Biocentricity and economy of scale: hypothesis (and product) testing when wood is a part of an experimental system evaluating durability

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Abstract

Wood is a biological material, and its structure and organization are relicts of its biogenesis. From the hydrogen bonding of water molecules in the cell wall to extractives bleeding from knots in siding, the characteristics and behavior of wood are derived from its biological origin; this is my unashamedly biocentric view of wood structure. The structure of wood dictates that different material properties emerge and take primacy at different spatial and temporal scales, all determined by the tree that produced the wood and the ways the wood was processed. The appropriate wood structural, spatial, and temporal scales are rarely considered in experimental designs for either hypothesis or product testing. Studies that fail to account for these parameters are not necessarily wrong or useless, but they are less correct and have less utility than those that do account for them; they fail by virtue of lacking well-reasoned null hypotheses. Intelligent experimental design requires appropriate selection of wood species, specimen size and shape, specimen environment, and duration of testing for the hypothesis or product being tested, in addition to a well-reasoned null hypothesis. This paper reviews the fundaments of wood structure and wood technology in the context of the experimental scales at which they are relevant. It also discusses how to apply a biocentric mindset to the design of experiments involving wood involving durability and thus achieve efficient testing by means of an economy of scale.

Introduction

The properties and behavior of wood can be described from many perspectives. An engineer typically focuses on mechanical properties of wood: modulus of elasticity, modulus of rupture, design specifications for building construction. An adhesive chemist might look at wetability of the wood surface. A paper chemist might be concerned with chemical constituents of wood that increase or decrease desirable properties of paper made from the wood under different pulping conditions. I am a biologist, a wood anatomist, and I have been accused of having an eccentric perspective on wood structure. My view of wood is based on the biology of the organisms—living entities—that produce it. To ameliorate the pejorative connotation of the eccentric moniker that has been applied to my point of view, I have combined this word with my interest in the biology of wood to coin a new term, biocentric [bio(logical) + (ec)centric] wood science. This paper outlines the biocentric view of wood science, discusses a series of scalar concerns necessary for implementing this biocentric view, and outlines how biocentricity and scale should inform our approach to durability experiments in wood-coating systems to achieve useful results in the most economical manner. It closes with a simple set of 12 recommendations to apply these ideas to the intelligent design of experiments for coatings testing when wood is a part of the experimental system.

Biocentric perspective of wood

The biological origin of wood is the prime determinant of wood structure, chemistry, properties, and behavior; this is the core premise of a biocentric view of wood science. Wood is produced by trees, shrubs, and lianas; even some plants, such as sunflowers (*Helianthus* spp.), that are normally considered herbaceous produce wood, though they are not widely recognized as woody plants. For our purposes, we will restrict our discussion to wood from trees, because they are the source of most wood to which coatings are applied. Trees produce wood, but they do so for physiological and evolutionary reasons, in response to the environments in which they grow. Humans use wood in conditions far different from those of the tree; we dry the wood, but trees use it in the green state; we produce rectangular boards, but trees use wood in the round form. Despite these differences of how wood is used by people and trees, much can be learned from a biocentric perspective of the structure and botanical function of wood. Though many thousands of species of trees exist in the world, their wood shares many general characteristics.

Cellular nature of wood

Cells are the basic building blocks of life, and in plants, cells are composed of two basic domains, the protoplast and the cell wall. The protoplast is the living core of the cell, and the cell wall is the exoskeleton-like sheath of tough material that surrounds it. In wood, most “cells” are actually only cell walls; the protoplasts have disintegrated, their contents moved elsewhere in the plant, their constituents used to nourish and sustain other living cells. The space left behind by the protoplast, the empty space bounded by the cell wall, is called the lumen. Thus, when we talk about cells in wood, we are usually speaking only of cell walls (Fig. 1 B,C).

Chemical constituents of cell walls

Cell walls are composed of three main constituents, mixed and integrated into a complex and incompletely understood composite material. Each of the three components—lignin, cellulose, and the hemicelluloses—have different chemistries, different physical and mechanical properties, and are thought to play different roles in the structure of the cell wall. Lignin is a highly branched, polyphenolic, and generally amorphous and hydrophobic substance, and it is comparatively rigid and stiff. It is has been called an encrusting substance but might be easier thought of as the matrix material in which the other two constituents are embedded. Cellulose is a hydrophilic linear polymer of glucose and is thought to be strongest in tension. Cellulose winds many thousands of times throughout the cell wall, oriented at various angles to the long axis of the cell. Hemicelluloses are short, branched, hydrophilic polymers formed from various sugars. They are considered to be comparatively flexible in their mechanical properties and are thought to be involved in transferring stresses between lignin and cellulose. All woods share these three constituents, though they are present in different amounts and composition in various woods. The physical and mechanical properties of wood have their roots in the chemistry of the cell walls. Because the three constituents have different chemistries, wood has chromatographic properties. Different materials have different affinities for wood based on their chemistries, and so will move into or along wood to at different rates and can affect the ways in which coatings interact with wood.

