The Carrot Quest, discovering the secrets of carrot market classes

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"The day is coming when a single carrot, freshly observed, will set off a revolution."

Paul Cezanne

My supervisor, the carrot breeder Professor Irwin Goldman, made shirts with the quote above by writer Paul Cezanne on the back. I proudly wear it everywhere. One man once asked me: "Son, do you think that is true?" and I replied: If you ask me, that revolution has already started! Let me expand.

Imagine you're at a grocery store, choosing the perfect bunch of carrots. Have you ever wondered why some carrots are long and skinny while others are short and blocky? Depending on where you are, the preferred carrot shape varies (Figure 1).

There are many types of carrots available to you. If you're all about convenience, baby-cut carrots are a go-to. If you are looking for a classic product, then the 1 lb. pack of carrots in a cellophane bag - or "cello carrots" is the option for you. The variety doesn't stop there; carrots come in sticks, noodles, crinkle-cut, and even diced.

Move away from the fresh produce aisle, and you'll find canned carrots and vegetable mixes with diced carrots in the canned vegetables section. My personal favorite? Carrot juice.

Did you ever stop to think about the carrot-infused diversity in your daily life? From the crunch of baby-cut carrots to those little diced ones in your canned soup - they all trace back to different carrot market classes, each selected and bred for specific purposes by carrot breeders.

This isn't just a matter of luck or coincidence. It's the result of years of scientific research aimed at understanding the genetic secrets that determine the shape, size, and overall quality of carrots.

The Journey of Carrot Domestication

Carrots weren't always the familiar swollen orange roots we know today. Originally, they were pretty normal looking roots and looked nothing like carrots (Figure 2), as we can tell from the carrot ancestor Queen Anne's Lace. Carrots later were slowly developed or domesticated, and a variety of colors started to emerge including purple and yellow.

It wasn't until the 1600s that orange carrots became prominent in Europe. This shift in color was just the beginning of understanding how carrots can vary in shape and size. Over time, horticulturists began to notice and select different root shapes, which led to the diverse carrot varieties we see today.

The art record has played a significant role in documenting and understanding the domestication of carrots. Early botanical illustrations provided detailed depictions of different carrot varieties, allowing scientists and horticulturists to infer and study their physical characteristics during the course of domestication. These illustrations were crucial for sharing knowledge about plant varieties across different regions and generations. Nevertheless, these illustrations tend to be subjective, and we see them through the eyes of the artist.

