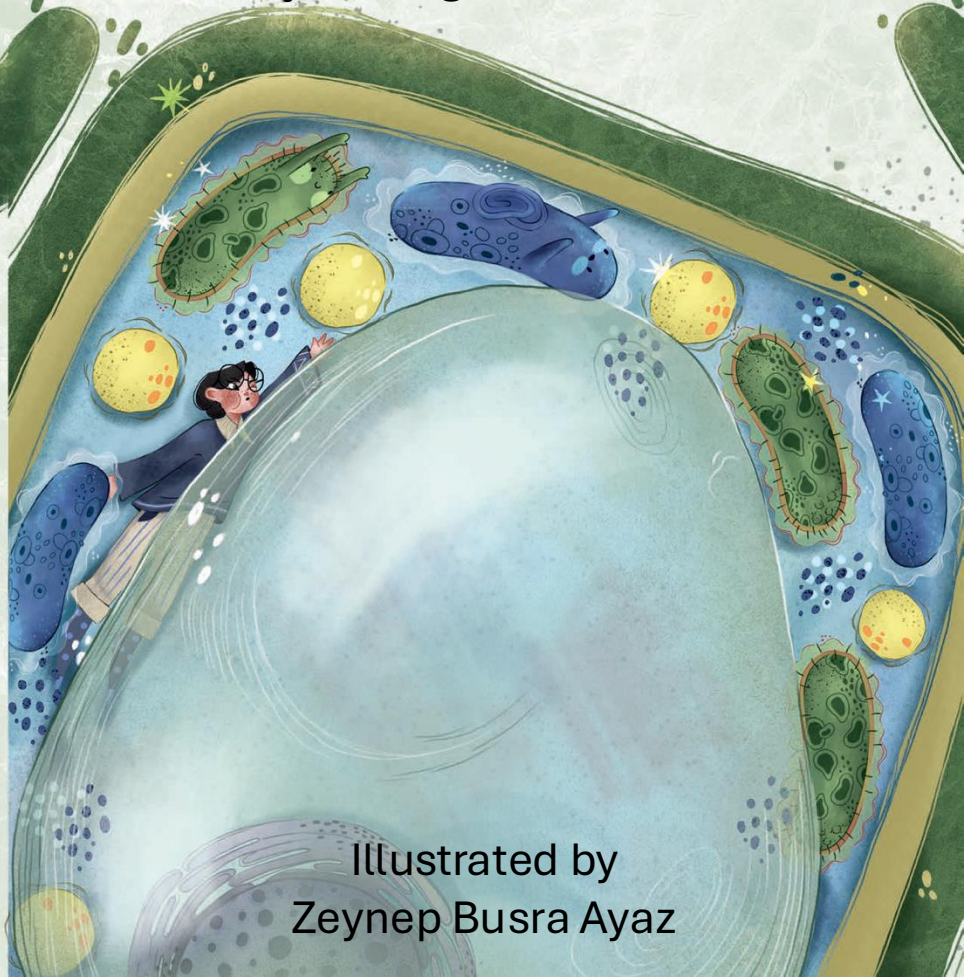
Neal has a new friend -- a plant! But one day, it looks sick. To learn more about his plant, Neal dives into a big book about plants -- and then into the plant itself.
He journeys through the roots and stem to the leaves, encountering unexpected challenges and some frightening obstacles along the way. But he surprises even himself when his curiosity wins out over fear every time.

NEAL'S ADVENTURES-II
THE QUEST FOR IRON

Written by
Seçkin Eroğlu & Esra Eret



Illustrated by
Zeynep Busra Ayaz

This work is produced as a science communication activity through COST Action 19116 "Trace Metal Metabolism in Plants (PLANTMETALS)" supported by COST, European Cooperation in Science and Technology.
COST is a funding agency for research and innovation networks. Our Actions help connect research initiatives across Europe and enable scientists to grow their ideas by sharing them with their peers. This boosts their research, career, and innovation.
www.cost.eu

Editors:
Nathalie Verbruggen (Action Vice Chair)
Jagna Chmielowska-Bak

We thank COST action members for fruitful discussions during the preparation of the work. We thank Carrie Kroehler for critical reading.

Dear Children,

We live in a world with other living organisms that we can see with our eyes, like animals, plants, and fungi and microscopic organisms like bacteria.

Plants provide us with food, medicine and clean air. They make our world a more beautiful place to live.