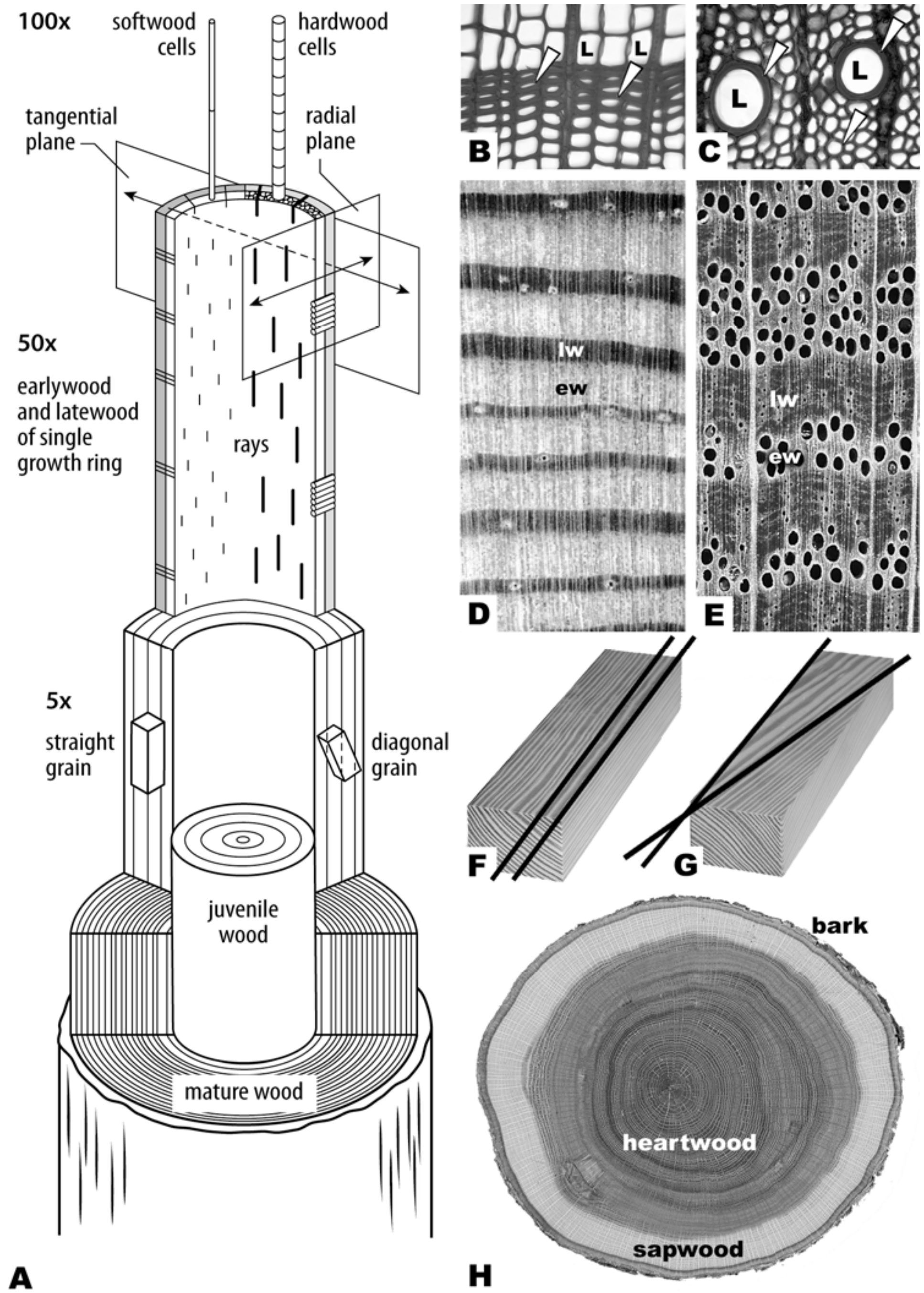

Figure 1. A. Illustration of a cut-away tree at various magnifications; it is intended to correspond roughly with the images to its right. At the top, at an approximate

magnification of 100x, a softwood cell and several hardwood cells are illustrated, to give a sense of scale between the two. One tier lower is a single growth ring of a softwood (left) and a hardwood (right), as well as an indication of the radial and tangential planes. The magnification is approximately 50x. The next tier, at approximately 5x magnification, illustrates many growth rings together, and how one might produce a straight-grained rather than a diagonal-grained board. The lowest tier includes an illustration of the relative position of juvenile and mature wood in the tree, at a 1x magnification. B,C. Light microscopic views of the lumina (L) and cell walls (arrowheads) of a softwood (B) and a hardwood (C). D,E. Hand-lens views of growth rings, each composed of earlywood (ew) and latewood (lw) in a softwood (D) and a hardwood (E). F. A straight-grained board; note that the line along the edge of the board is parallel to the line along the grain of the board. G. A diagonal-grained board. Note that the two lines are markedly not parallel. This board has a slope of about 1 in 7. H. The gross anatomy of a tree trunk, showing bark, sapwood and heartwood.

Topology of wood

Another characteristic that virtually all woods share is the overall topology of wood structure. Whether a softwood, such as pine or cedar, or a hardwood, such as teak, oak, or maple, wood is formed of two separate but interconnected systems of cells. The most easily recognized system is the axial system, the cells of which run the length of the trunk. The second system is the radial system, and it occurs as a series of bands or ribbons of cells, called rays, that run horizontally in the trunk, from the center of the tree out toward the bark. The interrelationship between the direction of cells in the axial and the radial systems give rise to the overall topology of wood; an interpenetrating warp and weft of cells with specific structures and different functions. Due to this organization, wood scientists have found three fundamental cuts used to prepare wood for microscopic observation, and we can translate this microscopic point of view to the macroscopic world.

Transverse surface and growth rings

The most readily understood way to view wood is to look at the transverse surface, the end grain. This is what we see when looking at the end of a board, or the cut surface of a stump (Fig. 1 H); the cut has passed across the grain, perpendicular to the axial system. This is the face from which we can most easily see growth rings—collections of cells formed during a single growing season and running around the circumference of the trunk. The growth rings form circles of wood around the trunk (Fig. 1 A), and as the rays of the radial system run from the center of the tree toward the bark, the rays appear as lines intersecting at an angle perpendicular to the curvature of the growth rings.

Longitudinal cuts and grain angle

The remaining two cuts of wood are parallel to the axial system; they are cuts along the grain. When we cut a board, for example a 1×8, it has six faces; two are end grain, two are wide faces along the grain, and two are narrow faces along the grain. The angle of the axial system to the long edge of the board is called the slope of grain, and can occur either as straight (Fig. 1 A, F) or diagonal (Fig. 1 A, G) grain. The orientation of the growth rings with respect to the wide surface of a board is referred to as grain angle. If the wide face of a board is cut parallel to the growth rings, it is flatsawn or plainsawn (Fig. 2 B), and in those places where it is exactly parallel to the growth rings, it is a tangential cut. The tangential face of a board will often show characteristic U or V patterns as the growth rings are exposed. If the wide face of a board is oriented perpendicular to the angle of the growth rings, a vertical-grain or quartersawn board is produced (Fig. 2 A), and in those places where the rings are exactly perpendicular to the face of the board it is a radial cut. On the radial face of a board, growth rings will typically appear as long, straight, alternating bands of light and dark. In species with large rays, such as oak or sycamore, a distinct and often-pleasing visual effect called ray fleck is produced on the radial surface. This is caused by the large rays reflecting the light differently from the cells of the axial system, though in many species, the rays are too small to see this effect with the naked eye.

