Chapter One

WHAT IS A TREE?

> A tree says: A kernel is hidden in me, a spark, a thought, I am life from eternal life, unique in the smallest play of leaves in my branches and the smallest scar on my bark. I was made to form and reveal the eternal in my smallest special detail.
>
> —*Hermann Hesse*, "On Trees"

A person wishing to describe a tree and the environment around it has a deceptively difficult charge. *Webster*'s dictionary defines *tree* simply as "a woody perennial plant having a single usually elongate main stem generally with few or no branches on its lower part." Most of us would point to other basic parts of a tree as being somehow characteristic as well: leaves, bark, roots. Indeed, trees can be as familiar to us as our own bodies. Trees and people are even built on the same general pattern: upright in form, with a crown on top and mobile limbs stemming from a central trunk. But this very familiarity can make it hard to define just what a tree is. Perhaps the difficulty arises because we take trees for granted, as simply part of us and our world. Or maybe we haven't developed the particular vocabulary needed to describe the complex joinings and curvings of branches, the clustering and nodding of foliage, and the nuances of the nearly infinite shades of green and brown that can change in an instant of breeze or dappling sun.

—sun.
[FIGURE]
[Fig. 5 about here]
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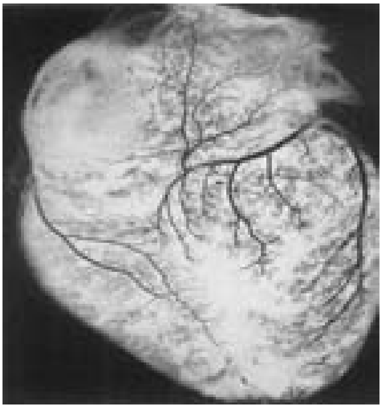


5. Dendritic patterns of veins and arteries, the vascular system of human bodies, are decidedly treelike. Photo courtesy Science Photo Library.

TREES FROM TOP TO BOTTOM

Consider one born in the forest, growing up
With canopies, must seek to secure coverings
For all of his theories. He blesses trees
And boulders, the solid and barely altered.
He is biased in terms of stable growth vertically.
And doesn't he picture his thoughts springing
From moss and decay, from the white sponge
Of fungus and porous toadstools blending?
He is shaped by the fecund and the damp,
His fertile identifications with humus
And the aroma of rain on the deepening
Forest floor. Seeing the sky only in pieces
Of light, his widest definition must be modeled
After the clearing hemmed in by trees.

—*Pattiann Rogers*, "The Determinations of the Scene"

My knowledge of the shapes and forms of trees is incorporated into the muscles and skinned knees of my youth, growing from my schoolgirl afternoons climbing maple trees in our front yard. Those early lessons in how trees are assembled complement my later formal studies in forest ecology. Tree structures can be seen not only in botanical trees, but in many other objects in nature and society. Sometimes magnified, sometimes miniaturized, tree forms are everywhere around us and within us. They exist in the mighty rivers of our landscapes, in the plumbing beneath our sinks, and in the passageways that lead us deep into caves. The walls of medical examining rooms are hung with images of the vascular system—trees writ large—allowing doctors to trace the flow of blood, lymph, and air through passages that mimic my maples. The family tree, the mathematical tree, and corporate hierarchies are all abstract forms that humans use to understand complex relationships. Tree forms even shape the way we think. Neurons are called "dendrites," from *dendron*, the Greek word for tree, and they convert outside stimuli into our awareness, our thoughts, and our memories. But before we explore these more abstract and human-centered realms, I invite you to look at the complex structures and environments that comprise real trees and real forests.

THE ABOVE-GROUND WORLD

If I strapped you into a tree-climbing harness and taught you some basic climbing and safety moves, we could take a voyage from the forest floor to the top of my favorite tropical fig tree, "Figuerola," in Monteverde, Costa Rica. There we would view up close and personal the remarkable body parts of an individual tree and experience the tremendous variability of the living conditions it creates.

A mature rainforest tree such as Figuerola is composed of a set of complex structures, from the networks of root tips that penetrate the earth for six stories below it to the skinny branch tips thirty stories above the surface of the forest floor. These twigs support the foliage of the tree, which carries out the critical job of collecting and storing energy. Most trees present their leaves at the outer edges of their crowns. In simplest terms, these leaves are the energy factories of the tree. They contain light-capturing pigments—mainly chlorophyll—that absorb sunlight energy and carbon dioxide from the air, mix them with water absorbed from the soil, and convert them to sugars and oxygen. The sugar is used or stored in the branches, trunk, and roots. The oxygen is released into the atmosphere, where it is used by humans and other animals for respiration (the taking in of oxygen and exhalation of carbon dioxide). Trees also respire, but the carbon dioxide they create in the daytime is masked by their simultaneous production of oxygen via photosynthesis. At night, however, they produce carbon dioxide, just as do people, dogs, and microbes.

This complex process of photosynthesis has been of interest to botanists for nearly four centuries. As early as the 1640s, the investigations of both the Flemish chemist and physician Johannes Baptista van Helmont and the English clergyman and physiologist Stephen Hales showed that plants require air and water to grow. In the 1700s Joseph Priestly, another theologian and natural philosopher, carried out his famous experiment of putting a mouse and a sprig of mint under a bell jar. The mouse survived, which demonstrated that green plants can replenish oxygen-poor air, thus supporting respiration and life. Following up on this work, the Dutch physiologist and botanist Jan Ingenhousz learned that plants can only create oxygen in the presence of sunlight, indicating that it is not the heat of the sun but rather its light that fuels the process. Research in the nineteenth century produced information on the specific processes and materials involved, and in the twentieth century the complex biochemistry of photosynthesis was unraveled.

Most trees arrange their leaves to maximize the capture of sunlight, but their basic structure dictates how they do it. Certain trees, such as Figuerola, have their leaves distributed in a thin "monolayer" along the entire outer envelope of the crown, which creates a shady area just beneath them. Other trees, such as the evergreen Douglas-firs of my home forests, with their tall, narrow crowns, also create foliage that is located in the self-shaded portion of their crowns. Their needles can carry out photosynthesis with less than 10 percent of the sunlight that arrives at the outer edge of the canopy, allowing them to maximize the capture of light that filters into the forest.

The major structural support for all of this energy-gathering apparatus is the trunk. Like our own trunk, it forms the main portion of the tree, rising from the ground and then differentiating into the crown, giving the tree its overall shape and strength. It is the principal conduit for fluids that transport nutrients, hormones, and sugars up and down and around the tree, just as our own vascular system distributes nutrients and energy throughout our body. In a tree, this transport is accomplished not by arteries and veins, but via xylem and phloem, a network of tubes that run between the roots and the leaves, respectively carrying water and minerals upward and moving sugar down from the leaves to the branches, trunk, and roots for storage.

The trunk consists of a series of nested layers—in the form of concentric cylinders, with heartwood at the center and bark on the surface. As the tree grows, xylem cells in the central portion of the tree become inactive and die, forming the tree's heartwood. This material is chock-full of stored sugars and oils, and so it is usually darker than the younger sapwood that surrounds it. In species such as western red cedar, the heartwood is also packed with tannins, which make it extremely resistant to decay. The heartwood of bigleaf maple, in contrast, is soft and unprotected by resistant chemicals, so nearly every individual over sixty years old has a hollow core.

The sapwood, also made up of xylem, comprises the younger layers of wood. Its network of thick-walled cells brings water and nutrients up from the roots through a connected set of hollow cells within the trunk to the leaves and other parts of the tree. Immediately beneath the outer bark is the phloem, or inner bark, which acts as a food supply line by carrying sap (sugar and nutrients dissolved in water) from the leaves to the rest of the tree. The all-important cambium is a very thin layer of tissue between the xylem and phloem; it produces new cells that become either xylem, phloem, or more cambium. The cambium is what allows the trunk, branches, and roots to grow larger in diameter.

A tree's outer bark is the functional equivalent of our own skin. It originates from phloem cells that have worn out, died, and been shed outward, and it acts as a first line of defense against insects, disease, storms, and extreme temperatures. In certain species, the outer bark also protects the tree from fire. This remarkably variable material can differ greatly in thickness, texture, and color, from the thin, papery bark of birch to the thick, multilayered bark of Douglas-fir, which can withstand fire-generated temperatures up to 1200°F.