As a sign of our gratitude, this work is dedicated to plants. It offers an adventure in the world of plants. In this adventure, everything might sound new for you. Don't give up reading; be courageous enough to explore this new world. You might read the whole work or the certain parts again and again to get familiar with the heroes of this world. In the end, you'll feel part of it.

Seckin & Esra

In Neal's first adventure with plants, he had germinated a seed for a school project. He soon developed a deep interest in plants and began to investigate what makes up a plant. He started with popular science books. But when he woke up one day smaller than the size of a plant cell, he had the opportunity to learn about plants from inside one.

He traveled through the plant and met the friendly inhabitants of the plant cell: **Nucleus**, **Chloroplast** (Chlo), and **Mitochondria** (Mito). Nucleus offered him the opportunity to go back home riding a dandelion seed -- but with a risk of time travel. Neal successfully grasped the dandelion seed but, shortly after, lost control and fainted. And that's where we left him at the end of "The Mystery inside the Plants."

Neal woke up at home. He was feeling dizzy. He ran to his plant and saw that it had recovered and was a beautiful green again.

"Mum, my seedling is happy again!"

"That is good news, sweetie!" The voice was not his mothers'. It was Mito's! Suddenly, Mito appeared at the door. He was huge. Neal felt someone behind him and then saw Chlo. Chlo was huge, too, and he was sitting behind a table. On the front of the table there hung a sign that read "Ice cold cocktails." Chlo was shouting: "Cocktails, sweet cocktails!" Neal opened his eyes and realized that what he saw was just a dream.
Neal found himself once again lying on a hard surface.

"Not again!" he thought, realizing he was back on the same stone where he had first entered the plant world. Nearby, he saw the crushed dandelion and was reminded of the thunderstorm that had tossed his dandelion seed this way and that. Slowly, he remembered what had happened to him. He felt a sense of peace in being here.

It was a beautiful day. He stood up, stretched, and looked at the plant he had visited. Everything seemed the same. But then he noticed that the once-green leaves had turned yellow. "Strange," he thought. "I hope the guys are OK." A gentle breeze lifted his hair, reminding him of his incomplete mission. He knew he couldn't waste time. He needed to climb up the plant, find another dandelion seed, and try to get home again. He would have to pass through the plant once again, come out of the **stomata,** and catch onto another dandelion seed!

He dove into the soil and swam to the plant. He knew how to navigate his way through a plant now. "Catching another dandelion to get home will be a piece of cake," he thought.

As Neal swam through the soil, close to the roots, he noticed something alarming: the **root hair**s had grown denser, almost like a thick forest. Passing through them felt like being brushed by a thousand little fingers. "First, the yellow leaves, now the enormous root hairs," he thought. "What is going on?" When he reached the cell membrane, he also noticed another striking difference. The membrane, once a challenging barrier to pass through, now looked like a strainer, with many more **nutrient gate**s than before**.**

Navigating through the root to the center, he entered the **xylem**, which swiftly carried him upward. Neal exited through the stomata, eager to catch the wind and find a dandelion. He moved mechanically, his mind preoccupied with the strange changes in the plant and worrying about the fate of his friends. Outside, despite the presence of wind, he could not see any dandelion seeds carried by the breeze. It didn't surprise him. Too much else had changed.

"Where are the dandelions?" Neal scanned the horizon.