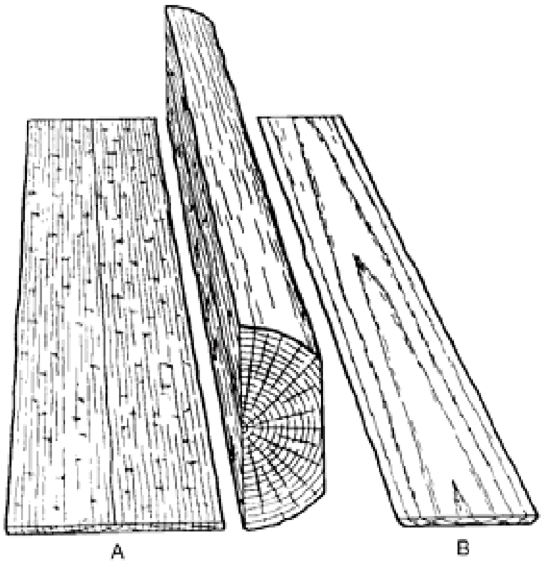

Figure 2. Grain angle in boards. A. Quartersawn or vertical grain; the growth rings are perpendicular to the wide face of the board. B. Plainsawn or flatsawn; the growth rings are parallel to the wide face of the board. Note the characteristic U or V shapes of the growth rings.

Hardwoods, softwoods, and their component cells

An additional layer of the biological complexity of wood is the different cellular composition of hardwoods and softwoods. Hardwoods are composed of three basic cell types: pores for conducting sap from root to leaf, fibers for mechanically supporting the tree, and parenchyma cells for carrying out the living functions of the wood. Pores and fibers occur exclusively in the axial system and are dead, empty cell walls at functional maturity. Parenchyma cells can be found in the axial system (depending on the species) and are the only cell type in the radial system; they are alive at functional maturity. Softwoods are composed of only two cell types:

tracheids in the axial system serving in both sap conduction and mechanical support (dead at functional maturity) and parenchyma cells in the radial system to perform living functions in the wood.

Classification of growth ring types

To understand wood-coating interactions, we must learn more about growth rings and their structure. In general, the spectrum of growth ring structure in wood shows three basic patterns, and each applies separately to hardwoods and softwoods, for a total of six classifications of wood. At one end of the spectrum are growth rings with no appreciable differences in size, shape, abundance, or proportion of cells from the earlywood, the first-formed part of a growth ring, to the latewood, the latter-formed part (Fig. 1 D, E). Hardwoods with these characteristics are known as diffuse-porous woods (Fig. 3 D); softwoods with these characteristics are said to have no transition in their growth rings (Fig 3 A). This intergrades with a phenomenon common in some tropical woods, the absence of growth rings. In such cases we cannot easily determine the beginning or end of a growth ring.

The other end of the spectrum is defined by an abrupt change in size, shape, abundance and/or proportion of cells from the earlywood to the latewood. In hardwoods this is most commonly seen when the pores in the growth ring change from quite large in the earlywood to much smaller in the latewood, commonly characterized by a reduction of 50–90%. Such woods are called ring-porous (Fig. 3 F). In softwoods, such a change is called abrupt transition and is characterized mostly by a sudden thickening of the cell walls in the latewood tracheids compared with those in the earlywood (Fig. 3 C).

Between the two extremes of no change and sudden change is a middle category of gradual change. Hardwoods with this structure are referred to as semi-ring or semi-diffuse porous; their pores gradually change from large in the earliest earlywood to small in the latest latewood (Fig. 3 E). The magnitude of the change can be as great as that of ring-porous woods. In softwoods, this pattern is known as gradual transition, and such woods have a gradual thickening of the tracheid cell walls from the earlywood to the latewood (Fig. 3 B).

Sapwood and heartwood

I have saved the easiest bit of wood biology for last, to ease us out of this topic. Many woods exhibit a chemical difference within a log, that between sapwood and heartwood. Sapwood is the generally light-colored wood beneath the bark (Fig. 1 H). The parenchyma cells, the living cells of wood, are alive in sapwood. Sapwood can be as narrow as a single growth ring in some species or can encompass most of the trunk of the tree. In either case, it is the portion of the trunk through which the sap actively flows. Heartwood is the generally darker-colored wood in the interior of the trunk, and its parenchyma cells are no longer alive; they have spent the last period of their lives assisting in the synthesis and deposition of the chemicals, extractives, that give heartwood its color. Extractives are also responsible for the natural durability of woods that have this property, and thus heartwood is generally preferred for most outdoor applications. Because sapwood generally has appreciably lower decay resistance, awareness of its presence in an experiment is critical, especially for long term or field-testing, as sapwood may decay before the field exposure is complete.

