National Aeronautics and
Space Administration

Educational Product	
Teachers	Grades 5-12

Teachers and Students Investigating Plants in Space

A Teacher's Guide with Activities for Life Sciences

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National Aeronautics and Space Administration

Office of Human Resources and Education
Education Division
and
Office of Life and Microgravity Sciences and Applications
Life Sciences Division

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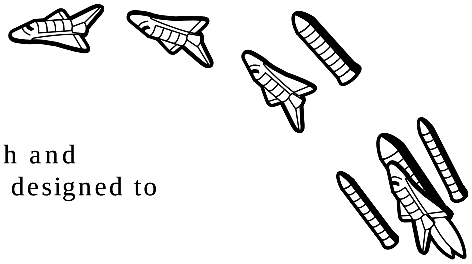
Overview of CUE-TSIPS

The Collaborative Ukrainian Experiment

In May of 1995, the presidents of the United States and Ukraine issued a joint statement on cooperation in space, directing the National Aeronautics and Space Administration (NASA) and the National Space Agency of Ukraine (NSAU) to cooperate on a joint Space Shuttle mission. The United States and Ukraine announced that a Ukrainian payload specialist would fly aboard this mission, STS-87, scheduled for October of 1997. The project was named the "Collaborative Ukrainian Experiment," or "CUE."

The CUE Science Questions

From plant science microgravity experiments on previous missions of the Russian, Ukrainian and American space programs, scientists have observed various abnormal growth and developmental phenomena in plants. The CUE projects are designed to address specific questions raised in prior experiments.



American scientists and their teams of colleagues and students, with Ukrainian scientists and their research teams, will be running 12 separate experiments as part of the science payload on STS-87. Several plant biology experiments will be run in an environmentally controlled Plant Growth Facility.

One experiment involves the controlled pollination and in-flight fixation of pollinated flowers of a special dwarf stock of rapid-cycling *Brassica rapa* (Wisconsin Fast Plants) known as "AstroPlants." A Ukrainian payload specialist will be performing these experimental procedures. The principal scientists and their question in this CUE experiment are:

Project acronym:	B-STIC
Investigation of:	microgravity effects on pollination and fertilization
Scientists:	Dr. Mary Musgrave, Louisiana State University, United States Dr. Antonina Popova, National Academy of Science of Ukraine
Question:	What developmental events during plant reproduction fail to function normally in the microgravity environment?

This question is part of the more general question: how will plants grow and function in microgravity considering that they have evolved and existed in an environment of the Earth's gravity?

The CUE Education Project: TSIPS

As a part of the total CUE mission, an Education Project has been established with the Wisconsin Fast Plants Program at the University of Wisconsin in Madison and the National Academy of Science of Ukraine, through the Ukrainian Junior Academy of Science in Kiev. The Education Project involves teachers and students in both countries and is called "TSIPS" – Teachers and Students Investigating Plants in Space.

During the same time as the joint Space Shuttle flight, students throughout the United States and Ukraine will be undertaking experiments to determine what is normal for biological events or stages in the life cycle of AstroPlants under the Earth's gravity. Seedlings of other plants may also be used to examine the effects of gravity and light on orientation and guidance in plants. The information that students gather will provide them with the basis for understanding a number of biological phenomena and principles, including phenotypic expression, variation, growth, orientation, reproduction and embryogeny. Students can compare their observations with those made in the microgravity environment by the CUE researchers.

The Central CUE-TSIPS Experiment

The CUE-TSIPS activities have been designed to address mainly those questions raised in the B-STIC investigation of Drs. Mary Musgrave and Antonina Popova, relating to the effects of microgravity on plant growth and reproduction.

The CUE-TSIPS activities center on the Science Exploration Flowchart (page 20). Students will grow AstroPlants through a life cycle, and in the process will become well acquainted with germination, orientation, growth, flowering, pollination, fertilization, embryogenesis and seed development.

Students will gain insight into the life cycle of AstroPlants by making many careful observations, measuring and recording what they observe, and organizing and displaying data in a way that they can make analyses. The data will provide both you and your students with a better understanding of what is "normal" development in AstroPlants and will serve as the basis for comparison with data taken by the CUE investigators to help determine what developmental events during plant reproduction are affected by microgravity.

The Science-Technology Partnership

Perhaps more than any other endeavor, experiments in space illustrate the essential interdependency of science and technology. Vast technological resources are marshalled in the execution of space-based science. Because of this interdependency of science and technology, the CUE-TSIPS project has emphasized both by including the design and construction of the experimental equipment as part of the science activities (page 19). Throughout the activities teachers are provided with instruction on how to engage students in this construction.

The CUE-TSIPS Questions

Are there any basic life processes that will be affected by microgravity in a way that will result in altered function? What are the significant growth processes that can be identified and observed under the conditions of microgravity?

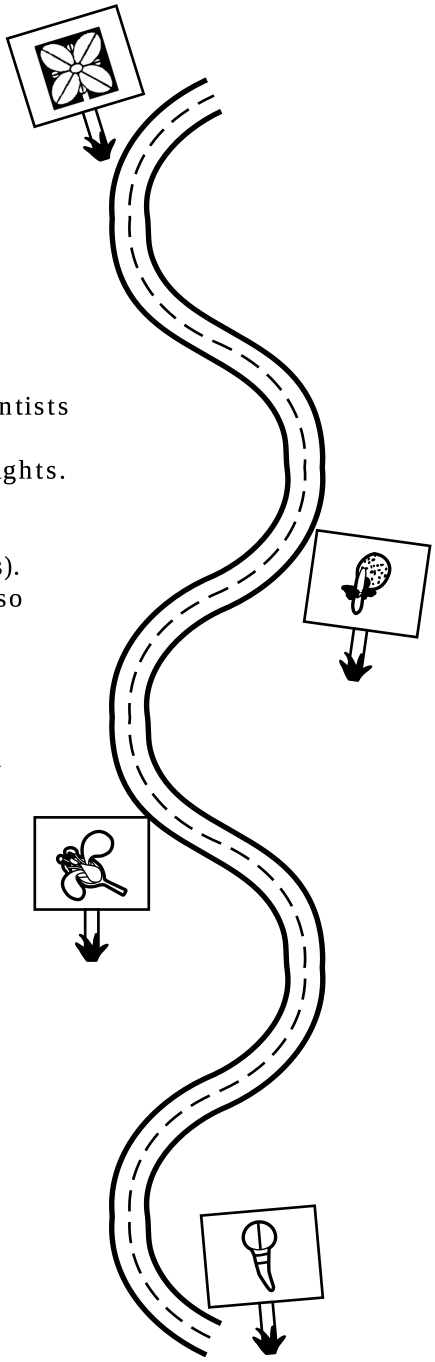
1. **Impact of the environment on a model organism.**
   Much of what the CUE flight and ground experiments will be about is coming to understand the many environmental variables that impact on the growth and development of the model organism, the AstroPlants. This stock was developed to grow rapidly under specified environmental conditions, in an apparatus with limited volume and restricted energy inputs.

2. **Microgravity.**
   If microgravity affects one or more life processes in AstroPlants such that deviation from the normal phenotype can be observed, then questions may be posed and research undertaken, leading to an understanding of how the processes are being affected.

3. **What is "normal"?**
   How would you define "normal"? In order to determine what the effects of microgravity are on AstroPlants, it is important to have an accurate understanding of how they grow under standard environmental conditions on Earth.

Road Map: How Do I Use This Guide?

The lessons in this guide can be used to engage your students in the fascination of space biology through plant investigations long after the CUE Space Shuttle mission has entered the history books. It is NASA's goal that the information in these pages will motivate both you and your students to become active and involved participants in the Space Life Sciences enterprise, now and in the future.



1. The CUE-TSIPS teacher guide.

- The CUE teacher guide is written for the teacher. Where "you" is used in the text, it refers to the teacher.
- The target audience for the CUE-TSIPS experiments is one of high school biology teachers and middle school life sciences teachers and their students.
- The CUE-TSIPS activities are intended to be run in "real time" with the NASA Space Shuttle flight, STS-87, scheduled for lift-off in October, 1997.

2. The plants being used for the CUE-TSIPS activities.

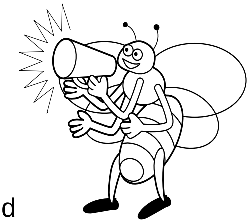
- A special genetic stock of Wisconsin Fast Plants called "AstroPlants" is used in the CUE-TSIPS activities.
  - AstroPlants are the research organisms being used by scientists for the Shuttle experiment that is the central CUE-TSIPS experiment for students and have been used in previous flights.
  - AstroPlants have a rapid life cycle and have been genetically selected to be very short, fitting within the limited space of the Shuttle Plant Growth Chambers (PGCs).
- Basic Fast Plants seed, as opposed to AstroPlants seed, will also work for the CUE-TSIPS experiments, however:
  - the plants will grow over the top of the student PGC, and
  - data on plants from the basic seed will be compiled separately from the AstroPlants data.
- Activities focused on germination (page 66) and orientation (page 78), are supplementary to the mission and may be done with other kinds of seeds (turnip, lettuce, alfalfa). These activities are marked with the bean symbol.

3. Performing the CUE-TSIPS activities.

- The central CUE-TSIPS activities focus on specific segments of the AstroPlants life cycle:
  - growth, development and flowering,
  - pollination, and
  - double fertilization and embryo development.
- If you have not used Fast Plants previously:
  - a trial run before the "real time" activities is advised, and
  - to be successful you must understand the biology of the plants and the importance of creating an environment conducive to growth. Essential reading includes "The Life Cycle of AstroPlants," "Understanding the Environment," and the background sections from "Growth, Development and Flowering," "Pollination" and "Double Fertilization and Post-Fertilization Events" (see Table of Contents).