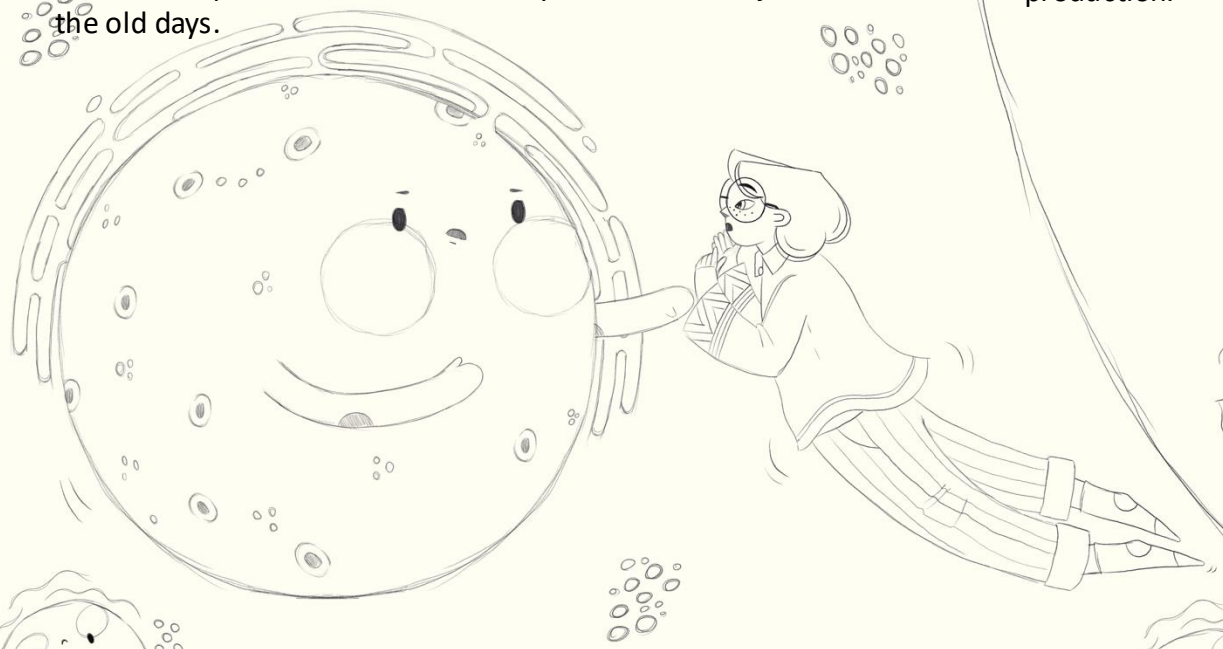
He sat in silence, reflecting on the oddities he had encountered: the yellowing leaves, the dense root hairs, the strainer-like **cell membrane**. All of it felt like pieces of a puzzle he needed to solve before he could leave.

After a moment, he decided to return to the cell and talk to his friends about what was going on. They might have some answers. With newfound determination, Neal turned back toward the plant, ready to dive back in and uncover the truth.

Neal entered the cell. Pushing from behind the vacuole, he saw that Chlo, once so vibrantly green, was now yellow. He delivered almost no sugary cocktail to Mito. Also, the number of chloroplasts and mitochondria are now fewer in number. He looked for Nucleus to find out what was going on. “Only Nucleus can explain all this,” Neal thought.

“Hey, Neal! Long time no see, Neal, long time no see!”
It was Nucleus! And he, at least, seemed normal. Neal felt a sense of relief; at least Nucleus had not changed. Indeed, Nucleus still looked calm and wise.

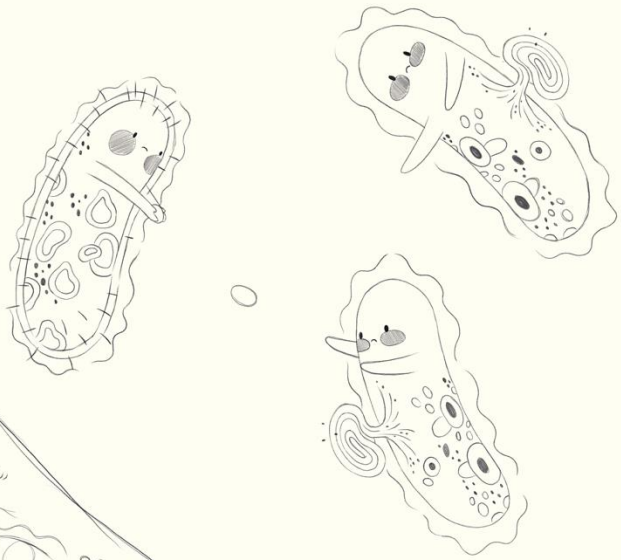
But Neal was puzzled: Why did Nucleus let the plant become sick and Chlo and Mito suffer? In that moment, Neal was certain that he could help his friends and that they would recover, just like in the old days.



Neal updated Nucleus: His attempt to return home had been unsuccessful because of a thunderstorm, and he had found himself back here near the plant the next morning.

Nucleus raised her eyebrows. This was not the case, and Nucleus knew it, but she decided to talk to Neal about this later. Neal continued, asking if Nucleus knew that the plant had turned yellow and that Chlo and Mito seemed to be in trouble.

“I gave the order to the plant to turn yellow,” said Nucleus, startling Neal. “This plant has not been able to obtain enough **mineral**s, specifically **iron**, from its roots. We had to save iron by decreasing chlorophyll production, although this means a decrease in our power supply.” Neal remembered that chlorophyll was essential for **photosynthesis** and required iron for its production.