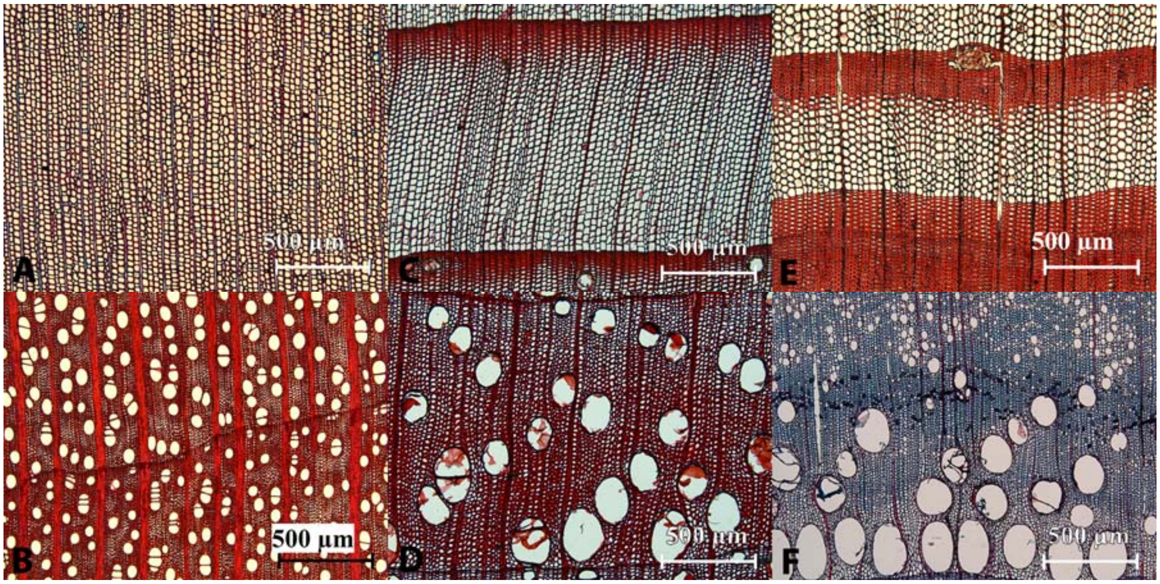

Figure 3. Classification of growth rings by transition type. Comparing paired woods vertically shows the general type of transition across softwoods and hardwoods. A. Softwood with no transition; growth rings absent. B. Diffuse-porous hardwood. C. Softwood with gradual transition. D. Semi-ring-porous hardwood. E. Softwood with abrupt transition. F. Ring-porous hardwood.

Summary of biocentric wood structure

Wood is a biological material, with its material properties conferred by a complex interaction of its cellular composition, cell wall and extractive chemistries, and topological and macroscopic organization. For more information on the biological aspects and effects of wood structure on wood properties, please see the proceedings from the 2007 FSCT conference (Wiedenhoeft 2007), or traditional wood technological texts (Panshin and deZeeuw 1980 and references therein; Hoadley 2000 and references therein; Wiedenhoeft and Miller 2005 and references therein). Although we have gained an initial understanding of wood structure, we have not yet addressed the topic of wood as a component of an experimental system for evaluating coatings durability. To begin to tackle this question, we must explicitly address the topic of scale.

Scalar considerations for coatings durability on wood: tipping the scales

Scale is an underappreciated concept in most experimental endeavors, yet we have, at least to a degree, an innate sense of appropriateness of scale. For example, most people would no more try to obliterate a mosquito on their arm with a frying pan than they would seek to stop a charging wildebeest with a pop-gun. Though whimsical, these examples illustrate two important and interrelated ideas: the choice of scale has practical consequences, and scale depends on and provides context. For our purposes, we consider three types of scale: spatial, temporal, and hierarchical.

Spatial scale

Spatial scale is well known in a day-to-day context. If someone asks me how long my commute to work is, I don't reply in inches; I judge the appropriate scale of measure to communicate the answer in a meaningful way. Spatial scale is also commonly understood when selecting similar tools for a job. If I plant a petunia in a flowerbed, I use a hand trowel, not a backhoe.

In wood, spatial scale is important because even a small piece of wood is made up of thousands to billions of cells. The spatial scale at which we approach wood affects our perception of it (Fig. 4) and changes what information we can glean from it.

For experimentation, the spatial scale of an analysis should be determined by the context of the question you are asking. If you wish to determine the protective effect of a coating on an exposed composite panel product, you might cut small specimens from a test panel and subject them to mechanical tests. If your panel is plywood with knots in it and your specimens are 2.5 cm wide and 30 cm long, the placement of any given knot could drastically affect your results and thus invalidate your measurement. If your panel is OSB, and the mean flake length is 20 cm, the smallest dimension of your test specimens should be some multiple of 20 cm so that any given flake does not unduly affect the results. Likewise with solid wood, if you have a flatsawn 1×8 board, the center of the board may present a truly tangential face, but unless the board was cut from a large-diameter tree, the wide face of the board will be progressively less tangential toward the edges, due to the curvature of the growth rings. Thus, if you select a small test specimen from near the edge of the board, you may no longer be testing the tangential surface and indeed could be testing a nearly radial surface. This is a case where the spatial scale of your question and the wood structure could confound your results, and you must be aware of the potential problem. To produce meaningful results, your test specimen must be either wisely considered relative to spatial variability in the larger experimental unit or overwhelmingly larger than any "defects" in it. A last scalar aspect is in the number of replicates tested; if selecting test specimens larger than the scale of defects is not possible, the noise of variability can be decreased by testing a large number of specimens.