- For the "real time" activities you and your students will:
  - provide the proper growing environment (lighting, nutrient, temperature, etc.),
  - construct the Plant Growth Chamber (PGC) from low-cost, readily available materials to simulate growing conditions on the Space Shuttle,
  - plant the AstroPlants in the PGC,
  - grow the AstroPlants through the entire life cycle, and
  - complete the AstroPlants Growth Data Sheets and Floral Clock Data Sheets.
- The "CUE-TSIPS Mission Calendar" (page 29) provides a clear day-to-day guide and schedule for the activities.
- Teachers may wish to customize the data keeping, depending on the age and ability level of their students.

For teachers:



The most important guidance items in this book are:

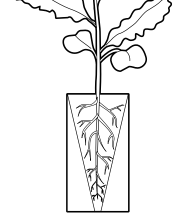
- "Understanding the Environment" (page 13), and
- the "CUE-TSIPS Mission Calendar" (page 29).

4. The supplementary activities.

- For students to fully benefit from the CUE-TSIPS experiments, the supplementary activities (7 to 11) in the "Germination" and "Orientation and Guidance" sections should be carried out prior to the experiments on reproduction.
- These activities are particularly rich in quantitative biology and mathematics.

5. Post-mission follow-up.

- Class summary statistics from the AstroPlants Growth and Floral Clock Class Data Sheets can be sent to the Wisconsin Fast Plants Program for compilation with data submissions from other classrooms in the United States and Ukraine (see page i for the mailing address).
  - Data will be entered for compilation only if specified environmental growing conditions have been met and recorded on the Class Data Sheets.
  - Parameters that must be reported with the data are:
    - ▲ irradiance (number of fluorescent bulbs, wattage, distance of plants from bulbs),
    - ▲ temperature of the growing environment (average daily temperature),
    - ▲ nutrient solution used,
    - ▲ root medium (e.g., specific soil or soilless mixture),
    - ▲ seed type (AstroPlants or basic Fast Plants), and
    - ▲ plants grown in a student PGC or in another capillary wicking system.
  - Data for compilation must be received by January 31, 1998.
  - Results will be posted on the Wisconsin Fast Plants World Wide Web site at the time of the National Science Teachers Association National Convention in April, 1998.
- Teachers complete evaluations by either:
  - completing and mailing in the printed "Teacher Reply Card" at the end of this guide, or
  - using the NASA EDCATS on-line forms (the "Teacher Reply Form," *http://ednet.gsfc.nasa.gov/edcats/teacher_guide* and the "Plant Experiment Follow-Up Form," *http://ednet.gsfc.nasa.gov/edcats/fastplants_report.html*).



Activity Matrix: Standards and Skills

Use the matrices on page 5 to align the CUE-TSIPS activities to the National Science Standards and Benchmarks. In each matrix, the teacher guide sections are listed along the left edge. If the activities in a given section fulfill a listed standard or include the development of a listed skill, the activity is marked with the symbol "✓" in the appropriate column. The section entitled "CUE-TSIPS Science and Technology" provides the foundations for experimentation and is aligned with many aspects of the content standards.

Science Standards

	Science as Inquiry	**Physical Science**	- position and motion of objects	- properties of objects and materials	**Unifying Concepts and Processes**	- change, constancy and measurement	- evidence, models and explanation	**Science and Technology**	- abilities of technological design	- understanding science and technology	**Science in Personal and Social Perspectives**	- science and technology in local challenges
Growth and Development	✓					✓		✓		✓		
Pollination	✓		✓			✓		✓		✓		
Fertilization	✓		✓	✓	✓	✓		✓		✓		
Germination	✓		✓		✓	✓	✓	✓	✓	✓		
Orientation	✓	✓	✓			✓	✓	✓	✓	✓		

Mathematics Standards

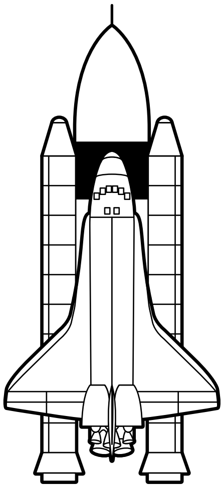
	Problem Solving	Communication	Reasoning	Connections	Number Relationships	Computation and Estimation	Patterns and Functions	Statistics	Probability	Geometry	Measurement	Functions	Trigonometry
Growth and Development		✓		✓	✓	✓		✓			✓		
Pollination		✓		✓	✓	✓					✓		
Fertilization		✓		✓	✓	✓		✓			✓		
Germination	✓	✓	✓	✓	✓	✓		✓			✓		
Orientation	✓	✓	✓	✓				✓		✓	✓		

Science Process Skills

	Observing	Measuring	Communicating	Collecting Data	Inferring	Predicting	Making Models	Making Graphs	Hypothesizing	Interpreting Data	Controlling Variables	Defining Operationally	Investigating
Growth and Development	✓	✓	✓	✓	✓	✓		✓	✓	✓	✓	✓	✓
Pollination	✓	✓	✓	✓	✓	✓			✓	✓	✓	✓	✓
Fertilization	✓	✓	✓	✓	✓	✓		✓	✓	✓	✓	✓	✓
Germination	✓	✓	✓	✓	✓	✓		✓	✓	✓	✓	✓	✓
Orientation	✓	✓	✓	✓	✓	✓	✓		✓	✓	✓	✓	✓

The Importance of Plants in Space

Contributed by Bonnie J. McClain (Purdue University Grantee, Education Programs Coordinator, NASA Space Life Sciences) and Tom K. Scott (Senior Scientist, NASA Space Life Sciences).

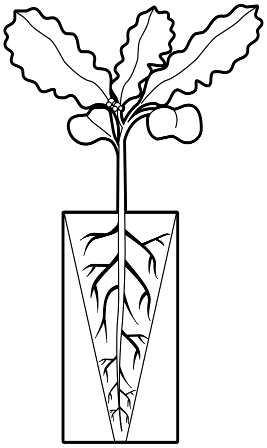


The relationship between plants and humans has always been a close and interdependent one. Research about basic plant processes helps in understanding and augmenting this interdependence. Ground-based investigations yield information vital to this understanding; however, the knowledge gained from plant research in space is exciting and extends potential for new discoveries beneficial to humans.

There is abundant evidence that microgravity affects virtually every aspect of plant growth. Space flight provides the only known environment in which fundamental biological processes and mechanisms can be studied in the absence of the sometimes overriding effects of gravity. Removal of the effects of gravity for long periods of time allows new perspectives in the study of plants.

Answers to important questions about the basics of plant growth and development lie in understanding the role gravity has on plant processes and responses to the environment. For example, gravitropism is the bending response of plants to the force of gravity with the roots growing downward and the shoots growing upward. Charles Darwin began experiments on plant gravitropism during the nineteenth century, yet the mechanisms of this process are still not clear. The more knowledge generated about how plants function, the more likely we can adapt that information into practical, useful new applications and products enhancing life on Earth and in space.

NASA's research with plants in space is dedicated to systematic studies that explore the role gravity plays at all stages in the life of higher plants. Research focuses on the interaction of gravity and other environmental factors with plant systems, and uses hypergravity, simulated hypogravity, and microgravity as tools to advance fundamental knowledge of plant biology. Results of the research contribute to NASA's efforts to further human exploration of space and to improve the quality of life on Earth through applications in medicine, agriculture, biotechnology and environmental management.

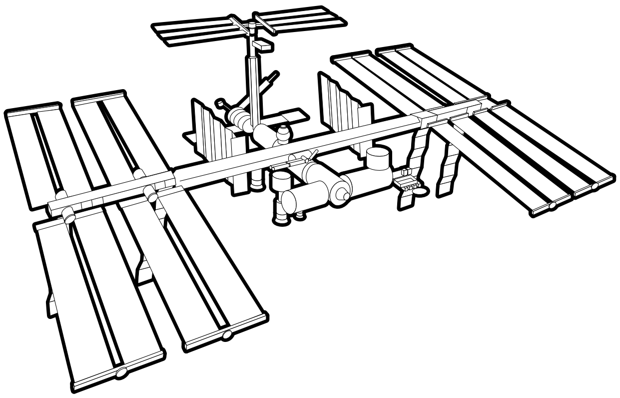


NASA's plant science research questions focus on five objectives:

- to explain the basic mechanism whereby plants perceive, transduce, and respond to gravitational force (example: comparisons of seedling vs. older plant responses to gravity);
- to understand the role of gravity and microgravity in developmental and reproductive processes in plants (examples: flower development and wood formation);
- to learn how metabolic and transport processes are affected by gravity and microgravity (examples: photosynthesis and long and short distance sugar transport);
- to analyze interactions of microgravity with other important parameters of space (examples: cosmic radiation and electromagnetism); and
- to study the role of plants within recycling life support systems for space exploration (examples: carbon dioxide production and oxygen revitalization).

Knowledge of physiology, cell biology, biochemistry and molecular biology of plants coupled with biotechnology advances contributes to our fundamental knowledge of plants and provides impetus for a new era of plant investigations. The opportunity to experiment at a micro level of gravity provides a new dimension that enables interdisciplinary plant research to answer important questions about the plant's reception of the gravity signal, the plant's biochemical interpretation of that signal, and how that interpretation causes a developmental reaction. It appears that this reaction system, in general, interacts with receptor systems that detect both internal and external signals. It is for this reason that understanding the role of mechanical signals, such as gravity, assumes such significance for plant science: these investigations could begin to reveal the precise control mechanisms involved in dictating plant form, structure, and function.

Understanding how basic processes can be manipulated and put into use in new ways that develop new products and increase productivity is the basis for biotechnological applications in agriculture, horticulture, and forestry. For example, understanding the interaction between gravity and light could be the basis for genetic engineering of plants resulting in increased crop productivity while minimizing the required growing space. Application to horticulture could include the ability to control plant form, and forestry could benefit from faster methods of regeneration of lost forest areas.