"So, the yellow plants should be the ones that synthesize less chlorophyll, and they do less photosynthesis," Neal generalized, thinking of his yellow plant at home.

"That's right," said Nucleus.

"Can the roots find **fertilizer** somewhere?" Neal asked. He had provided fertilizer when his plant's leaves turned yellow. The fertilizer should contain iron, along with other nutrients.

Nucleus explained that fertilizers are a mixture of nutrients that help plant quickly recover from **mineral deficiencies** when specific nutrients are missing. However, humans apply it to crops. This plant had no access to any fertilizer around and had to find natural iron-rich patches in the soil.

"So far, the search has been unsuccessful," said Nucleus, "forcing me to reduce iron use in photosynthesis and other processes like growth a few days ago."

"A few days ago?" Neal repeated, puzzled.

Nucleus explained, "Neal, you have experienced a time travel, child, a time travel. In fact, several months have passed since you left us here."

Neal opened his mouth, and his eyes widened in shock. He remembered losing control of the dandelion seed before he fainted.

He stepped back, leaned against the cell wall, and knelt down, staring at the cell floor as he began to talk to himself. "I must have time-travelled!"

That explained how so many things had changed so dramatically inside the plant. "It explains why I could not see any dandelion seeds carried by the wind. I'll have to wait for the dandelion season to return! No way out for now!" Neal cried. He closed his eyes, feeling a deep exhaustion. Slowly, he fell asleep next to Nucleus, like a cat resting at his owner's feet.

When Neal woke up, he evaluated the situation. If this wasn't a dream, and everything was real, had he really been away from home for several months? This would have been a very big issue at home.

This was the first time the possibility had occurred to him. Even when he first attempted to return home, he would have been gone for several days, he realized. But he hadn't made it! His anxiety increased. His family must be panicked!

"What if they called the police? What if they put up posters on the walls around the city? Are people talking about me?" Neal's heart began to pound.

This was not good for him. He tried to calm himself down. "Innnnn, ouuut... innnnn, ouuut..."
He took deep breaths, exhaling slowly, and soon he started to feel more in control. After all, he hadn't made a conscious choice to leave his family; he had simply found himself in this situation. He decided to focus on what he could do to make the most of this strange journey. Once again, he began to see it as an adventure - fear would not help him now.

He knew he had to wait for dandelion season to return. In the meantime, he could think of a way to help his friends and ease their suffering. He could also use the opportunity to learn more about plants from Nucleus, just as he had originally planned.

For a few days, Neal wandered around the plant and had time to examine the interesting structures closely. He also elaborated on what to do for iron deficiency. Then, he visited Nucleus again. His face was shining with determination. He had an idea.

