crucial for development of plant organs. While cellular growth pattern has been described in Arabidopsis thaliana sepal, little is known about subcellular growth variability and about its relation with the formation of specific cuticle patterns. Here, we postulate that mutations altering cell wall structure (e.g., csi1, mad5) or composition (e.g., pme32) affect both local cellular growth and cuticular pattern. We tested this postulate using in vivo time-lapse imaging with a confocal microscope to monitor cuticular ridges on the wall surface as landmarks for local growth at subcellular scale. We thus quantified local cell growth and cuticle pattern formation with unprecedented resolution. We found that the pattern of ridges changes with time. These changes are related to the local growth variability of the underlying cell wall, which in turn is influenced by the growth of neighbouring cells.

Keywords: Arabidopsis thaliana, growth, cuticle pattern

*Speaker

Rigidity charts of plant axes with various cross-sectional geometry and reinforcement patterns

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Plant stems differ in their cross-sectional geometry and tissue pattern, which influence the flexural rigidity, torsional rigidity and the ratio of these both rigidities, the so-called twist-to-bend ratio. For comparative analysis, we have designed artificial cross-sections with various cross-sectional geometries and patterns of vascular bundles, collenchyma or sclerenchyma strands, but fixed percentages for these tissues. Our mathematical model allows the calculation of the twist-to-bend ratio taking both aspects into account. Each artificial cross-section was placed into a rigidity chart, where cross-sections with the same geometry (e.g., circular, elliptic, triangular, square, U-profile) did not form clusters, whereas those with similar tissue patterns (e.g., central strand, peripheral closed ring, distributed individual strands) did. Flexural rigidity increased the more the bundles or fibre strands were placed in the periphery. Torsional rigidity decreased the more the bundles or strands were separated and the less that they were arranged along a peripheral ring.

Keywords: rigidity chart, twist to bend ratio, finite element method

*Speaker

Plant structure and motion: Inspiration for novel biomimetic soft machines and architecture

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Plants have inspired (ultra-)lightweight constructions with their fibre-reinforced stems since decades. This is demonstrated by the *liv*MatS fibre pavilion, which is inspired by the reticulate wood structure of columnar cacti and prickly pears. More recently, plants have also been recognized as valuable concept generators for biomimetic soft machines, as their movement is typically based on elastic deformation and lacks mechanically highly loaded localized joints. The potential of this approach is demonstrated by several recent research projects executed in collaboration of the Clusters of Excellence *liv*MatS and IntCDC. Examples include (1) bioinspired 4D-printed hygromorphic self-locking soft machines with differential hygro-responsiveness inspired by the bracts of the silver thistle, (2) self-adaptive hygroscopic building hulls and envelopes inspired by the movement of the scales of pine cones, and (3) computationally designed self-adjusting 4D-printed wearable orthotic devices with motion mechanisms inspired by winding lianas.

Keywords: biomimetics, bioinspiration, plant motion, wood structure, lightweight constructions

*Speaker

Stem Failure Initiation and Progression

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Stem failure often involves Brazier buckling, but the initiation of failure is poorly understood. In hollow tubes, buckling is controlled entirely by cross-sectional ovalization, but septated, pith-filled stems are more complex. The study the initiation and progression of stem failure, we created a measurement system consisting of a camera integrated with a universal testing machine. The camera moves with the loading anvil, thus preserving a consistent viewing perspective. The universal testing machine triggers the camera and records the time stamp of individual photographs. This system collects force, deformation, and image data during the test. Custom software tracked landmarks on stems, thus allowing a consistent cross-section to be tracked during testing, even if substantial rotation of the stalk occurs during bending. Results revealed two failure mechanisms. First, minute "rippling" of the stem increased mechanical stresses, which caused tissue failure and collapse. Second, tissue failure sometimes occurred spontaneously, thus initiating structural collapse.