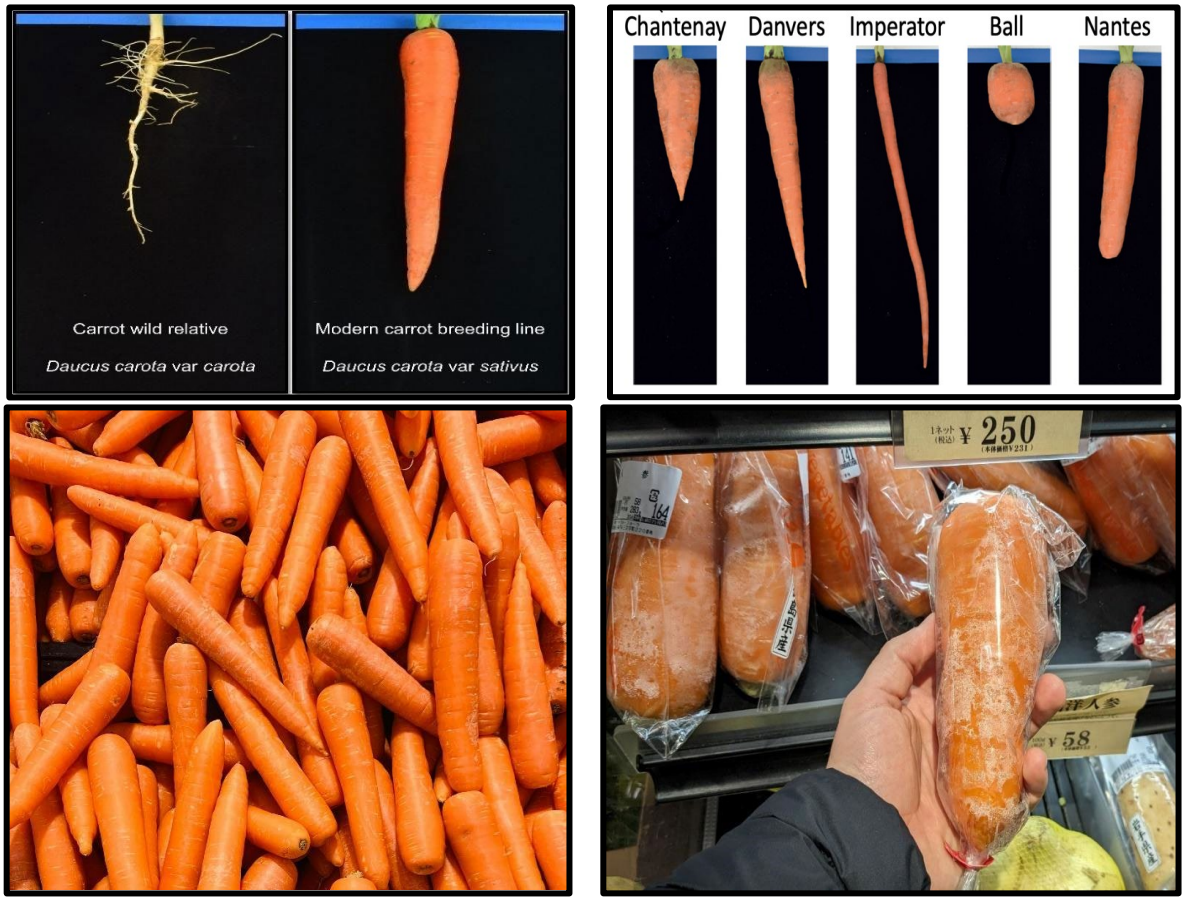


Figure 1. First row, on the left, the carrot wild relatives contrasted to the modern carrot breeding line. On the right, different carrot market classes. Second row, on the left predominant carrot type in a U.S supermarket, on the right predominant carrot type i n Japan, picture taken at Kyoto Yaoichi, Honkan. Nakagyo Ward, Kyoto Japan, by my colleague Tom, Bryan, PhD. Picture on the bottom left by Shanu Azhicode: Pexels.com.

For example, in the year 512 CE, depictions of carrots in the Juliana Anicia Codex (Figure 3) show differences between cultivated and wild carrots, such as lateral branching and biennial growth habit. Carrots have a special way of growing that scientists call a "biennial growth habit." This means they take two years to complete their life cycle from seed to producing new seed. In the first year, carrots are specially selected to not produce flowers. If they did, the root (the part we eat) would become very hard

and woody, making it inedible. Instead of flowering, the plant puts all its energy into growing a big, juicy root. This is the carrot we harvest and eat. This root stores a lot of energy, which the plant will need later. In the second year, If the carrot is left in the ground over winter, it will use the stored energy in the root to grow flowers and produce seeds in the second year. Once it produces seeds, the plant's life cycle is complete, and it will die. Early, wild carrots however, had an annual cycle, (just like Queen's Anne's Lace) but humans have carefully selected and cultivated carrot plants that won't flower in the first year. This selection process ensures that the roots remain soft and edible, making them perfect for us to eat. So, in simple terms, carrots are grown over two years. The first year is all about growing a delicious, edible root, thanks to careful selection by humans to prevent early flowering. The second year is for producing seeds, but by then, we've usually already harvested the carrot to enjoy! Breeding companies and farmers do this kind of work for us, and a portion of the annual carrot output is grown for seed.

In Figure 3, we can see how the author pictured the wild carrots with more branches and a flower and the cultivated carrots with less branches and no flower development. These illustrations may also include some of the oldest known depictions of allegedly orange carrots. However, the true color of carrot roots at that time remains unclear. Professor Phil Simon from USDA suggests that the brownish or orange color in the illustrations of the Codex may have been an artistic choice, rather than an accurate representation, as other plants depicted in the Codex with no known orange color in their roots also have been depicted in the codex with similar colors as that of the carrot!

Some authors propose that orange carrots appeared in the 6th century, a thousand years earlier than previously documented in European paintings. However, the widely accepted development of orange carrots is attributed to Dutch horticulturists in the late 16th and early 17th centuries. Prior to this, carrots were primarily purple, yellow, or white. Anecdotal evidence suggests that the orange color was developed in honor of the Dutch royal family, the House of Orange-Nassau, though this connection lacks definitive historical confirmation. The story of orange carrots produced in honor of the Dutch royal Family has become a popular belief but should be treated cautiously until confirmed with reliable evidence.