Before the first lunar outpost, the proposed Mars base, and other future missions from planet Earth can become realities, numerous scientific and technological problems remain to be solved. None of these problems is more important than that of supporting human life in space. Extended duration human exploration missions will require life support capabilities beyond those now available. A solution is to develop technologies that integrate physical and chemical processes into a dynamic, recycling life support system.

Studying plants in space will provide the scientific information necessary for development of such a life support system. Plants will be a primary component of atmospheric regeneration: carbon dioxide exhaled by humans will be taken up by plants and used in photosynthesis, in the process returning oxygen and food to the crew. Plants are also important in water regeneration. The productivity of plants relative to the input of energy (light) can be increased by using such techniques as carbon dioxide enrichment and hydroponics. To achieve a controlled life support system, ground-based research in growth chamber facilities will be conducted along with plant investigations in the microgravity environment of space flight.

Why study plants in space? The discoveries made, lessons learned, and technologies developed from these investigations will benefit those of us on planet Earth as we unlock and utilize gravity's mysteries to enhance our journey into space.

Microgravity

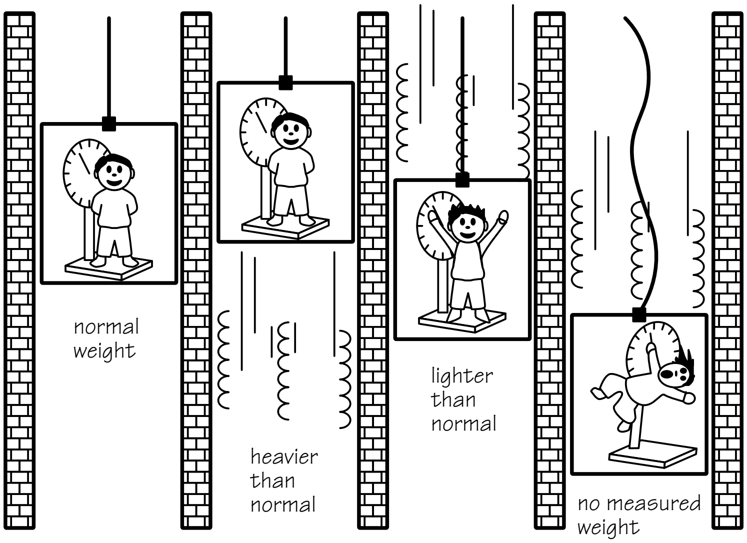
Contributed by Greg L. Vogt (Crew Educational Affairs Liaison, NASA Johnson Space Center).

Gravity is an attractive force that is a fundamental property of all matter. Whether an object is a planet, a feather or a person, each exerts a gravitational force on all other objects around it. Physicists identify gravity as one of the four types of forces in the universe (the others are strong and weak nuclear forces and electromagnetic force).

The strength of the attraction between two objects is directly proportional to the product of the masses of those objects and inversely proportional to the square of the distance between the centers of mass of those objects: in other words, the larger the objects the stronger the attraction between them and the greater the distance between the objects the weaker the attraction. When measured at the surface of the Earth, the acceleration of an object acted upon only by Earth's gravity is commonly referred to as "1 g" or "unit gravity." This acceleration is approximately 9.8 meters per second squared (m/s^2).

On Earth, gravitational force is important in providing orientation and guidance to many forms of life including plants. For example, plants orient themselves with gravity so that shoots grow up and roots grow down and water and nutrients are transported through the plants against the pull of gravity.

Although gravity is a force that is always with us, its effects can be greatly reduced by the simple act of falling. NASA uses the term "microgravity" to refer to the condition that is produced by a "free fall." The diagram at the right illustrates how a condition of microgravity is created. Imagine riding in an elevator car to the top floor of a very tall building. At the top, the cables supporting the car break, causing the car and you to fall to the ground. (In this example we discount the effects of air friction on the falling car.)



Since you and the elevator car are falling together, you feel like you are floating inside the car. In other words, you and the elevator car are accelerating downward at the same rate. If a scale were present, your weight would not register because the scale would be falling too. You would be experiencing free fall or what astronauts call "microgravity." The ride is lots of fun until you get to the bottom!

The term microgravity can be interpreted in a number of ways, depending upon context. The prefix "micro-" (μ) is derived from the original Greek "mikros," meaning "small." By this definition, a microgravity environment is one that will impart to an object a net acceleration that is small compared with that produced by the Earth at its surface. Another common usage of micro- is found in quantitative measurement, such as the metric system, where micro- means one part in a million. In practice, net accelerations will range from about one percent of the Earth's gravitational acceleration (aboard aircraft in parabolic flight) to about one part in a million (aboard the Space Shuttle orbiter).

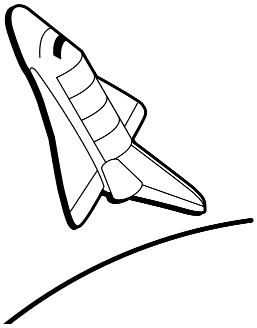
NASA uses airplanes, drop towers and small sounding rockets to create a microgravity environment for experimental purposes. In each facility, an experimental payload is put into free fall that lasts from a few seconds to several minutes. Eventually, free fall ends because the object will impact on the Earth's surface.

When scientists want to conduct experiments in microgravity for longer durations – days, weeks, months or even years – it is necessary to travel into space and orbit Earth. Having more time available for experiments means that slower processes and more subtle effects can be investigated. Today, the Space Shuttle and special satellites are the space facilities that provide opportunities for these microgravity experiments. The International Space Station will soon be an important additional means of accomplishing such investigations.

Orbiter Orientation

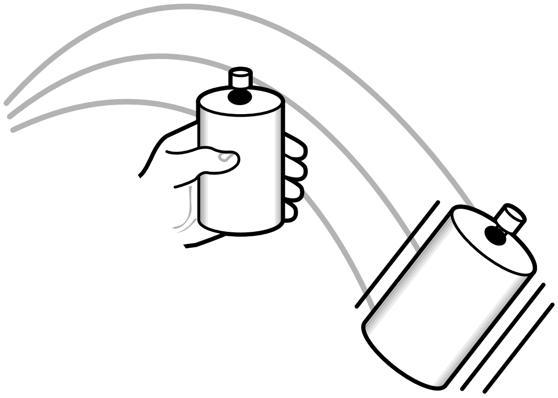
To obtain the most consistent microgravity environment in space, the Space Shuttle orbiter is oriented in a tail-down position. This is called the "gravity gradient mode." The tail of the orbiter is closer to the Earth and feels a stronger pull of gravity than does the more distant nose of the orbiter.

The difference in the strength of the attraction between the nose and tail has a stabilizing effect on the attitude of the orbiter. This means that the on-board crew is able to keep the orbiter stabilized with fewer corrective firings of the reaction control rockets (thrusters). Each firing produces an acceleration that interferes with the microgravity environment of the Space Shuttle.



Microgravity Activity

You can demonstrate a microgravity environment and the effects of freefall in the classroom. Collect an aluminum soft drink can, a nail, about 12 ounces of water and a waste basket.



Punch a small hole in the lower side of the can with the nail, about 0.75 cm up from the bottom. Hold the can with one end so that your thumb covers the hole.

Keeping your thumb tightly covering the nail hole, fill the can with water and position the waste basket below. You may wish to stand on a chair to gain a higher can altitude.

Slide your thumb off the hole so that a stream of water is visible to all. Then drop the can. The water stream stops. Why?

In free fall, gravity's local effects are reduced.

During the fall, no force is at work pulling the water out of the hole. The water and the can fall at the same rate, just as in the falling elevator example. The water is in the condition of microgravity, experiencing free fall (Vogt and Wargo, Eds., 1992).

The Collaborative Ukrainian Experiment provides many unique opportunities for understanding the effects of gravity and microgravity on plants.

The Life Cycle of AstroPlants

What are AstroPlants? AstroPlants are a special form of the species *Brassica rapa* (Wisconsin Fast Plants), a member of the mustard or cabbage family Cruciferae. Crucifers are distinguished by characteristic flowers with four petals in the form of a cross or crucifix. Other forms of *Brassica rapa* include turnips, Chinese cabbage, pak choi and canola. Some related crops in other *Brassica* species are cabbage, broccoli, collard, cauliflower and mustard.

Life Cycle Concepts and Questions

Beginning the Life Cycle: Growth, Development and Flowering

Germination is the awakening of a seed (embryo) from a resting state. It involves the harnessing of energy stored within the seed and is activated by components in the environment. Growth represents increase in size, number and complexity of plant cells and organs. Environment and genetics play fundamental roles in regulating growth. The energy for growth comes from photosynthesis.

Flowering is the initiation of sexual reproduction. The generation of male and female gametes (sperm and eggs) is one of the primary functions in flowering. The plant prepares for pollination by producing flowers. Each part of the flower has a specific role to play in sexual reproduction. The flower dictates the mating strategy of the species.

- *What are the main components of the environment necessary for germination?*
- *How does the seedling orient itself?*
- *What enables the emerging plant to shift its dependency from stored energy to the energy from light?*
- *What is the role of the environment in regulating plant growth?*
- *How do plants grow?*
- *How does a plant know when to produce leaves and when to produce flowers?*
- *Why does a plant have flowers?*

Pollination

Pollination is the process of mating in plants. In flowers, pollen is delivered to the stigma through a wide range of mechanisms that insure an appropriate balance in the genetic makeup of the species. In brassicas, pollen is distributed by bees and other insects. The flower is the device by which the plant recruits the bee. Bees and brassicas have evolved an interdependent relationship.