The limbs that attach to the trunk provide a network of woody material that in turn supports the leaves. Typically, branches are formed by the sprouting and extension of terminal and lateral buds at the tips of twigs. In tree species that grow in northern temperate regions, such as maples, these buds are created in the late summer and lengthen in the following spring. Tropical trees, whose annual rhythms are more subtle because of the lack of pronounced seasonality of temperature, are less predictable in the timing of bud burst. Some trees, such as Douglas-fir in the Pacific Northwest, are capable of sprouting "epicormic branches." These emerge from latent buds or from the cambium itself after the trunk has been exposed to extra sunlight following damage to its branches by a falling neighbor. Epicormics tend to have a very different structure than normal branches, often growing out in a fanlike and stubby shape that provides a horizontal structure on which birds may make their nests. The ability of Douglas-fir to form epicormic branches may explain these trees' amazing longevity—1,200 years is not an unusual age for a Douglas-fir in the absence of fire, severe windstorm, or the buzz of a chainsaw.

ARBOREAL HITCHHIKERS: THE EPIPHYTES

Branches and trunks also provide a home for epiphytes, "plants that grow on plants." I think of them as tree hitchhikers in slow motion—very slow motion—as they take up space but neither provide energy, nutrients, or water directly to the vascular system of their accommodating hosts nor take them. In contrast, true parasites such as mistletoes have specialized roots called haustoria that penetrate the bark and outer stem to draw water and energy from the host. Although epiphytes are sometimes called "air plants," they don't really live on air. Rather, through their leaves, they are able to take up dissolved nutrients that, delivered in rainfall and mist, occur in dilute concentrations. Some of their nutrient needs are served by rain that falls through the crown and leaches nutrients from intercepted host tree leaves that have fallen and decomposed within the interstices of the tree.

The distribution of epiphytes often reflects the microclimate gradients that exist along branches. A tree's microclimate—a set of specific environmental conditions—varies greatly with its height. At the base of a tree, the shade cast by the tree itself and by surrounding vegetation creates a microclimate that is damp, dark, still, cool, and moist. Growing on the moist lower trunk we might find delicate-leaved orchids in the shade-loving genus *Gongora*, which can tolerate almost no stress from sunlight-induced drought. Higher up in the tree, temperature, wind, and sunlight increase in intensity, and we find epiphytes such as *Peperomia*, which has thick succulent leaves that resist water loss. One of the intriguing insights I had when I first began climbing is that the same pattern of increasing temperature, wind, and sun intensity occurs as one moves out from the trunk onto the branches. Perched on branches at the outer envelope of the canopy we might encounter individuals in the cactus family—the genus *Epiphyllum*—looking for all the world as though they were resting stolidly on the sand of an Arizona desert.

And then there are plants that, Zelig-like, completely change their morphology in response to different microenvironments. Vines in the genus *Monstera*, for example, begin their lives on the cool, dark forest floor. Leaves of the juvenile plant grow in an alternating pattern, pressing themselves completely against the supporting trunk, creating a ladder by which the vine grows up to the sunny, windy conditions of the canopy. There, they produce thick, floppy leaves the size of a large pizza, with deep, irregular indentations along the sides and large blob-shaped holes in the center, a shape that reduces damage from the high winds the plant must endure in the canopy.

Recent experimental research by Martin Freiberg, a curious and energetic German ecologist at the University of Ulm, revealed that epiphytes can themselves affect the microenvironment within the crown, even at the spatial scale of a hummingbird's wing. He draped recording equipment on pairs of branches—half of which he stripped of epiphytes, half of which he left intact—and collected measurements of temperature and humidity over four weeks. He found that epiphytes around stripped branches became hotter by as much as 8'F during the day, and up to 5'F at night. Why? The mechanism Martin proposed is that the densely packed epiphytes reduced air circulation, trapping unheated air on branch undersides instead of allowing it to mix around the branch.

In other situations, however, epiphytes have a cooling effect. A team of German and Swiss researchers recently documented what they called "rainforest air-conditioning," a moderating effect of epiphytes on branch microclimate. Sabine Stuntz, Ulrich Simon, and Gerhard Zotz measured the temperature of the branch surface and the drying rate of leaves at various locations within tree crowns that had either different epiphyte assemblages or were epiphyte-free. They found that during the hottest and driest time of day, sites next to epiphytes had significantly lower temperatures than locations within the same tree crown that were bare of epiphytes, even though the latter were also shaded by host tree foliage or branches. Moreover, water loss through evaporative drying at sites next to epiphytes was almost 20 percent lower than at exposed microsites. Although the influence of epiphytes on temperature extremes and evaporation rates is relatively subtle, their mitigating effect could be of importance for small animals, such as the insects that inhabit an environment as harsh and extreme as the tropical forest canopy.

It turns out that epiphytes have a disproportionately large influence on the whole forest, relative to their small size. In the late 1970s, research into the ecological roles of epiphytes in the nutrient cycles of the entire forest—pioneered by Bill Denison and George Carroll of Oregon State University and the University of Oregon, respectively—looked at old-growth forest canopies in the Pacific Northwest, focusing on the relationships between forest structure and function. They determined that canopy-dwelling plants and lichens augment the amount of nutrients captured in the atmosphere, by "fixing" gaseous nitrogen and transforming it into forms of nitrogen—nitrate and ammonium—that can be used by plants and animals to build and replace their body parts. In Monteverde, Costa Rica, my students and I have measured the amounts—sometimes considerable—of nitrogen and other nutrients that the epiphytes intercept and retain from rain, mist, and dust. One study, for example, documented that 60 percent of all the nitrate that enters the ecosystem in rain and mist is sucked up and held in the canopy by branch-dwelling mosses. Thus, although epiphytes may be a barely visible and seemingly negligible component of forests to ground-bound scientists, in fact they perform a keystone function.

Last but not least, our inventory of tree structural elements includes arboreal soil. We expect to find soil on the forest floor, where tree roots are imbedded. But in many wet forests, such as Monteverde, where Figuerola grows, we encounter pecks and even bushels of soil on the large branches that support epiphytes. In a temperate rainforest, within the single crown of a mature maple tree, this soil can amount to as much as 280 pounds (dry weight). Where does this material come from? When the epiphytes die and decompose, they generate a layer of soil up to ten inches thick that rests on canopy branches. This soil provides a habitat for a huge diversity of insects, earthworms, and spiders, which in turn are critical sources of food for birds and tree-dwelling mammals.

THE FOREST UNDERWORLD

Roots and their associated animals and fungi are the most poorly understood portion of forests, overlain as they are by opaque soil that obscures the fascinating interactions going on beneath. Roots take many forms, from massive buttresses as imposing as a three-story cliff face to tiny root hairs just eight one-thousandths of an inch in diameter. Soil inhabitants—some, such as nematodes, mites, and bacteria, smaller than pinpoints, others as big as badgers—participate in food chains and energy cycles as complex as the subterranean networks of electrical cables that operate beneath the streets of great cities. Just as canopy researchers have learned how to safely climb into the tops of trees, scientists have recently invented techniques for understanding how to measure and interpret the belowground world.

One weekend in 1980 I accompanied a fellow graduate student, Mike Keyes, on one of his collecting trips into the field. He was studying the dynamics of fine roots (those less than a quarter of an inch long, and responsible for nearly all of the water and nutrient absorption of trees) in an alpine forest in Washington State. He had constructed a "rhizotron"—literally, a place to observe roots grow. Descending a ladder into the dark room that Mike had dug out twenty feet below ground, I felt my claustrophobia kick in with a vengeance. My request to bring up the lights received a quick "nope" from Mike, since he knew that the presence of light and warmth might affect the natural growth and death rates of the roots he was studying. In the faint glimmer of a 25-watt flashlight, Mike hung a sheet of plastic over one of the large windows that were set into each of the walls. On it, he had traced the path of each of the hundreds of roots that grew pressed up against the glass, marking each segment of line with a date. Mike now proceeded to carefully trace the growth that had occurred since his last measurement. Occasionally he let out a small grunt, which I learned meant that one of his roots had died. Shivering slightly in the alpine cold—since heating as well as light affects root growth—I picked up a marker and got to work as well, occasionally grunting myself. At the end of a year of this tedious but exciting work, Mike had a unique record of the growth and death of the nutrient- and water-apparatus of the forest, something that only a few other forest studies had accomplished. Among the many new insights he gleaned was that the collective length of the root system of a single seedling just six inches in height can be over one mile long.