Keywords: Maize, failure

*Speaker

Automating Cell Wall Finite Element Models from Microscope Images

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This study presents a methodology for a high-throughput digitization and quantification process of plant cell walls, including the automated development of two-dimensional finite element models. Custom algorithms based on machine learning can also analyze the cellular microstructure for phenotypes such as cell size, cell wall curvature, and cell wall orientation. To demonstrate the utility of these models, a series of compound microscope images of maize, Arabidopsis, and various sea grasses are processed, and stress and parametric analyses are performed on the resulting finite element models. Specifically, sensitivity analyses were performed for the structural stiffness of the resulting tissue based on the cell wall elastic modulus and the cell wall thickness. The results demonstrate that the cell wall thickness has a three-fold larger impact of tissue stiffness than cell wall elastic modulus.

Keywords: finite element model, phenotyping, stress analysis, parametric sensitivity

*Speaker

Molecular mechanisms controlling the interdependency between cell expansion and cell differentiation

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How topological and geometrical cell properties instruct cells behaviors is a fundamental question in developmental biology. Recently, we showed that the *EXPA1* gene, by controlling plant cell wall extension, triggers cell differentiation in the *Arabidopsis thaliana* root apical meristem. Despite the intrinsic relationship between cell expansion and cell differentiation, how cell expansion induces cell differentiation is still unknown. Using cell wall mutants to alter the cell wall mechanical properties and tissue specific transcriptomic analysis we aim to answer this question. Preliminary data suggests that a stiffer cell wall promotes cell division while a more elastic one triggers cell differentiation. This represents one of the first evidence that cell wall mechanical properties can instruct cells fate.

Keywords: Root Apical Meristem, cell wall, cell wall mechanical properties, cell expansion, cell differentiation

*Speaker

The central role of the cell-cell interface during tissue morphogenesis: local integration of wall stress and microtubule-encoded cell wall anisotropy

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In developing leaves, the rate and polarity of epidermal cell expansion influences the overall shape of the organ. However, it is not known how anisotropic growth is programmed at subcellular and cellular scales. Pavement cell interdigitation is a useful model to discover general principles of polarized growth. The combined use of multivariate live cell imaging and finite element (FE) mechanical modeling provided revealed how a small local bias in the persistence of transfacial microtubules templates oriented cellulose synthesis in the tough outer wall. The resulting local bias in wall anisotropy generate nanometer scale shape distortions that initiate lobe formation. Realistic cell cluster models predicted subcellular stress patterns. The magnitudes and directions stress predicted the location, orientation, and persistence of microtubules both at cellular scales and at finer scales that could explain lobe initiation. These results provide quantitative insights into the morphogenetic power of microtubules and the forces that pattern them.

Keywords: morphogenesis, multivariate live cell imaging, FE modeling, pavement cells, microtubule, cellulose

*Speaker

Paf1C denoises transcription and growth patterns to achieve organ shape reproducibility

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The exact contribution of transcriptional noise to morphogenesis often remains unclear. Here we take advantage of walled plant cells, where transcriptional noise happens in tissues with a fixed topology. Using different tissues, we demonstrate that mutation in VIP3, a subunit of the conserved polymerase-associated factor 1 complex (Paf1C), increases transcriptional noise in Arabidopsis. Such noise translates into growth and shape defects. Indeed, in vip3 sepals, we measured higher growth heterogeneity between adjacent cells, with molecular evidence of increased local mechanical conflicts. This even culminated in negative cell growth in specific conditions. Interestingly, such increased local noise makes the regional pattern of growth less clear-cut. Reduced regional conflicts lead to delay in organ growth arrest, ultimately making final organ shapes and sizes more variable. We propose that transcriptional noise is managed by Paf1C to ensure organ robustness by building up mechanical conflicts at the regional scale, instead of the local scale.

Keywords: Paf1C, morphogenesis, transcriptional noise, growth heterogeneity, mechanical conflict, shape robustness

*Speaker

Development of Testing Standards for Plant Biomechanics

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Development of testing standards and operating protocols are a fundamental tenet of scientific research. However, few testing standards for biomechanical plant traits are found in the scientific literature. Testing guidelines that adhere to strict engineering principles and measurement theory enable reproducibility and meta-analysis of biomechanical plant data. As part of a multi-institutional grant from the National Science Foundation we have developed a set of standard operating protocols for collection of internode diameters and lengths, rind thickness, bending strength, bending stiffness, puncture resistance and section modulus of maize stalks. These protocols follow best practices in the field of engineering material characterization. We have implemented these protocols across several institutions and acquired biomechanical plant traits on over 40,000 maize stalks. Our group is now expanding these guidelines to other plants and making them accessible and easily understood by those who may not have a background in material science / mechanical characterization.