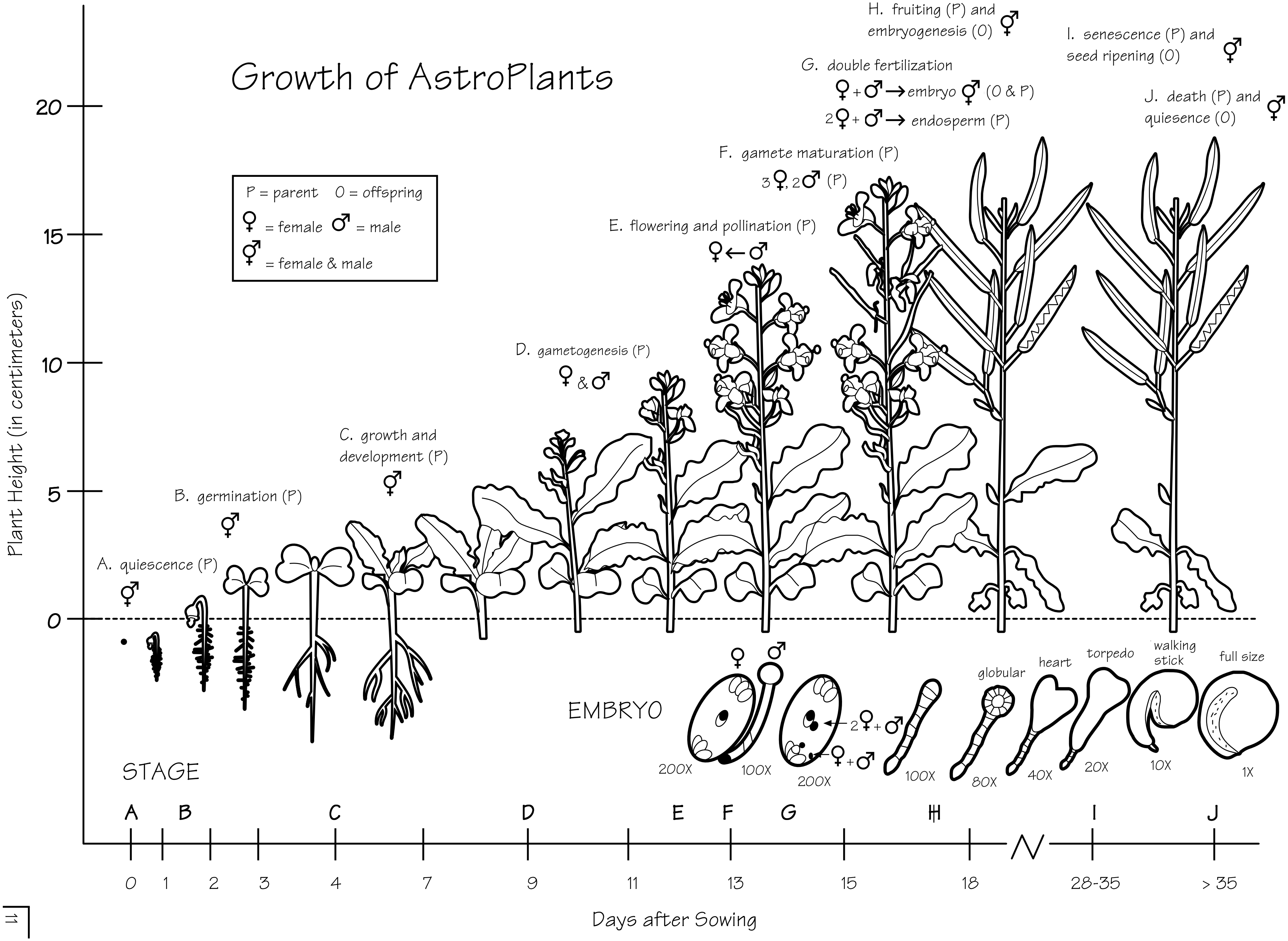
- *How do flower parts function to influence mating behavior?*
- *How does the flower recruit the bee?*
- *How does pollination occur?*
- *How does the flower discriminate between self and nonself in the mix of pollen?*

Double Fertilization and Post-Fertilization Events

Fertilization is the final event in sexual reproduction. In higher plants, two sperm from the pollen grain are involved in fertilization. One fertilizes the egg to produce the zygote and begin the new generation. The other sperm combines with the fusion nucleus to produce the special tissue (endosperm) that nourishes the developing embryo. In some plants endosperm nourishes the germinating seedling. Fertilization also stimulates the growth of the maternal tissue (seed pod or fruit) supporting the developing seed.

- *What is unique about fertilization in flowering plants?*
- *What is endosperm and what is its relationship to the embryo?*
- *How does an embryo develop into a seed?*
- *How does the maternal parent contribute to the developing embryo?*

Growth of AstroPlants

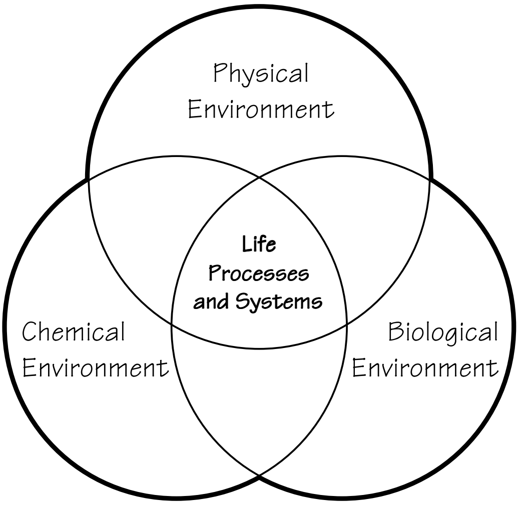


Stages in the Life Cycle of AstroPlants: Concepts of Dependency

Stage	State	Condition	Dependency
A. seed	• quiescence (dormant embryo)	• suspended growth of embryo	• independent of the parent and many components of the environment
B. germinating seed	• germination	• awakening of growth	• dependent on environment and health of the individual
C. vegetative growth	• growth and development	• roots, stems, leaves grow rapidly, plant is sexually immature	• dependent on environment
D. immature plant	• flower bud development	• gametogenesis — reproductive [male (pollen) and female (egg)] cell production	• dependent on healthy vegetative plant
E. mature plant	• flowering • mating	• pollination — attracting or capturing pollen	• dependent on pollen carriers; bees and other insects
F. mature plant	• pollen growth	• gamete maturation • germination and growth of pollen tube	• dependent on compatibility of pollen with stigma and style
G. mature plant	• double fertilization	• union of gametes • union of sperm (n) and egg (n) to produce diploid zygote (2n) • union of sperm (n) and fusion nucleus (2n) to produce endosperm (3n)	• dependent on compatibility and healthy plant
H. mature parent plant *plus* embryo	• developing fruit • developing endosperm • developing embryo	• embryogenesis — growth and development of endosperm and embryo • growth of supporting parental tissue of the fruit (pod)	• interdependency among developing embryo, endosperm, developing pod and supporting mature parental plant
I. aging parent plant *plus* maturing embryo	• senescence of parent • maturation of fruit • seed development	• withering of leaves of parent plant • yellowing pods, drying embryo • suspension of embryo growth, development of seed coat	• seed is becoming independent of the parent
J. dead parent plant *plus* seed	• death, desiccation • seed quiescence	• drying of all plant parts, dry pods will disperse seeds	• seed (embryo) is independent of parent, but is dependent on the pod and the environment for dispersal

Understanding the Environment

Three broad categories of environmental components interact to influence all life: 1) physical, 2) chemical and 3) biological. Understanding the many environmental factors and how they interact with each other to influence life is essential for good investigative science and is the key to successful experimenting with AstroPlants. In space life science investigations such as the CUE, scientists and engineers have worked together to develop technology that will create an environment to support normal plant growth within the hostile external environment of space.



Some environmental factors influence plant growth more than others. If one or more factors is reduced or increased such that normal functioning is disrupted, that factor is said to be *limiting*. When a factor that can be quantified becomes limiting, its observed effects can also be quantified.

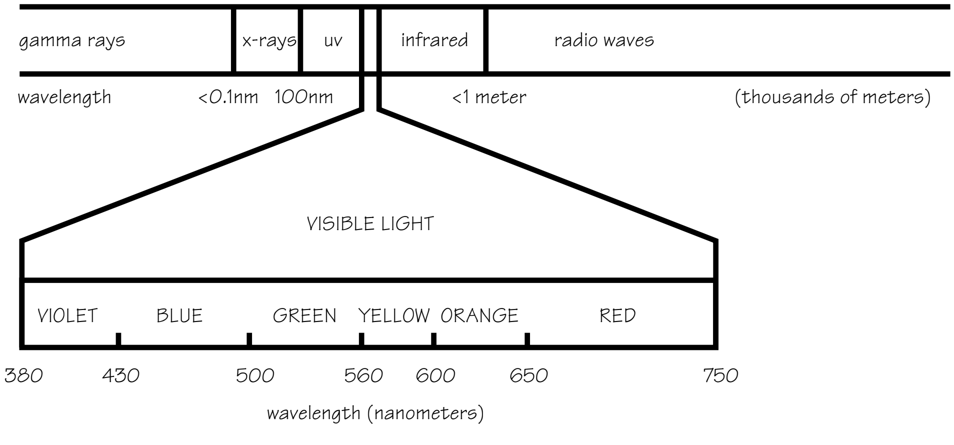
The Physical Environment

Light

Appropriate lighting is perhaps the most critical component of a plant's growing environment. Plants use energy from various regions of the visible spectrum to perform a number of functions essential to their growth and reproduction. Some seeds require red light to activate germination. Blue light is important for regulating elongation of stems and in guiding the direction of plant growth. Red and blue are the primary energy levels used for photosynthesis, whereas red and far red are important in the regulation of leaf expansion and certain pigment production systems.