Nowadays, "minirhizotrons" are more common, for which claustrophobes like me are grateful. Plastic tubes hammered into the ground provide a medium through which a soil scientist can lower a tiny video camera. As it passes through the different soil depths, the camera may capture the dance of a nematode or the squiggle of an earthworm as it records root length. Repeated measurements of the root's length—or disappearance—from the same tubes at subsequent monthly intervals allows the research to calculate the rate of root growth—or mortality. In 2001, scientists at the Environmental Protection Agency in Corvallis, Oregon, carried out a review of the research that has been enabled by this approach. The literature indicated that minirhizotrons provide an unprecedented way to study soils, as they afford a nondestructive, in situ method for directly viewing and studying fine roots. Questions that can now be more fully addressed include the role of roots in carbon and nutrient cycling, rates of root decomposition, responses to fertilization, and the significance of interactions between plant roots and soil organisms. Scientists also create sonograms of soil to differentiate solid objects such as roots and rocks in the soil matrix, in similar ways that obstetricians monitor the growth of an unborn baby in the matrix of amniotic fluid. They also inject radioactive dyes to understand the size and distribution of airspaces within the soil.

The roots and the materials they transport function as complex systems of communication and interchange. For example, the roots of many tree species can graft to roots of neighboring trees, allowing for the exchange of nutrients and water. This phenomenon can also make roots the pathway for the spread of infectious disease, as in the case of the infamous Dutch elm disease (so called because it was first described in Holland in 1921, though the pathogen originated in Asia, possibly China). Caused by the fungus *Ophiostoma novo-ulmi* and spread by a bark beetle, the disease appeared in the United States in 1930. From the point of inoculation, the fungus moves through the xylem—the vascular system of the tree—and quickly reaches the roots. Where elms are planted close together, root grafting may occur, and the fungus can move seamlessly from one tree to the next. Because the American elm is an important tree commercially and aesthetically, plant breeders have been trying to develop a disease-resistant variety.

Grafting to one's neighbor's roots can, however, provide support rather than sickness, as with the Puerto Rican tabonuco tree. Over 60 percent of all stems and basal areas of tabonuco occur in unions, leading to clumps of trees interconnected by root grafts. Researchers have documented that in the tropical lowland forests of the Caribbean, grafted trees grow taller and sustain far less hurricane damage than do nongrafted individuals. These results suggest that a noncompetitive force such as root grafting may be important in maintaining the forest community.

How might this ecological pattern extend to humans? Consider this observation by the writer Howard McCord: "A tree communicates with other trees most intimately and enduringly beneath the ground, as rootlets touch, entwine, and stay. The flickering contacts leaves and branches have with one another in the wind are so random and fleeting. . . . What's important to us goes on *up here*, what's important to a tree goes on generally down below, in a dense, hidden medium we inhabit only after death." In other words, trees symbolically manifest the importance of that which is hidden. Their roots are underground, out of sight, yet they provide support for the tree and are the gathering apparatus for water and nutrients. Tree roots can also symbolize that which we keep hidden from ourselves and others: our troubles, our failings, our addictions, our ill health, and our fears. We know that revealing these hidden roots to our spouses, our friends, our pastor—and most of all to ourselves—is the first step toward finding the strength to overcome them.

TREE FORM AND ITS EXPRESSION OF THE PAST

> The tree is more than first a seed, then a stem, then a living trunk, and then dead timber. The tree is a slow, enduring force straining to win the sky.
>
> —*Antoine de Saint-Exupéry*, The Wisdom of the Sands

The form of a tree is a frozen expression of its past environment and traumas. Just as a fifty-year-old man might limp from a high school sports injury, so do trees carry the physical signs of their history and experience. I know this from my own efforts as a would-be orchardist, which began when my family first moved into our house in Olympia. The fruit trees that we planted have been, to put it generously, disappointing. They were nibbled back badly by deer their first year, and even though we put fencing around them after that, they never recovered fully; their limbs remain asymmetrical and clublike. What explains this long-term memory of trees?

In the 1980s, Claus Mattheck, a German physicist, applied his research on the mechanics of tree structure to the field of arboriculture—the study of tree health and cultivation. Mattheck considers a tree to be a "self-optimizing mechanical structure," a construct that embraces two principles: first, trees make economic use of their resources; and second, they are only as strong as is necessary. If a structure such as a branch is evenly loaded and if all points on its surface withstand the same stress, it will have no overloaded areas (breaking points) and no underloaded areas (wasted material). Elephant tusks, bird wings, human leg bones, and tree limbs are also optimal structures, having evolved to withstand the loads placed on them by the environment. To gain a competitive edge on other plants, trees enhance their ability to survive by sending out branches in all directions, which allows them to present more energy-harvesting leaves to sunlight. To do so, they must develop structures that are strong enough to withstand the forces of gravity and wind. For instance, the taper of a trunk is a tree's response to wind. Wind places the greatest strain on a tree at its base (the "greatest bending moment"), so on windy sites a tree puts on more wood at its base than at the top of the stem. A tree protected from winds in a dense forest usually has very little taper. Branch attachments show similar adaptive behavior. Limbs have collars of extra wood at the point of attachment, so on windy sites, the collars are larger on the windward side of the tree.

When a tree's bark is removed or disturbed, for instance by a person idly carving into it with a knife, the cambium layer just under the bark senses the extra stress on the tree's surface and immediately begins to reduce the stress by growing callus tissue (new wood over the wound). Trees also produce so-called reaction wood in response to the force of gravity.

When a pine tree leans, it grows more wood on the lower side of the trunk to bring it back into an upright position, producing an asymmetrical annual ring. Therefore, sites on trees where extra wood has grown are hints to the arborist of internal injuries or mechanical stress. Sometimes, when I look at our little home orchard or take an evening stroll down a tree-lined street, I think about how tree bodies express themselves. I feel like a combination physicist, psychiatrist, and detective as I piece together the injuries and strains that each tree has encountered in its past and marvel at its ability to overcome such stresses.

THE ART AND SCIENCE OF TREE CLASSIFICATION

> trees are our lungs turned inside out
> & inhale our visible chilled breath.
>
> our lungs are trees turned inside out
> & inhale their clear exhalations.
>
> —*Bill Yake*, "inside out"

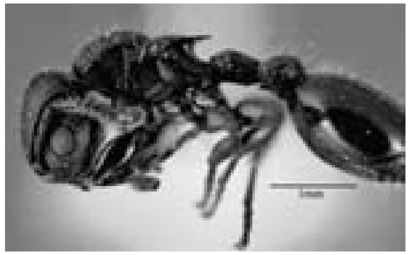
TAXONOMIC APPROACHES

Taxonomy is the scientific discipline in charge of classifying and naming living things, based on the similarities and origins of their physical structures. My husband, Jack Longino, is a taxonomist, specializing in the classification of ants. Jack and I met when we were both graduate students, carrying out our dissertation projects at Costa Rican rainforest research stations that were located on opposite sides of the country. I climbed trees in the cool, mist-kissed Monteverde Cloud Forest, while Jack collected ants in the sweltering lowlands of Corcovado National Park. Backdropped by the romantic tropical rainforests we studied, we fell in love quickly and deeply, and alternated visits to each other's field sites for over a year. In one of our most special courtship moments, Jack looked into my eyes and promised to name an ant after me. Nine years later, he presented me with his taxonomic paper describing *Procryptocerus nalini*, a rare ant species that he discovered high in the tropical treetops. He has numerous ants named after him by other taxonomists (it is poor form to name a new species after oneself). His 2005 Christmas present to our children, Gus and Erika, was naming ant species after each of them—*Pyramica augustandrewi* and *Pyramica erikae*—making us, perhaps, the only family whose members each have an eponymous ant. After twenty-five years of studying ants, he has learned how to differentiate hundreds of ant species, tying each one's name to information about its natural history, social interactions, and environment. This ant-colored outlook turns the world around him into a rich tapestry of diversity, whether he is in a remote rainforest or an urban parking lot.

—lot.
[FIGURE]
[Fig. 6 about here]

Trees, like ants, can be classified by their taxonomic groups. There are close to ten thousand identified species of trees on earth. Being able to identify them—or even to recognize the ten most common species around us—enriches our understanding of our landscapes. The plant kingdom is divided into a hierarchical set of subdivisions: classes, orders, families, genera, and species. A genus constitutes a group of individuals that share many physical characteristics. Within a species, individuals interbreed and produce fertile offspring. For general scientific use, botanists identify a tree by its genus and species; Douglas fir is *Pseudostuga menziesii;* bigleaf maple is *Acer macrophyllum.* The official "nicknames" used to abbreviate the names of trees when collecting data or making inventories are made by taking the first two letters of the genus and species: PSME and ACMA.