Keywords: bending, stiffness, strength, protocols, standards, measurement

*Speaker

Pressure dependent mechanical properties of pulvinus

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Plants move without skeletal muscle. The most famous plant atuator is the pulvinus. It creates fast and reversible motion of mimosa pudica leaves but many other plant species are equipped with pulvini. Pulvinus motion changes leaf orientation (to avoid hervibory, to follow sun's path, to make the rain reach the ground, etc.). It originates from the differential change of turgor pressure in parenchyma cells. We study the mechanical behaviour of pulvinus considering an artificial pressure-dependent cellular material made by silicone casting and micro-pneumatics. The macroscopic material properties are tested considering on different pressure values and patterns (some cells are pressured, some others are not). We propose a modelling grounded on elastic energy minimisation framework. Depending on pressurisation pattern and magnitude, material properties are changed and reversible buckling may occur. Results are compared to the reference paper by Nilsson (1958) and consequences about the design of pulvinus cells are given.

Keywords: cellular material, biomechanics, pulvinus, turgor pressure

*Speaker

An imaging pipeline for correlation between atomic force and confocal microscopy

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Atomic force microscopy (AFM) is being increasingly deployed to probe the properties of cells; for example, mapping the wall modulus and turgor pressures in live plant samples. This, in concert with confocal imaging, where cellular features of interest can be tagged with fluorescent markers, allows the correlation of cell mechanical properties with morphological, biochemical, or genetic aspects of the cells. However, images representing the same features appear slightly, but noticeably, different when acquired with AFM compared to confocal, suggesting that the nature of the relationship between images obtained *via* each modality is more complex than it appears. In this work we discuss concepts, practices, and tools to construct an imaging pipeline to visualise cell specific mechanical and morphological properties of confocal and AFM images. We also explore the nature of the misalignment observed between confocal and AFM images, and speculate on their origins.

Keywords: atomic force microscopy, nanoindentation, data visualisation, shoot apical meristem, multimodal imaging

*Speaker

Holding on or falling off: the attachment mechanism of epiphytic Anthurium obtusum (Engl.) Grayum changes with substrate roughness

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Secure attachment to their hosts is vital for the survival of vascular epiphytes. Yet studies detailing the adhesion mechanism are scarce. This study investigates the bioadhesion of epiphytes to their host. Seedlings of *Anthurium obtusum* were grown on substrate with different defined roughness, to identify how substrate micro-roughness relates to the root-substrate attachment strength and the underlying mechanism(s). Root anchorage strength was measured and root hair morphology was analysed by light and electron microscopy. The highest maximum peeling force was recorded on the smooth surface (0 μm). Maximum peeling force was significantly higher on finer than on coarse roughness. This study demonstrates for the first time that the attachment mechanism of epiphytes varies depending on substrate micro-topography, where the attachment mechanism shifts from an adhesive to an interlocking mechanism as the roughness increases. This is important for understanding epiphyte attachment on natural substrates varying in roughness.

Keywords: anchorage strength, bio, adhesion, epiphytes, glue, like substance, mechanical interlocking, root hairs, biomechanics

*Speaker

Analysis of geometry simplification in frequency-resonance method for non-destructive assessment of stem

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The application of the frequency-resonance method (FRM) on stems is limited by complex geometry. This paper presents the relationship among non-destructively tested material parameters of sugar maples and the numerical analysis of the effect of simplifications in FRM. Four standing stems were 3D scanned to describe the geometry, tested by pulling test to obtain moduli of elasticity (MOE) and cut down to process stem samples. Samples were measured by stress wave propagation using an acoustic tomography to measure sound velocities and evaluated by the FRM to record bending and longitudinal natural frequencies to calculate dynamic MOE; MOE based on different methods were compared. Finite Element Modal analysis working at three levels of geometry simplification (beam, simplified solid, and scan-based solid) was performed. The natural frequencies in bending and longitudinal mode shapes were computed, and the influence of geometry simplification on the resulting frequency response was described.