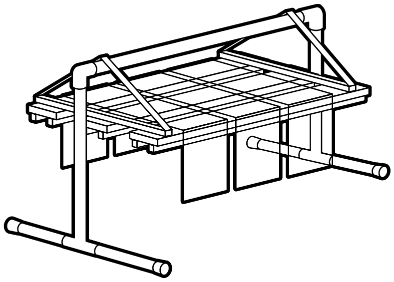
Light for AstroPlants is produced by fluorescent lamps which emit a mix of photons in the visible range that appear as white with warm (red) or cool (blue) tones in the mix. The quantity of photons reaching a surface is known as *irradiance* or *photon flux density* and is measured in micromoles (µM) or microEinsteins (µE) of photon flux per square meter per second.

Spectrum of electromagnetic radiation.



Irradiance of greater than 200 $\mu Em^{-2}s^{-1}$ is ideal for AstroPlants. Less than 100 $\mu Em^{-2}s^{-1}$ is inadequate.

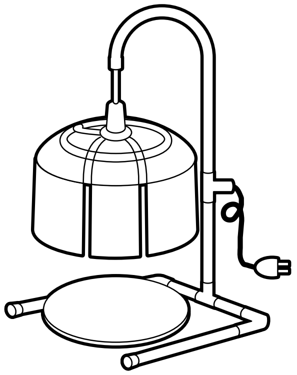
As with other electromagnetic forces and gravity, the inverse square relationship applies to light. That is, if the distance between the source of light and the receiving surface doubles, the intensity of the irradiance diminishes by a factor of four.



If you are using the standard four-foot Fast Plants light bank, you can use either eight 40 watt cool white or six of the newer 32 watt high efficiency bulbs which will require different fixtures than the 40 watt bulbs. Six 32 watt Sylvania Octron® 4100K FO32/741 bulbs spaced within two feet will produce ideal lighting for AstroPlants.

Fluorescent "circle" lamps can be suspended above and will adequately irradiate the plants growing within a circle of 30 cm diameter (12 inches). The Wisconsin Fast Plants Program has had the most successful growth under 30 or 39 watt circular or "folded" circular bulbs.

Reflectors made from aluminum foil or reflective mylar (available from fabric or stationery stores) greatly increase the irradiance reaching the plants, particularly those around the edges of the lamps. Aluminum foil "curtains" (15 cm x 25 cm) taped on the lamp fixture to hang down to about the soil level will contribute to uniform lighting across the plants.



Tips:

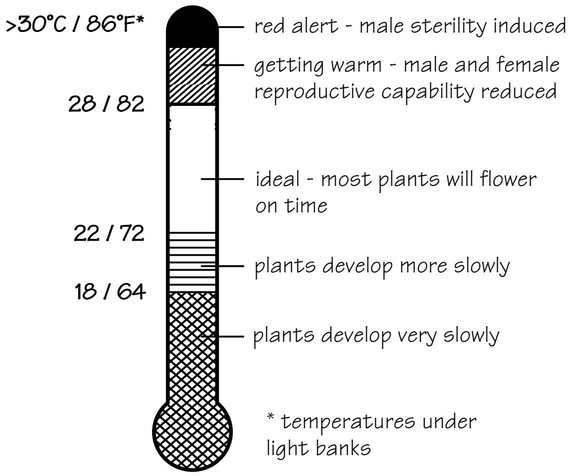
- Keeping the AstroPlants under constant 24 hour light will produce the most satisfactory results. Be sure to make arrangements (with custodians, etc.) so light banks are not turned off at any time.
- Bulbs should be kept 2 cm to 3 cm above the top of the experimental Plant Growth Chamber lid (page 32). Ideally the growing tips of the plants should be kept 5 cm to 10 cm from the lights. The height of the Plant Growth Chamber (PGC) lid will keep your seedlings about 15 cm from the bulbs. This is adequate provided reflective curtains are used.

Formula for growing successful AstroPlants – **LIGHTING** :

eight 40 W bulbs or six 32 W high efficiency bulbs, ***lighting 24 hours a day*** + use reflective foil curtains + keep top of PGC lid 2 to 3 cm from the lights = **Healthy AstroPlants**

Temperature

The temperature of the AstroPlants' growing environment will have an important influence on the growth of your plants. Temperatures that are too high or too low can affect the timing of developmental events such as seedling emergence and flowering. Optimal temperature is between 22˚C and 28˚C (72˚F to 82˚F).



Tip:

- Temperatures can be monitored under each bank using hi-low thermometers. Note fluctuations in the room temperature and variation in temperature among light banks.

Gravity and Microgravity

Of the many environmental factors that impact on life, *gravity* is one that exists on Earth with the greatest constancy (page 8). Gravity is an environmental factor that is difficult to vary experimentally without the support of space technology. Microgravity is what the CUE experiments are all about!

The Soilless Root Medium

In the CUE-TSIPS activities, a mixture of one part peat moss and one part vermiculite, known as *peatlite*, serves as the root medium that anchors the plant roots, providing support for the stem and leaves. Physical characteristics of the root medium must be such as to provide adequate capillary wicking of water to the absorptive surfaces of the root hairs and epidermal cells, yet there must also be adequate channeling within the matrix of the root medium to enable air exchange for oxygen diffusion to the growing roots. Under conditions of unit gravity, peatlite provides ideal capillarity and air channeling for AstroPlants.

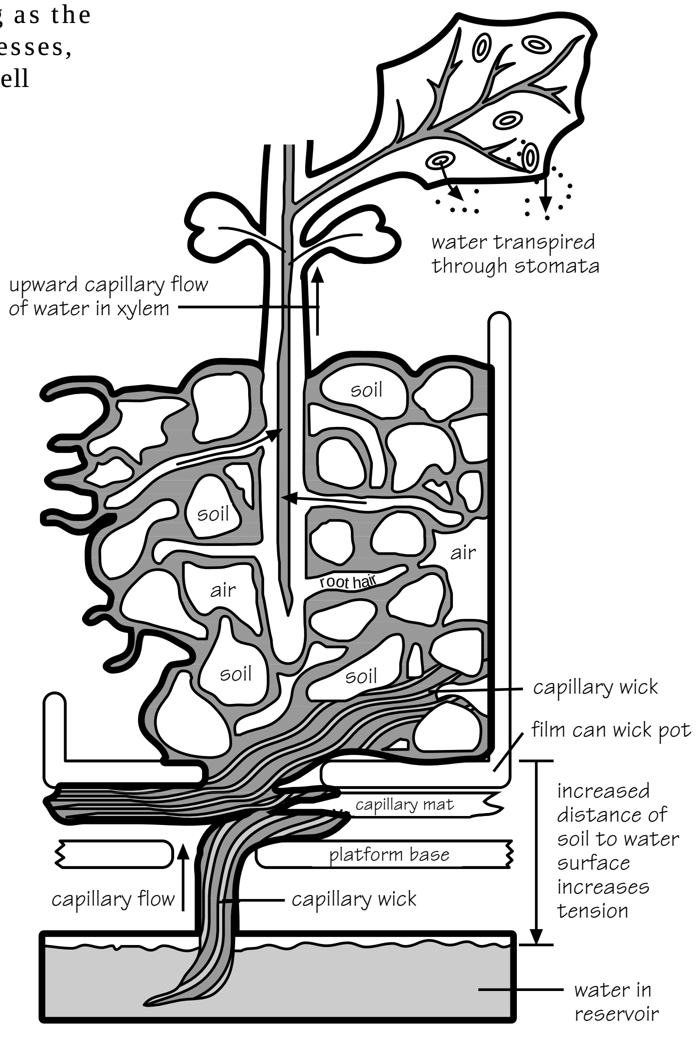
The Chemical Environment

Water

Water functions in many ways in plants, serving as the primary solvent supporting life's metabolic processes, generating *turgor pressure* (water pressure) for cell enlargement and growth, maintaining ionic balance and providing cooling via transpiration. Water is also the source of hydrogen reducing power when it is split by light energy in photosynthesis. Water enters the plant primarily through the root epidermis and hair cells, traveling through intercellular space and cortical cells to the xylem tissue where it is distributed throughout the plant.

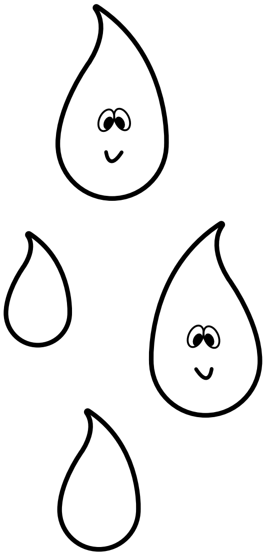
Within the root zone, water is found adhering to soil particles as a continuous film created through the *cohesive* forces of the water molecules. The *adhesive* forces that attract water molecules to the surfaces of soil particles and plant root cells pull the water into the minute channels within the soil and plant tissues via *capillarity*.

In the PGC, capillary wicking material is used to pull water from a reservoir to the root medium which has strong capillary properties. There is an unbroken continuity of water from the soil into and throughout the plants (see figure at right). Through this water course, the plant also gains access to inorganic nutrients. On Earth, gravity acts as a vertical counter force opposing the cohesive forces of water and adhesive forces of capillarity.



Atmospheric Relative Humidity

The atmospheric relative humidity of a classroom can affect the rate of *transpiration* and water uptake by plants. Under low relative humidity there can be rapid water uptake from the reservoirs. When reservoirs run dry, capillarity is broken and plants will desiccate and die. When plants begin to wilt, it is an indication that transpiration is exceeding water uptake. In some climates this occurs when there has been a rapid drop in atmospheric relative humidity. In these cases plants usually adjust by reducing transpiration and regaining their turgor pressure.



If wilting persists when using the PGC, check the reservoir and examine the capillary wicks and matting to be sure they have not dried out and broken the capillary connection between roots and reservoir.