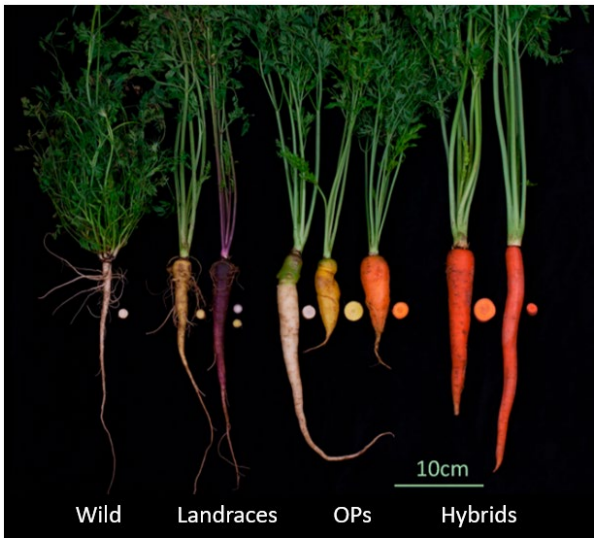


Figure 2. Domestication patterns of the carrot; from the left we have Queen Anne's lace, an ubiquitous weed in Wisconsin, followed by cream, purple, white, yellow and then orange carrots. Note that the last stage in the domestication process is improvement for shape. Image from: Ellison et al. 2018 Genetics:210:1497–1508.

One notable individual who tried to figure out the history of carrot domestication is Otto Banga, a Dutch agronomist who extensively studied the history and genetics of carrots in the late 1950s and early 1960s. Banga's research in the mid-20th century was pivotal in understanding the evolution and domestication of carrots. He used historical texts and artworks to trace the development of different carrot types, particularly the transition from purple and yellow carrots to the orange varieties that became dominant in Europe. Now that we recognize that carrots have a history and that they come in different shapes, colors and configurations, let us take a deeper look into Carrot Market Classes.

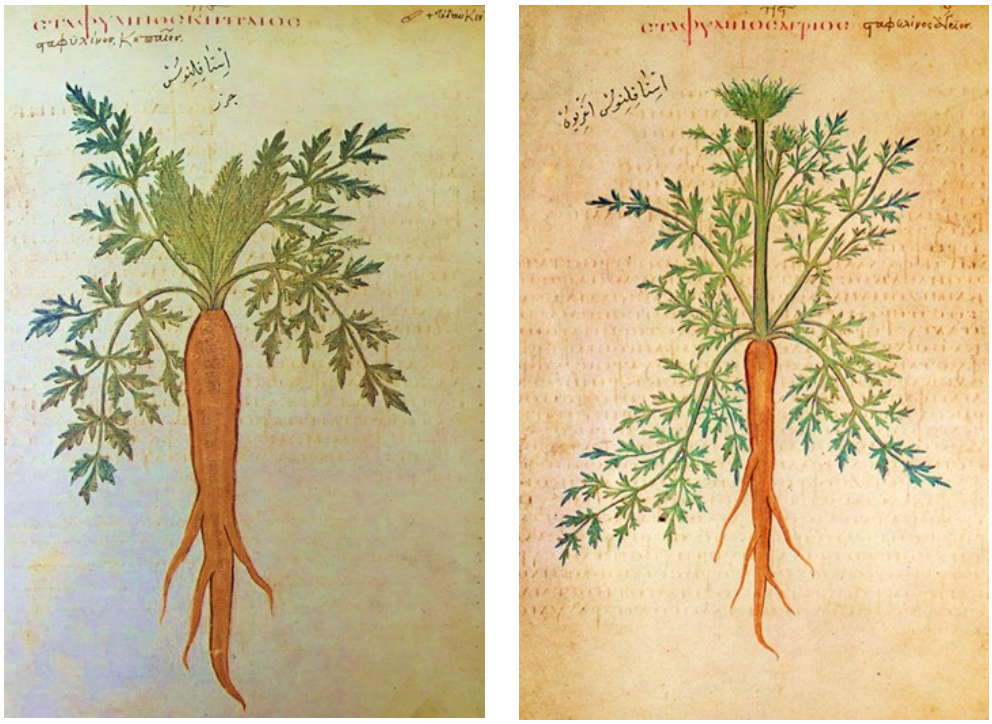
A Look into Carrot Market Classes

In the context of carrot breeding and economics, a market class is a group of carrot cultivars that share common attributes and therefore are grouped together to facilitate trade. Characteristics like root shape, size, and intended use, help group and market carrot cultivars.