Dendrologists—people who study trees—have established criteria to differentiate species based on physical appearance. To identify a tree using a botanical key, you break off the end of a tree branch and examine the pattern of its leaves, buds, or flowers. The arrangement of leaves on the stem, for example, may be alternate (individual leaves climbing the stem in alternating steps, with one leaf per node), opposite (two leaves across from each other, both emerging from the same node), or whorled (multiple leaves arranged in a circle, all sharing the same node). The flowers



6. This canopy-dwelling ant was named by the author's husband, an ant taxonomist, for her. Photo by John T. Longino.

may have three or five or even twenty-five petals. Fruits may be partitioned into three or five or more sections; the seeds may be winged, enclosed in pods, or entirely naked. The ways in which their structural parts are assembled provide clues for the classification of all the trees in the world. These distinctive characteristics also indicate evolutionary relationships among individuals, with more shared structural elements indicating closer genetic relationships. For example, oaks, in the genus *Quercus* all house their seeds in the form of acorns. Within that genus, hundreds of different species exist, for example, cork oak, live oak, and valley oak, and they exhibit subtle differences in their physical form—such as acorns that are hairy versus smooth and shiny, or leaves that are lobed versus smooth-edged.

—smooth-edged.
[FIGURE]
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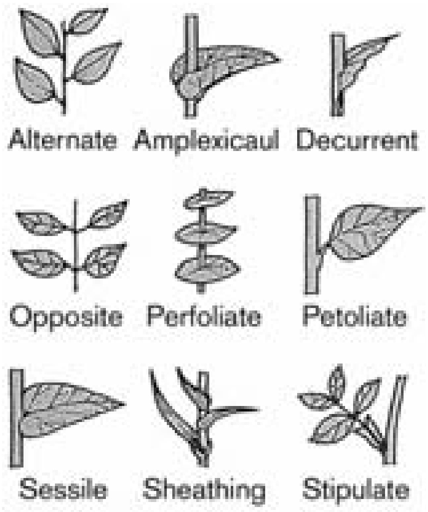
In addition to their scientific designations, nearly all trees have common names. These are useful in some ways: they may describe the habitat in which the tree grows (e.g., river birch), how the tree looks (quaking aspen, weeping willow), or some benefit to humans (sugar maple, canoe birch). However, a single kind of tree can have many different names, making it confusing to classify a tree based on its common name alone. *Quercus dumosa*, for example, is called post oak, blackjack oak, and scrubby oak in different parts of the country. In 1908, U.S. Forest Service botanist G. B. Sudworth published a landmark checklist of trees in the United States containing a thousand scientific species names that collectively yielded over nine thousand common names—a vivid demonstration of the multiplicity of common names.



7. Methods of classification of trees and other plants are partly dependent on the way leaves are arranged on their stems.

APPROACHES TO CLASSIFICATION

Classifying the bewildering diversity of trees taxonomically—whether by common name or scientific name—can be amazingly difficult, even for professional botanists. For many types of forests, especially in tropical regions, no botanical keys are available at all. A one-acre tropical rainforest plot in Amazonian Ecuador, for example, may have as many as 180 different tree species—including some that are as yet undescribed. It can take years, even decades, to learn all the botanical names of the trees that live in an area. Robin Foster, who has worked as a professor, a freelance tropical botanist, an ecologist for a conservation organization, and a research scientist for the Smithsonian Institution, is a heroic figure in the eyes of many botanists. He was, for a while, about the only person who could reliably identify virtually any tree in the diverse rainforests of lowland Central and South America. A soft-spoken man whose genial demeanor belies his sharp eye and strong drive to know every tree species in every forest, he spent years of his life (and a good part of his health, as he has suffered from numerous tropical diseases) learning the subtle differences between species of rainforest trees, relying on his prodigious memory to discern the difference between, for example, *Hieronyma oblonga* and *H. macrocarpa*, two tall tropical trees of Ecuadorean forests, based on the number of floral parts.

Robin, now an adjunct curator at Chicago's Field Museum, is currently working with Steve Hubbell at the University of Georgia to understand the distribution and abundance of trees by mapping and measuring every tree in a 50-hectare (125-acre) plot in a lowland tropical forest on Panama's Barro Colorado Island. Robin had the difficult job of identifying over 235,000 individual trees, from tiny seedlings to giant canopy emergents. The lack of resources for identifying plants in the tropics has been a bottleneck for researchers of tropical ecology and a barrier to public interest for a long time. It has inspired Robin and his colleagues to develop a variety of new identification guides and training materials, which take advantage of digital technology and the vast collections of the Field Museum's herbarium.

Not every location has the benefit of a Robin Foster, however. Because of the shortcomings of a strictly taxonomic approach in places where such expertise is not available, forest ecologists are now keen to establish a different approach—categorizing trees by their overall structure, rather than by a botanical key that depends on ephemeral parts of plants such as flowers and fruits. The goal is to be able to simply look at a tree, recognize how its branches fit together or how its leaves are arranged, and then categorize it according to this gross structure, regardless of its taxonomic group. Humans are adept at classifying objects into structural classes. Go to any sewing store and observe the racks of buttons and zippers, neatly arrayed by size, number of holes, length of teeth, and surface texture. A customer bent on finding just the right fastener for her soon-to-be-completed dress can locate it efficiently because of the way the shopkeeper arranged them—by structural category.

However, classifying trees with a structural approach is not completely straightforward. The diverse questions and interests that each individual researcher poses require using different pieces and perspectives of the forest. For example, an entomologist (like Jack) who is interested in the ants that march along branch surfaces wants to view the forest from the insect's perspective. An ant would perceive a tree as a set of interconnected transportation networks that consists of a series of two-dimensional planes that she can walk upon no matter what her orientation—upside down, rightside up. Her world is a set of flat surfaces. In contrast, an ornithologist who is interested in the distribution of eagle nests benefits from seeing the forest from a bird's-eye view and would consider the forest not as a series of flat planes, but as an array of static and discrete locations distributed in three-dimensional space—specifically as a set of intersections of branches six inches in diameter or more, and capable of sheltering a good-sized nest. And to a botanist interested in pollination ecology, trees might be viewed as a set of floral "hot spots" for hummingbirds to visit. In their nectar-seeking flights from one flower to another, pollinators connect these dots, either directly, as trap liners, or seemingly randomly, flitting from one point to another. In either case, the distance between flowers is a Euclidean measure related to that three-dimensional volume between flowers. In contrast to the ant, who must traverse the tree branch as a unit, for the hummingbird it does not matter which flower belongs to which branch. For tiny pollen grains, meanwhile, a tree is a giant solid obstacle on which to smack, as they float, nearly weightless, through the shared volume of three-dimensional air space.

This array of structural possibilities brings to mind a poem from my childhood, "The Blind Men and the Elephant" by J. G. Saxe, which describes six blind men examining an elephant. Each man chooses a different part of the animal to explore—the tusk, the tail, the leg, or the trunk—and each comes to a wildly different conclusion about what an elephant looks like based on his own small sample. In the end, as the poem goes, "each was partly right, and all were in the wrong!" Like the blind men and their elephant, forest ecologists look mainly at the parts. Our ant biologist, ornithologist, and botanist are partly "in the right" to insist on their network, nodal, or volumetric view of a forest, because each does indeed capture an important aspect of a forest's structural complexity.

But they would also be "in the wrong" if they insisted that their view was sufficient to describe forest structure as a whole.

Although as yet no single protocol exists to classify forest structure, several complementary systems are in use. One involves what I call the "Lost Luggage" approach, an idea that came to me on a cross-country airplane trip when my luggage failed to appear on the airline carousel. At the baggage office, the staff person handed me a chart that depicted the various types of luggage, keyed by various structural elements (one handle or two? zipper or no zipper? hard or soft?). Very quickly, I identified the number-coded image that most closely fit my errant suitcase, and almost as quickly, my bag was located in the huge roomful of lost luggage, all of which had been stored by code numbers. Thus, by means of a finite number of structural elements (handles, zippers, hardness), an individual object was identified with ease, just like the array of sewing goods in the fabric store.

