Introduction

"Though an old man, I am a young gardener." So wrote Thomas Jefferson. The longer I garden, the more I realize the truth of those words. Gardening is a lifelong learning experience that never ceases to capture, recapture, and then capture my interest once again. How could it not, representing, as it does, such a congenial confluence of colors, flavors, and aromas all seasoned with the weather, whatever pests happen to stop by that year—and the science behind it all?!

And the science behind it all is what this book is about. It's not a comprehensive overview of botany and related sciences, just some natural science that can be applied in the garden. No need to read from cover to cover or in one fell swoop to get the most out of this book. Each chapter can stand by itself—as, in most cases, can each section within a chapter. So dip in and out of this book according to your whim, the season, or what's happening in your garden.

Science may seem out of place in so bucolic an activity as gardening. After all, millions of years of evolution have prompted seeds to germinate and plants to grow in soils and climates as diverse as the Arctic tundra, the Arizona desert, and my garden in New York's Hudson Valley. So it's possible to have a decent garden with minimal effort or know-how.

But gardening can be something more than this business as usual, with commensurately more rewards.

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The genesis for this book came to me one day as I was piling scythed meadow hay and horse manure, along with old vegetable plants and sprinklings of soil and dolomitic limestone, into one of my compost bins. I realized that what I was adding to the pile and how much of each ingredient, even how I fluffed them up or patted them down with my pitchfork, and then watered, all reflected what I had learned over the past 40-plus years of gardening. My classrooms have included actual classrooms; gleanings from magazines, books, and scientific journals; conversations with other gardeners and agricultural scientists; and (most importantly) the garden itself.

My garden education has been unusual. Growing up in the suburbs, I initially remembered only a small vegetable garden whose tenure was soon eclipsed by a swing set. Wait! How about that potted banana tree and one hyacinth bulb that I nurtured under the purple glow of a Growlite in the basement during high school? Or the potted cactus that I bought to adorn my bedroom windowsill in graduate school. Hints of future interest? Perhaps.

Graduate study in those cactus days was in chemistry, a continuation of an interest kindled by my high school chemistry teacher. But coming to the conclusion that graduate study in quantum chemistry was not going to answer any fundamental questions, I dropped out, moved to Vermont, and got the gardening bug. Because I was living in a third floor apartment, I expressed that gardening bug with a voracious appetite for books—books about gardening.

A year later, I dove into agriculture in earnest, and was fortunate to land in a graduate program in soil science. My interest and education in chemistry proved a good foundation for soil science.

A small plot of land began my education "in the field" and complemented my academic studies. The university's agricultural library offered more books to further round out my education. (I remember coming across a whole book on lettuce seed!)

Eight years later, with two framed diplomas to hang on my wall, one for a master's degree in soil science, and the other for a doctorate degree in horticulture, I was still gardening with the same exuberance and learning about gardening through experience, the printed word, and contact with others "in the know." Thinking back, how little I knew about gardening. And so it goes.

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Back to my compost pile…I took into account the meadow hay's youthful lushness, which influences its ratio of carbon to nitrogen, as I layered it into the bin along with the horse manure. Manure is usually thought of as a high nitrogen material, but I looked at what was in the cart and, eyeing the amount and kind of bedding (wood shavings) with which it was mixed, made a rough estimate in my head of how much to use to make a good balance with the meadow plants. When the pile was finished, I checked my work by monitoring the temperature of the pile's interior with a long-stemmed compost thermometer. Etc., etc. There's art in making compost. But also science.

With this book, I hope to show you, the reader, how knowing and using a little of the natural science behind what's happening out in the garden can make for a lot better garden in terms of productivity, beauty, plant health, sustainability…and interest. Knowing some of the underlying science at work in the garden also makes for a more resilient gardener, better able to garden at a new location or in a changing environment. All of which makes for a perennially "young gardener," as Mr. Jefferson said it!

PROPAGATION AND PLANTING

A bit of deception helps me get some seeds to sprout that under natural conditions would wisely stay asleep.