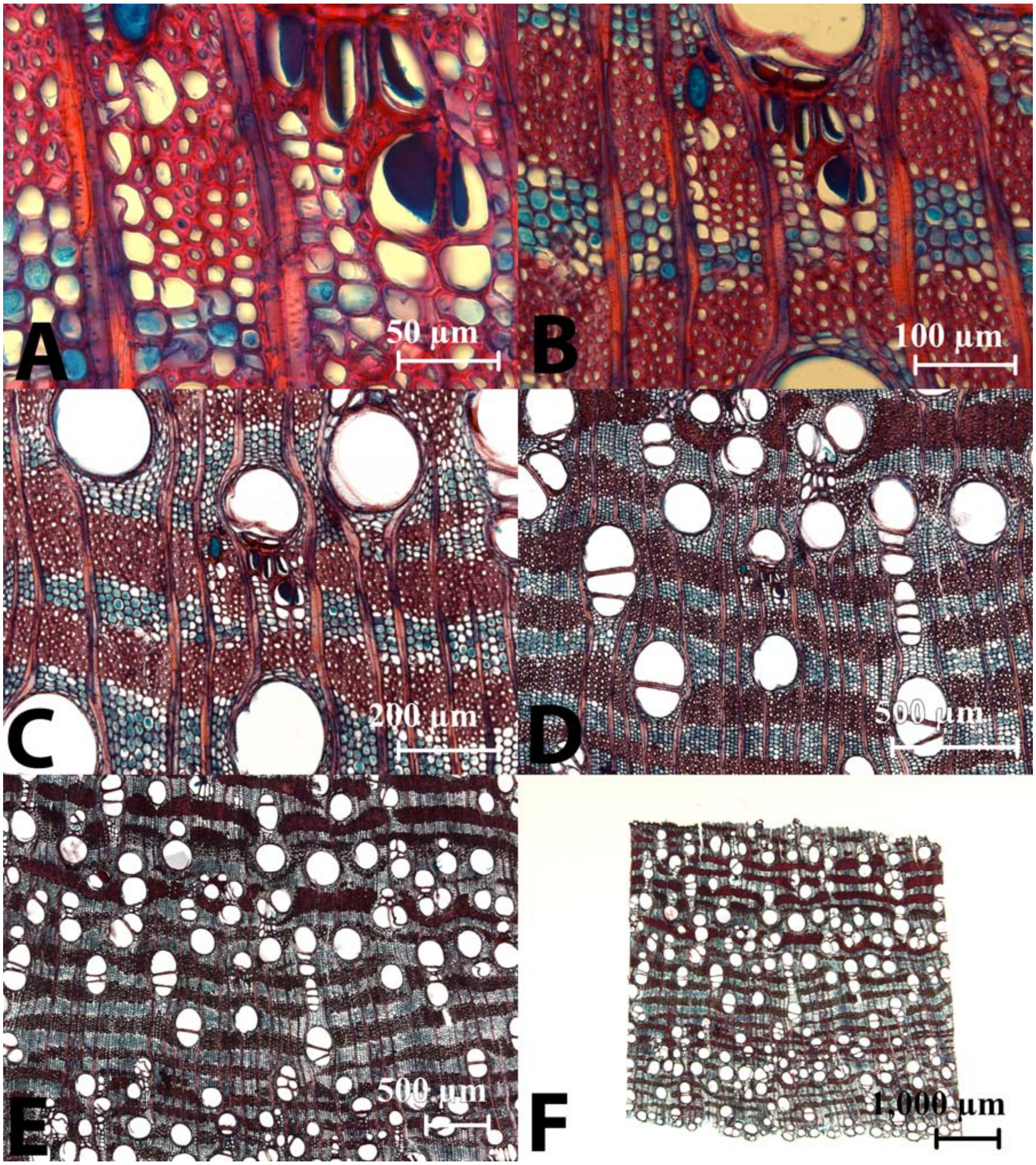

Figure 4. The simplest form of spatial scale: magnification. A. High magnification view of a comparatively small number of cells. B. Slightly reduced magnification shows more organization: vertical lines (rays) and one horizontal band of thin-walled cells. C. Still lower magnification reveals a distinct pattern in the wood, and D. exposes more of the pattern. E. With less magnification, the pattern becomes slightly muted, as detail is lost. F. Subtleties of structure in the pattern are lost at low magnification. The image is surrounded by white space because the section is smaller than the field of view.

Temporal scale

Temporal scale is important both to technical investigations and to normal life, such as when planning a vacation—climate is what you expect, weather is what you get. Climate characterizations have both spatial and temporal aspects: spatially, they are based on a given region of the world, and temporally they are twice calibrated. First, they consider the time of year in question (February or July?) to produce a relevant result. Second, they integrate and smooth data for that specified time period over a history of previous data for that period of reference. Temporal considerations are particularly important for experimental work in durability, because durability is an implicitly temporal behavior. You cannot ask about durability without invoking the question: *How long until failure?* The definition of failure, and a sensible definition of failure is not a trivial matter, will define the scale of the temporal question by providing and considering the context. If you have a coating formulation to be used on wood siding, your durability question might be one of *liability*: *Does it last long enough to remove liability for my company?* Liability could mean legal liability, or it could have a broader sense, regarding the reputation of your company's products. The experiment to answer this question is simple compared to a durability question regarding *reliability*: *How will my product perform over its lifespan?* A question of liability asks for a pass/fail result at a single point in time, while a question of reliability asks for an array of data over time. Mistaking one question for the other will result in unnecessary costs or useless information, depending on the temporal scale of the question.

Accelerated testing is another area where temporal scale is critical. Knowing the relations between exposure time, dose intensity, and damage done—the law of reciprocity—is critical to using accelerated techniques to predict long-term behavior or performance. It is similarly critical when baking a cake. If a cake must be baked at 300 °F for 60 minutes to be delicious, you cannot count on the cake being delicious if baked at 450 °F for 40 minutes, because the law of reciprocity is violated in this case. Likewise, over my lifetime I will be exposed to a certain dose of gamma ray radiation. Taken a little at a time over (I hope) many decades, I incur little damage. If I were to receive the same dose of radiation over a 30-second period, it would have different effects on my physiology and the likelihood of a many-decade existence. In wood and wood products, temporal scale is particularly important for wet–dry cycles and thermal, UV, and visible light irradiance. Considering the temporal scale is thus necessary in experimentation to ensure that the results produced are relevant to the question being asked.

Hierarchical scale: general introduction

Hierarchical and spatial scales are often confused as the same thing, but thinking of them as synonymous is erroneous. Hierarchical scale refers specifically to the nature of interactions and the properties of something, rather than to its size, though size may influence those properties. When considering hierarchical scale, one test to define a new scale can be the observation of a new set of rules or patterns governing interactions, a so-called emergent property at the new scale. A general example is the relationship between physics, chemistry, and biology. Chemistry, at its core, is a special case or emergent property of physics. Biology is a special case or emergent property of chemistry and physics. In this example, physics is the root cause of the other two phenomena, so it is a higher order phenomenon; it is at a different hierarchical scale than the other two. Most physicists I have met would surely agree with this statement. Leaving aside physicists' opinions of themselves, considering hierarchical scale is not the practice of making value judgments but of acknowledging which concerns are relevant at which scale.

An example of hierarchical scale in everyday life is social structure. You are an individual, influenced in your behavior by your own biology, chemistry, and physics (Fig. 5). You are also part of a family, your family a part of one of more communities, those communities a part of society or culture, those societies or cultures a part of a nation, and so on. The behavior of an individual is at one scale; the behavior of a nation toward another nation is a phenomenon at a completely different scale. For an individual, it would be impossible to choose objectively which scale of participation was most important. Such a choice would both depend on and influence the context of the question. Your qualifications as a "good" son or daughter may be relevant at the scale of the family or the self but is most likely irrelevant at an international scale. And so with wood; if you are testing a glulam support beam in bending, fretting over the properties of any single cell is irrelevant, not because of size, per se, but because of the relationships between the scales. Any given cell in a glulam beam could be removed from the beam without changing its performance because the operative mechanics in a glulam beam are of a completely different order, a different hierarchical scale, than the influence of the single cell. The same is true in the other direction: individual cells are fairly compliant and flexible, if you pick at them under a microscope with a finely pointed metal probe. When you try to drive that same probe one centimeter into the wood, the wood behaves differently. In trying to drive the probe into the wood, you change the scale of your attack on wood, and it behaves in a different manner; it shows emergent properties at a different scale.

