A New Approach to Research Communication: Sharing Results Through Stories

THESIS

Presented to the Faculty of the Department of Physics and Astronomy
in Partial Fulfillment of the Major Requirements
for the Degree of

BACHELOR OF SCIENCE IN
PHYSICS

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May 2018

A NEW APPROACH TO RESEARCH COMMUNICATION:
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ABSTRACT

Ever since the format of the formal scientific article emerged, it has constituted the standard mode of presentation for scientific research. This tradition, more effective for doing science than for sharing science, erects a wall of jargon between scientific knowledge and the public, especially for students exploring scientific research for the first time. Moreover, in the face of complex technological issues like global climate change, the public, now more than ever, ought to have the resources to understand the results specialized science research to inform their decisions. Hence, if science is to be communicated effectively, the method of communication must change. One approach supported by science communication research is the narrative form. In this thesis, I put these ideas into practice by giving two presentations of the biophysics research I completed at a Science Undergraduate Laboratory Internship at Oak Ridge National Lab. Chapter 1 consists of a traditional scientific paper detailing my research project entitled, "Characterizing the Association of Glucuronoarabinoxylan and Cellulose in the Plant Cell Wall." In Chapter 2, I share the same research but in an alternative presentation style, a set of short stories.

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INTRODUCTION

Physicists study the laws of the universe and the mathematical language in which they are written. Hence, they work with hard facts. For some, though, the beauty in nature is what draws them to science, and that beauty may inspire creativity. Both poets and scientists observe the world in awe, and this intertwines them. Science deals with measurable phenomena, and what is measurable may lack certainty. Indeed, physicists calculate uncertainty values for their research results. Although science best expands what we know about the world, the realm of the unknown remains: “Wings, alas may grow / Upon our soul, but our body is / Earthbound.” [1]. That may be the realm in which art is created. Both science and art make the familiar mysterious, whether by revealing to us how little we understand or by using description to provoke thought. Storytelling provides a way to capture an essence of humanity, the ability to experience beauty and wonder. Curiosity intertwines science and storytelling.

Nonetheless, much of the presentation of science, especially of scientific research, occurs in the format of an academic paper or textbook. How did the science paper become the standard? In his essay “Under the Surface of the Chemical Article,” Roald Hoffmann highlights the factors which led to the emergence of the modern scientific article. The natural philosophers, the earliest scientists, formed theories about how the world works based on thought and observation rather than experimentation. Indeed, their theories were grounded in imagination and ideals rather than fact. Take, for instance, the scientific theories of the Pre-Socratic natural philosophers Anaximander and Empedocles, respectively:

> “[Anaximander] further held that each of the heavenly bodies is a wheel of fire, surrounded by air, which separates it from the fire at the extremities. The air has little breathing holes somewhat like the holes in a flute, and through them the orbs are seen. When the hole of

the [solar or lunar] orb gets clogged an eclipse occurs. The moon goes through its phases as its breathing hole gets successively opened and stopped up. The sun's wheel is twenty-seven times as large as that of the moon, and is situated higher, while the wheel of the stars is lower." [2]

and

"Sea is the earth's sweat." [2]

Though storied with fantastical explanations, ancient natural philosophy was clearly not "scientific." To counter this lasting trend and to siphon out reliable scientific knowledge, the "early 19th century scientific article evolved." [3] The formal scientific paper must be factual, regardless of the author, and presented in the third person passive voice, in an unbiased and wholly unemotional manner. Some concepts "cannot be expressed in words but require other signs—structures, equations, graphs," but expressions of sentiment are disallowed and suppressed. The product was a "canonical form" of research presentation. In this format, unlike in the theories of the natural philosophers, scientific information was presented clearly, reproducibly, and objectively for the first time. Still, though the scientific article fosters accuracy, the public typifies scientists by the "nature of [their] product." [3]

Indeed, "dehumanizing our mode of communication" by removing all feeling has created a tradition which "propagates the notion that scientists are dry and insensitive." [3] This tradition erects a wall of jargon and equations between scientific knowledge and the public, making science less approachable, especially for students exploring scientific research for the first time. Moreover, in the face of complex issues such as climate change, the public, now more than ever, ought to have the resources to understand the results of highly specialized scientific research in order to make informed decisions. In addition, scientists need the trust and support of the public to gain research funding and impact, especially for hot-button issues such as global warming.

Hence, the way science is communicated must change to better engage students and the public, and current science communication research supports a narrative approach. For instance, in his paper entitled, "Using narratives and storytelling to communicate science with nonexpert audiences," Michael Dahlstrom underscores the differences between paradigmatic and narrative mental processing. Digesting textbook information requires paradigmatic processing, while interpreting the information presented in a story requires narrative processing. Narrative processing, "often associated with increased recall, ease of comprehension, and shorter reading times," has been found to be highly effective. [4] Because narrative processing facilitates "motivation and interest," the allocation of cognitive resources, "elaboration, and transfer into long-term memory," it may be a more efficient approach to understanding a science topic. [4] Moreover, in a study published in the International Journal of Education in Mathematics, Science, and Technology, entitled, "Influence of Scientific Stories on Students' Ideas About Science and Scientists," young students were given a series of lectures centered around scientific stories. After the program, the students were more likely to exhibit a heuristic view of science, in which scientists use their imaginations in their work, scientific research expands beyond one field, and there is more than one route to doing science. [5] Presenting science through narratives, it seems, is more approachable than the standard academic format. Perhaps, then, short stories could be a suitable medium for science research communication.

Therefore, in this thesis I put these ideas into practice by giving two presentations of the scientific research I completed during a Science Undergraduate Laboratory Internship at Oak Ridge National Lab. Chapter 1 consists of a traditional scientific paper detailing my biophysics research project entitled, "Characterizing the Association of Glucuronoarabinoxylan (GAX) and Cellulose in the Plant Cell Wall." The purpose of the project was to gain a better understanding of the chemistry behind biomass recalcitrance, plants' evolved resistance to enzymatic and microbial destruction. This phenomenon is a roadblock to harnessing the energy potential in the structural sugars of plants for biofuel, a more climate-friendly alternative to automotive fuel. The research involved computationally modeling the interactions among cellulose and the polysaccharide GAX in the plant cell wall. After I present my biophysics research in the standard format of a scientific paper in Chapter 1, I offer an alternative presentation style: storytelling. Chapter 2 includes a set of creative short stories—through which I more approachably share the motivation for and process and results of my biophysics research—and a comparison of the two methods of science communication.

CHAPTER 1: The Standard Format of Science Presentation

Characterizing the Association of Glucuronoarabinoxylan
with Cellulose in the Plant Cell Wall

I. Introduction

Both the economic dependence and climate changes incurred by fossil fuel combustion have brought serious attention to the development of alternative fuels. Our imminent energy needs have sparked extensive research on plant biomass as a sustainable alternative source of transportation fuel. Indeed, utilizing whole plants in biofuel production, if production efficiency were improved, would yield more than our current limited use of grains, corn, and sugarcane. However, biomass recalcitrance, plants' evolved resistance to enzymatic and microbial destruction, is a roadblock to harnessing the energy in the structural sugars in plant fibers in a cost-effective manner. Biomass recalcitrance stems from the hierarchical structuring of cellulose with other cell wall polysaccharides, or long chains of sugar molecules. [6]

Mostly lignin, cellulose, and hemicelluloses, the amounts and arrangements of which vary by plant type, compose the intricate molecular structure of biomass. Lignin, the visible woody portion of the plant, is an amorphous hydrophobic, or water resistant, polymer which links plant polysaccharides and fills spaces in the cell wall, especially around vascular regions. Lignin contributes the most to plant stiffness and resilience. Cellulose, comprising the majority of the polysaccharide portion of the plant cell wall, also greatly contributes to cell wall strength. Cellulose exhibits a rigid, unbranched crystalline structure composed of repeating units of glucose joined by chemical bonds called glycosidic linkages. These bonds are spatially-arranged in a way which yields long linear chains of cellulose molecules that stack in tough sheets held together by hydrogen bonds: electrostatic attractions between more positively- and more negatively-charged atoms. Moreover, only the few hydroxyls—negatively-charged functional groups containing hydrogen and oxygen—on the surface of the stacked sheets are available to hydrogen bond with water. The rest are occupied with sheet-stacking, making the polar cellulose microfibril only slightly water soluble. These stacks can bundle up into threadlike structures called cellulose microfibrils. The relative amounts of exposed hydrophilic and hydrophobic microfibril surfaces, which respectively interact with and repel water, influence its binding with other cell wall constituents. Cellulose associates with hemicellulose, which constitutes any cell wall polysaccharide bearing an amorphous structure and a lesser degree of polymerization, or the linking together of molecule chains, than cellulose. The chemical composition of hemicellulose varies widely, and the particular molecules in each type steer its interaction with cellulose. The aspect of molecular structure on which this particular project is focused is the scaffolding of cellulose microfibrils within a matrix of hemicelluloses. [7]

Though the biochemistry of the plant cell wall is highly regulated to contribute strength to its structure, little is known about the non-covalent interactions between the cellulose microfibrils and hemicelluloses. Hence, the aim of this project is to gain a better molecular understanding of the interplay between the cellulose and hemicellulose components of the plant cell wall and the resulting contribution to cell wall strength and, thus, recalcitrance. Particularly, we investigate the possible association of cellulose with the hemicellulose glucuronoarabinoxylan, or GAX. GAX consists of a xylose backbone studded with varying amounts of arabinose, glucuronate, and ferulate molecules. We use atomistic molecular dynamics simulations to investigate the non-covalent interactions between the cellulose microfibril and GAX, for varying degrees of arabinose substitution in GAX and levels of hydrophobicity on the cellulose surface. A better understanding of the interactions between GAX and cellulose will provide useful insight into the structure of the plant cell wall, which could help guide the development of technologies for harnessing the energy potential in plant biomass.

II. Methods

The experimentation involved first building computational models of a cellulose microfibril, with similar hydrophilic and hydrophobic surface areas, and two glucuronoarabinoxylan (GAX) hemicelluloses, with distinct amounts of arabinose, one of the constituent molecules. Then, systems consisting of a microfibril with a GAX polysaccharide each on a hydrophobic and hydrophilic face were put together. Each GAX polysaccharide was also simulated by itself for comparison. The systems' environments approximated that found in the cell wall, and the simulations were run for the equivalent of 80 nanoseconds (ns) using the molecular dynamics software NAMD. [8]

Cellulose Model. A hexagonal elementary cellulose microfibril with Iβ crystalline structure and a degree of polymerization of 30 was constructed using the program Cellulose-Builder. [9] The fibril has 24 chains arranged asymmetrically, with similar hydrophilic and hydrophobic surface areas so that the effects of hydrophobicity on binding could be taken into account. The exact structure of the cellulose microfibril has not been assuredly-determined, but 24 chains is one leading estimate. [10]

GAX Model. Model structures of the hemicellulose were built using the molecular dynamics program VMD, based on available experimental data for the chemical composition of GAX in the maize cell wall. [9] In a study conducted by Akira Tabuchi and Daniel Cosgrove, our collaborator at Pennsylvania State University, the average GAX in the maize cell wall has the following composition: 56 xylose monomers, 67% substituted with arabinose, 2 ferulates, and 1 glucuronate. [12] Thus, for example, one of the computational models has a ratio (Xyl/Ara/Fer/GlcA) of 56:38:2:1. Models with both 67% and 25% arabinose substitution were constructed; this variation was made to consider the influence arabinose has on binding. Indeed, GAX is found widely in all grasses, and it is possible that the level of arabinose substitution could vary in nature. [13] The weighted arabinose and ferulate substitution was generated randomly using a Python script. It is important to note that the glucuronate was purposely bonded to the last xylose residue; this was done because the experimental aspect of deciphering its molecular structure involves using an enzyme to break the GAX chain on the xylose residue bearing the glucuronate. [12] After its construction, the GAX polymer was hydrated in a water box and neutralized with sodium (Na^+) ions to simulate its environment. The polymer's structure was then minimized and equilibrated with the molecular dynamics program NAMD, for approximately 80 nanoseconds, using the CHARMM force field, periodic boundary conditions, and a timestep of 2 femtoseconds (fs). [8, 14]

Simulation. Each GAX-cellulose system (see Fig. 1) included a cellulose microfibril with two of a single model of the GAX polysaccharide—either 67% or 25% substituted with arabinose—approximately 7 angstroms (Å) from a hydrophilic face and 7 Å from a hydrophobic face. The hemicelluloses placed above the cellulose surface had been minimized for roughly 4 ns so their structures would be more natural. Both of the GAX-cellulose systems were solvated in a water box and neutralized with Na^+ ions. The systems were then minimized and equilibrated for approximately 80 ns using the CHARMM force field, periodic boundary conditions, and a timestep of 2 fs. [14] All simulations were carried out using, with permission, the Titan supercomputer at Oak Ridge National Laboratory.