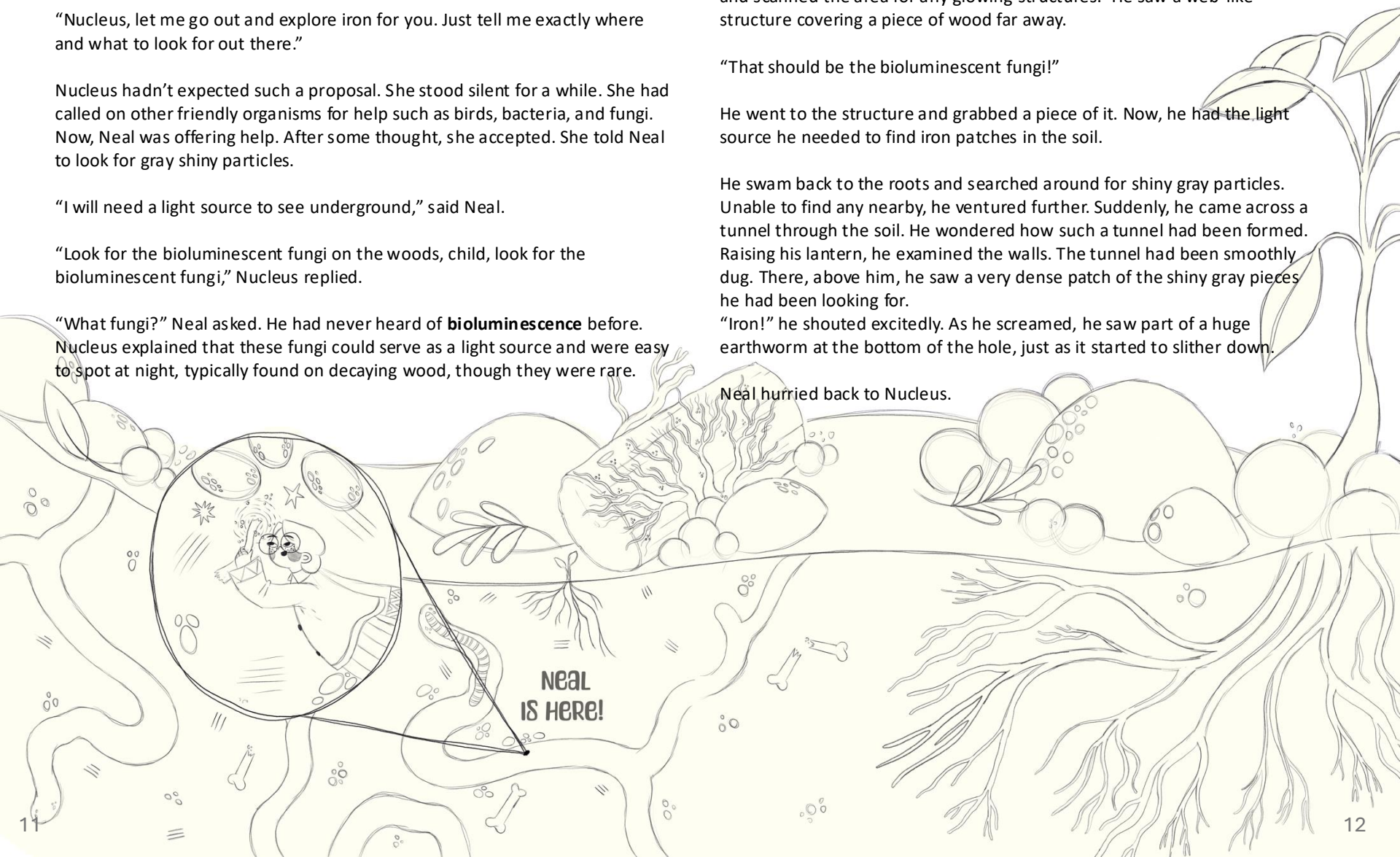
“Nucleus, let me go out and explore iron for you. Just tell me exactly where and what to look for out there.”

Nucleus hadn’t expected such a proposal. She stood silent for a while. She had called on other friendly organisms for help such as birds, bacteria, and fungi. Now, Neal was offering help. After some thought, she accepted. She told Neal to look for gray shiny particles.

“I will need a light source to see underground,” said Neal.

“Look for the bioluminescent fungi on the woods, child, look for the bioluminescent fungi,” Nucleus replied.

“What fungi?” Neal asked. He had never heard of **bioluminescence** before. Nucleus explained that these fungi could serve as a light source and were easy to spot at night, typically found on decaying wood, though they were rare.



Soon, Neal left the plant through the roots and swam through the soil up to the ground’s surface. It was nighttime, and as he walked in the darkness, he realized it would take forever to find bioluminescent fungi this way. He went back and through the plant, climbed to the top of the yellow leaves, and scanned the area for any glowing structures. He saw a web-like structure covering a piece of wood far away.

“That should be the bioluminescent fungi!”

He went to the structure and grabbed a piece of it. Now, he had the light source he needed to find iron patches in the soil.

He swam back to the roots and searched around for shiny gray particles. Unable to find any nearby, he ventured further. Suddenly, he came across a tunnel through the soil. He wondered how such a tunnel had been formed. Raising his lantern, he examined the walls. The tunnel had been smoothly dug. There, above him, he saw a very dense patch of the shiny gray pieces he had been looking for.
“Iron!” he shouted excitedly. As he screamed, he saw part of a huge earthworm at the bottom of the hole, just as it started to slither down.

Neal hurried back to Nucleus.

“Iron, my child, iron!” Nucleus exclaimed, her eyes wide with excitement. Neal had never heard her shout before.

“Go, Neal, go! Lead the roots to the iron!” Nucleus urged.

“To the iron!” Neal replied.

“But beware, child, beware! Once the root reaches iron, the acidification program will begin. Enter the root immediately!”

Neal travelled through the soil and towards the iron patch. He could see and hear the roots following him. He reached the tunnel, and roots filled the empty space. But suddenly Neal felt a burning sensation spread through him.