If the atmospheric relative humidity is very high (>95% RH), mature anthers in flowering AstroPlants may fail to open (dehisce) to expose their pollen. This occurs when plants are grown in closed containers in which the relative humidity builds up. It can be remedied by circulating air over the plants with a fan; mature anthers will then usually dehisce within a few minutes.

Inorganic Nutrients

In addition to the elements carbon, oxygen and hydrogen which make up the main structure of organic compounds in plants, 13 other elements are required to support the range of metabolic processes that constitute life. Six elements – nitrogen, potassium, calcium, phosphorus, magnesium and sulfur – are known as *macronutrients* because they are required in relatively greater quantities than the seven *micronutrients* – iron, chlorine, copper, manganese, zinc, molybdenum and boron (Raven, Evert and Eichorn, 1992).

In the CUE-TSIPS experiments, inorganic nutrients are added to the root media as Wisconsin Fast Plants Nutrient Solution (page 96). Nutrients can also be added as commercially available fertilizer, such as Peters® 20-20-20 N-P-K (page 96).

Formula for growing successful AstroPlants – **NUTRITION :**

water + air + inorganic nutrients (6 major and 7 minor) = **Healthy AstroPlants**

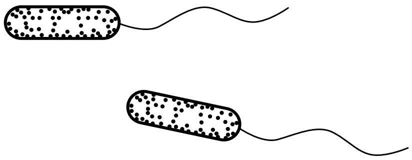
Atmosphere

Ambient air contains nitrogen (78%), oxygen (21%), hydrogen and helium (<1%). Carbon dioxide in air is approximately 350 parts per million and is the primary source of carbon incorporated into organic molecules via photosynthesis. In closed systems such as the Space Shuttle orbiter, where humans and other organisms are respiring, CO_2 may build up to toxic levels. Plants have the potential role in space flight of extracting CO_2 from the air and converting it into edible biomass. In the Space Shuttle orbiter, CO_2 levels are carefully monitored and excess removed from the atmosphere by chemical trapping in filters.

The Biological Environment

Types of Organisms

There can be many types of organisms associated with the plant's environment, from algae to insects. These organisms may reside together in various *symbiotic* relationships, from mutually beneficial to *parasitic* (one partner benefits) and even *pathogenic* (one partner harms the other). Some symbioses may be strictly neutral. Controlling undesirable organisms in the plants' environment requires continuous attention. Possible residents include:

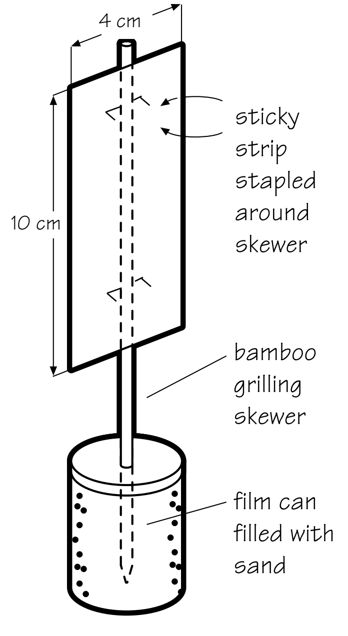


- various soil *microflora* (bacteria, fungi) and *microfauna* (nematodes, worms, insect larvae) which may colonize the root zone or *rhizosphere*;
- *phytophagous* (plant-eating) arthropods which may be found on stems, leaves and flowers (mites, thrips, aphids, leaf-eating beetles, moth and butterfly larvae);
- the larvae of fungus-eating (*mycophagous*) flies which may exist in large numbers, emerging from the root medium and water mat as small black gnats; and
- various algal populations which may live on the moist root media, capillary wicking material and in the nutrient solution reservoirs. Most common are blue-green algae (*cyanobacteria*) on root media and mat surfaces and green algae in reservoirs.

Controlling Undesirable Organisms

Fungi and Bacteria: Fungi and bacteria rarely attack the above-ground parts of plants as long as the relative humidity is less than 95% and there is good air flow. The best control for fungi and bacteria is sanitation. Be sure to use pathogen-free root media – most commercially available peatlite mixtures are sanitized and pathogen-free. Keep the root media well aerated and drained by not packing it in the growing containers. After growing, it is important to rinse, then soak all pots, reservoirs, capillary mats and wicks for at least 30 minutes in a 10% chlorine bleach solution. Do not reuse root media.

Insect Pests: The continuously illuminated plants can be attractive to many insects, especially at night. Daily surveillance and removal of insects is good practice. Sticky yellow pest control cards work well to trap incoming insects and flies emerging from the soil. The sticky strips available from garden stores can be cut and stapled to bamboo grilling skewers and mounted in film cans filled with sand and placed among the plants. These are very effective for white flies, aphids, fungus gnats and thrips.



If colonies of aphids, white flies or thrips appear or evidence of larval feeding is observed (holes chewed in leaves or flowers), plants may be sprayed with insecticidal soap or another safe chemical control agent. Read labels carefully before applying chemicals. Surveillance and careful removal by hand is the best control practice.

Algae: The most common residents with AstroPlants are algae. Most do not affect plant growth but can become unsightly and occasionally will build up in reservoirs and wicking to consume nutrients and retard water flow. Algae growth can be suppressed by adding copper sulfate ($CuSO_4 \cdot 5H_2O$) to the nutrient solution at a final concentration in the reservoir of between 50 and 100 parts per million (milligrams/liter).

CUE-TSIPS Science and Technology

Science begins when a person of any age is curious about something and begins to question and explore the relationships of a phenomenon to his or her understanding of the world. The scientific process begins with an observation and questions and proceeds through a process of inquiry involving exploration, investigation, experimentation and analysis, and communication and persuasion. That process engages the creative energy of the individual and leads to deeper understanding, a sense of pleasure and increased self-worth. Even young children quite naturally say: "Look what I found!"

Dr. Mary Musgrave and Dr. Antonina Popova are successful scientists who are curious about the growth of plants in space. Their interest is broad, but the questions they are asking in the CUE are very specific. They are successful as scientists because they pay a great deal of attention to the details of the questions they ask and to the design and execution of the experiments they have run to test their questions. They are both analytical and critical in their approach to the science they do; before they accept an answer to their questions, they want rigorous proof that there are not more plausible alternatives. Indeed, many scientists believe that they come closest to an understanding of what is true through an exhaustive quest which seeks, yet fails, to disprove a hypothesis. This chapter deals with many of the essentials that will lead you and your students through the discipline and pleasure of good science.

As the result of microgravity experiments run on previous missions from the former USSR, from the Russian, Ukrainian and U.S. space programs, in which the gravitational force was about one million times less than on Earth, Drs. Musgrave and Popova have observed various abnormal growth and developmental phenomena in plants. The CUE B-STIC experiments are designed to address aspects of the more specific question: what developmental events during pollination, fertilization and embryo development fail to occur normally in the microgravity environment?

Science is All About Questions

As you and your students proceed with the CUE-TSIPS activities, you will be progressing through the stages illustrated in the Science Exploration Flowchart (page 20). The following questions are designed to assist you. Remember the power of writing as an assistance to learning. Have your students pose questions and answers, document ideas and diagram relationships.

1. **What do you observe?**

2. **What is your question about your observations? What is the question you are exploring?**

3. **How would you convert the question into an assertion, which is the idea you are experimentally testing (your hypothesis)?**

   - Can you also write this as a *null hypothesis* in which you may state the hypothesis having the opposite, or null, outcome?

4. **What variable will you change in your tests? What is your treatment? What potential variables will remain constant?**

5. **What are your control treatments? How will each serve as a control?**

6. **How many observations for each result are enough? Is n = 1 enough to be representative? If not, what is enough? Why?**

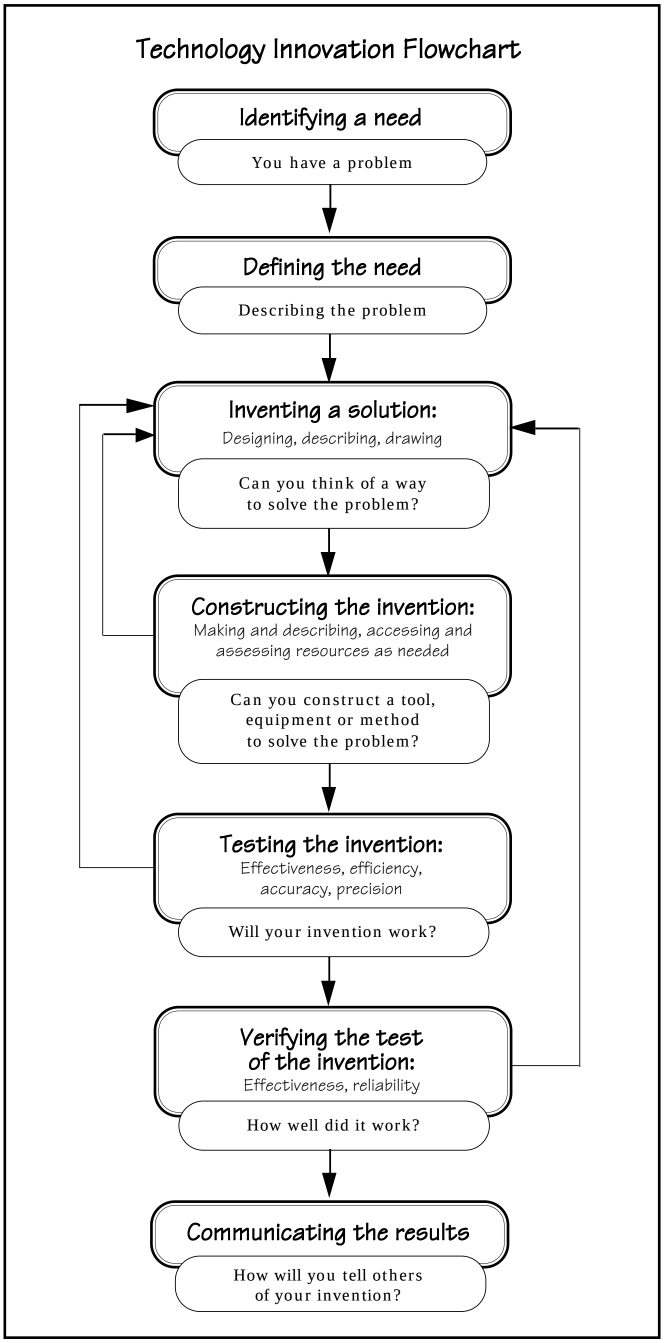
7. Is there any special experimental design of the treatments and/or replicates needed in the experiment?