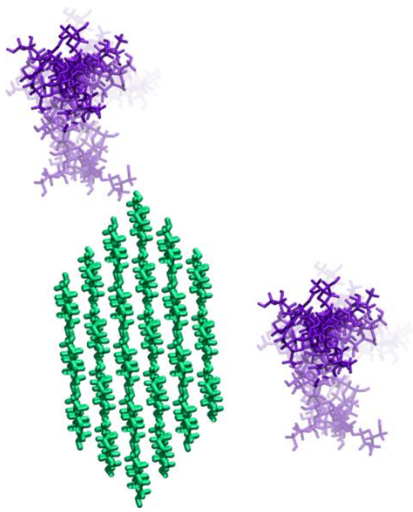


Fig. 1: Orthographic view of the GAX-cellulose system with one of a single type of GAX (shown in purple), 7Å above the hydrophilic and 7Å above the hydrophobic cellulose surface (green).

III. Results

To analyze the GAX-cellulose systems, both the amount and type of binding between the microfibril and hemicellulose and the effects this binding had on the conformation of the hemicellulose were studied. For all the data analysis, only the trajectories in the 45-80 nanosecond (ns) range, after the system had approached convergence, were analyzed. Convergence was determined by plotting the normalized contacts to cellulose as a function of time for each GAX residue in each variation of the system: the hydrophilic cellulose surface with the GAX with 25% and, separately, 67% arabinose substitution and the hydrophobic cellulose surface with the GAX with 25% and, separately, 67% arabinose substitution (Fig. 2-5).

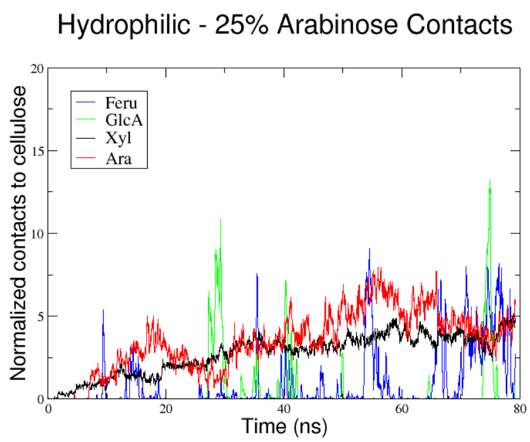


Fig 2: Normalized contacts, as a function of time, between the hydrophilic cellulose surface and each residue in the GAX 25% substituted with arabinose.

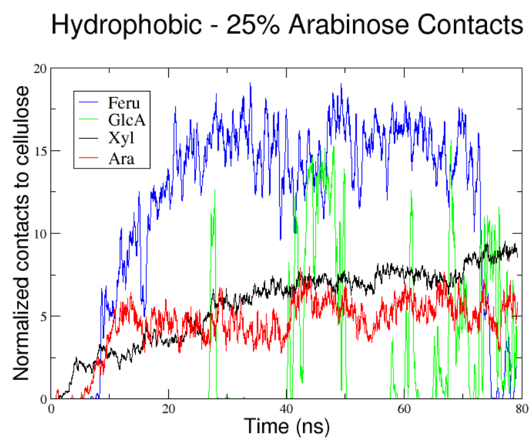


Fig. 3: Normalized contacts, as a function of time, between the hydrophobic cellulose surface and each residue in the GAX 25% substituted with arabinose.

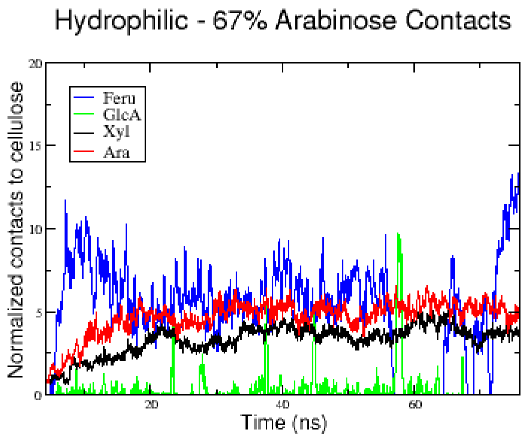


Fig 4: Normalized contacts, as a function of time, between the hydrophilic cellulose surface and each residue in the GAX 67% substituted with arabinose.

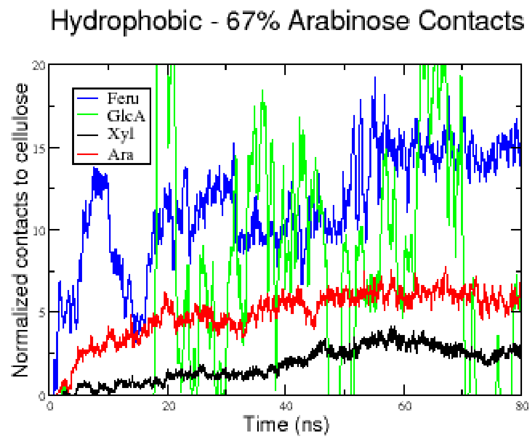


Fig. 5: Normalized contacts, as a function of time, between the hydrophobic cellulose surface and each residue in the GAX 67% substituted with arabinose.

A contact is defined between two atoms which fall within a certain proximity. Ferulate (plotted in blue) and glucuronate (green) form significantly more contacts with the hydrophobic surface for both degrees of arabinose substitution. Xylose (black) binding, on the other hand, is greatly influenced by the degree of arabinose (red) substitution, especially when paired with the hydrophobic cellulose surface. Arabinose does not appear to be influenced by either the amount present or the hydrophobicity of the cellulose surface.

Next, to consider what stabilizes this non-covalent interaction between cellulose and GAX, the electrostatic and van der Waals interaction energies between the microfibril and hemicellulose were computed for each variation of the system (Table 1).

	Average Electrostatic Energy (kcal/mol)	Fluctuation and Range (kcal/mol)	Average VdW Energy (kcal/mol)	Fluctuation and Range (kcal/mol)
Hydrophobic - 67% Arabinose	-133	26 (-159 to -107)	-225	21 (-246 to -204)
Hydrophilic - 67% Arabinose	-234	27 (-261 to -207)	-220	14 (-234 to -206)
Hydrophobic- 25% Arabinose	-153	21 (-174 to -132)	-257	17 (-274 to -240)
Hydrophilic - 25% Arabinose	-182	25 (-207 to -157)	-186	12 (-198 to -174)

Table 1. Average electrostatic and van der Waals interaction energies for each GAX-cellulose system.

Comparing the interaction energies across the table, the van der Waals, rather than electrostatic, interactions appear to dominate for the hydrophobic cellulose face, whereas the electrostatic interaction energies do not differentiate very much between the hydrophobic and hydrophilic faces. Entropic effects were not taken into account in this energy calculation, but our qualitative analysis of the conformational changes of the hemicellulose suggests a stabilization of its structure as a result of the cellulose binding.

Next, the effects of the GAX-cellulose interaction on the conformation of the hemicellulose were considered. In this aim, the radii of gyration (Fig. 6-7) and the persistence lengths (Fig. 8-9) were calculated for each variation of the GAX-cellulose system, in addition to each lone hemicellulose only in solution.

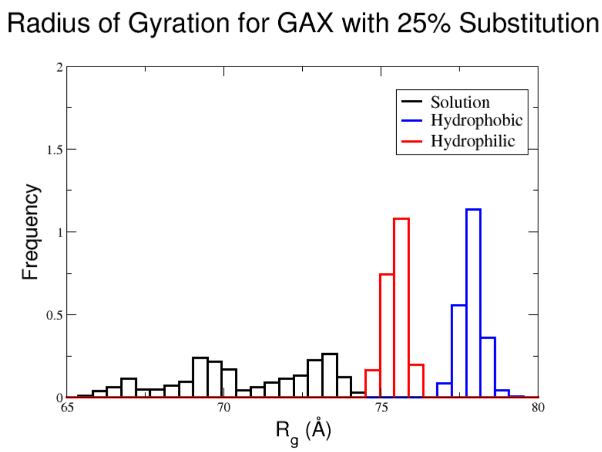


Fig. 6: Radius of gyration (R_g) of the GAX 25% substituted with arabinose, both in solution and paired with cellulose.

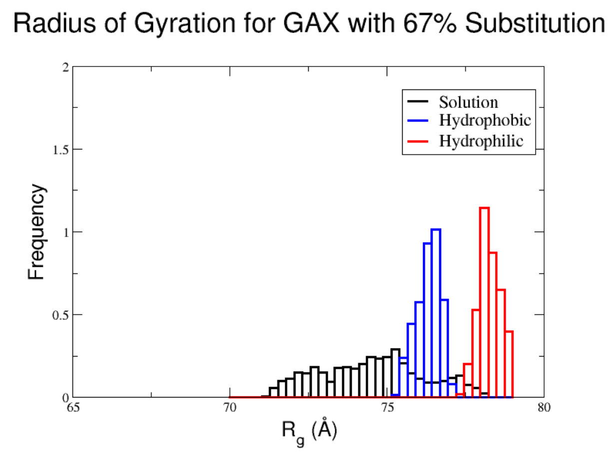
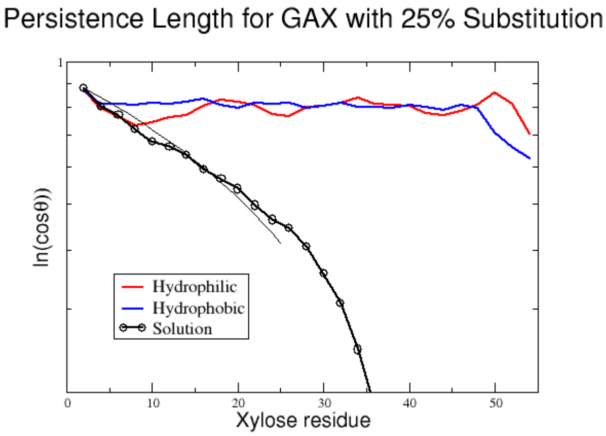


Fig. 7: Radius of gyration (R_g) of the GAX 67% substituted with arabinose, both in solution and paired with cellulose.

The radius of gyration is an approximation of the area about which an object's center of a mass freely moves. The radius of gyration has a much broader distribution for the hemicelluloses by themselves in solution (black), for both 25% and 67% arabinose substitution, indicating a more flexible conformation. When GAX associates with cellulose (red, blue), its structure changes dramatically as it loses this flexibility, and the radius of gyration becomes much steeper as a result. That the GAX polysaccharides only in solution have not yet converged during the 80 ns period suggests a greater stabilization of GAX's structure when paired with cellulose. To investigate further, the persistence length was calculated.



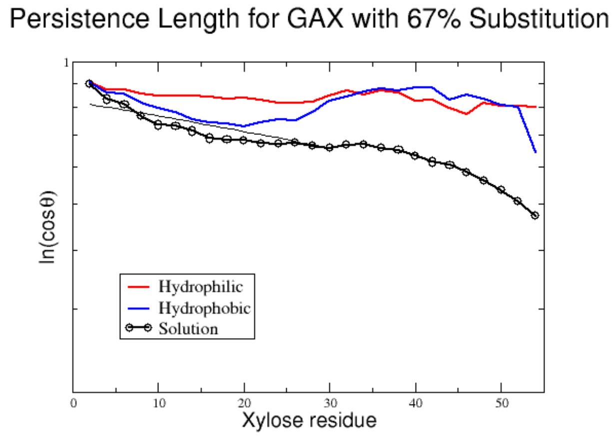


Fig. 8: Persistence length as a function of the xylose backbone residue for the GAX with 25% arabinose substitution, both in solution and paired with cellulose.