After attending discussions on carrot market trends and genetics at the international carrot conference in York, UK 2023, I visited a field trial in Malton, Yorkshire. The soil of Malton, deposited over the years by wind, is perfect for carrot production. Similarly, Wisconsin's Central Sands and muck soils, which share the light, sandy characteristics of Malton soil also provide ideal conditions for carrot growth.

Walking through the field trial, I marveled at the diversity of carrot varieties, in every color and shape imaginable. I want to highlight that the display of thousands of carrot varieties was organized by their market class! I was able to guide myself and look at cultivars within my preferred market classes either for the fresh or the processing market.

One plant with purplish leaves (in the specialty market class) caught my eye, reminding me of the rich history and variety in carrot domestication. Carrots come in many colors and shapes, making them versatile for both global cuisine and the processed vegetable industry, and breeders classify them according to their shape and end use in market classes.



Cultivated carrot Wild carrot

Figure. 3 Carrot illustrations from the Juliana Anicia Codex (512 CE) depict the cultivated carrot (left) and the wild carrot (right).

Despite all cultivated carrot varieties sharing the same scientific name, *Daucus carota var sativus*, they have different observable shapes tailored for their specific uses. Carrot cultivars are categorized by these shapes into market classes, each named after a founding member with distinctive characteristics. For instance, the 'Imperator' market class includes long, slim carrots, originally developed by crossing 'Chantenay' and 'Nantes' varieties (Figure 1). Other market classes are fun to grow in gardens, like ‘Ball’ carrots, and the ‘Danvers’ variety is likely what carrot juice is made out of.

As I noted, the varieties within the Imperator market class are long and really slim. That is because these carrots are usually peeled and cut to form the crunchy and lovely baby-cut or cut-and-peeled carrots we find in grocery stores. I am ashamed to admit that I thought baby carrots were regular carrots harvested when they were really small but that’s not how baby-cut carrots came to be. Read more about baby-cut carrots here.

I also wanted to discuss the trends in carrot market classes in the United States. By examining historical and recent data, we will see how market classes evolved and gained popularity over time.