You wouldn't think that the dead of winter would be a good time to sow seeds. But it is, for plants whose seeds need some kind of long term treatment before they will sprout. Such is the case for the tree peony seeds I recently planted.

"Planted" is really too gardenesque a term for what I did with those seeds. After soaking them in water for a few hours, I merely tossed them into a plastic sandwich bag with a handful of moist potting soil. The bag will sit on the kitchen counter for a couple of months, then go into the refrigerator for another couple of months.

Peony seeds need this treatment because they must lay down roots before any shoot growth can begin. To grow roots, those seeds need some rain (or a good soaking) to leach inhibitors from the seeds, and they also need some warmth. The shoots, however, won't sprout until they've been exposed to a period of cool, moist conditions—outdoors or in my refrigerator. Under natural conditions, all this might take two years. In my house, all systems should be go by spring. Lily and viburnum seeds also respond to this type of treatment.

A reluctance to sprout as soon as touching down on moist soil often makes sense for ensuring the survival of tender, young seedlings. Not rearing their heads until convinced that winter is over and they have the support of an established root system is just the ticket for survival of wild tree peony seedlings in a climate characterized by cold winters and periodic drought.

Germination quirks of other kinds of plant seeds reflect other natural environments. Some seeds have a double dormancy, one for the seed coat and one for the embryo. Still others (goldenseal, for example) ripen with underdeveloped embryos. The same warm, then cold, treatment needed by tree peonies also prepares seeds with either of these quirks for germination.

Where moisture is more or less consistent throughout the year, it is winter cold that would kill a young sprout that began growing in the fall. Fall-ripening seeds won't sprout until they feel that winter is over, a condition that could be mimicked by a couple of months in the refrigerator in a sandwich bag along with moist potting soil. After doing time in the refrigerator, it's not unusual for a whole batch of seeds to sprout in unison, as if a switch has been turned on, even before they're released into warmth. That cool, moist treatment is called stratification because in the past nurseries effected this treatment by spreading alternating layers of seeds and soil in flats kept outdoors for the winter.

Stratified yellowhorn seeds sprouting.

Hormones within seeds are what bring them to life at the appropriate moment. Although lying apparently lifeless in a bag on a refrigerator shelf, all sorts of things—hormonally—are going on. Levels, for instance, of a germination inhibitor called abscisic acid are decreasing while levels of another hormone, gibberellic acid, are increasing. These hormones have been extracted from seeds and synthesized. Some seeds shed their normal reluctance to sprout with nothing more than a dip in an appropriate concentration of gibberellic acid. All is not so simple, though, because other hormones are also at work, and other compounds, such as potassium nitrate, hydrogen peroxide, or malt extract can also promote germination.

Not all fall-ripening seeds need stratification before they will germinate. Two examples of tree seeds in this class are those of catalpa and those of sycamore (although sycamore's relative, the London planetree, does need stratification). Perhaps catalpa and sycamore seeds have evolved without a need for stratification because they hang on the trees late enough into the winter so that, by the time they drop to moist ground, temperatures are too cold for germination. Or else spring has arrived, and it's just the right time for germination.

Let's not blame dormancy only on hormones; some seeds stay asleep for purely mechanical reasons. The tough seed coats of honeylocust, black locust, and black cohosh are among those that can't imbibe water as soon as their seeds hit the ground. A seed that remains too dry inside will not sprout. These are examples of seeds that need scarification before they can be stratified.

In nature, tough coats are eventually softened—as soil microbes chew away at them, by cycles of freezing and thawing, by abrasion, and by passage through animals. Microbes work best at warm temperatures, so a couple of months in a sandwich bag along with some potting soil could awaken these seeds just as they do those of tree peonies. The potting soil, in this case, should contain some real soil or compost to supply living organisms to work on the seed coats.