Fig. 9: Persistence length as a function of the xylose backbone residue for the GAX with 67% arabinose substitution, both in solution and paired with cellulose.

The persistence length of a polysaccharide is the length over which its structure retains its correlation. The free polysaccharides (black) show an expected decay of the structural correlation over time, as the conformation becomes less artificially-linear and more amorphous. When they associate with cellulose (red, blue), though, they retain this correlation. For example, the GAX 67% substituted with arabinose has a calculated persistence length of approximately 179 angstroms (Å), whereas the persistence length of the GAX with 25% substitution is only 49 Å. Though the former is already more rigid due to the steric hindrance brought on by the extra arabinose molecules, its structure becomes detectibly more rigid when associated with cellulose.

IV. Conclusions

In summary, both the level of arabinose substitution in GAX and the hydrophobicity of the cellulose surface influence the microfibril-polysaccharide association, and this association, in turn, affects the conformation of the hemicellulose. In particular, both ferulate and glucuronate are conducive to binding, especially when paired with the hydrophobic cellulose surface. Xylose interaction, on the other hand, varies with the level of arabinose substitution. The cellulose-polysaccharide association significantly stiffens the structure of the GAX polysaccharide, suggesting a stabilization effect. Further, cellulose hydrophobicity influences interaction energy, and van der Waals forces dominate on this surface. To investigate further, we plan to re-run the simulations with the positions of one ferulate and the glucuronate residue switched, repeat the analysis of our current systems for 160 nanoseconds, calulate the interaction energies with water taken into account, and calculate the conformational entropy of GAX and the water entropy.

<u>CHAPTER 2: An Alternative Format of Science Presentation</u>

Characterizing the Association of Glucuronoarabinoxylan
with Cellulose in the Plant Cell Wall

I. Candy Shop Chemistry

Day 1

"Say, it sure is hot outside for February. How about root beer floats for Louise-Marie and me?" Johnny asks, as he sits down at the town's only ice cream parlor on a Wednesday afternoon. Johnny and Louise-Marie were the town's cutest couple. Their friends all fought over who might be the bridesmaids and groomsmen whenever they inevitably got married someday.

"There's an early spring storm approaching," said Mr. Pearl, the Soda Pop Shop clerk and owner himself, as he gently plopped a scoop of vanilla each in two tall glasses.

A few stools down, Mildred overheard Johnny and nudged her friend Sam. "You think we oughta head home then?"

Sam didn't look up. "Ehhh." Mildred knew that meant no.

Sam was drawing a comic strip, while Mildred read. Many other teens were sitting at booths, idlily doing their homework, or pretending to while tether-talking: the meaningless chitchat we used to have as kids while playing tether ball at recess. We'd be so focused on making sure we didn't miss the ball when it came back around that our conversation would be wholly nonsensical; often, we'd be each be talking about completely different things, unknowingly. The girl clique, Sue, Betty, and Joana, sat in their favorite booth by the window and gossiped. It was their favorite spot because they could stoke their conversation with people-watching. A new couple, Stacy and Jim, was flirting shyly over by the shiny jukebox, beaming out The Everly Brothers. It was too soon to tell how they'd turn out, but they sure were cute. In a couple of hours, families would start piling in for an easy dinner.

A low thunder rumbled, and Mildred jumped. This time Sam looked over and winked. "Aw, just another hour, Mildred. Don't be a wimp." Mildred was used to Sam's teasing. They had been next door neighbors their whole lives, and best friends for almost as long. Once, when they were about nine, they found an old silo while wandering around in their neighbor's cow pasture. Sam climbed right up to the top to peak in, but Mildred was too scared. That adventure set the stage for the rest of their friendship. Mildred didn't really mind Sam's teasing because she admired Sam's courage. Sam didn't really mind Mildred's hesitance because it kept her grounded. They're each the exact compliment of the other. Sam is fearless and artistic, whereas Mildred is more careful and bookish.

"Whatcha drawing?" Mr. Pearl smiled warmly, after he topped Johnny and Louise's floats with cherries and slid them over. Mr. Pearl, with his round, gold-rimmed glasses—which still couldn't compete with his sparkly eyes that lit up his face—his slicked-back hair and white moustache, matching the white button-up shirt that he paired with a black bowtie so reliably that you'd think they were sewn together, was the whole town's second grandpa.

Sam turned her drawing around and showed it to Mr. Pearl. It was a hyper-realistic futuristic comic strip, set in their town Covington in 2000, in which the square was full of shiny glass buildings, except for the old brick Soda Pop Shop, which had been turned into the Covington Museum. The comic characters were part-robot-part-human people involved in a reenactment of the old Covington. Mr. Pearl's sparkly eyes widened. "That's very good Sam. I look forward to reading your comics in a newspaper someday!"

"Thank you, Mr. Pearl," Sam grinned. Secretly, Sam didn't even really like ice cream. Mr. Pearl's feedback was the real reason she came to the Soda Shop Pop to practice drawing. Her own grandpa had passed away a few years ago, and they always used to draw together when she was a kid.

Mr. Pearl turned back around to dry some ice cream bowls from earlier in the day. Though his encouragement was genuine, something in the metallic, unrecognizable newness in Sam's drawing left him feeling a bit winded.

It began to rain.

Day 2

"All right, everyone, it's 7:00 a.m. on Thursday, and our grand opening of Candy Co is happening tomorrow at 3:00 p.m., right when all the kids will be getting out of school. We need to be as prepared, and as chipper, as possible by then, so work hard today!" Mr. Walross announced to his team of clerks, cooks, janitors, and one candy chemist. A burly man, with dark eyebrows which sharpen his face almost as much as his strong jawline, always looks in-command. And with eyes which sparkle when he needs them to, he usually gets what he wants done.

After dismissing everyone, Mr. Walross pulled his candy chemist aside.

"Okay, Frank, pop out another batch of our ice cream and soda flavorings so that we can run a final taste test before tomorrow."

"Will do."

Frank turned and headed to his lab. Months ago, to maximize potential profit, he had designed a line of synthetic flavors. He made artificial vanilla and malt flavoring for the ice cream that will be used in soda floats and shakes, sassafras flavoring for the root beer and every fruity flavor you can imagine for their line of candies they'll sell in the ice cream parlor, and a few secret flavor-enhancers added to every item on the menu. He whipped out batches of each to check for any final tweaks that needed to be made.

Frank had done the flavor experiments so many times that he could do them in his sleep: and he had many times, in stress dreams. By the afternoon, when Mr. Walross stopped by the lab again, after checking the final wax and scrub of Candy Co, Frank's syntheses had finished.

The tweaking was minor, compared to the last round of taste testing, but irritating, as Mr. Walross complained, "The vanilla needs a kick, and the sassafras tastes too root-y and not enough beer-y."

"Okay," Frank conceded. The revision was laborious, but by late that night, with an achy back, Frank had the final products. He locked up the building after himself, went home, and fell asleep, still wearing his lab coat.

Candy Co was due to open just down the street from the Covington town square, where the Soda Pop Shop was located, in thirteen hours.

Day 3

"Candy Co GRAND OPENING TODAY! Come try our famous root beer float, malt shakes, and our wide selection of hard candies. We also serve plate lunches and dinners. First fifty guests receive a free vanilla cone. Ribbon cutting at 3:00 p.m.," Sam read from a flyer she was handed on walk to school with Mildred.

"Neat! Wanna go after school?"

Unlike Mildred, Sam wasn't smiling. "Shouldn't we be loyal to our grandpa Pearl?"

"No harm in stopping by for a free cone, though, right?" Mildred giggled.

Sam shrugged, unconvinced.

"Please!?"

"If you really want to. We're not going to the ribbon-cutting though. It's too cheesy."

"Yay!" Mildred jumped.

. . .

Everyone in Covington must have had the same idea, even the regulars at the Candy Pop Shop. The line at Candy Co nearly went out the door. Sam and Mildred barely made the free-cone cutoff. They sat on brand spanking new red leather bar stools, in a line of a few dozens of them. No seats were empty. They were in the heat of the after-school rush. Hordes of high schoolers were enticed by the shiny excitement of the first new building in town since the major grocery store was build when they were all toddlers. The huge chrome soda fountain was twice the size of Mr. Pearl's, and the jukebox held all the newest songs from the radio. There was even a pinball machine, the only one in town, which they all fought over since as soon as someone started playing, his eyes were glued.

Mr. Pearl had only a couple of customers for most of the afternoon, so he used the free time to polish all his dishes.

"Okay, we got our free cone. Can we go now, Mildred?" Sam grew antsy.

"Yeah, sure."

Though a few families rolled in for dinnertime, most of the teens began to leave. Knowing their small-town manners, they went elsewhere before talking about Candy Co. Many headed to the Soda Pop Shop because that's where they always spent their evenings. Mr. Pearl, who had grown bored of polishing, was delighted to see familiar faces back in his parlor. He asked them all how they liked the new shop down the way. The consensus was that Candy Co was fun and new but a little too flashy for Covington. Candy Co lacked the sense of hominess that you get when, say, you're served an ice cream float by your grandpa. Mr. Pearl was too sweet to say anything bad about his competition: he just delighted in the return of his favorite customers.

. . .

"I can't believe this. It's 7:00 p.m. on a Friday, and our most important customer base, the teen-scene, has skedaddled. Families bring in a good chunk of revenue, but our biggest draw is supposed to be as a hang-out spot for the younger crowd! That's the whole reason we bought a state-of-the-art pinball machine! No one around here has probably even seen one before!"

Frank wasn't sure if Mr. Walross was yelling with him or at him. "Well, I think today was still a success. The booths are still nearly full of families out for dinner, and we gave away all our free cones within twenty minutes."

Mr. Walross was not convinced. "Yes, but our most important customers are gone! We're supposed to be a nighttime hang-out spot for country bumpkins who've never seen a pinball machine before, and they're gone! Go check the square and see where they all went."

"Okay, Mr. Walross." Frank, whose occupation was candy chemistry, went out on a snooping job. Enjoying the break from the pressures of opening day under an intense boss, he took his time strolling. Once he got to the square, he took a few loops around it before bothering to look for the clientele. He might have forgotten to look for them at all, had he not been startled out of his thoughts by loud laughter. He turned his head to see the Soda Pop Shop, filled to the brim with the town's youth. He stood outside for a few minutes and watched them, excitedly talking and dancing. They all looked comfortable there, like they were at home. He almost wished he could pass as a youth so that he could join them and forget the stress of his job for a while. But, this is their Friday night. He musn't make them share it.

> I only wanted to tell you that this is a wonderful time of life for you. Don't let any of it go by without enjoying it. There won't be any more merry-go-rounds, no more cotton candy, no more band concerts. I only wanted to tell you that this is a wonderful time for you. Now. Here. That's all . . . That's all I wanted to tell you. God help me. That's all I wanted to tell you. [15]

Oh, yes, his job. He started back toward Candy Co, bowing his head under the weight of the message he carried.

Mr. Walross was acting as a greeter at the front door, but, really, he was waiting for Frank. "Took long enough."

"Sorry about that Mr. Walross. I was following a rabbit trail."

“Well, where were they?”

“I hate to have to tell you this, but . . .”

“WHERE WERE THEY?!”

“They were at, um, well, the Soda Pop Shop, sir.” Mr. Walross’ face resembled a tomato that kept swelling and swelling until Frank was sure it was going to pop, boiling tomato soup all over the street right then and there.