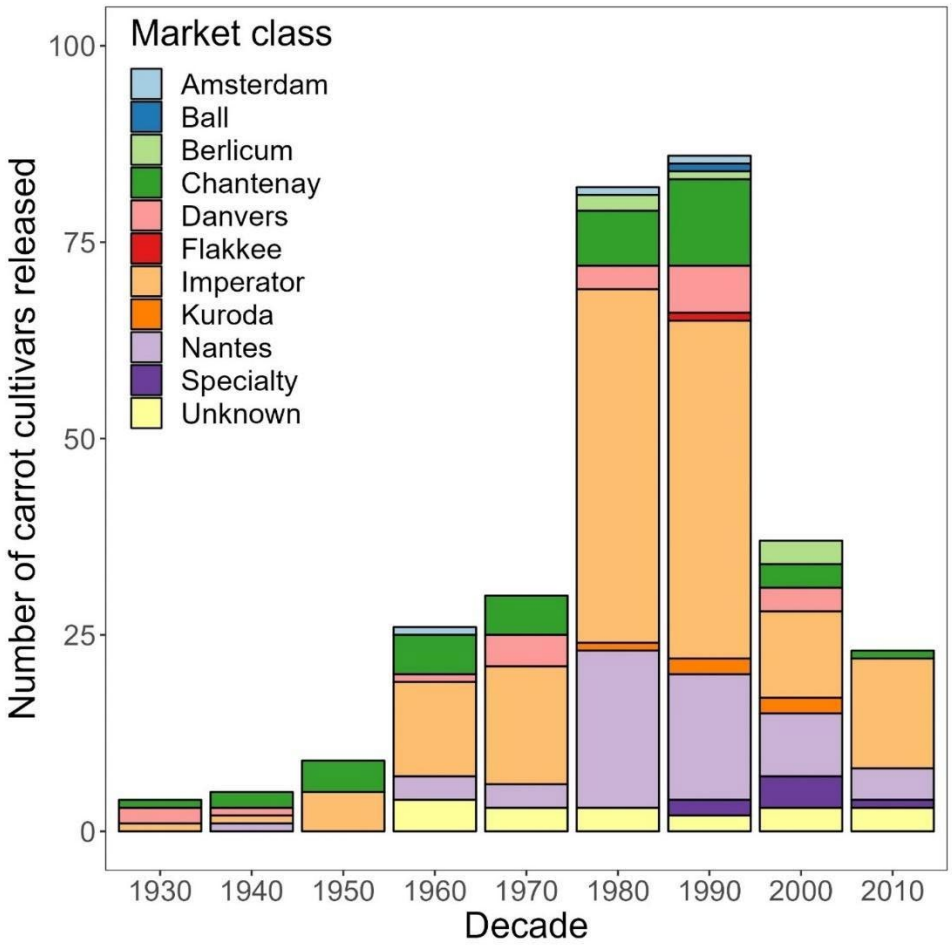


Figure 4: Trends in the release of carrot cultivars in North America from 1930 to 2019, categorized by market class.

This bar chart (Figure 4) tells the story of how different types of carrots have been developed and introduced over the decades. Each color represents a different "market class" of carrots, like the long and slender Imperator or the stubby Chantenay. From the 1930s to the 1950s, only a few new types of carrots were developed. But starting in the 1960s, there was a boom in carrot breeding, especially for the Imperator variety, which became very popular. The peak of carrot innovation happened in the 1980s and 1990s, when many new types were introduced. This peak coincided with the development of baby-cut carrot technology. After that, the pace slowed down, but there were still many different varieties being developed. The data shows a significant increase in the release of Imperator and Nantes carrot cultivars during the 1980s and 1990s, highlighting the prominence of these market classes in breeding efforts, and their economic importance.

Digging into the Genetics of Carrots

We have established that carrots come in many shapes and sizes, and carrot cultivars that have similar shapes or uses are categorized into market classes. These market classes differ in shape substantially. We also have discussed the historical trends of market classes in North America. You will not be surprised to know that much of this diversity is controlled by their genes. Genes are like tiny instruction manuals inside every living thing, telling it how to grow and develop. My research focused on

identifying specific genes that influence carrot root shape – a crucial trait for both farmers and consumers.

To do this, I studied different carrot varieties and mapped out their genetic information. Think of it as creating a detailed blueprint of each carrot type. By comparing these blueprints, I was able to pinpoint regions in the carrot genome linked to root shape. This process is known as linkage mapping.

Linkage mapping is like assembling a giant puzzle. Each piece represents a small segment of the carrot's genome. A genome is the complete genetic material found in a cell. By studying how these pieces fit together, I identified parts of the genome associated with specific shape traits. For example, I discovered regions responsible for making a carrot wider, or contributing to giving it a particular shape. In the breeding scientific literature, this is called "describing the genetic architecture of a trait". The whole story is far from finished, as these findings are localized and may not apply to all carrots. We are just beginning to scratch the surface, but our understanding of carrot shape genetics has improved!

My research involved growing hundreds of carrot plants from different genetic backgrounds, measuring their root shapes -with a cool digital imaging pipeline- and analyzing their DNA. It was a meticulous and time-consuming process, but the results were worth it. We identified several key regions in the carrot genome that play significant roles in determining root shape. We even think that these candidate genes fall under the category of master regulators that control shape in other plants like tomato fruits, and grape leaves! If you can't resist yourself, google OFP-TRM and IQD plant shape regulon. Please note that we still don't have evidence to pinpoint a single gene, but we are reducing the complexity of the problem by reducing the search space.

But Wait! Why Does Root Shape Matter?

Root shape affects how carrots grow in the soil, how they are harvested, and even yield. Farmers prefer certain shapes because they are easier to harvest, process into a product or package. Home gardeners with limited space or tilling capabilities may prefer short ball-shaped carrots. Consumers might prefer a particular shape for cooking or snacking. By understanding the genetic factors that control root shape, we can help breeders improve carrots to meet these preferences more efficiently.