Keywords: non, destructive testing, sugar maple, sound propagation, natural frequency, finite element method, modal analysis, 3D scan, cross section, modulus of elasticity

*Speaker

Energy-based overset finite element method for 3-D deformation simulation for plants.

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This study presents a simple energy-based overset finite element method (EbO-FEM) to compute the static/dynamic response of plants. The present method is developed for efficiently working with the overlapped solid meshes. The continuity of the displacement field in the overlapped regions is enforced by minimizing the "Continuity Constraint Energy" (CCE). The procedure of computing the CCE by the Gauss-point projection and the point-to-point projection has been discussed. Validation and verification of EbO-FEM are performed by comparing the numerical solutions of the 1-D and 3-D cantilever-beam bending problems to the analytical solutions. Subsequently, 3-D modal analysis of the single-plant has been conducted, and it is demonstrated that the EbO-FEM can accurately compute the eigenmodes and the eigenfrequencies of plant structures. We also applied the EbO-FEM for 3-D modal analysis of the single-plant problem, the result shows that the EbOM is applicable for estimating eigenmodes and eigenfrequencies of plant structures.

Keywords: Finite element analysis, Modal analysis, Overset mesh, In silico plant

*Speaker

Modelling the growth stress distribution during the life of tree branches: impact of different growth strategies

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This work aims to model the consequences of different strategies used by tree branches to ensure a given posture. If branches were simple beams, they would collapse under their weight. However, branches do control their orientation, and the two known strategies of the branch to straighten itself are the asymetry of maturation stress (including reaction wood formation) and eccentric growth. Both strategies are often observed simultaneously and influence the stress distribution developed in the branch each year. This so-called growth stress reflects the mechanical state of the branch. In this work, a growth stress model was developed at the cross-section level in order to quantify the biomechanical impact of each strategy. To provide realistic input to the model, branch profiles were modelled using the growth simulation software AmapSim. For different types of branches and species, the impact of the two postural control strategies was then examined.

Keywords: biomechanics, tree branches, gravity, growth stress, reaction wood, excentricity

*Speaker

Mechanics and dynamics of cell-cell adhesion in plants

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How cell-cell adhesion is achieved is a fundamental question in the development of multicellular organisms. Surprisingly, this question remains largely under-explored in plants. In our current work we combine micromechanical approaches with molecular, cellular and developmental biology to investigates this question. Notably, we are developing and adapting a set of micromechanical tools to characterise the mechanics of cell-cell adhesion in plants (Atakhani et al., 2022, qPB). We are also developing new transgenic lines in which we can impair cell adhesion in a controlled spatio-temporal manner (adhesion lines). Here, I will present our latest advances with the use of micro-extensometer, microfluidics and micropipette single cell micromanipulation for adhesion mechanics quantification as well as the characterization of the new adhesion lines. Finally, I will open on how we use these tools to uncover fundamental molecular and biophysical mechanisms that regulate cell adhesion in plants.

Keywords: Cell adhesion, Cell wall, Micromechanics, Mechanosensing, Development

*Speaker

Marantaceae as inspiration for technical fiber-reinforced structures

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The pantropic Marantaceae are monocot plants which exhibit distinctive characteristics such as an explosive style movement for pollination and conspicious angled branching pattern. Although their growth is limited to primary growth processes, as typical for many monocotelydons, they are capable of developing a variety of growth forms, including scrambling (e.g., *Maranta leuconeura*) and self-supporting (e.g., *Marantochloa purpurea*) plants. The growth form diversity and unique branching pattern is designed on the basis of an atactostelar arrangement of individual fibrous vascular bundles embedded within a viscoelastic ground tissue, hence a fiber-reinforced interior architecture. Knowledge of the vegetative anatomy of the internal plant structure can lead to novel design principles in technical fiber reinforced components. As part of a biomimetic approach we compare the vascular bundle placement and distribution in the nodal and internodal regions of the scrambling *Maranta leuconeura* and self-supporting *Marantochloa purpurea* using light microscopy, μCT and MRI techniques.