Mr. Walross took a slow, deep breath, with which his overripe visage cooled down. And kept cooling down, until it was so cold and stoic that Frank shook in his boots. “Okay, candy chemist, here’s what you’re gonna do. You’re going to experiment to find some way to taint Mr. Pearl’s product, giving his regulars the push they need to see that we offer more, and giving Mr. Pearl the push he needs to realize that it’s his time to retire. We’re going to clam that man before he ever gets a whiff of our plan.”

“What if we maybe gave it a few days to see if business picks up? You, know, as word of mouth spreads?”

“No, the whole town has been here. We have to tank the Soda Pop Shop now or never.”

“I’m not sure if this is . . .”

“Not sure if you still have a job? Don’t worry, if you don’t do this, you won’t.”

Frank gave in. “Yes, Mr. Walross.”

. . .

Frank’s back ached. Another all-nighter.

Months prior to the grand opening of Candy Co, the private investigator that Mr. Walross hired found out the secret ingredient to the unbelievable thickness of Mr. Pearl’s homemade ice cream and shakes: he mixes starch in with the warm milk before he blends it with the sugar. The starch absorbs liquid and swells up, thickening the mixture. Of course, Mr. Walross then instructed his chefs in the candy kitchen to do the same.

As a chemist, Frank knew a thing or two about starch, and, moreover, polysaccharides: carbohydrates consisting of many sugar molecules bonded together. Frank quickly realized starch, because of its unique molecular structure, was the key to ruining Mr. Pearl’s ice cream.

Starch is a polysaccharide made up of hundreds to thousands of units of the simple sugar glucose, bonded together by covalent bonds called glycosidic linkages. Glucose consists of a ring of carbon, hydrogen, and oxygen atoms. Glucose comes in alpha (α) and beta (β) three dimensional arrangements. In α-glucose, the alcohol group (the —OH group plus the carbon it’s attached to) on the first carbon in the ring points down, whereas in β-glucose the alcohol group on the first carbon points up.

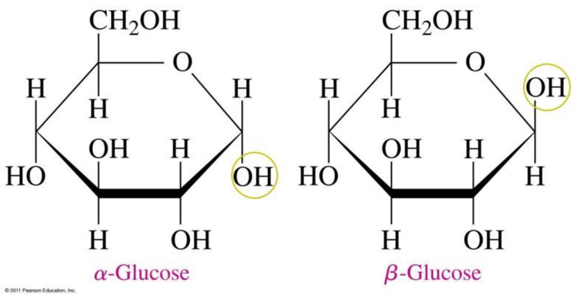


Fig. 10: Structural formulas showing the difference in arrangement of the hydroxyl group on the first carbon of α- and β-glucose, respectively. [16]

Starch contains many molecules of α-glucose held together by glycosidic linkages between the carbon rings. So, before joining together to form starch, each glucose has its alcohol group on the first carbon in the ring pointing down. When two glucose rings covalently bond, the hydroxyl (the —OH group) on one ring snatches a hydrogen atom from the other, thereby covalently-bonding to one another as a water (H_2O) molecule is released. The carbon groups involved in the covalent bond point the same way in each glucose ring; this directs the three-dimensional shape of starch. The linked glucoses can either form a straight or branched chain, like a line of people holding hands, all facing the same way. When a chain becomes very long, the bond angles associated with the ring shape of glucose, and its α-configuration, allows the chain to hydrogen bond with itself. Hydrogen bonding is an electrical attraction which occurs between atoms which are, in a sense, more negative, such as oxygen, and atoms which are more positive, such as hydrogen. When a starch molecule hydrogen bonds with itself, it kinks up, adopting a helical shape.

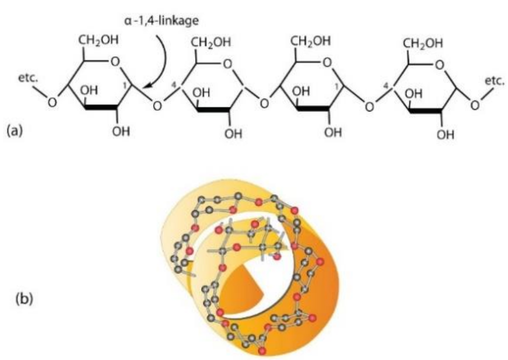


Fig 11: Structural formula and resultant three-dimensional model of starch. [17]

Because Frank spends such long hours in the lab, he usually ends up talking to himself. "Yes, the key is in the starch. If I can ruin the starch in Mr. Pearl's ice cream, I can ruin his business. But should I? . . ."

Both cellulose and starch are made up of only glucose molecules. Think of it like a stack of wood. The stack can be made into either a bedframe or a shed: both are made of the same thing but look and function very differently. Starch is branched and helical, can hold water, and can be broken down in the body by the enzyme amylase. Cellulose, on the other hand, forms into strong stacked sheets, nearly impenetrable by water, and cannot be broken down in the body—and can't even easily be broken down in the lab.

The apparently-minor difference in cellulose's structure is that it consists of β-glucose, with the alcohol groups on the first carbon pointing upwards on the first carbon, rather than α-glucose. In cellulose, then, the geometry between bonded glucose rings is such that each glucose is flipped with respect to the ones before and after it. This type of glycosidic linkage generates long and rigid linear chains of glucose. Then, strands of cellulose stack into tough sheets held together by hydrogen bonding.

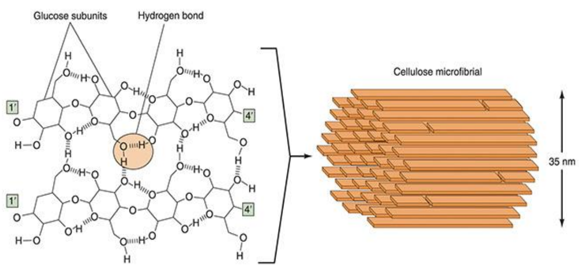


Fig 12: Linear chains of cellulose and their resultant stacking. [18]

"Because starch and cellulose are so similar in one way—in that they are made of the same building blocks, glucose—I can likely find a way to transform the one into the other. Because starch and cellulose are so different in another way—in that starch contains α-glucose, giving it a helical structure that can be easily broken down, whereas cellulose contains β-glucose, giving it a dense tightly-stacked fibrous structure that cannot be broken down—when I do find a way to transform Mr. Pearl's starch into cellulose, his ice cream will be utterly disgusting. Now to find a way . . ."

"But Mr. Pearl seems like such a nice man."

"But if I don't . . ."

Frank remained silent for the rest of the night.

Day 4

Mr. Pearl's Saturday started out fairly normally. He arrived at the Soda Pop Shop way before the noon open time to make fresh batches of ice cream—he was especially excited for this morning because he had a shipment of starch coming in—as well as coffee and a few sandwiches for display. Customers slowly trickled in: most were families stopping by for a light lunch before an outing to, say, the park or, a few towns over, the movie theater. It wasn't until the late afternoon that any of the young regulars showed up, but that was to be expected, as they tended to sleep in.

The girl clique made their way in first.

"Why hello there, Sue, Betty, Joana," Mr. Pearl smiled, "What'll it be today?"

Betty was the leader, so she usually ordered. "The usual. Cherry soda with a scoop of chocolate."

"Be right up. You girls go have a seat. You have your pick of the place today." Mr. Pearl turned to prepare their drinks. He knew they always ordered the same thing, but he asked every time anyway. By the time Mr. Pearl made it over to their favorite table, the girls were talking about all the new songs on the jukebox at Candy Co.

"Here you go!" Mr. Pearl slid their drinks over. "Oh! Wait a second. I forgot the most important part, the cherry topping! I'll be right back."

The girls couldn't wait for him to return with the maraschino cherries to dig into their desserts. Sue squinted. "Does your chocolate ice cream scoop look weird, Betty?"

"Yeah, actually. The brown scoop kind of looks like those knobby tumors that grow on tree trunks . . ."

"Mr. Pearl's homemade ice cream is always fresh. I'm sure it's fine," Joana convinced them.

When Mr. Pearl made it back, jar of cherries in hand, the girls' mouths gaped in horror. They had each just eaten a spoonful of chocolate ice cream. Except it wasn't chocolate ice cream. It couldn't have been. No ice cream any of them had ever tasted had been that dense. It had the texture of shredded wheat cereal, but with a woody taste. It was almost like taking a big bite of tree bark. . . Betty spit hers back into the cup, and the others followed.

"What's wrong girls?!?" The fear shined through Mr. Pearl's sparkly eyes.

"I'm sorry, Mr. Pearl, but there's something wrong with your ice cream," Betty admitted. She hated to see his smile fade.

"Oh my! I apologize! Here, let me get you another!" But, when he went to make them new soda floats, he realized the new scoops weren't any different. In fact, the whole tub was too tough to be edible. So was the tub of homemade vanilla. He apologized again and explained to the girls that the ice cream might have gotten freezer burnt. He refunded them, offering complimentary cherry sodas.

"That's okay, we didn't have much time today anyway. My brother's having a birthday party tonight, and we're all going." Betty got up to leave, and the others followed. Mr. Pearl, disheartened, asked Betty to give her brother his best wishes.

"I don't know what could have gone wrong. I guess I didn't seal the lid tight enough when I made the batch early this morning." Mr. Pearl threw all the chocolate and vanilla ice cream away and started on fresh batches.

He was still working on them when the rest of his regulars trickled in. When Johnny and Louise asked for root beer floats, he told them it would be half an hour or so until the vanilla was finished, and they agreed to wait. They had brought a board game to play anyhow.

Customers kept rolling in.

By the time the ice cream batches were finished, Mr. Pearl had a backload of orders: root beer floats for Johnny and Louise, malt shakes for Stacy and Jim, hot fudge sundaes for a handful of the kids who always come work on their homework during the week, and vanilla cones for a group of Boy Scouts who sometimes stop by after their troop meetings.

Sam and Mildred showed up as Mr. Pearl was handing out the last of the orders. They plopped down on their usual barstools. Sam got out her sketchbook, and Mildred got out her book. "Mr. Pearl sure is busy today. That's good to see."

Sam agreed.

Mr. Pearl was out of breath once he got back to the counter. "Hey you too! What'll it be?"

"Oh, just hot tea tonight. I want to finish my comic strip."

"And I want to finish my book!"

"Sounds good. Be right up." Mr. Pearl wiped the sweat off his brow with the back of his hand.

"Poor thing," Sam cooed.

When Mr. Pearl turned around to hand Sam and Mildred their tea, he saw a hoard of horrified faces. One by one, Johnny and Louise, Stacy and Jim, the homeworkers, the Boy Scouts—they all spit ice cream or milkshake back into their glasses and cones. Their disgust was palpable. Their complaints were the same as before: hard, fibrous, mossy-tasting. Like eating a chunk of bark. Mr. Pearl's heart dropped. How could he have messed it up again?

Nearly all of them crowded around the register at once, asking for refunds. Some demanded. Mr. Pearl apologized excessively, offering them complimentary soda and candy, but only a few took him up on it. All the others promptly left.

Amidst the chaos, Sam tried to ask Mr. Pearl what happened, but he couldn't hear her. Once almost everyone had gone, she asked, "Are you okay, Mr. Pearl?"

He had his head in his hands. "I seem to have forgotten how to make my homemade ice cream. It was my grandmother's recipe, you know. I'm doing her an injustice."

"Aw I'm sure it's not that bad. Could I try it?" Mr. Pearl gave Sam a scoop in a little bowl. The consistency was pretty chunky, but the taste wasn't as bad as everyone made it seem. Sam actually kind of liked the woodsy taste; it reminded her of the health smoothies her parents sometimes made her drink. "It's not that bad, Mr. Pearl. I'm sure it's just a minor mistake. I'll help you make new batches if you want."

"That's very kind of you, Sam, but I think I ought to wait until morning when I have a clear head. Plus, the shop isn't open tomorrow, so I'll have all day to work the problem out, if I can."

"We know you can, Mr. Pearl." Sam and Mildred convinced Mr. Pearl to at least let them help clean up before they left. The walk home was gloomy.

"I sure hope everyone forgets what happened today. Mr. Pearl knows what he's doing, and he doesn't deserve to lose his good reputation."

"Me too, Mildred."