One critical aspect of my research involved conducting density trials, because we thought that the environment may also affect the shape. In this case, I modified the environment by creating a high or low density of carrots. That is, I modified the growing environment to create plots with high density and low-density populations. I planted carrot plants closely together to create a high-density environment, where carrots were growing right next to each other, and spaced them farther apart (up to 10 cm) to create low density environments.

These density trials helped determine the optimal planting density for different carrot varieties. By planting carrots at varying densities, we can observe how crowding affects root shape and size. Too many carrots planted too closely together can lead to misshapen roots, while too few can be an inefficient use of space. Our density trials provided valuable data that will help farmers make informed decisions about planting strategies to achieve the best possible crop. In a nutshell, we found that extremely high densities don't affect shape! You can crowd them, and they will keep the shape but guess what? They will grow reduced in size by up to 50%! We believe that high-density growing

conditions emulate a state of low physiological maturity in which less biomass is accumulated, and size is reduced. But shape, because it is genetically determined early on, does not suffer dramatic changes.

Overcoming Challenges and Looking Ahead

Every scientific journey has its challenges. One major challenge was dealing with the variability caused by different growing conditions. Just like how some people thrive better in warm climates and others in cooler ones, carrots respond differently to various environmental factors. To get accurate results, we had to account for these differences by running the trials over multiple years to ensure our findings were reliable across different settings.

Another challenge was the sheer complexity of the carrot genome. It's like trying to read a book where some of the pages are out of order and some are just missing. Despite these hurdles, we made significant progress in understanding the genetic basis of root shape. Looking ahead, there's still much more to discover. Future research will focus on exploring other traits important for carrot quality, such as color, flavor, and nutritional content. We'll also look into how these traits interact with each other, which is crucial for developing the perfect carrot.

Our research has practical implications. By providing a deeper understanding of carrot genetics, we're helping to pave the way for the development of superior carrot varieties with ease and efficiency. These improvements can translate years later to higher yields for farmers, better quality carrots for consumers, and potentially new varieties that are more resilient to environmental stresses. But the impact doesn't stop at carrots. The techniques and knowledge gained from this research can be applied to other crops, helping to improve food security and sustainability in agriculture.

My dissertation combined genetics, careful statistics, and experimental design techniques. Unexpectedly, I also found that integrating art and historical documents provided a fuller picture. This experience showed me that science and art can indeed be combined. To illustrate this, I'd like to share a Haiku about carrot domestication. Haikus are short Japanese poems with a 5-7-5 syllable structure that often capture moments in nature. Here is mine describing the domestication process of the carrot:

Carrot

Three dresses you tried.

White, purple and then yellow

but orange looks best!

This haiku is an overly simplistic summary of the domestication journey of the carrot. The first carrots were white, then purple and yellow carrots were developed by selecting naturally occurring mutations. Orange carrots are a very recent development. It is unclear when they were developed exactly, but like I have described, Otto Banga, and other prominent researchers of carrot history, have suggested that orange carrots were first observed in the Netherlands in the late 16th and early 17th century.

I also examined art to understand carrot shapes better. I found two similar paintings with different carrot shapes (Figure 5). On the left panel of Figure 5 is a painting by George Moreland featuring a carrot that resembles the Danvers shape. On the right is a similar painting by an unknown artist from the East Coast of the United States. I suspect the right painting is by an art student emulating Moreland's work for educational purposes. However, the carrot in this painting has a different shape, more like a Chantenay carrot, one of the oldest varieties in the U.S. It is unclear if the carrots depicted differently is artistic freedom or a representation of what was available at the time. Examining the art record relies on the subjective decisions by the painter, but provides an idea of how vegetables looked in the past.

Figure 5. Carrot depictions in the art record. Left panel, Girl with Pigs by English painter George Moreland, 1797. On the right panel, a painting by an unknown author from the east coast of the United States.

In conclusion, my research on carrot root shape is a testament to the beauty and complexity of nature. It shows how even something as simple as a carrot can hold fascinating secrets waiting to be uncovered. Through careful study and analysis, we can unlock these secrets and use them to make the world a better place, one carrot at a time.

So next time you enjoy a crunchy, sweet carrot, remember the science behind it and the journey it took from the field to your plate. Science is everywhere, even in the humble carrot, and it has the power to enrich our lives in countless ways.

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