Scarification means "to scratch" and with large enough seeds I take this meaning literally, with a file. Nicking seeds or nipping out a little piece of seed coat with a wire cutter are other ways to let water in past a tough seed coat. A quicker way to scarify a batch of seeds is with very hot water or even sulfuric acid, but care is needed not to kill the seeds. As a general rule, bring almost to a boil 5 times the volume of water as the volume of seeds, then pour


Scarifying hard yellowhorn seeds with a file.

the water over the seeds and let them stand in the water for 12 to 24 hours. With sulfuric acid, suffice it to say that familiarity with using this caustic chemical is needed, along with goggles and gloves. Timing is critical, and varies with the kind of seed. The acid must be thoroughly rinsed off following the treatment.

The easiest pretreatment is that needed by many grasses and most annual flowers and vegetables. Seeds of these plants need nothing more than a period of dry storage of from one to six months before they'll germinate. Cold is not needed, but does keep them fresh longer—so my vegetable and flower seeds wait out winter sitting in airtight plastic boxes and Mason jars in my garage.

Burial in tundra might be ideal for seed storage but I choose more practical storage for my vegetable and flower seeds.

Few seeds have as short a viability as onion; after only a year they might not be sufficiently viable for sowing.

A better story is the reported longevity of the 10,000 year old lupine seed that germinated after being taken out of a lemming burrow in the Yukon permafrost. Just think: the plant that produced this seed was up and growing when humans first walked across the Bering Land Bridge, and saber-toothed cats and woolly mammoths may have brushed up against its leaves. Except that the story of the 10,000 year old lupine seed turns out to be apocryphal, as confirmed by radiocarbon dating.

The true record for seed longevity was, until recently, 2,000 years, and was held by a date palm grown from seed recovered from an ancient fortress in Israel. A more recent discovery broke that record by a long shot.

A kind of campion seed (*Silene stenophylla*) found buried, this time in a squirrel burrow in Siberian tundra, could very well be 32,000 years old. The seed sprouted and was grown into a charming, white-flowered plant. Some coaxing was needed to get that seed to sprout. Actually, the seed itself did not sprout, but new plants were propagated from a few cells that were removed from the placenta and multiplied under sterile conditions on a specially concocted growth medium. Once cells had multiplied sufficiently, the growing medium was altered to induce growth of leaves, stems, and roots, and eventually the plants were robust enough to be planted in soil. The plant flowered and set seed, which germinated readily to produce more seedlings.

As short as is onion seed viability (I purchase new seed every year), other seeds have even shorter viability. Seeds of some members of the subfamily Tillandsioideae, related to pineapple, remain viable for only 4 to 6 weeks. Silver maple, *Acer saccharinum*, seeds retain their capacity to germinate for only about a week, making the many silver maples in the view out my bedroom window testimonial to the trees' fecundity.

Viable seeds are living, albeit dormant, embryonic plants which do not live forever. It's wasted effort to sprinkle dead seeds into furrows either in the garden or seed flats.

When purchasing a packet of seeds from a local store or mail-order seedhouse, you are assured of the viability of the seeds. There are government standards for the minimum percentage of seeds that must germinate for each type of seed. The packing date and the germination percentage often are stamped on the packets. (The germination percentage must be indicated only if it is below standard.) I write the year on any seed packets on which the date is not stamped.

Old, dog-eared seed packets may or may not be worth using this season. It depends on where the packets were kept and the types of seeds they contain.

Conditions that slow biological and chemical reactions, such as low temperature, low humidity, and low oxygen, also slow the aging of seeds. During spring and summer, the airtight plastic boxes and Mason jars in which I store seeds find their low temperature and low humidity home in the depths of my freezer or, more recently, in the cool temperatures of my basement. By fall, when frozen fruits and vegetables claim freezer space, I move seed boxes and jars back to the garage. An easy way to keep the humidity low in the storage containers is with silica gel or by sprinkling in some powdered milk, from a freshly opened box. Renew the powdered milk each year. Silica gel can be renewed in a hot oven.

It's not impossible for a backyard gardener to store seeds in a low oxygen atmosphere. I reverse engineered a bicycle pump to become a weak vacuum pump which, along with a Foodsaver® Wide Mouth Jar Sealer Vacuum Sealing Accessory, evacuates some of the air from my seed-containing Mason jars. Thinner air is also drier air.