They passed Candy Co on the way to their house. It was filled to the brim. Neither Sam nor Mildred could acknowledge it; they were too worried about Mr. Pearl.

Day 5

Both Candy Co and the Soda Pop Shop are closed on Sundays, but neither were empty.

In Candy Co, Mr. Walross and Frank met to discuss the shop's progress. "Whatever you did must have worked, Frank. Did you see how many of them poured in here last night? Good work."

"Thank you, Mr. Walross. It took nonstop experimentation after you assigned me the task, but I devised a chemical solution which transforms the glucose in the starch Mr. Pearl uses to thicken the milk in his ice cream from α-glucose to β-glucose. In doing so, I changed the starch, a digestible thickening agent into indigestible cellulose—the stuff that makes plants rigid and sturdy. In the reports from the private investigator you hired, I knew that Mr. Pearl was due to get a shipment of starch Saturday morning, and that he makes fresh batches of ice cream in the mornings. So, when I finished the solution around 4:00 a.m. on Saturday, I snuck over to the Soda Pop Shop and poured it all over the starch and then resealed the container and the box it was in. Mr. Pearl, as we see now, must have been completely out of starch and used this new container to make his batches of ice cream before opening yesterday."

"Genius, Frank. I knew I kept you around for a reason."

"Thank you, sir." Frank's stomach nearly inverted at the thought of what he had done.

"Keep this starch manipulation up, indefinitely. We'll snuff this old man out of business in no time."

"Yes, sir." Frank excused himself. He went to splash water on his blood-drained face in the bathroom. How could he have done this to a sweet old man?

. . .

At the Soda Pop Shop, Mr. Pearl tried all day long to make his homemade ice cream, the right way. Each time, it came out the same: hard as bark.

"I just don't know where I've gone wrong," he said to himself for the dozenth time.

He looked at the old photograph of his grandmother framed on the wall, next to the first dollar the Soda Pop Shop made back when it opened, and a tear melted down his face.

Day 6

"CLOSING IMMEDIATELY. It is with deep regret that I inform you that the Soda Pop Shop will be closing permanently. From the bottom of my heart, I wish to thank my loyal customers, rather, my friends, for their continued patronage, support, and friendship over the past few decades. Though I'm now going into immediate retirement due to unforeseen personal circumstances, I hope to keep in touch with all of you. Love, Mr. Pearl."

Sam’s jaw dropped. She and Mildred had stopped by the Soda Pop Shop on their walk to school to see how Mr. Pearl was doing. This was some of the worst news they had ever received. Sam felt as though she lost her grandfather all over again.

“I’m so sorry, Sam.” Mildred hugged her best friend.

“Me too, Mildred. Come on; we’re going to be late for class.” Sam wiped her nose.

. . .

Mr. Walross received the news before noon. He called Frank into his office. “You’re my star employee, Frank. I’m sure you’ve heard that Mr. Pearl has gone out of business and into retirement, as he should. You’ve been such a huge factor in the success of this business that I’d like to offer you ten percent of our stock.”

Frank’s jaw dropped. Not at the generosity of his boss’s offer but at the gravity of what his obedience had wrought.

He was in too deep now to back out now. His heart had hardened to bark, for it was either do that or break. “Thank you, sir.”

. . .

Monday night, all the former Soda Pop Shop regulars were instead at Candy Co, sipping soda floats, flirting, doing their homework, tether-talking, gossiping, dancing to the juke box, or whatever they usually did in the evenings at Mr. Pearl’s parlor, with the addition of pinball playing. To celebrate their business success, Candy Co gave out free bags of candy and malt shakes.

That is, all the former regulars other than Sam and Mildred. They were too sad. They tried visiting Mr. Pearl at home after school, but he didn’t come to the door. So, they went their separate ways and drew and read, respectively, in their own bedrooms at their own homes.

Amidst the glamor of the latest jukebox tunes in the shiniest building seen in Covington for the entirety of their lives, and amidst the fun of doing-something-new, the teens hanging out in Candy Co on that Monday night each, unknowingly, shared a private feeling. At first, they didn’t even notice, for they were too distracted by the lively atmosphere. But the ominous feeling was louder than the jukebox. Something that ran deeper than their sugar-induced bellyaches. They all felt a bit . . . synthetic.

Sam finished her comic strip that night . . . realizing that the fate of the Covington square may have come a bit sooner than 2000.

II. Recalcitrant Walls

Getting In

Thud, thud. “Nope, nothing,” said Sandy, carrying a walking stick, which doubled as a tool, in her slightly-sweaty hand.

“Let’s just push a little further down the tree line.” Gabe carried a map rather than a walking stick. He was equally sweaty, though.

“There’s got to be a break in the wall somewhere,” agreed Shane.

They had all backpacked as far as they were allowed, as far as the government deemed safe: to the outer wall of the Societal-Improvement Zone. Now, thanks to the Beautification Act of 2030, the wall, which was once made of unsightly concrete, had been torn down and replaced by a tree wall in order to join seamlessly with the rest of the wilderness in the outskirts of the cities. Though the replacement wall had been impeccably engineered, guards kept watch over it from forts scattered along the tree line. The purpose of the enclosing wall, we were told, was to protect the nation’s citizens, by keeping industrial hazards like noise, pollution, and heavy machinery out of the cities. The Societal Improvement Zone also held a group of industrial factories and farms, consolidated and run by the government to systematically improve efficiency and reduce cost. Some parts enclosed wildlife reserves along the wall’s inner rim. It also contained the drilling site for a huge oil reservoir, in the middle of the country, that had been discovered right before the Zone was established. The reservoir was the saving grace for the most recent oil crisis, which had people walking dozens of miles to work every day. Petroleum is extracted from the reservoir and refined into gasoline, which is then sold to gas stations outside the wall.

By taking all of the dirty work outside of the cities, the wall has given them the room to grow, which they have at an unbelievable rate. Of course, when the concrete wall was first replaced by the tree wall, the guards had to fend off intruders by the hoards, but once the initial wave of daring kids, fed-up taxpayers, and anarchists realized that trees, too, can be impenetrable, the border situation had quietened down tremendously. Many people almost forgot it was there, and by then a generation had grown up with it. Sandy, Gabe, and Shane are three members of that generation—except they hadn’t forgotten history, nor could they accept the wall as just another feature of their national landscape. They were too curious.

“I’ve read whispers in online forums about cracks between adjacent wall segments. We’re really close to the latitude of one of them. It’s one of the few I could jot down before the post was deleted.” Gabe had one eye on his map and the other on his notes and somehow still managed to walk in a straight line. Gabe was the most dedicated and the most methodical of the group, but Sandy was the most daring.

“Yeah, it was probably deleted for a good reason, Gabe…” Shane, hobbling along behind the others, was the least daring. He had been friends with Gabe long before Sandy had come along and put all these crazy ideas in his head in their gen. ed. history class.

"We've been hiking all day, Shane. We're not wimping out now." Though Sandy could get a little impatient with him, she still liked Shane: he was fun to mess with, and he was Gabe's childhood friend, after all.

Just as Sandy was about to drop her walking stick in front of Shane to playfully trip him, he shouted, "Wait! I think I found something!" Sandy and Gabe looked at each other doubtfully but turned back anyway, going along with it when Shane told them, "Here, feel this." Turns out Shane was useful after all. When they patted their hands on the part of the wall at which he pointed, their fingers disappeared through the foliage.

Sandy was, of course, the first to stick a leg in. "We'll have to leave our backpacks here, but I think we can make it through." Shane wanted to grab onto her arm, yank her out, and ask her to give it a second thought, but his guilt in being the one who discovered the door to danger was overshadowed by his pride in having been a catalyst for adventure. Plus, Sandy was already gone.

The three walked in sideways single file, barely able to hear one another in the nearly-2D crevice. Their bodies felt pounded out like aluminum foil, as they tip-toed on and on, now searching more for a place to breathe than anything.

Finally, they reached a thin junction. Another perpendicular crevice formed a crossroads with the one down which they walked. Their lungs filled to the brim.

"Maybe we should turn back," Shane inevitably admitted his hesitation.

"Nope, things are just getting interesting! You can go back and keep watch of our backpacks if you want." Sandy was hastily getting back into the sideways single file position.

Though Gabe patted Shane on the back consolingly, he nonetheless yelled, "Wait, can you take my map back with you? It won't do us any good here—we're in the blacked-out region. Thanks bud, good luck out there!" as Shane turned to leave the Zone. Shane nodded and shoved it in his pocket.

Gabe ran sideways, as best as he could, after Sandy for a long time. They passed a few more intersections before stopping to catch their breath. "Wait a second," Gabe interrupted their panting, "it feels like we've been here before."

"Yeah, you're right. It all looks the same as it did half an hour ago. Let's risk getting a little off track and turn right at this intersection."

"That's a good idea." Gabe turned to follow her. Once they reached the next intersection after turning, though, everything still looked the same. "Are we in a maze?"

"I think these are just repeating units…that's odd. It's like they sectioned off garden plots." Sandy felt nervous for the first time during the trip, and she didn't know why.

"Oh, so the path traces out square forest-chunks, like a bunch of big plant cells?"

"That's an interesting way of putting it, but, yeah, I think you're right."

“Maybe we should start tapping on the walls as we walk by to see if we can figure out a way to get inside.” As soon as Gabe said that, he noticed a small hole in the wall, close to the ground, a few feet ahead of them. He looked around to find a few more. They had been so scrunched up while walking that they hadn’t noticed these tiny pores. All of them were closed, though, except the first one that drew Gabe’s eye, by chance. “Sandy, look at that!”

“What? I don’t see anything. Oh! Wow, good eye. I know we’ve done well in these corridors, but I don’t know if we’re gonna fit through that…”

“Want me to try first?”

“Of course not! Don’t you know me?” It took some configuring and reconfiguring, but Sandy managed to lie on the ground. She then squeezed herself inward like beef jerky and used her arms to pull herself through the opening. “Ew, it’s slimy, Gabe!”

“I guess I’m about to find out for myself.”

Sandy didn’t hear him. She was on the other side of the wall, wiping the gunk off her clothes and trying to get her bearings to stand up with generous breathing room for the first time in a few hours. By the time she collected her balance, Gabe joined her. “Oh my.”

. . .

Shane, who stopped to breathe at every intersection, decided to go back to his friends but got a bit lost on the way, and so turned back around toward the exit, had just now made it to the backpacks. They were in the same disarray as when they had been left behind. Shane could relate to that.

He plopped down next to them, leaning against the wall and hoping the nearest guards, who were miles down the wall according to that forum post Gabe found, wouldn’t decide to patrol today.

. . .

Sandy and Gabe both gasped and jumped back. Right in front of them, where Sandy’s foot had almost been, was a small but ankle-twisting hole in the ground, out of which spurted hot steam. It wasn’t the only one, either. The enclosed area was so pitted they were going to have to hop around to get anywhere. Where the earth wasn’t scarred, there were strange organelle-like machines set up. Their function was a mystery.

“Okay, we have to be really careful if we’re going to get around in here without losing a leg.” When Gabe looked over at Sandy, she was effortlessly tap-dancing around the holes, and he just rolled his eyes. He followed her path, as she had already found the firm spots, though not as gracefully. They stopped to take in the whole panorama once they reached the middle of the cell. “These tree walls sure do look strange—kinda hazy. Like they aren’t real. I mean, how could they naturally be so tall they’re almost blocking out the Sun?”

“But why would the government waste all this money on fake trees, Gabe? Isn’t the point of this outer section of the Zone to preserve our woodlands?”

"I don't know. It just doesn't feel right."

"Come on, we've got more to see, not feel."

They took their time lobbing over the rest of the pits on the way to the far side of the wall. It's a good thing they did, or else they might not have noticed the brownish-green ladder, which appeared to have infinitely many rungs but nonetheless leaned inconspicuously against the brownish-green wall.

They looked at each other knowingly. Neither of them gave it a second thought: they had to figure out where in the wall they were. Once they reached the other side of the enclosure, they began their ascent. Sandy let Gabe go in front this time. They were mostly silent as they slowly rose, rung by rung, though they did whistle some to pass the time.