Using this same principle, orchardists have developed a way to classify the different growth forms of their fruit trees in order to impose horticultural regimes. For example, the founders of the Dumfries and Galloway Orchard Network, an organization that encourages sustainable fruit-growing in Wales, examined a large number of trees and partitioned them into a small number of categories based on the form of the trunk and branches. They created a booklet depicting the shapes that occur in orchards under varying sunlight exposures and soil types. For each category, such as "fan-trained," "maiden," "bush tree," and "pyramid," they recommend specific pruning and fertilizing treatments. The system works well because they deal with only a small number of tree species (apples and pears) and a limited number of growth forms.

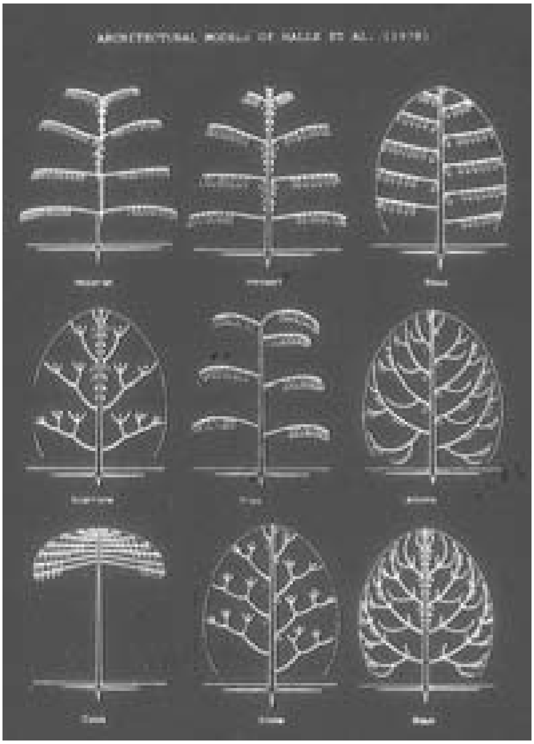
In real forests, however, a nearly infinite roster of tree forms exists. Thus, the lines that separate one tree form from another in orchards are not useful for natural forests. An approach to classifying forest structure was needed. In 1978, a trio of scientists—the French botanist Francis Hallé, British plant anatomist P.B. Tomlinson, and Dutch ecologist

R. A. A. Oldeman—devised a system called "tree architecture." Although they used it to classify tropical trees, the principles of the system apply to all trees. They examined the arrangements of buds and documented the way these units "iterate" or repeat through time. Anatomically, trees are constructed in a finite number of ways. Some trees put out many buds from a single point at the tip of their branches, while others grow a series of lateral buds. If each bud grows into a branch, that tree exhibits its fullest structural potential—its "true architecture." Hallé and his colleagues determined that all possible growth forms fall into one of twenty-three categories, or architectural models. Leafing through their book on tropical tree architecture is like flipping through an automobile showcase catalogue, with each individual tree species presented in its ideal Platonic form. However, individual trees in the wild—even those of the same species—almost never end up looking like their potential self. They encounter wind, climbing primates, and shade from nearby trees, all of which cause certain branches to fall and some buds to shrivel. So finding model trees with perfect architecture in a rainforest is somewhat like locating a perfect automobile in a used-car lot—possible in theory, but probably not in fact.

—in fact.
[FIGURE]
[Fig. 8 about here]

A third approach to classifying tree forms occurred to me one morning at a jewelry store where I was getting a necklace repaired. As I waited, I picked up a brochure that described how jewelers classify diamonds. Originally, when there were very few diamond-producing mines, rough stones could be traced to their source by their "signature look." When diamonds were discovered in Canada, Australia, the Congo, and other countries, however, distributors needed a more inclusive and objective system. So they created the "4C" system, in which stones are rated from 1 to 10 on each of the so-called 4C's, four characteristics that all stones possess: cut, color, clarity, and carat (weight). With the ability to describe individual stones by a set of four digits, jewelers seeking a particular form and look of diamond can easily query suppliers.

This system contrasts with the Lost Luggage technique, which sub-



8. These drawings illustrate Hallé, Oldeman, and Tomlinson's system of classifying trees according to their "architecture." From F. Hallé, R. A. A. Oldeman, and P. B. Tomlinson, Tropical Trees and Forests: An Architectural Analysis (Berlin: Springer-Verlag, 1978).

jectively sorts things (baggage, trees) into recognizable groups based on whether or not they have specific features. It also contrasts with the tree architecture approach, which is based on one narrow aspect of arboreal biology—bud arrangement—but does not address subsequent growth dynamics in real environments. Each has its value, however. One of my computer science colleagues, Judy Cushing, and I have been working to develop a new and integrative conceptual framework to categorize trees, using two of these approaches. First we look at general form, following the Lost Luggage model. As in the 4C system, each of the general "representations" we define is then modified by a set of more specific descriptors—such as number of spatial dimensions and whether it is spatially referenced. We hope this will provide a systematic way of describing forest structure that ecologists can use to document not only how forests look, but also how they function and change through time.

DESCRIBING WHOLE FORESTS

Let us shift our perspective from single trees to the whole forest. Except for trees in very dry regions, very cold landscapes, or urban venues, trees occur growing together. A forest stand is much more than a collection of individual trees, just as a city is much more than a group of humans living in the same area. When I visit New York City, I always marvel that something so large and complex can provide a venue for eight million people—and their pets and houseplants, not to mention the wild birds, rodents, and insects that still live there—to awaken, eat, communicate, exchange goods and services, play, and go to sleep. To enter a forest is to marvel at the varieties of trees and their associated plant and animal species, all of them circulating and storing energy, water, and genetic information. The mechanisms used to gain sustenance from soil, rainfall, and air in forests are at least as complex as, and generally far subtler than, the subway systems and office buildings of a bustling urban center. Just as architects and sociologists examine urban physical and social structures, forest ecologists have developed similar approaches to describe how forests are organized.

The definition of a forest in *Webster's Third* is simple: "a dense growth of trees and undergrowth covering a large tract of land." The word's linguistic root reaches into Medieval Latin, in which *forestis* means "outside." The term applies to ecosystems as diverse as the sparsely treed seasonally dry woodlands of Latin America, the exuberant rainforests of the Asian tropics, and the monochromatic spruce forests of Siberia's taiga.

Forests have been a major feature of planet Earth for more than 300 million years. The extent of forests has grown and shrunk with climate changes, ice ages, and human population growth and technological innovations. Today, about 30 percent of the world's land surface is covered by forest.

The vast land area that trees cover, the rapid conversion of original forest types to others (usually commercially preferred types), and the difficulty of obtaining information in some countries have until very recently precluded a reliable census of the world's tree population. But lately, that situation has been changing—thanks in part, and somewhat incongruously, to NASA, an agency created to study the presumably lifeless landscapes of outer space. Planetary scientists have invited life scientists into their arena of satellites and supercomputers to help interpret images snapped by satellite sensors of complex patchwork quilts of forests, fields, and urban spaces, connected by rivers. Calibration and interpretation of these images must be coupled with ground-based studies to help foresters inform land use managers, conservationists, and policymakers about the state of the world's forests. As a result, some of the finest forest ecology studies being carried out today are the result of NASA-funded multidisciplinary collaborations.

With these emerging tools, geographers have been able to make reasonable inventories of the world's trees. Using such diverse sources as tree counts by rural forestry departments and remote imagery supplied by NASA, foresters at the Food and Agriculture Organization, based in Rome, produce estimates of tree cover every five years. In 2005, they reported the area of forested land as 3,952 million hectares, or 15,258,853 square miles, an area equal to the United States and Australia combined. Coupling those numbers with estimates of tree density, they calculated the total number of trees on Earth to be about 400,246,300,201. I wondered how many trees that would be per person—or perhaps it would work out to how many people per tree. I looked up the world's human population and learned that as of December 31, 2005, humans are

6,456,789,877 strong. Punching the figures into my calculator, I calculated that the world supports sixty-one trees for each person on Earth. When I think of the millions of people living in the densely populated and virtually treeless urban landscapes of Mexico City, Tokyo, and New York City, that figure seems very large to me—sixty-one trees for each person walking through Times Square! But when I told my husband, Jack, about this tree-to-human ratio at breakfast, he reflected for a moment and then voiced wonder that the ratio was so small. "Each person gets only sixty-one trees in a lifetime?" he mused over his muffin. "That seems hardly enough to supply just the firewood we'll use in our woodstove for the next few winter seasons, let alone the lumber that's in our house and the paper I put through my printer." His reflections made me revise my original impression, and reinforced the sense that I need to think about ways to look after my sixty-one trees, wherever they might be growing in the world.