“Oh, acid!” he cried, rushing into a root before he got hurt.

From inside the root cell, he watched what was happening in and out of the cell to carry the iron into the plant. Outside of the cell, acids removed the iron patch from the rock. As iron was released, other **molecule**s secreted from the cells bound and brought the iron back to the cells.

“Ah, so this is how iron is carried in!” he thought. He smiled. “Chlo and Mito will be surprised when iron-binding molecules arrive.”

With plenty of iron, Chlo and Mito soon recovered, and they all had good fun together, like back in the old days when Neal had met them for the first time.

Neal was now waiting for dandelion season. He visited Nucleus every day, as if he was regularly going to school. He asked Nucleus about her experiences with various **stress**es.

He learned about how the plant had fallen into iron deficiency after he left. Like other metals, iron is required to build proteins. At certain stages of a plant's life, such as during seed production, the demand for proteins increases, and the available iron stores in the plant can be quickly depleted. Nucleus had received information that iron was lacking and had ordered roots to grow deeper, where iron was more likely to be found. The roots began to secrete acids to solubilize solid iron particles, and their root hairs grew larger to increase their surface area and facilitate uptake. In addition, **iron-carrying molecules** were sent out from the roots. Neal had seen all this with his own eyes, and he felt lucky.

Nucleus also talked about other stresses that plants face. Unlike stress in humans, stress for plants is anything in the environment that limits their growth. In theory, plants have the potential to grow indefinitely. But in reality, their growth stops or slows down because of unsuitable environment factors.

Neal thought about how difficult it must be to direct a plant's growth and navigate it through various stresses. He remembered reading in his book: "Plants are **sessile** organisms, and since they cannot escape from stress, they developed very complicated ways to deal with them." He remembered that animals can travel far away to find water, shelter, and food. For example, birds migrate to warmer places when it's cold. But plants must stay where they are, adapting to survive in a changing environment.

“Once upon a time,” Nucleus began, “it became extremely hot, my child, extremely hot. The sun shone in the sky, without a single cloud to hide it. Only at night did we get some relief from the heat and the sun. I immediately ordered the stomata to open wide, so water could **evaporate** and cool us down at the fastest pace possible. Soon, we noticed that the water we were taking in also diminished, as the sun was drying the soil out quickly. Then we fell into a bigger trap than the heat; drought, my child, drought. I ordered the opposite, to close the stomata and save the precious water, but then the top leaves started to burn; it was so hot, my child, so hot.”

Nucleus paused to gather her thoughts. “Then, all of a sudden, when we were burning under the sun, I heard strong laughter coming from the sky. A thunderstorm, my child, was coming from far away. In an hour or two, my child, an hour or two, the dark clouds hid the sun and dropped us water – life! -- when we were most hopeless.”

“Once upon a time,” Nucleus began another day, “**caterpillar**s appeared. It was the caterpillar season, for some reason nobody knows. There were so many, my child. They started biting us, piece by piece. I knew there were friendly birds around that could hunt those caterpillars, and I ordered the leaves to produce a **scent** that would lure the friendly birds. They came, my child, they came in numbers. They were so loud! They sounded like an army approaching the battlefield. They hunted the enemies for us, one by one. We still call them time to time, those good old birds, whenever we‘re bitten by caterpillars.”

Neal smiled. “Did you have good days?” he asked.

“Oh, yes!” said Nucleus. “We also had beautiful days, my child, beautiful days that we didn’t want to end. Among all the nutrients, we need **nitrogen** the most. The soil at that season had plenty of nitrogen. Nitrogen fell from the sky to the earth with the lightning. We had a lot of lightning, continuously. I ordered the plant to grow as fast as possible, and we thrived within a few days. But when the lightning stopped, we were still growing fast and soon needed more nitrogen.”

“What did you do then?” asked Neal.

“Then we called other friends, the friendly **symbiotic bacteria**. We cooperated! We gave them the sugary cocktail, and they provided us with nitrogen and some metals. It was a fruitful collaboration that lasted a long time.”

Neal began to notice dandelions sprouting. The time had finally come. On his last evening before taking off, Neal said goodbye to Chlo and Mito. Turning to Nucleus, Neal warmly thanked her for teaching him about how plants cope with stress. He told Nucleus his growing worry: Because he had been absent for months, his parents must be worried sick. He feared what state his parents might be in when he returned.