Somewhere on the way up, they stopped to rest. Inspecting the wall close up, they could see further through it. Inside was a thick matrix of trees and the vines which intertwined them, in an apparently mutualistic relationship, for both with health.

When they made the mistake of looking down, their hearts dropped, but thankfully their hands didn't. "It's a good thing Shane didn't come with us. He wouldn't be having any of this." Sandy embraced the ladder tighter to protect herself against a strong gust of wind that swept by them, hoping Gabe wouldn't slip and fall on top of her.

"Oh yeah, I hope he and the backpacks are getting along all right."

"He's probably wondering if we're ever going to come back."

"Yeah, I've wondered that too…" Gabe sounded exhausted.

"We'll make it just fine. Let's get to the top of this wall, figure out what kind of maze we're in, and then start our trek back."

"That sounds good. I could use a nap in my tent."

They started to climb again. The Sun was nearing the horizon by the time they reached the top, now both standing on the same rung, which meant it would already be pitch black down in the trails. At first, they couldn't take their eyes off the sunset. Because the wall interrupted the view of the sky even from the city, they hadn't seen this much of a sunset, well ever, and they were enchanted. But, when their eyes drifted down from the sky, their jaws gaped. The harsh contrast—between the tearfully-beautiful orange-turned-hot pink-turned-yellow sunset and the rows and rows and rows of wasteland divided up like a spreadsheet beneath them—took their breath away more than did the entire lung-squeezing journey through the maze.

Finding Out

The wall-enclosed units weren't just like plant cells: they essentially *were* plant—rather, forest—cells. Unlike plant cells, though, they weren't organic. The walls and organelles in each were the exact same, down to the last pixel. Except for the enclosure right next to them. It resembled a screen that had flickered out; only a dim, unreal shadow of the cell remained.

This wasn't a woodland reserve on lockdown in the outskirts of a dangerous consolidated industrial area. It was a fake forest: duplications as far as the eye could see of a single cube-shaped cake slice of a simulation called the Plant Cell, first typed out as thousands of lines of computer code and then hosted at an outdoor site. The Plant Cell is now the basic unit of forest life in the Zone, where the land was depleted. Though its thick walls keep it hidden from the public, the simulation cannot cover the damage that has been done to the ground. Like the cell they were still in, the ground in the next, and all the rest, was torn up with holes which reached down to the heart of the Earth. Though neither wanted to mention it, Sandy and Gabe recognized these from the geology textbook they shared as core samples, taken in search for oil pockets. The oil reservoir which had staved off the most recent oil crisis, of many, must have been running on empty. Why else would the once-lush landscape be so peppered with desperate attempts to find more? But that was too dark to say out loud.

Sandy clung to the ladder and ducked her head under the wall, pulling Gabe with her. “Shhhh!”

“What is it, Sandy?” They peaked their eyes just barely over the wall, and they saw a man in a white lab coat. The walls have small openings called plasmodesmata, which only unlock for people who have permission to be there. The reason it was open today is that research was being done on the wall.

They overheard the scientist talking on the phone to his supervisor. He must have still been a graduate student because it sounded like he was taking an oral lab exam. “Yeah, everything looks like the microscopic plant cell wall, in which cellulose microfibrils—the thread-like bundles of stacks upon stacks of hydrogen-bonded glucose chains, which constitute cellulose polysaccharides—are tethered together by hemicelluloses—any polysaccharides in the cell wall which are smaller than cellulose: in this case, the hemicellulose we've used as a model is glucuronoarabinoxylan, because that's what we found in the cell wall experimentally. The microfibrils and the tethers together form a cellulose-hemicellulose network within the cell wall's carbohydrate matrix, giving the cell wall immense strength. In the simulation here, the vines, playing the role of hemicellulose, leash together the trees, or microfibrils, in a tight bond which makes the wall nearly impenetrable, which we need it to be for the protection of the public. It appears that all the code in this test run is correct, and we're ready for the official test of this remodeling we've done to make our wall more like the plant cell's in order to test its strength. So I'll get out my strength-testing equipment, and then all systems go.”

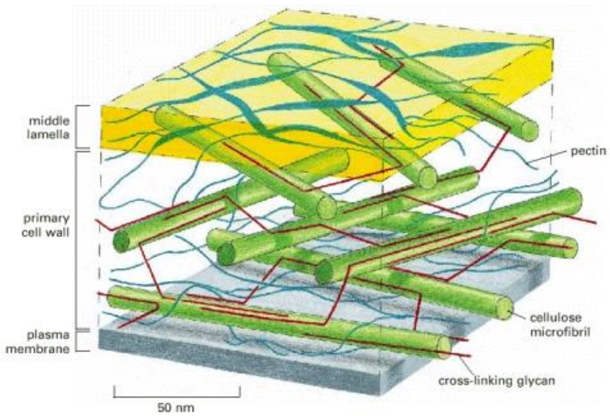


Fig. 13: Molecular structure of the primary plant cell wall. [7]

Sandy and Gabe ducked back down when the student researcher hung up the phone.

Gabe whispered, “They’re modeling these walls off the cell walls of plants so that they can be just as impenetrable, on our scale... You know—and I didn’t want to point out those holes, which we both know are sad attempts to find oil—but the reason that plants can’t yet replace gasoline is that the strength of their cell walls make them so difficult to break down that harvesting the energy potential in their structural sugars is impractically-expensive.”

“Yep,” Sandy said, “I remember studying that in biology. Isn’t that phenomenon called biomass recalcitrance?”

“It is. If it wasn’t such a technical setback, engineers wouldn’t even have to dig up the ground because we would be using biofuel instead of gasoline,” Gabe sighed.

“We’ve been massively-fooled.” Sandy’s angry face resembled a beet.

“In the future, there won’t be any more forests, if we keep doing what we’re going. Heating our Earth until the trees melt. No, not if we work against rather than with them, returning the oxygen they give us with so much of the carbon dioxide they need that their, and our, home becomes toxic. Not if we exponentially-deplete all our resources, digging up our land for gasoline-ingredients and then just paving over the scars. Then, in place of the few woods we have left we’ll have only these faux-forests. Simulated Earth.” Gabe’s head hung.

“We have to get back as fast as possible and tell Shane, although, it’s going to be hard to convince him we didn’t just faint from a lack of oxygen in that tight maze and hallucinate all this. You know how Shane is; he won’t interact with anything physically dangerous, much less mentally. He’s too afraid of getting hurt.”

“If we struggle to convince our friend, who was right on the edge of all this with us for a while, imagine how difficult it’s going to be to convince anyone else. And even if they do believe us, they’re not going to want to risk getting themselves in trouble…” Gabe’s disappointment turned into nervousness.

“We have to try, though. If we do nothing, this problem is going to keep encroaching until there’s nothing natural left on Earth. This is our future at stake, for all of us. We have to reveal the truth." Sandy was nervous too, but she knew this was too important to cower away from. She started down the ladder.

"You're right. We don't have a choice…"

Sandy and Gabe navigated their way back through the maze.

—Will the public keep a wall over its eyes?

III. A Golden Molecular Mean

Preliminary definitions

1. Carbohydrate: an organic compound, such as any sugar, which contain carbon, hydrogen, and oxygen, with a hydrogen-oxygen ration of 2:1
2. Cellulose: a carbohydrate made up of linear chains of repeating glucose molecules, often stacked into sheets which can bundle into threadlike structures called microfibrils
3. Hemicellulose: a class of plant cell wall carbohydrates which have a simpler structure than cellulose
4. Primary cell wall: the inner portion of the plant cell wall, consisting of cellulose, hemicellulose, and other structural carbohydrates
5. Radius of gyration: an approximation of the area about which the center of mass, or the average position of the matter in an object, freely moves
6. Persistence length: the length over which a structure retains its correlation; quantifies its stiffness

. . .

A young tree sprout in the great big woods,

If she grows up too tall and close to the Sun

She'll wither, melted for good.

That'd be no fun.

On the other hand, if she's not tall enough,

Where she stands,

By her crowded neighbors she'd be snuffed.

There is a demand,

If her blooms are to beam.

As the saying goes,

She must remain within the happy mean

From her cells to her toes,

All through the little tree,

Inside and out,

But in her primary cell walls, especially,

If she is to have clout.

Within the plant cell wall,

Are many components:

Cellulose microfibrils, first of all,

For which hemicelluloses are proponents.

One such hemicellulose is glucuronoarabinoxylan, or GAX,

Which protects cellulose with a leash,

Tethering microfibrils to form pacts,

So each cell wall component stays in its niche.

Now, the mechanism for this strength-building is unknown.

If GAX goes too close, cellulose pushes it away,

As their atoms will moan.

But, like a limp noodle GAX'll stay,

If it's too far.

Hence, Goldilocks we must station,

For GAX is like a firefly in a jar.

There's a property called the radius of gyration,

Approximating the area about which the center of mass freely-moves.

The radius for GAX alone has a wide distribution,

But when GAX and cellulose get close, as they may choose,

You can see its evolution

As the radius of gyration shoots up like a post,

which means, at most,

GAX has only fixed wiggle room.

Its flexibility is lost as its cellulose-contact yields strength,

Allowing the little tree to grow sturdy and bloom.

There's another property called the persistence length,

Which is the range over which the structure retains its correlation.

When GAX is on its own,

It takes a vacation:

Its persistence length decays, as my research has shown.
This means its structure is lost over time.
But, when it approaches celluloses to make a deal,
Its form is fine,
And way up its persistence length is reeled.
Again, this result shows
That the reason GAX and cellulose form a pair
Is that, somewhere deep down, GAX knows
That, together, they are as tough as lumber built into a chair.
Indeed, within the Goldilocks zone,
GAX-plus-cellulose is as strong as a bone,
Just as the young sprout will have grown.

APPENDIX: Selected Scientific Short Stories

I. Charles Bukowski

Sydney Smith

March 3, 2014

If I could have told myself. I wouldn't have. But if I did do what I wouldn't do, I would have said this.

Charles, you are *born into this*. You will be the fly trapped in the web of the spider. His web of pain causes your web of pain that lasts even after his death. It's the cycle of life. There is no escape. You will learn how to survive without asking for mercy—because you won't receive any from your father, who begged for it through what he did to you. He was too weak to do it any other way.

You will lose yourself—or find it—in rebellion to him. In rebellion to society. In rebellion to existence.

You will escape your home and go to college and drop out of college to become a writer because normalcy—family, nine-to-five, sobriety—offends you. Ironically. In the cold and mechanical face of rejection, you will become a part of what you loathe: humanity. Twelve years you will spend staring at stamps and envelopes carrying written messages of hope and good will and best wishes to addresses that have none and, you know, will find none. At least that's what you see. That's what your glass is half-filled with: no hope. Jaded. You will long for death and seek it—ferment in your desire to suffocate in its froth--but froth it will not, for *death doesn't always / come running / when you call / it, / not even if you call it / . . . from the best bar on earth*. [19] You've mastered endurance, though, too much to bring yourself to end yourself, yourself.

The stomach ulcer should be your first warning. Or will it be the bait swinging back and forth, back and forth in front of your face? No, no. That will come when the love of your life drowns in the same poison you swim in, trying so hard to sink.

The poison is ethyl alcohol and, once you pour it into your body, is stripped of two hydrogen atoms by alcohol dehydrogenase, forming acetaldehyde. The molecules don't look that different, but what do you know about looks. This is just what the doctor will tell you, but obeying never did you any good before, so why should it now. The acetaldehyde is further oxidized to acetic acid and eventually carbon dioxide and water through the citric acid cycle. The hydrogens reduce NAD^+ to NADH. The excess NADH is used to produce lactic acid, leading to acidosis from buildup of lactic acid. The NADH can also be used as a reducing agent to synthesize glycerol and fatty acids, causing fat production in your beer belly. When your liver is saturated with acetaldehyde, it leaches out, intoxicating you by inhibiting your mitochondria. That relaxed, giddy, angry, depressed, fuzzy, buzzy, thoughtful, confused, uninhibited feeling reflects the damage being done to your poor little dendrites, slowing your brain's ability to convey messages between neurons. If you go really far, you could even lose a few neurons and a few memories. But not the bad ones, though. Those stay. Because alcohol is a zeroth-order reaction, it has a steady state rather than a half-life metabolism because the breakdown of the toxin creates another toxin, slowing the process.

