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Close examination of growth rings reveals how a damaged tree trunk slowly healed over a thirty-year period

THE POINTS, LINES, AND TRAJECTORIES OF PLANTS

Time-lapse imagery allows us to witness, first-hand, how plants grow and heal, sway in cyclical motions, and even “dance” in reaction to various environmental factors.

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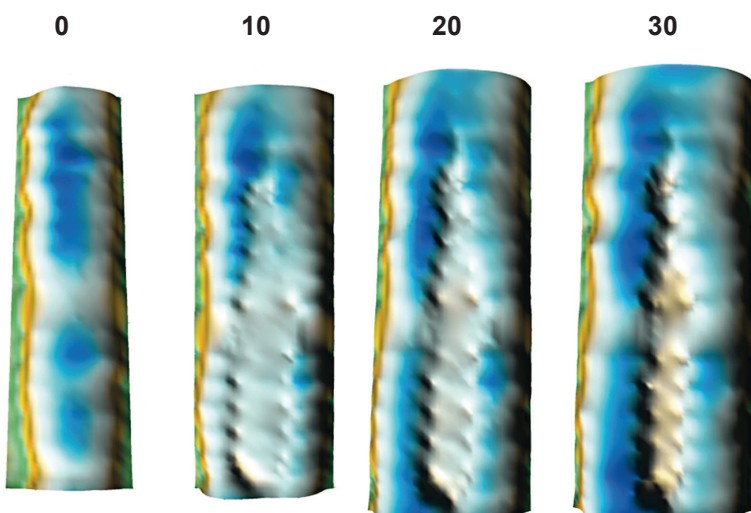
Look at plants differently because they live at a different pace than we do. The cells of their bodies are bound together by the middle lamella and are almost completely enclosed inside the cell walls, while the whole organisms are rooted in, or attached to, the ground in a single location where their lives both begin and end. A great deal of time must therefore elapse before any sort of plant reactions become