Keywords: Marantaceae, node, 3D imaging, vascular bundles, growth form

*Speaker

Validation of Numerical Model of Tree Dynamic Response by Optical Measurements

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The current research is dedicated to the topic of tree dynamics as its natural response to wind loading. The dynamic response can be described by the shape and frequency of oscillations defined by the geometry and material properties (global stiffness). These parameters are often derived from displacements (inclinations, accelerations) measured by locally coupled devices. While the complex response of the stem can help to define the overall oscillation tree shape and find the weak points of failure. The movement of twelve trees was captured by optical technique during "pull and release" tests and displacements (2D, 3D) along the stem in the time domain were reconstructed. The experimental work was accompanied by a series of computations with the parametric finite-element model of the tree. The validated numerical model provides a testing group for what-if scenarios which enables observation of the effect of the internal defect on the dynamic response of trees.

Keywords: digital image correlation, finite element, transient analysis

*Speaker

Self-similar tip growth links exocytosis profile with cell wall shape

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Exocytosis plays a crucial role in regulating the growth and migration of filamentous tip-growing cells. We present a mathematical framework that infers the spatial profile of exocytosis from the cell morphology in self-similar growing cells that elongate while preserving their apical domain shapes. By applying the framework to cell wall outline data from experiments across walled cell species, we find that while tapered cells have their exocytosis concentrated at the apex, cells with a flatter tip shape beyond a threshold require exocytosis to peak in an annulus region away from the apex.

Keywords: exocytosis, elasticity, growth, morphogenesis

*Speaker

Pavement cells of Arabidopsis thaliana dwarf mutant – growth analysis

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A model cell type for studies of growth and complex shape formation is jigsaw puzzle-shaped pavement cells of Arabidopsis thaliana. Morphogenesis of such cell comprises the formation of interdigitating lobes by anticlinal (perpendicular to the leaf surface) walls of adjacent pavement cells. Mutation in the gene (DWF4-102), responsible for the biosynthesis of a key enzyme in the brassinosteroid pathway, leads to reduced growth and cell divisions, and plant dwarfism. We investigate the mutation effect on pavement cell morphogenesis using two combined protocols for growth analysis of outer periclinal walls of abaxial leaf epidermis. Fluorescent microbeads applied on the wall surface serve as artificial landmarks for growth tracing at the subcellular scale, which is combined with in vivo long-term time-lapse imaging in a confocal microscope. This method enables detailed quantification of pavement cell growth (both anticlinal and periclinal walls) and lobe/neck development.

Keywords: pavement cell morphogenesis, Arabidopsis Thaliana

*Speaker

Receptor kinase signaling of BRI1 and SIRK1 is tightly balanced by their interactomes as revealed from domain-swap chimaera in AE-MS approaches

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Plant cell expansion can be regulated by different external and internal stimulation through the activation of signal transduction pathways. Here we use affinity enrichment mass spectrometry acquisition (AE-MS) of the LRR receptor kinases BRI1 and SIRK1 to study the stimulus-dependent interactomes in response to brassinolide and/or sucrose, which regulate cell expansion. Our results reveal the different recruitment abilities of BRI1 and SIRK1 under BL and sucrose treatment. Specifically, BRI1 and SIRK1 are involved in fine-tuning the readiness of the plant to respond to the internal balance of the brassinolide and sucrose levels. By using domain-swap chimera, we attribute structural features of the receptors to the interactome. We found both LRR-RKs regulate cell expansion through different interactomes, the chimeras could compliment both the sirk1 and bri1 phenotype, but not the double mutant. Our work reveals a tightly controlled balance of signaling cascade activation dependent on the internal status of the plant.