CLASSIFICATION OF WHOLE FOREST STRUCTURE

Foresters do more than count trees. They have also developed ways to classify whole forests by their structure—how they are put together, their shapes and collective forms. Just as a zookeeper might herd together all of the four-legged mobile animals and put them in a pen, and then guide all of the slithering legless animals into a secure glass cage, so do foresters rely on the salient structural elements of forests for classification. Geoffrey (Jess) Parker, an ecologist at the Smithsonian Environmental Research Center in Edgewater, Maryland, has for decades been working to understand the structure of the aboveground parts of forests, both in his native eastern deciduous forests of Maryland and in other forests around the world. His formal definition of forest structure is "the organization in space and time, including the position, extent, quantity, type and connectivity of the aboveground components of vegetation, as well as standing dead trees ('snags'), fallen logs, and the open spaces between canopy elements." He notes that many terms have been used interchangeably in reference to forest structure, but they emphasize different aspects. Those who study *forest physiognomy*, for example, focus on the shapes of individual crowns. *Forest architecture* describes the growth patterns and resultant forms of stems. *Forest organization* implies the statistical distribution of forest components in space or time, and *forest texture* refers to the sizes of crown units composing the overstory, apparent only from above the stand.

Ecologists such as Jess recognize the central place that structure plays in many critical forest attributes. The arrangement and vertical distribution of leaf area within tree crowns, the distribution of branches around the trunk, and the distribution of trees of different heights can have a strong effect on microclimate in the forest understory, forest functions such as photosynthesis and respiration, the cycling of water and nutrients, rates of growth, the diversity of understory plants, and suitability for wildlife. An abundance of snags, for example, greatly increases the number of nest sites for cavity-nesting insects, mammals, and birds such as woodpeckers and resplendent quetzals. Primary and secondary cavity-nesting birds comprise a substantial proportion of the avifauna in both tropical and temperate forest ecosystems.

FOREST AIRSPACE

Until recently, structural classification systems focused on the arrangement of solid objects within a forest—the trees, stems, and foliage. But recent work has involved measuring the "negative space" as well, that is, the volume not occupied by solids. Dr. Roman Dial, a fit, bearded researcher from Alaska Pacific University who completes triathlons as easily as he writes database routines, quantitatively describes the airspace of world forests in order to better understand their structure. Roman first shoots off a single long rope to connect two trees, which serves as his horizontal aerial transect. The height of the line depends on the forest in which he works, but Roman almost always works in tall, old-growth forests where his horizontal transect stretches over two hundred feet above

—Two spreads short in a row to keep heading and SEPO together on next spread, ok? RH/ICS the ground. He then hangs a set of vertical ropes at five-yard intervals along the transect, to create his sampling grid. Attaching himself in his climbing harness to the top of the first dangling rope, he uses a laser rangefinder to measure the distance from his eye to the nearest solid object (a branch, a leaf) in eight compass directions around himself. He then lowers himself twenty feet down the vertical rope, and again shoots in all directions. He repeats this at twenty-foot intervals down that rope and from all the other ropes hanging along the horizontal transect line. From these data, he calculates the volume and shape of the airspace of that chunk of forest. His work, which leads ultimately to graphic representations that are both stunning in their beauty and intriguing in their meaning, allows us to visualize a bird, pollen grain, or pollutant particle interacting with the interstices of the forest. With Roman's images, we can better see the possibilities for airborne entities in the forest: they can move around, crashing into or settling gently on the surfaces of the solid canopy that they encounter. This is a first step in getting a new and integrative understanding of how all the elements of the forest interact.

Roman's work can be extended into other areas. I once described his airspace research at a public lecture for gardeners, which was attended by a Buddhist monk-in-training. After the lecture, he told me how Zen arts epitomize the relationship between form and emptiness. In painting and calligraphy, he explained, empty space is as important as pigment and lines. Start with a blank piece of paper. If an artist paints on that sheet of paper, say, a small bird on bamboo gazing out over an infinite horizon, everything changes. Now you have form: the bird, the bamboo, the horizon. And you have emptiness, as the bird's gaze draws your eye to the vast expanse beyond the horizon. Only out of form does emptiness become possible—and vice versa. Every object has both form and emptiness—a painting, a forest, a human being. Even major evolutionary processes can be affected by forest structure. For example, the gliding habit of a variety of unrelated arboreal animals—flying squirrels, gliding lizards, flying snakes—has been influenced by the distances between large trees.

A MATTER OF PERSPECTIVE

It is foolish
to let a young redwood
grow next to a house.

Even in this
one lifetime,
you will have to choose.

That great calm being,
this clutter of soup pots and books—

Already the first branch-tips brush at the window.
Softly, calmly, immensity taps at your life.

—*Jane Hirshfield*, "Tree"

We measure trees and forests, both absolutely in terms of girth, height, and volume, and relatively by scaling them against human size. Large trees are mysteriously riveting. More than a few of my canopy research colleagues sporadically leave excited messages on my voicemail: "Hey! I touched the top of a 293-foot-tall tree today at noon!" But even groundbound people find extremely big trees fascinating. For example, we grant a special status to the tallest living tree in the United States. In 2002, the title of tallest tree was awarded to a coast redwood named the Stratosphere Giant, measuring 369 feet, five stories taller than the Statue of Liberty. Four years later, however, that title was challenged by three other coast redwoods, and the championship for tallest tree was finally settled on a tree called Hyperion. Named for a Titan, the son of Gaea and Uranus and the father of Helios, Hyperion is 379.1 feet in height. It was discovered by amateur naturalists in Redwood National Park during the summer of 2006 and is now accepted to be the world's tallest living thing. In their lofty grandeur, I revere these extremely tall trees as examplars of Herman Hesse's "penetrating preachers"—trees that "stand alone . . . like lonely persons. Not like hermits who have stolen away out of some weakness, but like great, solitary men, like Beethoven and Nietzsche."

The tree with the largest volume is the Del Norte Titan, discovered in June 1998 in Jedediah Smith Redwoods State Park, California, by Humboldt State University ecologist Steve Sillett and naturalist Michael Taylor. This tree has an estimated stem volume of 1,366.4 cubic yards and is 306.98 feet tall, with a diameter at breast height (4.5 feet) of 23.68 feet. Its mass is equivalent to fifteen adult blue whales, the largest animal on earth. Each year, this tree produces enough new wood to make a ninety-foot-tall tree with a trunk twelve inches in diameter. If all of the Del Norte Titan were cut into boards one foot wide, twelve feet long, and one inch thick, the line of planks laid end to end would stretch over a hundred miles and could build 120 average-sized houses.

Many other trees give us plenty to ooh and ahh over. For example, consider the great banyan in the Indian Botanical Garden of Calcutta, whose canopy covers an area of three acres. Or the aspen, which forms large clonal colonies of genetically identical trees in the northern Midwest of the United States. Because new stems arise from root sprouts originating from the parent tree, what appears to be a large grove is actually a single individual. One such grove covers thirty-five acres and has a mass of 6,600 tons.

Although the fascination with extremely large trees is understandable, I consider them more as freaks on the midway of the arboreal world than the living things I relate to daily. What intrigues me more is trees' effects on and interaction with our physical world. Several years ago, I worked on a scientific project measuring throughfall (the amount of rainfall passing through the canopy that reaches the forest floor) and stemflow (the amount that slides down the branches and trunk). I spent weeks analyzing the data and then teasing apart the structural features of the canopy (foliage? twiglets? bark texture?) that determine how, and how much, rainfall finds the ground. At one point, I leaned away from my computer screen and shrunk myself in my imagination to the size of a single raindrop. I then envisioned myself participating in the dance of the raindrops as they fell through the canopy, ricocheting, fragmenting, coalescing, turning into tiny bubbles, and finally disappearing into vapor.

Human beings tend to see trees as single entities, scaled to their own needs. But what about the fascinating array of other organisms that interact with them? I did some calculations to arrive at an answer of sorts—at least for an ant's-eye perspective. First, imagine a *Procryptocerus nalini* ant, one-twentieth of an inch long, walking along a branch to gather pollen and spores to bring back to her arboreal nest. This corresponds to me, a human Nalini about five feet five inches tall, walking along a road to shop for, say, pasta and tomato sauce for tonight's dinner. Except that if I were to scale my road up to be equivalent to the branch the little ant is on, ten inches in diameter and fifty feet long, it would have to be a thousand feet wide and twelve miles long. We experience another major difference in how we navigate our surroundings as well. Because the ant weighs so little, she is not restricted topologically to the upper surface of the branch, as we humans are, but can walk along its underside; indeed, she can encircle its entire cylindrical surface. For me, this would equate to tying on Velcro shoes and casually stepping out to stroll along the underside of a suspension bridge that arches over the vast empty space below it.