8. What equipment, tools, etc., will you need for your experiment?

- Draw your experimental set-up.

9. What form will your observations take? How will you describe or measure your observations?

- Use descriptors, comparators, scales and quantitative estimates.



10. How will you record or tabulate your data?

11. How will you organize your data? How will you display your data?

- Use statistical summarization.

12. What is your conclusion relative to your hypothesis? What further conclusions can you draw from your analysis of your experiment?

13. What other questions come to your mind as the result of this experiment?

14. What is the next experiment that you plan to run? Why?

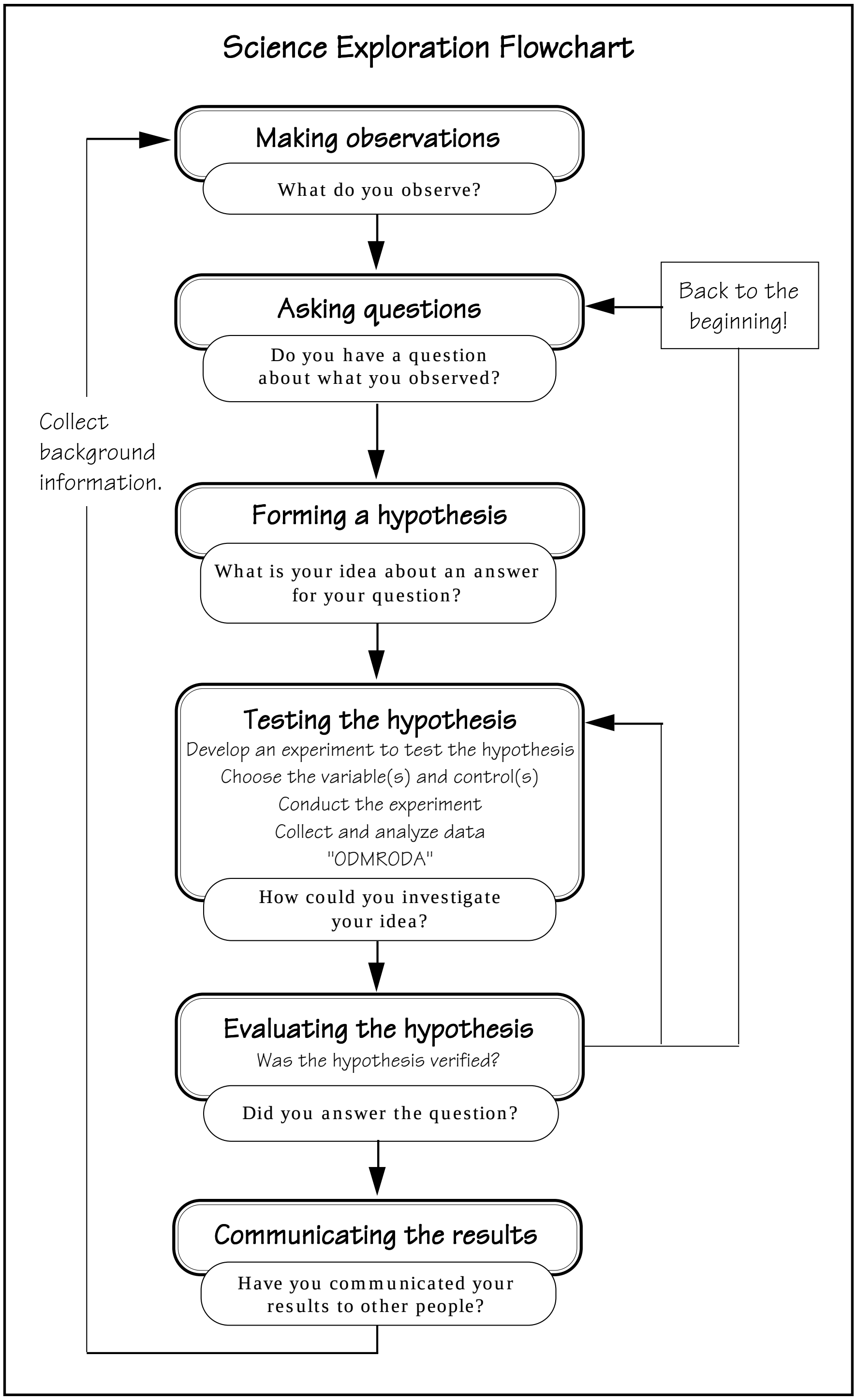
The Science-Technology Partnership

As students design and execute experiments the need for technological assistance from tools and equipment is ever-present, from the moment of the first observation to the time when new insight is shared with someone across the ocean or across the classroom. Technological innovation, like science, follows a logical progression, resulting in a successful invention and its application to a need or problem.

Design of the Experiment – Testing the Hypothesis

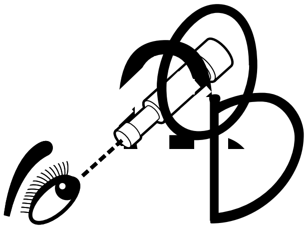
The heart of science activities lies in the design and execution of the experiment developed to test a hypothesis. It is in this phase of the process of science that technology plays an essential role. To conduct any experiments, technological requirements will arise and will need to be addressed. If the question and hypothesis have been carefully thought out and refined to be experimentally testable, then the design and execution of the experimental phases should yield satisfactory results. As you plan your experimental design, consider the following:

- Keep focused on the question and hypothesis.
- Think of the simplest way, both in the design and in the equipment needed, to run the experiment.
- Alter one variable (treatment) with each experiment and analyze the results.
- Always run control treatments for each experimental treatment such that for each variable in the experimental treatment there is an adequate basis for interpreting the information from the treatment.
- The careful choice and execution of the control treatments is as important in the experiment as that of the experimental treatments.
- Information from the control treatments serves as the basis for determining whether information from the experimental variables is valid and, thus guides the researcher in conclusions as to the validity of the hypothesis.


Science Exploration Flowchart

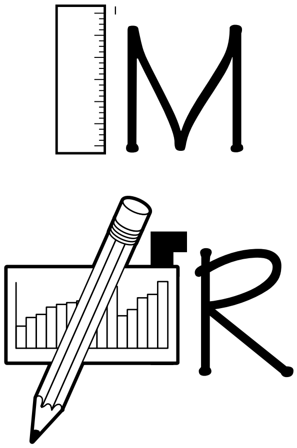
Execution of the Experimental Investigation

Below are some of the activities involved in the experimental investigation of an hypothesis. For your investigations, use "ODMRODA" :



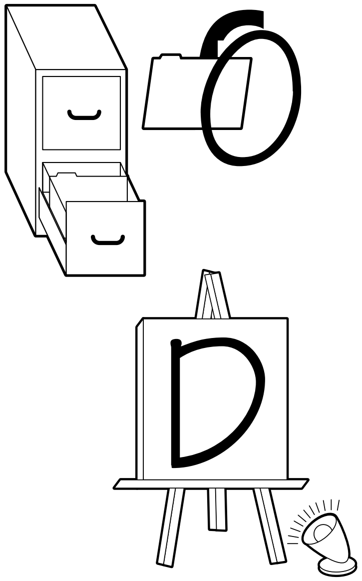
Observe and Describe:

Using your eyes and other tools to assist in observation (lenses, microscopes, etc.) together with insight from your brain, observe various phenomena or characteristics associated with the experiment and determine the way that you will describe them.



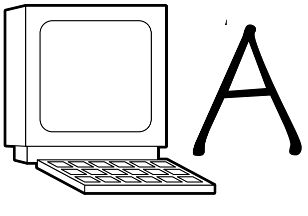
Measure and Record :

Using tools and devices (eyes, brain, rulers, scales, comparators and experience), measure (quantify) and record numeric and descriptive characteristics as *data*. Estimate, count or compare what you observe while adhering to an understanding of the precepts of *accuracy* and *precision*.



Organize and Display:

Organize and display recorded data in various ways (tables, charts, graphs, diagrams, drawing, photographs, videos, audios, multimedia, etc.) that will provide insight into phenomena associated with the experiment.



Analyze:

Observe the data displays (tables, graphs, etc.) for comparisons among treatments, including controls. Apply statistical analysis to the data that provides information from which to derive and develop inferential insight that will be useful in the evaluation of the hypothesis.

Observing and Describing

Observation is frequently assisted by tools such as lenses, microscopes and other devices that amplify what we see, hear or detect chemically. In living organisms, characteristics which are observed constitute the *phenotype*. Phenotype is the genetically and environmentally determined appearance of an organism. Variation in the phenotype among individuals of the same grouping is a fundamental attribute of life.

In order to be useful in an experiment the phenotype must be described using terms that are widely understood and easily communicated. For these reasons scientists have agreed upon various standards or *descriptors* to describe characteristics in the natural world. Descriptors take many forms (Table 1). The choice of how to describe what you observe is important, because it will determine the kinds of descriptors used and establish the basis for recording, analyzing and communicating results.

Table 1: Examples of descriptors.