Nucleus, the wise and calm, paused for some time, then leaned in and whispered something in Neal's ear. Neal's eyes widened in surprise. "How did I not think of it!" exclaimed Neal.

He hugged Nucleus tightly, kissed her goodbye, and went to the dandelion to spend the night resting before his journey.

The next morning, Neal woke up, his body trembling.
"An Earthquake!" he thought, but then he realized with a smile, "No, the dandelion seed is lifting off the ground!"
He passed over the plant that has been his home for so long. The plant was now completely green, a contrast to how it looked when Neal had first arrived. As the dandelion fluff rose higher, the plant beneath him appeared smaller and smaller.

Neal wanted to go home. He remembered the whispered advice Nucleus had given him. Closing his eyes, Neal turned the dandelion seed in the direction to take him back in time. He did this slowly and in a very controlled manner, just as Nucleus had instructed him. Behind his closed eyelids, he saw flashing lights, and he felt an immense need for sleep. Trusting the dandelion seed to guide him home, he drifted off to dreamland.

Glossary

Acidification: The process by which something becomes more acidic. In plants, roots sometimes release acids to help dissolve nutrients like iron in the soil.
Bioluminescent fungi: Special fungi that glow in the dark. They can be found on decaying wood and sometimes help plants by breaking down materials in the soil.
Caterpillar: The larval stage of a butterfly or moth. Caterpillars feed on plants and can cause damage by eating leaves.
Cell membrane: The thin outer layer of a cell that controls what enters and leaves the cell. It acts like a gatekeeper for the cell.
Chlorophyll: A green pigment found in chloroplasts that helps plants capture sunlight for photosynthesis. Without chlorophyll, plants wouldn't be able to make food.
Chloroplast (Chlo): The part of a plant cell that uses sunlight to make food through a process called photosynthesis. Chloroplasts are what make plants green.
Evaporate: The process of turning liquid into vapor. In plants, water evaporates from the leaves, helping to cool the plant and draw water up from the roots.
Fertilizer: A mixture of nutrients added to soil to help plants grow better. It provides essential minerals that plants need to stay healthy.
Iron: A mineral that plants need to make chlorophyll and grow properly. Without enough iron, plants can turn yellow and become weak.
Mineral deficiencies: When plants don't get enough essential nutrients from the soil, they can suffer from mineral deficiencies. This can cause problems like yellowing leaves or slow growth.
Mitochondria (Mito): Known as the powerhouses of the cell, mitochondria produce energy that the cell can use to do its work.
Molecule: The smallest unit of a substance that still has its chemical properties. In plants, molecules like water and nutrients move in and out of cells.

Nitrogen: An important nutrient that plants need to grow. It is a key ingredient in many fertilizers and helps plants make proteins. The main source of nitrogen in soil is nitrogen-fixing bacteria. Lightning also increases nitrogen in soil.
Nucleus: The control center of a plant or animal cell. It holds the instructions (DNA) that tell the cell how to grow and function.
Nutrient gate: Special channels in the cell membrane that control how nutrients enter and leave the cell.
Photosynthesis: The process by which plants make their own food using sunlight, water, and carbon dioxide.
Proteins: Molecules that are essential for the structure, function, and regulation of the body's tissues and organs. In plants, proteins are needed for growth and making new cells.
Root hairs: Tiny hair-like structures on plant roots that absorb water and nutrients from the soil. They help the plant drink more efficiently.
Scent: A smell produced by plants to attract or repel animals. For example, some plants release a scent to attract helpful animals like pollinators or predators of harmful insects.
Stomata: Tiny openings on the surface of plant leaves that allow the plant to take in carbon dioxide and release oxygen. They also help control water loss from the plant.
Stress: For plants, stress is anything in their environment that limits their growth, such as too much heat, drought, or lack of nutrients. Plants cannot move to escape stress, so they develop special ways to cope with it.
Symbiotic bacteria: Helpful bacteria that live with plants and provide nutrients, like nitrogen, in exchange for food from the plant. This relationship helps both the plant and the bacteria survive.
Vacuole: A large storage area in a plant cell that holds water, nutrients, and waste. It helps the plant stay firm and healthy. Note that Vacuole is an inhabitant of cell, but in the story, we depict it as noncommunicating on the grounds that a plant's nucleus, mitochondria, and chloroplast communicate with one another with signals but not with the vacuole.
Xylem: Tubes inside the plant that carry water and nutrients from the roots to the rest of the plant.