Another question of scale concerns the distance between branches—a concern especially for epiphytes, such as orchids, ferns, and bromeliads, that have evolved in the canopy, deriving structural support but not nutrients from their host trees. When epiphytes fall to the ground, the lack of light, the greater relative humidity, and the presence of terrestrial pathogens cause them to die within months. Although their niches in the canopy provide access to the right amounts of sunlight and rainfall, when it comes to reproduction they face a perennial challenge. Whereas trees merely need to create seeds that will fall or be blown to a site on the forest floor where they can successfully germinate, epiphytes need to get their seeds to a suitable spot on another branch high in the canopy. To do so they must rely on the wind or on flying mammals and birds—and a great deal of luck, given the widely dispersed branch space amid vast amounts of airspace in that high treetop realm.

Let's rescale the forest again, this time using measurements made in the cloud forests of Costa Rica. A typical adult epiphyte is four inches in height, the width of a typical branch is six inches, and the distance to the next branch is about sixty feet. Extrapolating to human size, the equivalent distance to the next branch over is nearly one thousand feet. Thus, if you were to accomplish what a canopy bromeliad must do to get its seeds to the next available safe spot, you would have to fling a BB across three football fields and have it land on a surface eight feet wide. Considering what is required, it is remarkable that any bromeliad successfully reproduces at all. It also explains why many canopy-dwelling plants make huge numbers of spores and seeds. Certain species of orchids, for example, produce seedpods that hold exceedingly small, dustlike seeds, as many as 400,000 per capsule. The sheer number of seeds escaping and being blown through the canopy ensures that at least a few will beat the odds and land on a hospitable site to start the next generation.

DYNAMICS OF FOREST STRUCTURE

Contrary to the image we often hold of their being ancient, timeless places where time stands still, forests are dynamic. On a blustery day in the windy season, I walked out to my study plot in the tropical cloud forest of Monteverde, Costa Rica. Three miles up the trail, one of the largest trees in the plot had toppled, an individual I knew intimately from scores of trips up and down its trunk. I had named this tree "The Mansion" because its giant crown suggests a gracious home of many rooms, each branch festooned with orchids, bromeliads, and ferns and inhabited by a diverse assemblage of arboreal animals. But the tree had fallen in the previous night's windstorm, tearing open a huge gap in the fabric of the forest canopy, which created a sunlit area on the ground that had previously been held in deep shade. I took a seat on the toppled trunk, feeling sadness at its transformation from vertical to horizontal, living to dying. Yet the sunlight that could now penetrate to the previously dark forest floor would, I knew, awaken the dormant seeds that lay buried in the soil at my feet. In a few months, new tree seedlings would sprout and make their own way to the canopy. By the time I stood to leave the light gap, I had shifted my saddened attitude, viewing the trunk of the fallen tree now as a fallen hero who inspires his followers to move from stasis to action, from darkness to light.

Techniques for measuring how forests change through time are well established. The traditional tools of a timber cruiser—a forester who measures the location and volume of trees in a forest—are simple, inexpensive, and can fit into a small backpack. The cruiser measures a tree by wrapping her measuring tape around the trunk at a level exactly 4.5 feet above the ground, to arrive at "diameter at breast height," or DBH. Special "D-tapes," calibrated in units of pi, allow the cruiser to read the diameter directly. Height is worked out by triangulation: standing a measured distance from the base of the tree, the forester looks through a clinometer, a small metal box that measures the angle from her eye to the tip of the tree. Using trigonometry, she then calculates the distance to the top. At the end of a single day, a cruiser will have generated enough information to report on the average height and volume of all the trees, and their variation, thereby creating an accurate static picture—a snapshot—of the forest stand.

Documenting the dynamics of the stand—making a *moving* picture of the forest—involves more work. To do this, foresters establish permanent plots, round or rectangular, to which they return at intervals of months and years. They then measure the distances and angles of trees relative to fixed reference points. Very few humans can remember what individual trees look like for more than a few months, and so researchers identify each tree by nailing a quarter-sized aluminum tag to the trunk. Attaching a tag to a hitherto anonymous tree is like giving a new puppy a name—it becomes known to us as an individual, and information on it can be retrieved at any time. Tagged trees are remeasured at intervals of a year, five years, or a decade. With these data, an ecologist can estimate the longevity of trees and estimate the replacement time for a whole stand.

Without the tags, and the ability to follow individual trees and parts of trees that last far longer than the lifetime of a single field season or the spatial memory of a researcher, we would not be able to understand the basic dynamics of the forest. Tags are such a ubiquitous tool in the measuring of trees that ecologists use them without thinking. Although no studies have revealed that nailing a tag into a trunk damages the tree, they can, however, have a profound effect on the forest, one that I had not considered until I went tree-climbing with a conceptual artist named Bruce Chao. Bruce is chair of the glass-blowing department at the Rhode Island School of Design and a creator of giant and thought-provoking three-dimensional installations that he places in forests of New England. A few years ago, Bruce became interested in the forest canopy as a medium for art. In 2003, he joined my colleagues and me when we were mapping trees for our studies of forest structure. We worked in an old-growth site, where five-hundred-year-old Douglas-fir trees pierced the sky to heights of 250 feet. Branches were muffled in soft green moss that was decades older than my parents. We noted the location of every branch of all the trees in our study sites to get baseline information that we and other ecologists could use. This involved rigging tall conifers with ropes, ascending the ropes with climbing harnesses and Jumars (mechanical ascenders), and hauling up a laser rangefinder to measure the x, y, and z coordinates of each intersection of branch and trunk. Every five meters up the trunk, we nailed a round aluminum tag to indicate our height above ground. Placement of those tags would help us readily find branches again in the three-dimensional world of the tree crown when we returned to remeasure our plots.

Bruce stayed in the tree all day with us, listening to us shout numbers to each other, speculate on which tree had the greatest volume of wood, and argue over which trees we would include in our personal Top Ten Tree Species lists. At day's end, we rappelled to the ground and repaired to the campfire. I asked Bruce if he had been inspired to create a piece of art by anything he witnessed that day in the canopy. He paused. "To me," he said in his quiet voice, "the most interesting sight was the tags." The tags? He explained that the presence of the tags permanently changed the nature of the stand of trees. Each of the trees we had climbed had a faint but distinct "trail" of small silver dots going up the trunk, signifying that humans had been there and that they would come back. The tags, he said, gave a ping of the past and the future to the present. He was neither offended nor repulsed, but simply affected by the handiwork of humans in something that was previously only forest. His comments made me realize that all of our access techniques, which we so glibly call "nondestructive," have an effect on the forest, even if it is just the sound of a Jumar clinking against a carabiner or the glint of a tag against bark.

TREES AND FOREST FORMS IN OTHER REALMS

Trees help you see slices of sky between branches
Point to things you could never reach.
Trees help you watch the growing happen,
Watch blossoms bursts then dry,
See shade twist to the pace of a sun,
Birds tear at unwilling seeds . . .
A tree is a lens,
A viewfinder, a window.
I wait below
For a message
Of what is yet to come.

—*Rochelle Mass*, "Waiting for a Message"

TREES AS RIVERS, RIVERS AS TREES

From three hundred feet above the forest, individual trees blur together, becoming a landscape seen by the eye of a raptor or the eye of a hurricane. From this vantage point, too, rivers become trees that have fallen, flattened, and filled with water. I have always been a bit jealous of hydrologists (people who study streams and rivers) because they have developed consistent ways of mapping stream courses and predicting their movements, a capacity that exceeds the ability of forest ecologists to create maps of individual trees. Drawing on the field of morphometry (the measurement of the shapes of things), two researchers, Robert Horton and Arthur Strahler, established a classification system in the 1940s and 1950s based on the hierarchy of stream segments. The main stream of a river, or "main trunk," receives materials from its tributaries, just as tree trunks receive moisture from rainwater flowing over their upper branches. Stream channel segments are ordered numerically from a stream's headwaters to a point somewhere downstream. Numerical ordering begins with the tributaries at the stream's headwaters, which are assigned the value of 1. A stream segment that results from the joining of two first-order segments is given a value of 2. Two second-order streams form a third-order stream, and so on. Horton and Strahler were interested in spatial properties that relate to the entire stream system, and deduced that the ratio between the number of stream segments in one order and the next—called the bifurcation ratio—was consistently around three, which is the same ratio as the root system and branch structures of trees.