The air in a sealed jar could, instead, be displaced before sealing it with a gas other than oxygen. Carbon dioxide is readily available in cartridges; a carbon dioxide bicycle tire inflator could be used to direct this gas into the jar. Argon gas is another option (Bloxygen®) that's used to preserve various products. Important when using either of these products is to introduce the gas slowly to avoid turbulence and allow it to settle. Both gases are heavier than oxygen.

Although some seed companies market their seeds in hermetically sealed, plastic-lined foil packets, I've never noted superior germination from these foil packets, as compared with plain old paper packets. Matter of fact, my own casual observations over the years are that germination of seeds kept in these hermetically sealed packets is worse. Perhaps the extra cost of the packaging is a disincentive to a seedhouse to discard old seeds or open the packets for re-testing. Perhaps my casual observations are too casual.

Seeds differ in how long they remain viable. Except under the very best storage conditions, as with onion seed, it's not worth the

Vegetable Seed Longevity Under Good Storage Conditions

Vegetable	Years	Vegetable	Years	Vegetable	Years
Bean	3	Cucumber	5	Parsnip	1
Beet	4	Eggplant	4	Pea	3
Broccoli	3	Endive	5	Pepper	2
Brussels sprouts	4	Fennel	4	Pumpkin	4
Cabbage	4	Kale	4	Radish	5
Carrot	3	Kohlrabi	3	Rutabaga	4
Cauliflower	4	Leek	2	Spinach	3
Celeriac	3	Lettuce	6	Squash	4
Celery	3	Muskmelon	5	Tomato	4
Chard, Swiss	4	Mustard	4	Turnip	4
Chinese cabbage	3	Okra	2	Watermelon	4
Collard	5	Onion	1		
Corn, sweet	2	Parsley	1		

risk to sow parsnip or salsify seeds after they are more than one year old. Two years of sowings can be expected from seed packets of carrot and sweet corn; three years from peas and beans, peppers, radishes, and beets; and four or five years from cabbage, broccoli, Brussels sprouts, cucumbers, melons, and lettuce.

Among flower seeds, the shortest-lived are delphinium, aster, candytuft, and phlox. In general, though, most annual flower seeds are good for one to three years, and most perennial flower seeds for two to four years.

In a frugal mood, I might do a germination test for a definitive measure of whether an old seed packet is worth saving. Counting out 10 to 20 seeds from each packet to be tested, I spread them between two moist paper towels on a plate. Another plate inverted over the first plate seals in moisture and the whole setup then goes where the temperature is warm, around 75 degrees. After one to two weeks, I peel apart the paper towels and count the number of

Testing germination of bean seeds.

seeds with little white root "tails". If the percentage is low, the seed packet from which the seeds came gets tossed into the wastebasket or compost pile (I don't give them away!). Or, I might use the seeds and adjust their sowing rate accordingly.

No one knows exactly what happens within a seed to make it lose its viability. Besides lack of germination, old seeds undergo a slight change of color, lose their luster, and show decreased resistance to fungal infections. There is more leakage of substances from dead seeds than from young, fresh seeds, so perhaps aging influences the integrity of the cell membranes. Or, since old seeds are less metabolically active than young seeds, the old seeds leak metabolites that they cannot use.

Electricity temporarily suffices when access to sunlight is lacking.

When God said, "Let there be light," He didn't make quite enough. At least, not enough for raising seedlings indoors in late winter. But way back then, "In the Beginning…" who could have predicted that gardeners in cold winter climates would have wanted to sow tomatoes and marigolds and lettuce indoors to get a jump on the season?

Fortunately, electricity was created, or at least harnessed, over a hundred years ago, and with electricity came artificial light. Early in the 20th century, Cornell scientists embarked on the first experiments in "electro-horticulture," the term they used for growing plants under artificial light, carbon arc lamps initially. Raising seedlings under artificial light is a lot easier and more effective now than it was then.