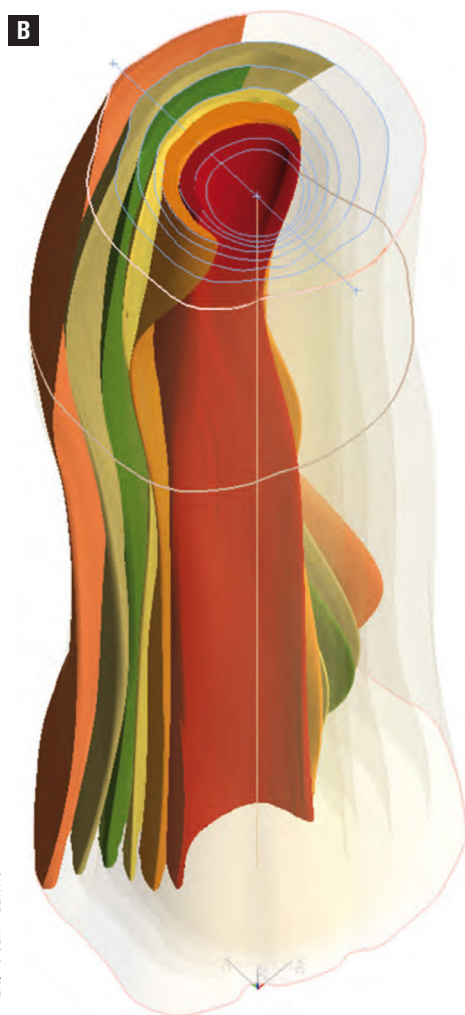
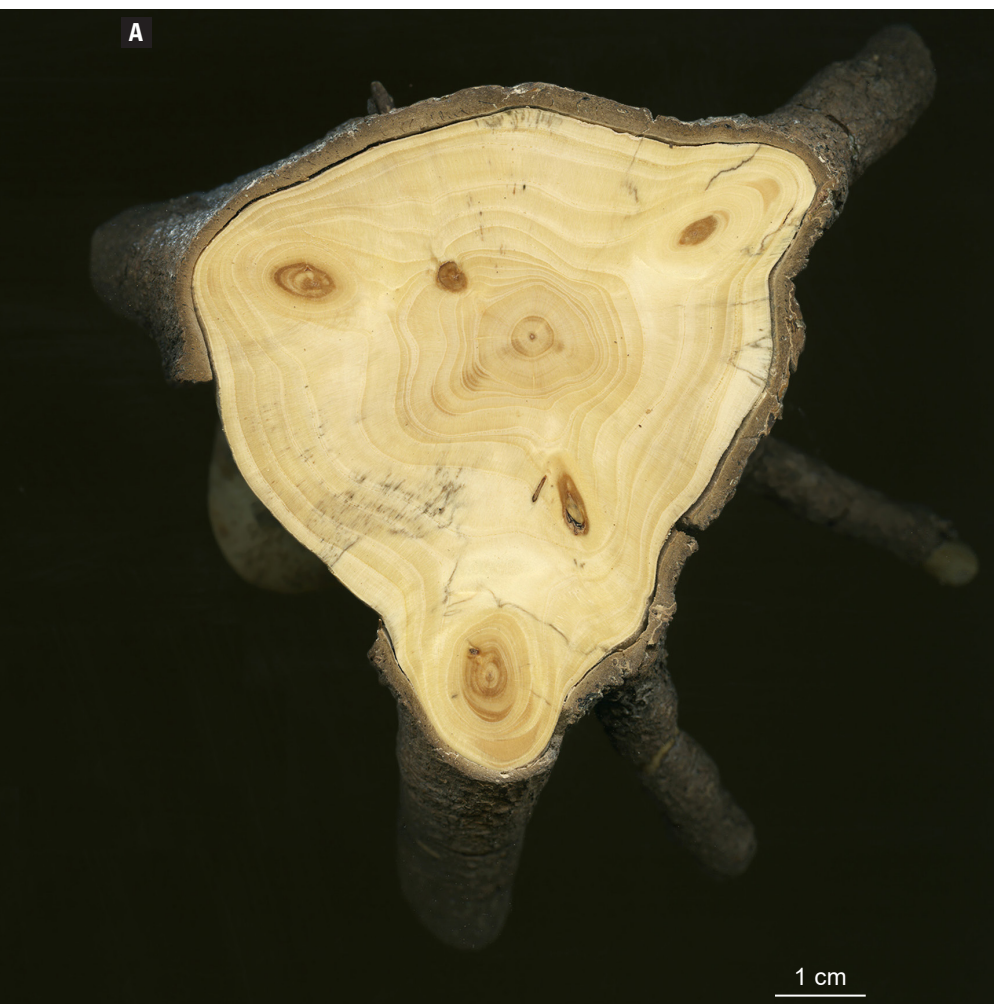
visible to us (I am not speaking here of *Arabidopsis*, but of trees). For instance, trees growing at the edges of forests in windy areas do adapt to the environment, their crowns responding so that they form streamlined shapes that slant and taper towards the forest. Yet such a reaction takes decades, rather than seconds: this is the difference between us and plants.

Wounded trees

Some plants produce what are known as growth rings, which form throughout almost their whole lives. These consecutive growth rings record the plant’s physiology and the environmental conditions it experienced in the individual years in which they were formed, and so inside the trunks, branches, and roots the plant preserves a sort of life history, inscribed in its very anatomy.

It is possible, by looking at the growth rings formed on the wounds of old trees and in the abundant folds surrounding former scars, to retrace the entire healing process of a tree. A tree heals, overgrows the wound, and then creates new growths – the process can be reconstructed and observed using spatial data visualization and mapping software, such as ArcGIS. For instance, a certain battered fifty-year-old pine was unable for several decades to cover over a damaged part of its trunk. Such an injured tree, with a very damaged cambium – the tissue responsible for all secondary wood growth – is unable to form cyclical, orderly growth layers and instead forms chaotic structures. The wood that forms around wounds is different from normal wood – just as a scab on the body of an animal does not resemble normal skin. This is mainly the result of dysfunction in the transport vector for aux-





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in – a plant growth hormone. Auxin forms in young leaves and shoots and is transported from the apex to the root by the living cambium. It is what stimulates cell division, and it also serves as the spatial signaler for tissue polarity and for the whole organism – so that, irrespective of how a tree is positioned in space, its individual morphological parts maintain distinct and differentiated. A severed cambium, however, loses contact with this source of information, so that the flow of auxin is disrupted. From this moment on, its derivatives cease to resemble orderly strings of cells and instead begin to resemble knots.