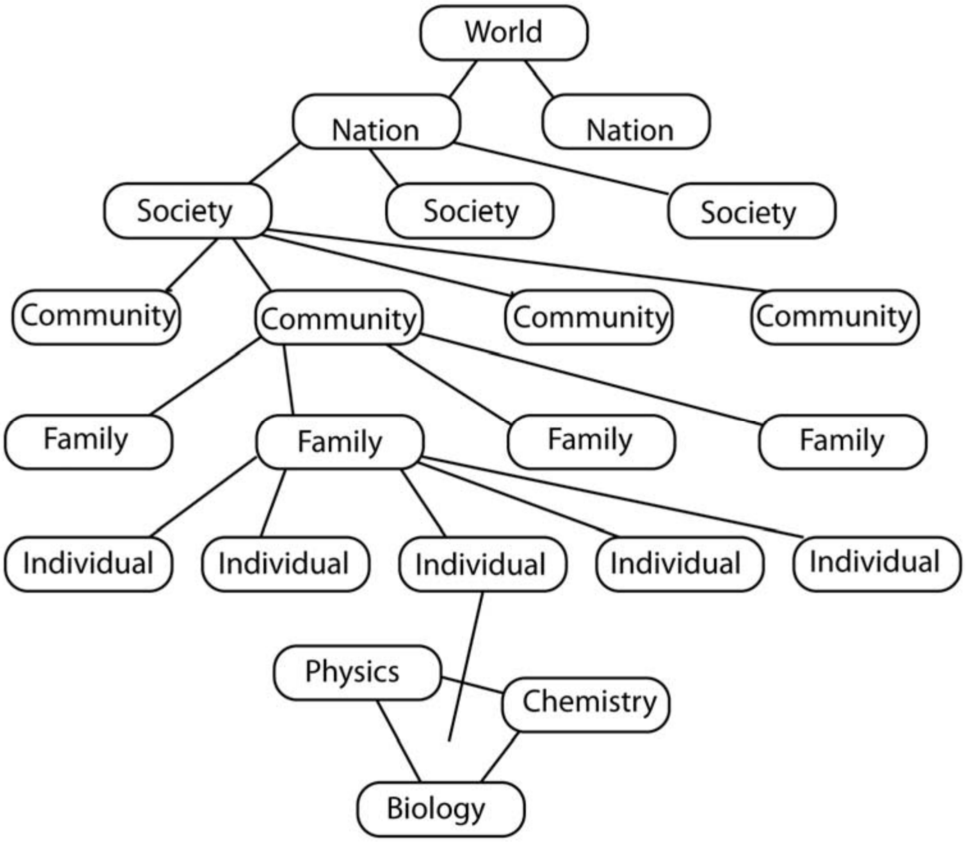

Figure 5. Schematic of a vastly simplified human hierarchy. Note the inclusion of physical, biological, and chemical components to the individual. This schematic does not attempt to illustrate feedback loops between components, or how the part interrelate.

Hierarchical scale: the epistemics of scientific thought and inquiry

Another critical area in which hierarchical scale plays an important role is in the structure of scientific ideas and how that structure influences scientific inquiry. If you ask a high school student for the definition of a hypothesis, they will likely respond with an answer such as an "educated guess," a wholly inadequate definition. This definition not only lacks intellectual rigor but also influences the fundamental thinking about the scientific method by presupposing a single expected result. It pauperizes the thought process and decreases the likelihood of designing a robust and intelligent experiment because it does not correctly identify the scale of a hypothesis. By defining explicitly the scales of scientific ideas, we can understand how they relate to each other and thus empower ourselves to fit them together insightfully and ultimately design effective experiments for testing wood-coating durability.

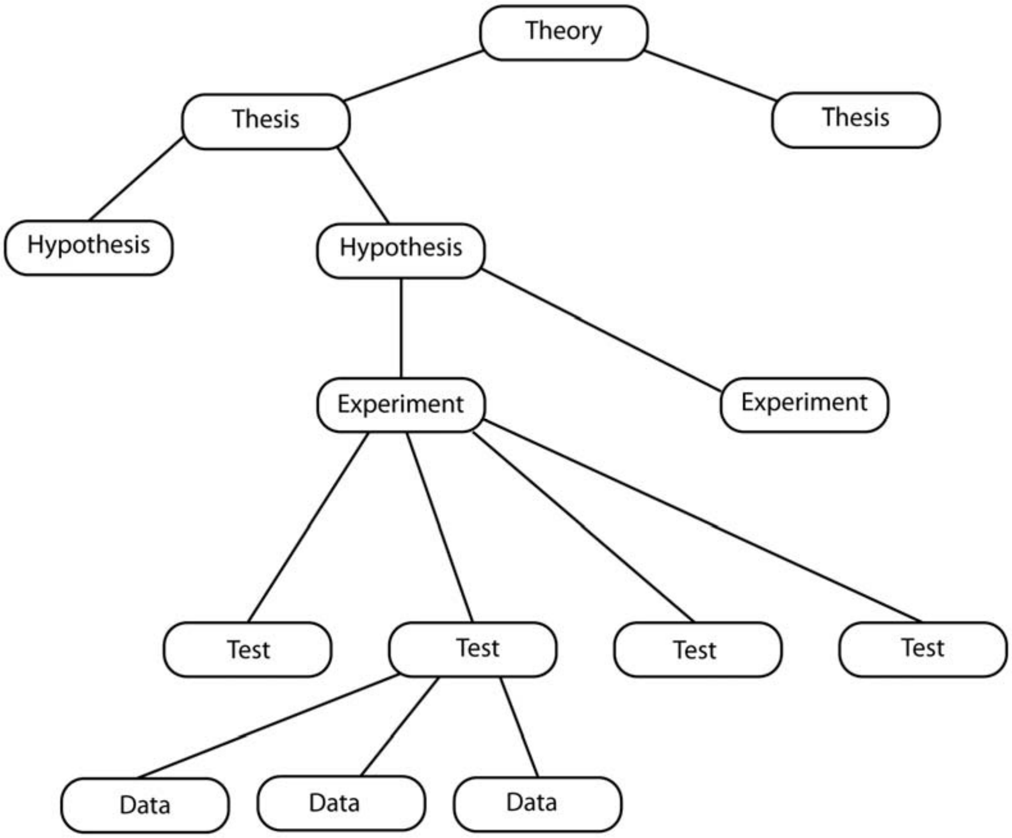

Figure 6. Schematic of the (simplified) hierarchy of scientific ideas used in this manuscript. The most critical aspect of the scientific idea, human thought, is left out of the illustration. I have spread out the bubbles so that the reader may make arrows and notes and fill in the diagram as an exercise.