Good quality, yet inexpensive, lighting for raising top quality seedlings can be had with a combination of ordinary cool or warm white fluorescent tubes, and incandescent bulbs. Why both? Because if you fed sunlight through a prism, and then tested each color separately for its effect on plant growth, you would find that the most effective colors were red and blue. Red and blue light each have their own effects on plants, with, to simplify, red promoting longer stems and larger leaves and blue having pretty much the opposite effect, promoting compact growth. Too much of the former light makes for spindly plants, too much of the latter light makes for stunted plants. Not that green and yellow and orange are without effect, just less so.

Fluorescent lights are rich in blue, with some red. "Cool white" fluorescent bulbs emit very little red light, "warm white" bulbs emit a little more, and "full spectrum" bulbs more still. Incandescent lights are rich in red. Combine fluorescent and incandescent light, and you have a good approximation of sunlight, rich in the most important wavelengths. The combination even looks sunny.

Seedlings could also be raised in the glow of LED lights. Light from an LED spans a very narrow spectrum; if in red, just a narrow band in red, and similarly for blue or any other color. So narrow, in fact, that a different recipe for light seems to be needed for optimum growth of different kinds of plants, or different stages of growth. Performance is generally enhanced with the addition of a small amount of light in the green as well as far-red spectrum (the part of the electromagnetic spectrum just beyond the red that we can see, but shorter wavelength than infra-red). LED "grow lights" are on the market, but research with plant growth under LEDs is in its infancy.

Although the various combinations of fluorescent, incandescent, and LED bulbs offer reasonably good spectral quality, the intensity of these lights does not even hold a candle— pardon the pun—to good Ol' Sol, outdoors. A "foot-candle" is a measure of light intensity, and the sun bathes the Earth with 10,000 foot-candles on a sunny summer day. Indoors, even near the sunniest window, drop that figure to 500 foot-candles or less.

Light intensity drops with the inverse square of distance from a light source, so doubling the distance from a source results in only one-quarter the intensity, tripling the distance results in one-ninth the intensity, etc. Which is to say that seedlings need to be snuggled fairly close to artificial light sources, which aren't all that bright anyway, for best growth. A plant six inches below a standard double fluorescent lamp fixture is bathed in about 600 foot-candles of illumination. Be careful not to put plants too close to incandescent bulbs, however, because these bulbs can generate enough heat to burn a plant. Overall, artificial light works well for seedlings because only a small amount of incandescent light is needed to balance the blues of fluorescent light, and because 600 foot-candles is enough light for them. Double that distance, to about 12 inches, for LEDs.

When I began gardening, I lacked either a greenhouse or sufficient south-facing window space, so I built a phytotron, which is an enclosed space where temperature, light, and other parameters of plant growth can be regulated. I headed down to the local hardware store and purchased two double fluorescent fixtures, with reflectors, and porcelain sockets for incandescent bulbs, along with wire, a plug, a switch, some wood, and assorted fasteners. The reason for two double fluorescent fixtures is because the 600 foot-candles mentioned earlier is the minimum amount of light needed to raise seedlings; a double fixture boosts light levels enough to send seedlings to Winter Plant Paradise. I mounted the porcelain sockets to a 2-by-4 sandwiched between the two fluorescent fixtures, and hung it all on chains for easy lowering and raising. White paint everywhere helped eke maximum light from all sources, as did an occasional dusting off of lights and reflectors.

A good ratio—from the standpoint of a plant—for watts of fluorescent to incandescent light is about 3 to 1. If each fluorescent fixture is 4 feet long, the four 40 watt bulbs offer a total of 160 watts. I balanced that light with three 15 watt incandescent bulbs. A timer turned the lights on for 16 hours each day. Less time would have been needed if the light had been supplemented with natural light through a sunny window, but my phytotron was in the basement.

Exiting my phytotron, after a few weeks of growth, were top notch seedlings. Even so, artificial light is…well…artificial, and not nearly a match for natural light. The sooner plants get out in the sunlight, the better.