Keywords: LRR, receptor kinase, domain swap chimera, cell expansion, signaling specificity

*Speaker

Distribution of non-cellulosic polysaccharides and lignin in tension wood fibers with multi-layered structure in Mallotus japonicus and Ficus erecta Thunb. var. erecta

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Cell wall layered structure and distribution of non-cellulosic polysaccharides, arabinogalactan protein (AGP) and lignin were examined in tension wood fibers with multi-layered structure in *Mallotus japonicus* and *Ficus erecta* Thunb. var.*erecta* using UV microscopy, transmission electron microscopy, and immunofluorescence microscopy with monoclonal antibodies. In both species, thin-lignified layers (L-layers) exists in G-layers of tension wood fibers. However, distribution of cell wall components in L-layer and G-layer was different between the two species. In L-layers, lignin with 8-*O*-4' linked structure, xylan, glucomannan and AGP were distributed in *M. japonicus*, whereas lignin and AGP were distributed in *F. erecta* var. *electa*. In G-layers, lignin with 8-*O*-4' linked structure and glucomannan were distributed in *M. japonicus*, in contrast, lignin with 8-*O*-4' linked structure, rhamnogalacturonan-I (RG-I) and AGP were localized in *F. erecta* var. *electa*. These results suggest that the two species may have different mechanism to generate tension stress.

Keywords: Tension wood, G, layer, Mallotus japonicus, Ficus erecta var. erecta, lignin, xylan, glucomannan, rhamnogalacturonan I, arabinogalactan protein

*Speaker

Which compression wood behaviors depend on high MFA or thick S2L? - A new mechanical model to explain origin of longitudinal dimensional changes peculiar to conifer compression wood tracheid

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In the conifer compression wood fiber (CW-fiber), a large compressive growth stress is generated in the longitudinal direction, which enables the leaning stem to erect upward again. CW-fiber elongates also by the hygrothermal (HT) treatment (i.e., boiling in hot water), and shrinks by the drying treatment. Normal wood (NW) shows only traces. How does CW-fiber exhibit such peculiar dimensional changes? This question can be answered by a 60-year-old established theory (Reinforcing-Matrix theory) that focuses attention on the role of large microfibril angle (MFA) in S2 layer in CW-fiber. However, we are skeptical of this established theory. In the present study, we explain the important role of S2L layer, which is formed in the CW-fiber wall, in controlling the longitudinal dimensional changes of CW. This will be experimentally verified through comparing the strains of HT- and drying treatments between CW and juvenile wood (JW) fibers, both showing quite higher MFAs.

Keywords: compression wood, cell wall, tree biomechanics, cellulose microfibril, X, ray diffraction

*Speaker

Nonlinear mechanics of epidermal cell walls contradicts classical viscoelastic behavior

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Epidermal cell walls mechanically support and limit the growth of plants. To understand the mechanical behaviors of primary cell walls, 7-μm thick onion epidermal wall strips were characterized with a series of uniaxial tensile tests. Under monotonic stretching, the wall displayed nonlinear three-phase stress-strain curve. Using cyclic loading tests, we identified three prominent mechanical properties: elasticity, plasticity and hysteresis. Contrary to typical viscoelastic materials, stress-strain curves of onion walls were essentially identical when strain rates were varied 100-fold and when temperature was lowered by 20degC, indicating that stretching of onion walls was not mechanically limited by viscous flow of pectins. With progressive cyclic loading tests, a novel analytical framework was developed to quantify different mechanical parameters, which varied by wall stress. These series of tests revealed the complex mechanical dynamics of epidermal cell walls and provide a systematic method to quantify the nonlinear stress-dependent mechanics of wall materials.

Keywords: primary cell walls, nonlinear mechanics, viscoelasticity, hysteresis

*Speaker

Plant tendril mechanics and development

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Plant tendrils are filament-like organs allowing plants to attach to support. Mechanosensing-driven growth results in particular patterns because the overall winding of tendril must be identically zero. To preserve its highly curled form, pairs of helices with opposite handedness are formed and connected by a perversion. We report experiments on living tendrils of grape vine and cucumber deciphering main events and mechanisms of tendril growth: search for support by nutation, attachment to support, writhing and subsequent development of helix-perversion-antihelix fold.Typically, torque and pulling force were monitored along the tendril development. (Bio)inspired by tendril mechanics, we also conceived an artificial elastomer device with mechanical properties similar to living tendrils. Findings on both living and synthetic tendrils are reproduced within a linear theory of elastic rod with intrinsic curvature and twist. Stereophotography and subsequent 3D reconstruction allowed us to compare the growth pattern of tendril to our theoretical results.