In classical teaching of scientific thought, the highest-order thought is the theory (Fig. 6). Such teaching says that a theory can never be proved, only disproved. I am inclined to agree with the former statement, and the latter statement is true as far as it goes, but this unprovability is not by any means limited to the theory. So, what makes a theory? For our purposes, let's say that a theory is an amalgam of observations, inductions, and higher order human synthetic thought yielding an explanation or an incomplete interpretive model. That incomplete model, the theory, suggests a family of theses, each of which will have one or more families of hypotheses associated with them. A hypothesis, in turn, suggests sets of experiments that can be used to evaluate the premises and predictions of the models or hypotheses. Note that nowhere in this (simplified) cascade do we find the concept of *testing.*

This is because tests look for answers to *What*? questions, rather than *Why?* or *How?* questions. Many published works in scientific journals are test results, rather than experimental results. This is in part because scientific journals tend to shy away from works of synthetic thinking, instead publishing the meat-and-potatoes descriptive pablum of test results. They give generally short answers to simple questions: *Which coating, A or B, performs better under the conditions of the test? Will my new formulation pass the ASTM standard?* Tests are easy to design and execute compared with experiments, and this suits their comparative modesty of scope. If they are designed correctly, tests give answers that are meaningful. Such answers are as valuable as their antecedent questions are well thought out. My intent is not to impugn tests or scientific journals; both are valuable, efficient, and answer questions of *liability* as discussed above. In many cases, a company or a scientist wants to know little more than this, and so tests may be wholly appropriate. For questions of reliability, the topic of intelligently designed experiments must be tackled, and to do this we have to recognize these three scalar concerns—spatial, temporal, hierarchical—and allow them to inform how we ask a question. By incorporating these ideas we can tip the scales to our favor when we design an experiment, and in doing so we save time and money.

Intelligent experimental design: the role of intelligent design in science

Overstating the importance of experimental design in the scientific process is nearly impossible, yet it remains a comparatively little-taught set of skills. An advanced degree in science may be obtained from a well-regarded institution without any requirement to study this field. A careful examination of published works in many scientific fields will demonstrate the consequences of such a lack of training. These problems are endemic in our system, and honestly recognizing this is critical to interpreting the research literature on a topic so that elements of a hypothesis can be stated correctly and an experiment designed intelligently.

Experiments and tests

One of the first concerns is the not-so-simple matter of distinguishing between a true experiment and a test. An experiment, especially one that is intelligently designed, is an embodiment of a framework of working hypotheses, distillations of predictions from models or theses, and represents a concrete attempt to uncover some truth in the scientific system by testing hypotheses. We can reduce an experiment to a series of tests, but the thing that makes an experiment truly experimental is the way in which human thought is guiding those tests to work back toward the weaknesses of the guiding principles that inspired it. That is to say, the intelligence and insight of people are the characteristics that separate true experiments from a menagerie of tests. An experiment thus tests a hypothesis, pushes at its assumptions and limits, and generates useful data regardless of whether the data conform to the expected results. This approach, hypothesis testing, relies on a well-reasoned null hypothesis (see a statistical text like Sokal and Rohlf 1995 for a detailed treatment of this topic). For our purposes, we consider a well-reasoned null hypothesis to be one that provides a mechanistic framework for the default assumptions regarding the outcome of the individual tests in the experiment but that intentionally leaves room for unexpected results and includes in its framework a way to interpret such results with the hope of learning something new.

Experiments are typically inherently multivariate, and their component tests depend on isolation of variables, not so that the one true answer can be found, but so that the data that they produce are comprehensible by the scientist who designed them. Isolation of variables can be critical—in many cases it is altogether necessary for a deductive logical process—but it is an artifice, nearly an affectation, compared to the conditions of the real world. In many cases we reduce the number of input variables to the experimental system, and in other cases, we are ignorant of the relevant variables or such variables are not currently measurable. Similarly, on the output side, we make decisions about what responses to measure. Such decisions are influenced by what we are able to measure and also what we know to measure. This disjunction between what is known, what is measurable, and what we think to do is one of the reasons isolation of variables can be seen as highly artificial. This is an important point; nothing about the isolation of variables is holy, it is merely a convenience to keep the results accessible to our minds. A related danger arises when data are analyzed; we tend to be careless about extrapolating results to conditions that violate the assumptions under which the data were produced (Fig. 7). Again, an intelligently designed experiment will give not just results, but also a glimpse toward a truth. As with scale, the import of that truth will be guided by the contexts in which the experiment was designed and implemented and by how thoroughly people then think about the results.

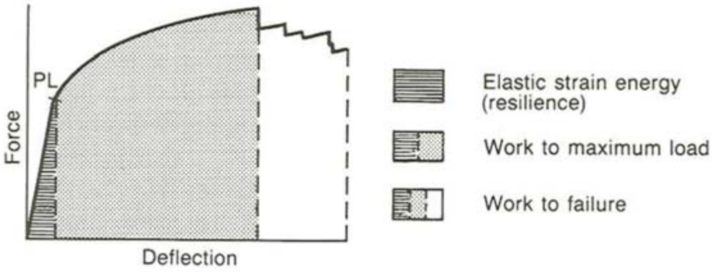

Figure 7. A graph of force vs. deflection in wood. The inflection point labeled PL is the proportional limit, the point after which the wood changes its response to the stimulus. If your experiment gives results to the left of PL and you use those results to extrapolate to the right of PL, your predictions will be wildly inaccurate.