How can the scale of this plant-cell disarray be described? When is it possible to state that a tree has begun to restore its systemic order, and thus to heal? A method of three-dimensional digital analysis, adapted to record the cell arrangement seen in simple preparations of a tree trunk in the process of healing, was applied to investigate the collagen fibers. It uses colors to visualize what is known as a structure tensor. This makes it possible to quantify the level of cellular order and hence to express the extent of trunk regeneration numerically.

Retracing the process by which a damaged plant reorders its structure or, to put it another way, analyzing how tree wounds heal, is therefore an extremely

interesting way to explore the very fundamentals of plant physiology and differentiation. In the case of plants, it would appear that a very tight set of equations describe their symmetry and spatial interrelationships, so that the breakdown of these axes of symmetry and the reshuffling of these equations initially finds expression in the chaotic form exhibited by cells. But subsequently, everything slowly changes – sometimes even across the span of a human lifetime. Science, then, makes it possible to investigate the various stages of this process and to present it in the broader contexts of the environment, evolution, and morphogenesis.

The tools I use in my research are very straightforward: a microtome, a microscope, glycerin and a computer. This equipment is sufficient to elucidate what causes the tangles known as “witch’s brooms” that can sometimes be found in the crowns of trees. Usually, they are caused by a fungal or viral infection. In a very restricted portion of the tree crown there is a tremendous flurry of budding activity, but these new shoots are all kept to a certain minimum length. Witch’s brooms are visible as a distinctive thickening of the tree crown, as dark forms suspended high among the branches. Inside their cross-sections (along their axes of symmetry), the incremental

Photo A
Cross-section of the primary trunk of a witch's broom in a spruce tree

Photo B
Layers of compression wood in the trunk of a spruce tree gradually straightening itself out

Trajectory followed by the apex of a mint plant, as viewed from above, with movements being recorded over three days



wood growths do not form concentric growth rings, but again irregular forms encompassing a multitude of lateral branches.

Following gravity

Aberrations and disturbances in the growth of plants are extremely fascinating. Plants live out their lives suspended between various forces and tensions, not only within their own bodies but also in the surrounding environment, with which they maintain a constant relationship. Of these forces, the gravitational field is one of the most important. Gravity is independent of wind direction and of the degree of sunshine or shade. It is an autonomous, independent spatial information sys-

tem that plants have long recognized and responded to. The search for the vector of gravity through the main axis of a plant – in trees, through the trunk – is one of the most important factors organizing its growth. A tree trunk planted at an oblique angle to the vector of gravity will produce a whole series of outgrowths of a special type known as reaction wood (tension or compression) in order to reorient its axis to a position that will cost the tree the least energy to maintain, that is, to a position consistent with gravity. Often, this takes several years and is not always successful. Reaction wood is very different from the kind we encounter when touching tables or walking on a wooden floor. The stress distributions present in reaction wood serve to reposition the trunks and branches of trees, which is why it can never be harnessed in woodworking. A board made of reaction wood will always become crooked and warped; it will always remain active.