The poison may help you write about the pain, but it only adds to it. You won't stop, though.

You will sit in and foam in and ooze through the gutters of life—the dulled stupor brought by dishwashing, truck-loading, truck-driving, mail-carrying, parking lot and gas station and bathroom-attending, stocking, clerking, elevator-operating, slaughtering, poster-hanging, cookie-packing, living—coming to a complete understanding of the common man. You'll know it's complete when you can describe him in feelings and in words.

Early in life you will come to know groundless pain; why will you later cause yourself more discontent after you've escaped? I'm you, and I still don't know. Scratch that with your dulled pencil. I do know. You can't see that there is a way to transcend the bane. And the pain. Of life. You see the poet's role as that of a fly, but if you're a poet, why can't you see that the way to heal the acne scars of pain is to really feel it without the numbness of alcohol, without the adrenaline of violence, without the nothingness of post office work. You see the poet as anti-courageous in real matters, anti-courageous in the sting of the apathy of nature. The sting of the apathy of the fangs of the spider who pierces your back and won't let go.

But I've already said that you've learned how not to ask for mercy.

And I said I wouldn't have told myself that. Even if I could. Because I wouldn't change it.

I was am will always be

the fly.

II. Microbeads

Sydney Smith

October 1, 2013

The Calchas of the zooplankton clan speaks:

"Listen, Iphigenia. The humans, through their exorbitance, have begun to include microbeads in their scrubs. For them, the benefit is rejuvenation; for us, the opposite is true. Their extravagance brings our demise. The polyethylene beads they have created possess toxins—such as phthalates, added for malleability; colorants; polybrominated diphenyl ethers, added for heat resistance; and plasticizers—that can directly harm us. Further, because these evil globes are hydrophobic and possess a large surface area relative to their volume, they are likely to acquire additional poisons, such as those present in our ocean: polychlorinated biphenyls, dichlorodiphenyltrichloroethane, and polycyclic aromatic hydrocarbons—as well as toxins from common sources such as coolant fluids, automobile grease, copy paper, fluorescent tubes, and industrial waste. These chemicals can cause us great harm such as disrupting our endocrine system and growth as well as causing cell mutation, fecundity, and even death... I see it now: the stomach pain, the writhing. Yes, this will destroy you. Your body will mercifully stop functioning, but—before—you will suffer. The beads will adhere to your antennae and your swimming legs on the outside of your body and to your gut on the inside. You will not move—not even from a predator; you will not eat; you will not mate; you will not feed. You *will* die."

"And this is necessary?" Iphigenia, albeit raising the pitch of her voice at the end of her sentence, meant it as a statement of fact, not as a question.

"I'm afraid so, my dear. But think of what your sacrifice will do. Think of what it will show."

"The humans will see. They must. They have to—or else my life will be wasted for nothing."

"Don't worry, my child, they will hurt; then they will see. Humans are that way; they must be affected. But, as I have said, once you ingest the accursed beads, you will die. Then your body will be consumed by a small fish; then that fish will be poisoned by what will poison you. The small fish will be eaten by a larger fish. The larger fish will be caught by a human. The human will fall ill. He will face endocrine and nervous system disruption, and cell mutation, among a range of other health defects—perhaps even death."

"'What if the fish escapes the human,' they all ask me. But I believe in your vision, Calchas. You have seen the truth."

"You are wise, young one. That is why you must be the one to go; you understand. You understand the damage the bio-accumulated toxins will do to the human's body: that the land-dwellers will realize that the human has been poisoned. But they will not know why at first. Once they seek the answer, though, they will find it. And once they know that the damage they are doing to our ecosystem also affects theirs, they will cease—slowly, but they will cease."

"It will take a long time to reverse what they have done here, even once they stop washing microbeads down their drains, through their water treatment plants (which cannot even catch the evil spheres), and into the ocean. Our ocean."

"Yes, it will, and that is inescapable. But our clan—superior, it is—will move to better waters, which I hope to exist beyond these. We will warn the other clans of our kind, who already consume the counter-food, for they do not possess the knowledge that I do. Then, we will leave. We will avoid the microbeads while we can, but only our millionth decedents will see even a slight drop in the evil floating in our waters. But the healing must begin now."

"Yes. I am ready." Iphigenia, unafraid, ingests one, then another, and so on. Until she cannot fill her body anymore, she ingests the poisonous spheres—welcoming death. And life. Not for herself; for those to come.

III. Precariously-Stacked

Sydney Smith
10 November 2016 (edited in July)

Speak, Shakti—
Oh Form of Mother Nature.
Fertile source of all life and holder of all cosmic energy
Creator of change, gentle prime mover,
Wavemaker on a sea of potential.
You whose essence manifests in the material world as the unchanging Moon,
On whose face all natural laws are engraved.
Speak
Of Parvati, the goddess of love and devotion,
Who lives through you.
The embodiment of your motherliness,
Who nurtures the Earth and guards your secrets.
Speak
Of the people over whom Parvati keeps loving watch,
As they grow wiser, more curious,
Challenging Parvati in her duties,
Inevitably transforming her into her dark aspect, Mahakali, goddess of time and death,
Who emerges in crisis,
Protecting your secrets at all costs.
Speak, divine mother,
Remind the people, the scientists, why they now must struggle.

Our earliest ancestors knew that the face of Shakti—the Form of Mother Nature, manifest in two goddesses—welcomes all who will look, though her timid smile shines only in the night sky, when darkness veils her. Alas, the people of antiquity spent many nights gazing at her face, for they knew that the secrets of the Earth are folded into her pores. They studied her until they found the way in which they could learn: inconspicuous numbers are engraved onto her face. The people grew keen, as they began to abstract meaning from this set of numbers which forms her face: meaning manifested as sequences in this infinite set of numbers. The individual's own initial conditions determined which sequences they abstracted. Meaning was disentangled from her face and twined to the soul.

“It is time for the people to wake,” said Parvati the goddess, who resides on the Moon. The manifestation of Shakti’s nurturing aspect, her job is to care for all living things on the Earth and to preserve the secrets on Shakti’s face.

As Parvati gripped her fingers onto the Moon’s craters, pushing it down in the sky and directing the Sun to rise, she thought to herself, “This daily task, though a labor of love, never becomes less arduous.” Parvati started every morning in this way, energizing the Earth. At night, she catalyzed dew’s formation, watering the land, and conducted the locusts in their peaceful hymn.

“Bless these seeds, oh Shakti,” Parvati prayed, “anoint them with possibility, growth, and hope.” She kissed and then dropped the seeds onto the Earth, nourishing them as they sprouted and taking pride in their development.

This routine went on for many years. Though the living things on the Earth evolved over the generations, Parvati’s duties remained the same, as did her loving affection for all life. As the centuries passed, the people continued to study the Moon. They gained familiarity and a sense of intimacy with Shakti’s face, though they met great difficulty in discerning the numbers within her pores. So, they began to construct. Tree-climbing was insufficient to magnify their view, so they contrived their own heightened-trees by hacking down sturdy ones, digging deep ridges into their trunks to form steps, and, over time, finding ways to support additional trunks atop the base. Of course, this primitive ladder could not stand on its own, so they buried it deep within the ground, supporting it with the heaviest rocks they could push. With the sustained effort of the people, the heightened tree grew and grew.

Parvati kept close watch. “The function of ladder height is additive, meaning the people’s approach grows exponentially,” she brooded.

Now the whole world had one language [of science] *and a common speech.* [20]

“If the clever people, of whom I take loving care, discover how to extract meaning from within the Moon’s craters—thereby cumulatively unraveling the secrets Shakti has so tightly swaddled within herself—she will soon be empty. As her pores hollow, her face will pit and crumble.”

The more Parvati worried, the redder her eyes grew, and the closer to the sky the people grew.

One morning, after completing her most demanding chore, the sunrise, Parvati boiled, “I am indispensable to the living; how could they threaten my post this way? They could do nothing without my care! I’ll show them what it’s like to lose me!” She gripped the Moon once again, but on the opposite side this time, as she intended to push it back into place, forcing the people into eternal darkness.

Right as she sunk her fingers into its craters, though, her eyes rolled back into her head. All her limbs tightened as her muscles contracted haphazardly, and she began to convulse, choking on her breath. Her wet, snaky tongue drooped out of her mouth, revealing lengthening fangs under her reddening lips. Her hair tangled into a dark thorny mass. She heard a popping noise, which she hoped was as far away as it sounded. Four extra sets of arms sprouted from her back, like the seeds she so lovingly planted on the Earth. A shrill scream leaked from her still open mouth, rattling her tongue.

Her eyes, now glowing embers, returned to their place.

Parvati’s rage induced her total transformation into her dark form: Mahakali. In a trance, she relinquished her painful grip on the Moon and returned to her post, completely forgetting she was once Parvati. She looked out over the vulnerable people, who were not yet awake.

“I must not allow their pursuit of knowledge to be a cumulative enterprise. Scientific truth cannot cumulate like plants growing atop a mountain composed of their ancestors,” Mahakali snarled.

If as one people speaking the same language they have begun to do this, then nothing they plan to do will be impossible for them. [20]

By nighttime, she had made a plan.

“No, science must be like a crystal which has mutated over and over, growing in a new direction each time, so that if the precariously-stacked crystal atoms were relied on to support anything heavier than the hearts of men, the entire structure would break.

“Like so, I will morph the pursuit of knowledge. The people are defenseless against my power,” Mahakali decided, with laughter.

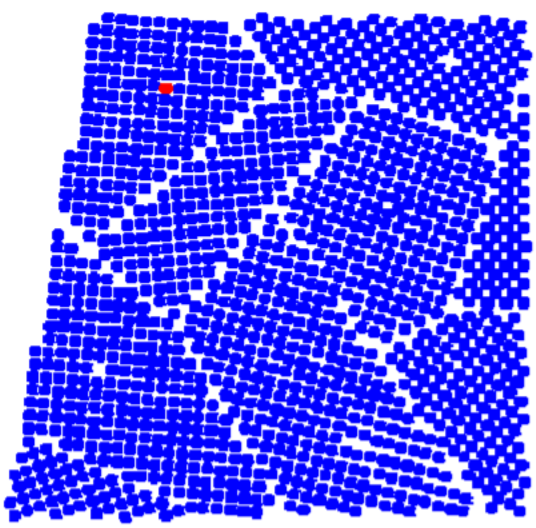


Fig. 14: A mutated crystalline structure. [21]

Mahakali commanded the clouds in the night sky to ring ear-shattering, knee-buckling thunder and shoot jagged lightning onto the ladders, destroying the people's efforts. She heartlessly scattered the people among the Earth, splitting up families and sects, *confusing their language so they would not understand each other*. [20]

She made incommensurable the theories each group had concocted regarding the sequences hidden in Shakti's pores.

"From now on, a group of language-sharing people may find each other, join together, and articulate a scientific theory about a sequence they found within the series of numbers hidden on the face of the Moon. This I cannot stop.

"However, the growth of their science will no longer be linear. After developing a theory, they would, with tunnel-vision, interpret all other number relations in light of the particular knowledge basis they continually-developed. Some may eventually uncover fracturing inconsistencies within the theory and question it. These few will continue to find anomalies, widening the crack and ultimately leading them to develop a new theory, which they believe better fits the given sequence of numbers.

"The followers of the old theory will not comprehend the new theory, for the two are like incommensurable numbers within Shakti's set: their ratio is irrational. The two numbers cannot even be measured by the same ruler, nor can the two theories. One must choose a theory to follow by the gut. [22]

"These impediments, though divisive, may inspire the people to work harder to uncover the secrets so fiercely concealed from them. But, they cannot get past me."