My intent is not to take a wholly epistemic approach to this topic, though in my opinion most of us have too little of this sort of dialogue in our formal training. To end on a more practical note, let us tackle a simple case study involving wood siding and some new coating formulations. In this case we wish to apply all that we have discussed this far: awareness of the possible influences of biocentric wood structure; the effects of spatial, temporal, and hierarchical scales of analysis; and, the principles of intelligent experimental design.

Hypothetical application of biocentric wood science, scalar considerations, and intelligent experimental design

Let's say that you have two new coating formulations, A and B, and the current accepted product, C. They are intended to be used in outdoor applications, predominantly siding. Historically you have sold product C as a coating for wood siding in North America, a market in which the predominant woods are softwoods, but your company is interested in expanding internationally. In other countries, exterior grade tropical hardwood plywood siding is common, as is solid wood siding made of species with which you are unfamiliar. Added to this is the fact that the countries into which you wish to grow your market are at tropical latitudes. With this information, we can begin to consider some questions.

The first relates to your new products, A and B. *Are the formulations for A and B already fixed, with production already scaled-up to a commercial price point, or do you have flexibility in tweaking them?* If they are fixed, we are looking at a test scenario. If they are flexible, we may have the opportunity to pursue an experiment, depending on your company's goals. If A and B can be adjusted but represent essentially proven technology, a series of tests is probably appropriate to gather data for small refinements of the formulae. If, instead, A and B are part of a new technology on which the company is banking, experiments are probably more appropriate; the long-term commitment and relative lack of experience with the technology underlying A and B would justify the additional expense of experimentation. For either testing or experimentation, formula C can be used as a control or reference point, based on your previous experience—both real-world and laboratory—with its performance. Remember, with a test we are looking for a simple yes/no result, but with an experiment we are pursuing a greater understanding of the various mechanisms of the product, and to do that you must have a framework from which to interpret results. Inclusion of formula C can help you gain this.

The next questions are wood biological: *What are the characteristics of the range of species to which your coatings might be applied? Can you group several species with like characteristics and thus use just one of those species as a proxy for that group, or must they all be evaluated? What are the wood structural and extractive characteristics of these species, and how are they likely to affect the results of any tests or experiments? Are three of the species light-colored, diffuse-porous woods with water soluble extractives?* If so, you can probably select just one to represent the group. A review of the literature combined with a quick-and-dirty laboratory test could help you justify such a choice. Remember that solid wood and plywood will not behave the same; subtle differences in chemistry may result based on the adhesive used to glue the panel, the dimensional changes in the panel will be less than that of solid wood from the same species, and lathe checks in the plywood from the veneering process may affect coating uptake or coverage. The species choice for the core plies could also affect the results: *What if it is a non-durable species, or contains appreciable amounts of sapwood?* This should influence your decisions for testing, and ultimately, the roll-out of your product.

The next series of questions is one of scale. Spatial: *How many specimens of what size do you need for each test? Do your testing facilities mimic tropical exposure? Do construction practices differ, such that joints or other details drastically change exposure effects on one part of a test panel differently from the rest of the panel? Do you have experimental facilities large enough to conduct tests with enough replicates to give meaningful data?* Temporal: *Can you employ accelerated testing to achieve meaningful answers, or must you use field tests? How long a period do you have before your company must make a decision?* Hierarchical: *How do different experimental conditions affect the mode of failure for your product? Do local construction practices result in a building envelope that processes moisture differently? If you are interested in experimental results, how does the role of various experimental setups influence your observations, results, and inferences?*

Note that these questions of structure and scale inform the context of your experimental or test design; we cannot establish for this example the correct choice of parameters without thoughtful, accurate answers to each of these. The answers to each of the above questions change the way we need to think about the problem, so no one way will resolve these issues. One last note of great import: if the answers to these questions tell you that the resources (space, time, money, intellectual capital) devoted to answering the questions are insufficient to glean meaningful results, say so. I have heard people say that a bad experiment is better than no experiment. From my perspective, this is akin to saying "tainted seafood is better than no seafood"—a dangerous position to take.

The intelligent design of your testing or experimental system will depend on questions like these, along with many other facets of the problem. Only by applying your best-informed understanding of the relevant components of the system can you move away from blind testing toward well-reasoned testing or intelligent experimental design. By doing so you can save yourself and your company time and money; economy of scale is to be had in the scientific process as well as in manufacturing. Using knowledge gleaned from a biocentric perspective allows you to design a test or experiment that produces meaningful and suggestive results regardless of the outcome, and this is the key to intelligent design and achieving this economy of scale when wood is part of an experimental system. Below is a series of suggestions outlining the guiding principles for product and hypothesis testing. My hope is that these suggestions will help you achieve an economy of scale in your testing or experimental work.

A twelve-step program for product and hypothesis testing: take two aspirin and call a statistician in the morning

1) Identify the real question to which you need an answer.
2) Determine if this can be answered by a test or if it demands an experiment.
3) Make a list with three headings:
    a. Wood
    b. Scalar considerations

   c. Design considerations
4) Under each heading list all known or possible variables or system behaviors, making no effort to filter your list at this step. Be thorough, but not whimsical (e.g., the color of the car you drove to the lab is probably not relevant; if it is, you are in trouble).
5) Go back to #1 and refine the question.
6) Return to #2 and check your answer.
7) Make a new list as in #4 if any changes resulted from #5 or #6.
   a. If you need a test, design it in detail on paper. Include the inputs (raw materials, labor costs, data acquisition materials, etc.) and estimate the outputs, including the expected magnitude of differences between treatments in your test.
   b. If you need an experiment, do as in #7a, but also include copies of all the references that support the underlying hypothesis that you wish to test. Formally state your null hypothesis and your intended criteria for rejecting or modifying it.
8) The process from #1 to #7 should take a few hours; if it didn't, you probably haven't invested the intellectual commitment to the project necessary for success.
9) Take two aspirin for your headache, go home and sleep.
10) Call a statistician and review your whole plan, then repeat step #9 when they give you the bad news.
11) Repeat #1 to #7 in light of the statistician's recommendations.
12) Execute your much-improved study plan to the highest standards that are appropriate to the scale of your question.

Good luck (and better designs!)

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