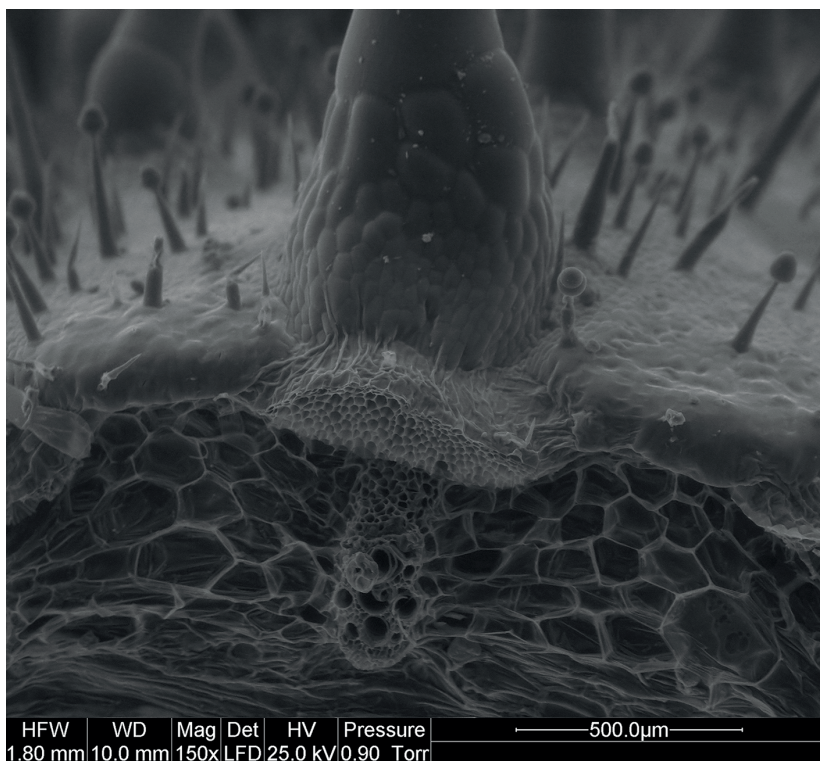
In one experiment investigating this type of wood, carried out at the Warsaw University of Life Sciences (SGGW) arboretum in Rogów, a set of spruce were planted obliquely. After three years, the trees were growing straight. The angles of the cell wall microfibrils were then analyzed to develop a spatial model of compression wood active in such tree trunks, which made it possible to retrace the changes in the cell walls. The whole process is a pure marriage of mechanics and biology – it is truly beautiful.

Dancing plants

Another method of studying plants involves observing them for a long period of time to see at what rate they grow. This is made possible by time-lapse filming technology. At the SGGW Faculty of Forestry we use this technique to investigate nutation, phototropic and climbing movements, the ways in which tendrils attach themselves, leaf vibrations, and phenomena associated with plant death.

Time-lapse filming allows us to condense the observation period. Plants can be recorded over several

Trichome of pumpkin leaf petiole lying on a band of collenchyma – of living, reinforcing tissue



HFW	WD	Mag	Det	HV	Pressure	
1.80 mm	10.0 mm	150x	LFD	25.0 kV	0.90 Torr	500.0 μm

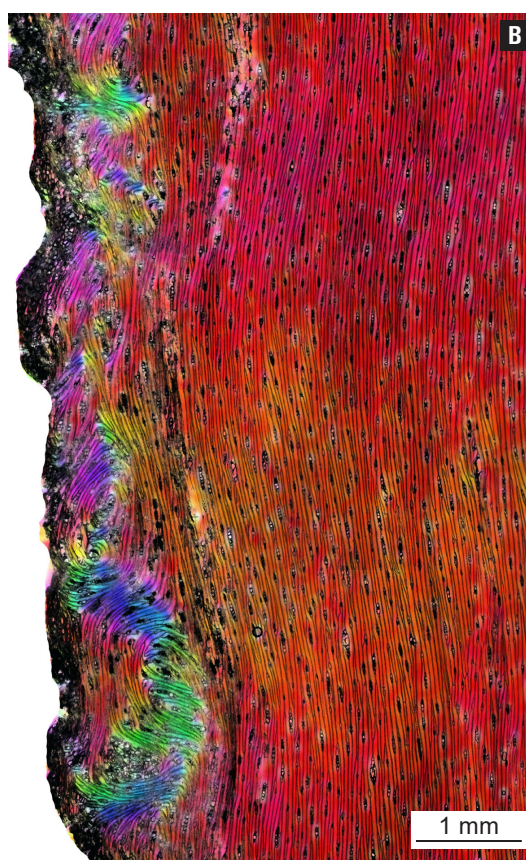
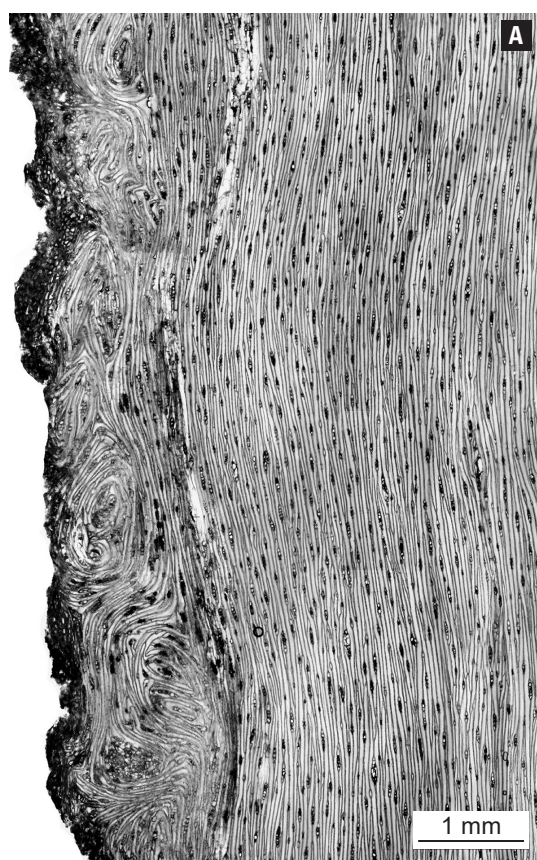