—trees.
[FIGURE]
[Fig. 9 about here]

Other natural branching networks have patterns similar to this stream order model, including, somewhat surprisingly, certain marine animals. Coral reef ecologists, for example, use tree-based analyses to understand how corals grow. *Acropora*, or staghorn coral, dwells on the Great Barrier Reef in Australia. Common in shallow water, it is successful because individuals of this genus have light skeletons that allow them to grow quickly and overcome their neighbors, much as the weeds in my garden rapidly outgrow my sluggish tomato plants. *Acropora* has a distinctive way of branching. As its central axis increases in length, it buds off smaller radial branches. Using Horton and Strahler's methods, researchers determined the bifurcation ratios of the staghorn corals and found them to be similar to those of real streams.

TREE FORMS AROUND AND WITHIN US

Tree structure extends to the things we use in everyday life. Plastic is made up of long chain molecules called polymers, which in turn are composed of many smaller molecules, called monomers, that are covalently bonded together. About 60 percent of the chemicals used by the plastics industry are used to make polymer products, including nylon, film, and kitchen countertops. Specialized polymers result when the molecules are oriented in specific ways. Many small side groups along the polymer chain,

9. Streams and rivers are "dendritic" in form, structurally analogous in many ways to trees and other objects in nature. Courtesy NASA's Applied Research and Technology Project Office.

for example, create more restricted movement and a very strong structure; Kevlar, which is used for policemen's bulletproof vests and windsurfing sails, is one such polymer. Another specialized polymer is the dendrimer, whose name indicates its treelike structure. Here, branches keep growing out of branches, and more branches grow out of those branches. This shape lends the polymer unusual properties. One silicon-based dendrimer can trap oxygen molecules in its branches, making it a candidate for the production of artificial blood.

A wide variety of objects in nature, too, follow these patterns and can be quantified, visualized, and understood in terms of trees. These include blood vessels, the trachea of our lungs, neural pathways, cave tunnels, grounded lightning strikes, trail systems, and even the microcrystalline formations of frozen water. Recently, my family and I visited the "Bodies" exhibit at a museum in Seattle. This popular show invites visitors to examine the intricacies and complexities that lie beneath our very own skin. The use of a polymer preservation process allows the living to view the dead from remarkable perspectives, with each room focusing on a different body system: skeletal, digestive, respiratory, integumentary. Far and away, the favorite room for each member of my family was the one devoted to the circulatory system, in which the delicate patterns of arteries and veins were depicted in bright red and blue. I gazed for half an hour at the structure of capillaries in the lungs. These were clearly trees that branched out into the tiny alveoli of our breathing apparatus. The heart revealed the broad trunk of the aorta, which bifurcated into the separate trees of arteries and veins within the auricles and ventricles. I could as well have been mapping the branches of trees in my study site in Costa Rica, but instead I was looking into the very core of a human who, perhaps like me, held trees in her heart.

ZEN GARDENS AND INVISIBLE TREES

Some remarkable work relating to tree structure and its power over the human psyche has been done in Zen gardens. For centuries, monks have explored life metaphors in the carefully raked and tended areas around their temples. Ryoanji Temple in Kyoto, for example, has been a Zen place of worship and meditation since its construction in the 1450s. The temple garden is a rectangle surrounded by earthen walls on three sides, fronted on the fourth by a wooden veranda. Inside the rectangle is an expanse of white pebbles and fifteen rocks of various sizes, arranged in five separate groupings. The white pebbles are raked every day, with perfect circles around the rocks and perfectly straight lines in the rest of the space. Over the centuries, various explanations for the garden's layout have been suggested, such as that the white gravel represents the ocean and the rocks the islands of Japan, or that the rocks represent the Chinese symbol for heart or mind. In any case, there is no doubt that the site exudes a strong sense of serenity, as many thousands of worshipers and tourists can attest.

In 2002, visual-imaging scientists Gert van Tonder and Michael Lyons published a series of papers that revealed a possible explanation for the strong power of the garden. Applying a shape-analysis technique that revealed hidden structural features in the garden's empty space, they theorized that it is the empty space created by the placement of the rocks, rather than the rocks themselves, that has so intrigued visitors over the centuries. Studies of how humans and other primates process visual images suggest that we have an unconscious sensitivity to the "medial axis" of shapes—that is, our mind subconsciously inserts lines to connect the edges of the shape. At Ryoanji, van Tonder and Lyons concluded, when a visitor looks at the clusters of rocks on the expanse of white pebbles, he is subliminally able to discern the image of a tree—its trunk and branches. The accompanying feeling is one of calm peace.

TREES, RELATIONSHIPS, AND ABSTRACT THINKING

Trees give us ways to think about relationships. Genealogy, the study of how families have descended from their ancestors, depicts individuals as living on family trees. Dozens of software programs and companies have been developed to help identify lost branches of people's family heritage. More recently, this effort has been expanded, and rather than mapping a single human family, we are now attempting to map the family that is all of life—all 1.7 million known species. The Tree of Life, as the project is known, traces the patterns of descent of life over millions of years to one common ancestor. Groups that are more distant from each other evolutionarily have more branches between them. Some branches are longer or shorter than others, indicating whether they are distantly or closely related. It is a collective international project involving supercomputers and hundreds of scientists, from beetle taxonomists to molecular geneticists to database engineers, whose goal it is to find patterns of relationships that best account for the DNA sequence data. Once completed, scientists will have a framework for incorporating newly discovered species into the tree of life and a better understanding of the patterns of biodiversity. Despite data gaps and tremendous computational challenges, the building blocks have an elegant simplicity, thanks to the underlying structure of trees.

Tree forms permeate the way we think and understand in other abstract modes as well. The evolution of human language, for example—its families and its dialects—is typically described in terms of a tree. Here again, evolutionary proximity is graphically portrayed by the positioning and density of branches, with the Finno-Ugric languages, say, which are spoken in scattered areas from Finland to Siberia, taking up a relatively small part of the tree's crown relative to the Romance languages. Philosophy and computation, too, rely on trees as models. For example, intuition and analogical reasoning use the tree structure in applications as diverse as school grading systems, musical analysis, and establishing pathways of information dissemination. Branching models are used to represent networking theory, web design, and application development for artificial intelligence and robotics.

Tree forms also surface in medicine, as I learned a few years ago when my brother Mohan, a specialist in internal medicine, invited me to speak to a group of medical residents about how trees ameliorate human health. When I joined Mohan on his rounds, his students alerted me to another link between trees and medicine, the use of "decision trees" to maximize the accuracy of their diagnoses. These trees—in the form of a Web page or printed document—are used to analyze a particular set of symptoms, leading a doctor to a decision that is informed by thousands of preceding cases. Let's say a patient comes to Mohan complaining of chest pain. Guided by a published decision tree for that symptom, Mohan will ask questions that lead him to decide whether the pain originates from a cardial cause or an intestinal one. He starts with the first of two bifurcating branches in his tree: Is the pain sharp or is it tight? Does the patient burp, or not burp? At some branches, specific tests, such as an EKG, are ordered, and the results direct the further branching of the diagnostic tree. Finally, the doctor arrives at a "leaf," or the terminal point of a series of branches, which articulates the diagnosis and the optimal treatment. The very structure of the tree, with its enforced pauses at each diverging pathway, allows the doctor to think carefully about the diagnosis at multiple points along the way.

These models function as points for reflection. Robert Frost, in his evocative poem "The Road Not Taken," describes his own decision to follow one branch in the path of life, rather than another.

> Two roads diverged in a wood, and I—
> I took the one less traveled by,
> And that has made all the difference.

I think back to those afternoons of my childhood, the hours spent learning how to cross from one branch to another in my favorite maple tree, BigArms, as well as the moments when I would pause in my arboreal acrobatics to imagine the different pathways I could take on my way to becoming a grownup. Each idea would start in my mind as a single point, a specific vision of what I wanted to be—a doctor, a dancer, a veterinarian, a cabin girl on a sailing ship—and then my imagination would branch into the multiple directions I would travel in the future to make that dream happen, branches as complex and ordered, as definite and mysterious, as the twigs at the tops of my tree.