Mahakali's job was done, and her body melted back into Parvati's. Because of the difficulty in developing and communicating sequence abstractions after Mahakali burned the ladders and jumbled the languages—and the resulting jump from theory to theory in science—the progress of knowledge acquisition slowed greatly. The process has been hindered ever since. From then on, science grew not like plants atop a hill but like a tornado, meandering and circling about itself.

Parvati resumed her affectionate care of the people, without any memory of what they had forced her to do, and without any remains of the pride which reduced her from mother to aggressor. She had only some inkling of a moment of exasperation, in which she considered hurting the people of Earth for whom she felt so much love, and had fainted out of unbearable anger—a moment of which she felt deeply ashamed and to which she vowed never to return. She has not returned to that state since.

The secrets of nature in Shakti's pores are encrypted, for now. Though, through Mahakali, she certainly encumbered the people's progress toward the essence of Mother Nature in order to guard her well of cosmic energy, they were quite stubborn, and so are their descendants: us. Who knows what with time we will discover, even if the staircase to the Heavens is a spiral one.

IV. The Beauty in a Waterfall

Sydney Smith

20 March 2017 (edited in July)

"Day and night, aloof, from the high towers

And terraces, The Earth and Ocean seem

To sleep in one another's arms, and dream

Of Waves, flowers, clouds, woods, rocks, and all that we

Read in their smiles and call reality."

—Percy Bysshe Shelley [23]

The three waterfalls told me a story. As I sat on a mossy rock, arms hugged tight around my knees, they told me a story of nature. A story which rode the mist, soaking into my lungs.

I asked them, "Why is a waterfall so beautiful?" But they had another question in mind.

Before even seeing the falls, I could hear their constant, throaty shhhhh preparing me to listen to their story as I hiked toward them. All at once, the horizon line became white, as the three God-sized waterfalls could not help but seep through the tree gaps. I forged my way down the slippery, rocky trail like I was walking on buttery corn-on-the-cob with a few bites missing. I trekked until reaching a suitable rock: decently flat and with a prime view of the falls. About equivalent to the perspective of watching a movie from the second row of the theater. Except that there was a raging river sweeping by between the view and me. The falls' audible power seeped into my ears, taking residence in the space my own thoughts had occupied. It was time to listen.

From afar, a waterfall's beauty is in its massive power—the total conceived at once.

But, to consider why, I must peer inside. I shift my focus from the sum to a handful of water droplets. What I see no longer resembles a waterfall: rather, a chaotic path of descent. The fast, unwieldy spurts trace out sporadically-intricate patterns. The waterfall's character is exposed, with sinewy ligaments holding together the bare bones of its essence.

Hence, each individual droplet is a necessary but not a sufficient part of the whole waterfall's beauty. A discrete component of the waterfall, a droplet is a separate entity in itself. When a waterfall is quantized, its behavior changes radically.

The falls whisper, "Think of the electron."

From afar, the electron has power in the uniformity of its arrangement within the atom, understood by the Bohr atomic model, and the predictability of its interactions with the electrons of other atoms, deciphered using a Lewis structure. In the Bohr model of the atom, the nucleus is analogous to the Sun, with electrons—planets—revolving around it in discrete circular orbits generated by an electrostatic, rather than gravitational, attraction. The Bohr model operates under classical mechanics, which describes the motion of macroscopic objects. In a Lewis structure, the valence electrons, found in the outermost orbit, are drawn as dots around an abbreviation of the atom's name. This diagram provides a consistent method for deciphering the interactions of valence electrons in different atoms.

From a distance, electrons behave reliably, as does the sum of a waterfall in its power and common path. Up close, electrons are sporadic and complex, like a single droplet within the fall.

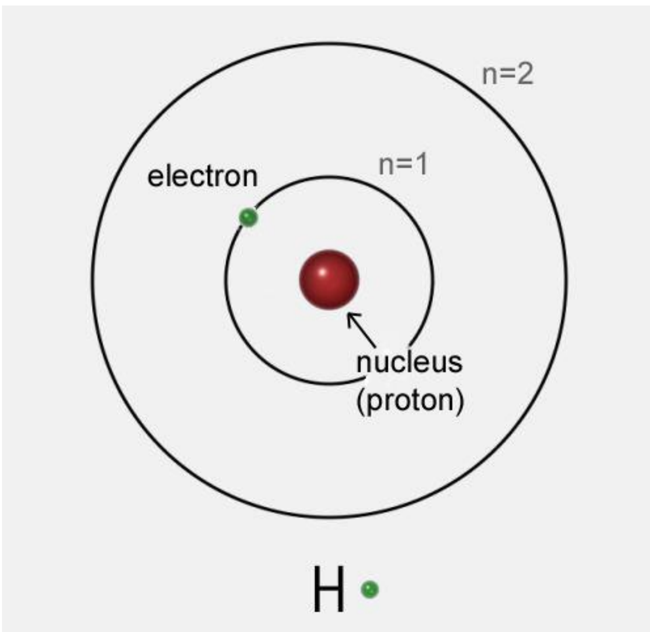


Fig. 15: A sketch of hydrogen, with its Bohr atomic diagram at the top and Lewis structure beneath. [24]

Classical mechanics has given way to quantum mechanics as the best system for understanding the very smallest bits of nature, for the time being. In quantum mechanics, electrons aren't so predictable. Electrons act not like everyday particles but like particle-wave hybrids, with both particle and wave properties. Water serves as an approximate example of this paradox: when a droplet plummets from the falls, the water appears to display a particle nature, but when it hits the river its reverberations demonstrate its wave nature, though still made of the same matter. Further, measurement of quantum objects is inherently inexact. The Heisenberg uncertainty principle imposes a fundamental limit on the precision to which complementary properties, such as position and momentum, of the electron can be known. If a particle's momentum is measured in a lab, then its position cannot be found: one complementary property hides the other. A quantum mechanical electron travels not in a circular orbit of the Bohr model but within a region, described by an atomic orbital, surrounding the nucleus. An atomic orbital is a mathematical function used to calculate the probability of the electron residing in any given area around the nucleus. Hence, in the quantum mechanical atomic model, the electron's location is probable rather than certain. An electron resides in a metaphorical atmosphere rather than a planetary orbit.

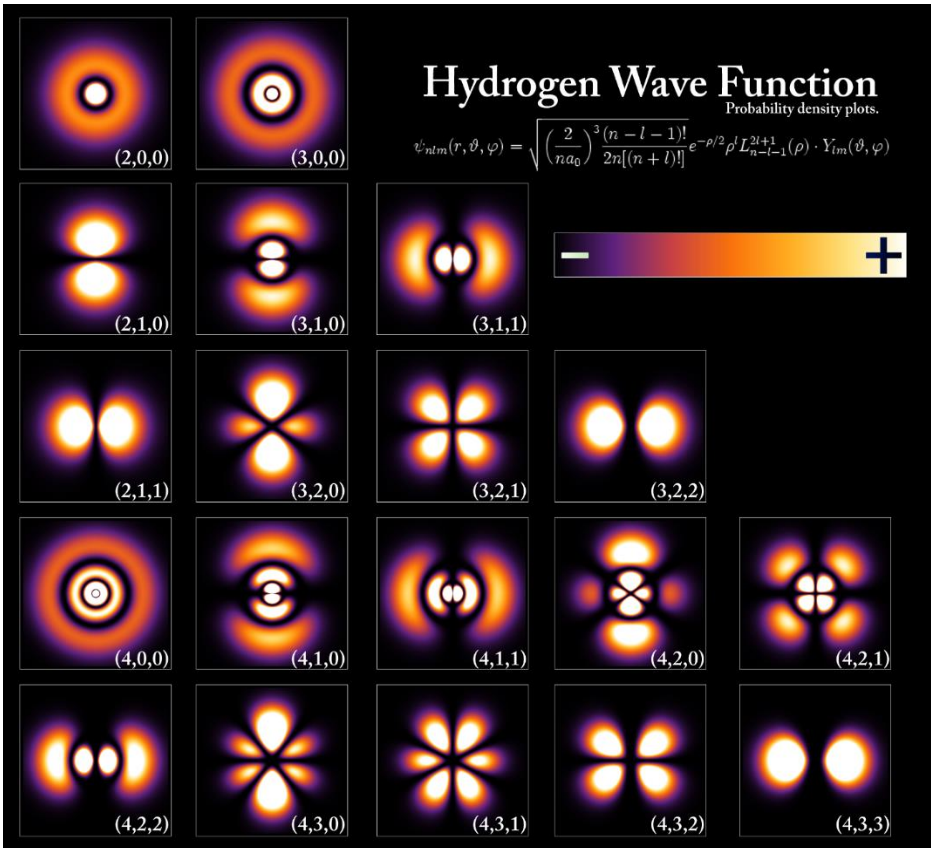


Fig. 16: Hydrogen atomic orbital probability density plots, in which purple marks the most probable regions for electrons to be found. [25]

Do particles like electrons have properties independent of our knowledge of them? The wave properties of a particle are described by a mathematical object called a wave function. A specific particle's wave function is like a big suitcase, which holds the neatly-folded probabilities that the particle will be found in each possible state. A state is a physical arrangement in which the particle has a certain position, momentum, energy, and so on. To predict where a particle will be in the future, its wave function is, in short, plugged into Schrödinger's wave equation, which models wave movement and thus describes the evolution of a quantum system over time. Though a wave function provides the fullest description of a particle—all of its measurable information, before observation—it contains only a statistical prediction that a particle will be found in a given state in the future. Observation of a particle—the mingling of the micro- and macroscopic—irrevocably changes its wave function. Indeed, when the particle's state is measured, its wave function collapses. The wave function, which once held the probabilities for the particle to be found in any possible state, reduces to the single state, or a spread of states, in which the particle is found. It seems that particles may not possess definite properties independent of our observation of them after all.

Hence, maybe our view of reality could be mended, as a rock is smoothed by the flow of water. Scientists operate under the assumption that there really is a thing out there to know. This view of reality as that which exists regardless of our recognition of it fuels scientific inquiry, underscoring the distinction between the observer and the observed. A scientist, given the gift of consciousness, is so distinguished from the rest of nature that she can study it objectively, sieving natural laws and regularities through her magnifying glass. But, there is a problem with this observer-observed dichotomy: it blurs at the quantum level. A quantum system, like an electron, lacks the objectivity of an ideal external world independent of the human mind. Our interaction with a system changes it. Namely, measuring the state of an electron essentially kicks the stand out from under the particle's probability function, and it collapses. Maybe what we call reality is just a big map of the universe with its corners held taught by four weights: space time, matter, and energy. Maybe our consciousness doesn't separate us from the world, and mind and matter intermingle. Maybe we have forgotten that we *are* nature.

An electron within the Bohr atomic model finds itself enmeshed in a rigid framework with strict causal properties, as the structure of a waterfall, in its entirety, appears causally-related to gravity alone. However, a quantum mechanical electron exists in a superposition of all possible states, that is, until we measure one of its properties. A single water droplet within the falls has a chaotic path of descent, much unlike the structure of a waterfall perceived in its entirety. The waterfall interacts with its surroundings. When a jutting rock detects a droplet, thereby measuring its location, the rock alters the droplet's route, sending it spurting out another way until detected by another rock. Hence, outside interaction adds to the chaos of the droplet's path. Quantum mechanical electrons also possess properties defined by outside interaction: our measurement of them.

So, the relationship between human and nature (or a physicist and an electron or a jutting rock and a waterfall) is not one of observer and observed—subject and object—as previously thought. We are as much a part of nature as nature is a part of us. We each help form the world in which we live, as we live, "Ceaselessly musing, venturing throwing, seeking the spheres [of meaning] to connect them, / Till the bridge [of understanding] [we] will need be form'd, till the ductile anchor hold, / Till the gossamer thread [we] fling catch somewhere, O my soul." [26]

What, then, of the waterfall? Why is it so beautiful? Humans form a subset of nature, which itself is the subject. Maybe beauty is a transcendent, objective thing which we do not yet have the words to explain.

The waterfalls, satisfied with my understanding, have signaled for the Sun to set, darkening the trail, so I get up to leave. Next time I visit maybe then they will whisper to me the quiet, trembling truth of their beauty.

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