Photo A
Radial cross section of growth in the vicinity of a wound on a pine. Chaotic wood growth structure is evident on the left side of the picture, while the orderly wood growth structure prior to the wounding is visible on the right.

Photo B
Color-coded analysis of the orientations of the structures shown in photo A

months, and then the film can be shortened to a minute so that the changes are readily observable. One of the films so produced at our laboratory has been entitled the “Metamorphosis of Plants,” after the title of a major work by the German thinker Johan Wolfgang von Goethe. In the film, plants can be observed to “dance” – huge pumpkin leaves are seen rising up; the leaf petioles (stalks) are hollow, while the leaves themselves are huge and extraordinarily sensitive to the direction of light.

Leaf petioles are often covered in hairy outgrowths known as trichomes (seen in the lower figure on the previous page), arranged in even rows. If these trichomes are shaved off, the leaves become unable to react to the direction of the incident light. To try to discover the underlying cause of this, the stresses present inside the plant cells were tested with the help of an indenter at the PAS Institute of Fundamental Technological Research and the severed fibers were tested on a tensometer at the SGGW Faculty of Human Nutrition. The solution proved to be surprising: the pumpkin trichomes turn out to form a reservoir of turgor pressure. As a result, the leaf petiole is in a phase of high preliminary stresses, so that it really does not have to strain itself much in order reorient its leaf from the east to the south in just a few hours.

Plants not only move to the rhythm of day and night and orient themselves to the vector of the in-

cident light, but they may also change orientation in relation to the position of the Moon and the influence of its mass on the Earth’s gravity. As they grow, plants exhibit “nutiation” (rocking or swaying movements), following ellipse-like paths like those seen in the upper figure on the previous page. Their velocities are not constant and they depend very much not only on the vitality of the plant but also on various factors in the environment, including the very distant environment in the form of the periodical changes in the geometrical configuration of the Earth, Sun, and Moon. Indeed, all plants (including the swaying mint plant described in the figure above) are sensitive to changes in the positions of the Moon and Sun. This is demonstrated by their response: more precisely, by the cyclical changes evident in the speed of movement of their apex and in the pulsations of their leaves.

Plants are therefore sensitive to an incredibly complex spatiotemporal mesh of interactions. As Goethe aptly noted in an essay: “In living nature nothing happens that is not in connection with a whole. When experiences appear to us in isolation or when we look at experiments as presenting only isolated facts, that is not to say that the facts are indeed isolated.” Both the indigenous peoples of Canada and the ancient Slavs knew this through their deep immersion in the workings of nature. We can rely on science and on keeping our eyes open wide. ■

Further reading:

Goethe J.W., “The Experiment as Mediator of Object and Subject,” 1792, trans. C. Holdrege.

Zajączkowska U., “Metamorphosis of Plants” <https://vimeo.com/161297124>

Zajączkowska U., Regeneration of Scots pine stem after wounding, *IAWA Journal* 2014.

Zajączkowska U., Overgrowth of Douglas fir (*Pseudotsuga menziesii* Franco) stumps with regenerative tissue as an example of cell ordering and tissue reorganization, *Planta* 2014.

Zajączkowska U., Ordering of the cellular arrangement and xylogenesis in wounded shoots of willow, *IAWA Journal* 2015.