Keywords: tendrils, climbing plants, mechanosensing, thigmotropism, 3D reconstruction, force and torque measurements, elastic rod theory

*Speaker

Influences of a microtubule mediated mechanical feedback during early stages of flower development

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Quite a lot is known about the association between genes, their interactions and growth during floral morphogenesis. More recently, spatiotemporal mapping of gene expression data on *in silico* templates of developing flowers has further revealed the contribution of individual and combinatorial gene actions on cellular scale morphometrics. Less is known about how mechanics stress-based feedback of cells and specific spatial domains of cells in developing flowers impact morphogenesis. To understand the importance of mechanical feedback in developing flowers, we combined finite-element based simulation and transient spatio-temporal perturbation of mechanical feedback. Our results reveal mechanically districting contribution of different spatial domains of developing floral meristem in influencing morphology of floral organs. We propose that development of computational models and its iterative improvement to it based on experimentation is necessary to develop a comprehensive understanding of a complex and important morphogenetic process in plants.

Keywords: mechanosensing, flower, development, finite, element model

*Speaker

A deeply conserved polygalacturonase functions in flower development in Arabidopsis thaliana

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Flower development depends on the patterned emergence of floral primordia from mechanically uniform meristem tissue. Pectin comprises a third of the primary cell walls of eudicots and maintains wall integrity and cell-cell adhesion. Enzymes such as pectin methylesterases and polygalacturonases (PGs) metabolize pectin and can affect wall stiffness, variation in which influences flower growth and development. Here we found that knocking out a deeply conserved exo-PG gene in Arabidopsis causes flowers with reduced or absent petals, altered sepal morphology, and ectopic flowers that initiate from within existing flowers, reminiscent of the apetala1-1 phenotype. In addition, this mutant has increased PG activity, suggesting overcompensation by other PG genes. Biochemical characterizations are underway, but these phenotypes indicate that this PG is critical for proper flower development and reveal a new link between cell wall mechanics and the transcriptional regulation of flower development.

Keywords: Polygalacturonase, flower development, Arabidopsis thaliana, cell walls, pectin

*Speaker

Mechanical guidance of pollen tube growth at the stigma surface

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In the flowering plant Arabidopsis thaliana, the pollen tube navigates thought the female organ to deliver the sperm cells to the ovules for fertilization. It first penetrates the cell wall of the female epidermal cells also called stigmatic papillae, to make its path within this layer towards the cell bases. We recently showed that advancement of the tube is linked to the mechanical properties of the invaded stigmatic cell and started to develop a framework for modeling pollen tube growth on the stigmatic surface. We aim at providing accurate experimental data using in vivo high-resolution imaging and innovative in vitro biomimetic experiments to orient our modeling effort and to get a mechanistic understanding of pollen tube growth guidance in a complex environment. Our hypothesis is that both the elongated papilla cell geometry and the cell wall elasticity would combine to provide a robust guidance mechanism.

Keywords: stigma, pollen tube, guidance, arabidopsis

*Speaker

Root growth trajectories in arrays of physical obstacles

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Rooting depth is critical for plants to acquire water and nutrient efficiently. However, when progressing deeper into the soil, the growing root has to circumvent physical obstacles such as stones or zones of higher mechanical impedance and frequently biased or tortuous trajectories are observed. In this study, we investigated how the gravitropic root response is modified by the presence of obstacles. We have developed a model system in which maize roots grow in artificial medium made of a customized array of 3D-printed stiff and round obstacles embedded in a 2% agarose gel. A high-throughput root phenotyping platform was used to capture time lapse images of roots. Image analysis techniques were used to track root responses to obstacles. The study revealed that there may be only a limited number of growth responses with a transition from a vertical to an oblique trajectory function of size and distance between physical obstacles.

Keywords: root, model, obstacle, trajectory, gravitropism, root tip angle and curvature

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