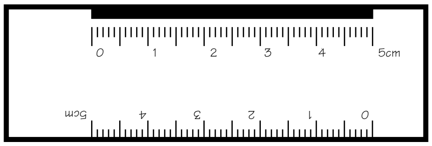
Descriptors	Method of description	Examples
number	1. direct count 2. comparator scale	1. hair on margin of first leaf 2. very hairy = 8-9 on a scale of 0 = no hair to 9 = very many hairs
size	1. use of a tool to measure (estimate dimension), e.g. ruler, calipers 2. comparator scale	1. height of a plant in mm 2. short, medium, tall compared to a range of measure
color	1. visual comparison using standard color chart or scales 2. describe with words using hue, lightness and saturation	1. no purple (anthocyanin) color in plant 2. very light yellow-green leaves
shape	1. descriptive language (often Latin) 2. comparator charts	1. leaf margin lobed edge 2. leaf spoon-shaped

Measuring and Recording

Size, Scale and Magnification: "Compared to What?"

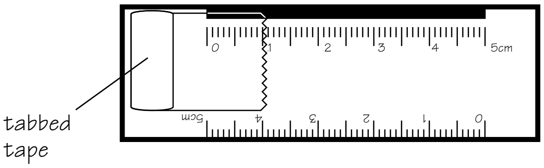
It is at the time of observing that students will understand the notions of size, scale and magnification. Some of the CUE-TSIPS activities require that students become familiar with observing, drawing *to scale* and measuring under magnification. To help them view specimens and understand the magnification, *dissection strips* and *dissection cards* have been developed as tools for use in the CUE-TSIPS activities.

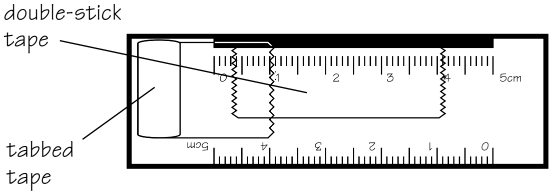
Making and Using Dissection Strips



Dissection strips can be made by copying the black line master (page 100) onto a transparency sheet. The copied transparency sheet can be stuck, printed side down, to a "do it yourself" laminating sheet or piece of clear contact paper, and then the individual strips can be cut out. Using the laminating sheet or contact paper as a sealer protects the printing from being pulled off during use of the strip, so strips can be reused.

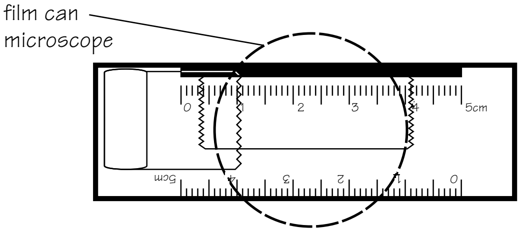
Once the strips are finished, they are ready for use. Begin by cutting a piece of clear 2 cm adhesive tape to be about 3 cm long. Fold over about 0.75 cm of this piece of tape to make a tab. Stick this tabbed piece of tape to the dissection strip, with the tab at the end of the strip.



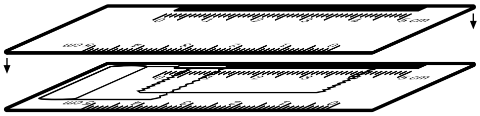


Cut a piece of clear double-stick tape. Place this piece near the top edge of the dissection strip so that the end of the piece overlaps the tabbed piece of tape by a few millimeters.

Specimens for dissection are placed on the double-stick tape. Once your specimen is in place, the specimen and strip can be placed under a dissecting microscope or a film can magnifier (page 97) to make observations.



On the dissection card (page 99) are spaces for measuring and recording observations. Each card has two circular fields for sketching what is observed in the field of view delineated by the microscope or film can magnifier.



Once a dissection has been completed, the dissected specimen may be taped in a student notebook or removed from the strip by pulling up on the tabbed piece of tape. As this piece of tape is removed it will pull off the used double-stick tape and the strip will be ready for a new dissection. Alternatively, a second dissection strip may be placed over the first to preserve your specimen.

Much of the emphasis in the supplemental activity "Getting Acquainted with a Seed" (page 67) is designed to familiarize students with the use of lenses and scales. As they draw and measure what they observe under different magnifications, students will begin to understand size relationships. Drawing to scale requires practice and sharpens students' hand-eye coordination and sense of perspective and scale. This understanding will be useful to them as they undertake more detailed dissection of AstroPlants embryos.

Dealing with Variation: The Nature of Normal

Measurable differences will be found among individuals in a group or population. It is therefore important to know how much variation in a particular phenotype (observable trait) might be expected so that it can be determined whether the variation observed experimentally may be viewed as *normal* for that population. Normal would be defined as that range of potential phenotypes that a population would exhibit in a specified range of environmental conditions.

The species *Brassica rapa*, of which AstroPlants are a specially bred stock, is inherently genetically variable. Within a population of AstroPlants one can observe considerable phenotypic variation in some traits such as plant height or intensity of purple stem color. For this reason, it is important to determine what is a normal range of phenotypes for AstroPlants.

Organizing and Displaying Data: Graphical Representation

When, for example, the heights of a population of 48 AstroPlants are measured in millimeters at Day 10 and recorded (Table 2), considerable variation can be noted. Height is measured from soil level to shoot apex.

Table 2: Height, in mm, of 48 AstroPlants measured at Day 10 (hypothetical data).

33	40	32	59	18	45	73	21
49	52	60	55	33	56	32	52
50	84	54	25	57	45	68	41
43	53	43	76	49	39	36	50
62	27	66	39	41	51	55	41
30	47	72	37	44	35	45	48

The "Stem and Leaf Table"

Simply listed as a set of 48 numbers, relatively little information can be gained from them other than to note that they are variable. An easy way to begin to organize the numbers is to put them into what is commonly known as a *stem and leaf table* (Table 3).

Table 3: AstroPlant height data from Table 2 organized into a stem and leaf table.

tens, "stem"	digits, "leaf"
0	
1	8
2	7, 5, 1
3	3, 0, 2, 9, 7, 3, 9, 5, 2, 6
4	8, 3, 0, 7, 3, 9, 1, 4, 5, 5, 5, 1, 0, 8
5	0, 2, 3, 4, 9, 5, 7, 6, 1, 5, 2, 0
6	2, 0, 6, 8
7	2, 6, 3
8	4
9	

To do this, note that each number is broken into "tens" and "digits." Examine each number, breaking it into its tens and digits, e.g., 48 becomes 4 (tens) and 8 (digits). Make a vertical column "stem" listing from zero to 9 that represents the tens. Then enter the digit from each number in the horizontal row "leaf" corresponding to the appropriate ten or stem position; e.g., 48 is listed as an 8 in row 4 in Table 3. Numbers in the range from 10 to 19 go in the "1" row, while numbers in the range from 20 to 29 go in the "2" row, etc.

Considerable information about the population of 48 plants begins to become apparent from the stem and leaf table. For example, it can be observed that the most plant heights in this data set fit into the "4" stem. The numbers representing the plant heights in the population are a set of size 48 (n = 48).

The Frequency Table

The set of 48 plant heights can be organized into groupings or *classes* representing a specified range of values or *class interval* (i). In this example the class interval is 10 mm: i = 10 mm. The number of plants having heights within a particular class interval (e.g., 20 to 29 mm) is the *class frequency* (f_i). The *relative frequency* of a class is determined by looking at the number of measurements in a class (f_i) relative to the number of measurements in the entire data set (n): f_i/n.

With the above information the set n = 48 can be arranged in a *frequency table* by counting and recording the numbers in each class (f_i) and calculating the proportion of numbers in each class to the total set (f_i/n). The relative frequency of the class interval 20 to 29 mm in the example set of 48 plant heights is $f_i/n = 3/48 = 0.06$.

Table 4: Frequency table of heights, in mm, of 48 AstroPlants at Day 10, grouped in classes of 10 mm intervals and relative frequency of each class.

class interval, i	0	10	20	30	40	50	60	70	80	90
class frequency, f_i	0	1	3	10	14	12	4	3	1	0
relative frequency, f_i/n	0	0.02	0.06	0.20	0.29	0.25	0.08	0.06	0.02	0

n = 48, i = 10

Note: relative frequency fractions should add up to 1, rounding numbers in this example reduced this to 0.98.

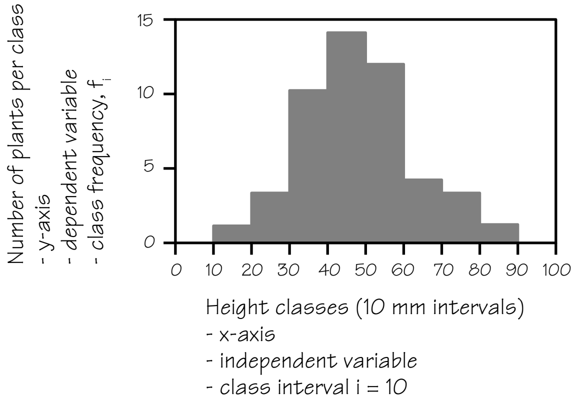
The Frequency Histogram

The relationship among the numbers in each class can be more effectively visualized by displaying them as a *frequency histogram* in which the data are treated as two variables, x and y, and plotted in relation to each other in a two-dimensional graph with the x and y axes at 90° to each other.

The first variable, the class interval (i), was chosen to be i = 10 is the *independent variable* as it was predetermined by choice. The independent variable is arrayed on the *x* or *horizontal axis* just as it appears in the frequency table (Table 4).

The second variable is the class frequency (f_i) and is known as the *dependent variable* because the number in the particular class (i) depends on the class chosen and is arranged and plotted on the *y* or *vertical axis* of the graph. When plotting the x and y axes of a graph it is important to consider the size or scale of a unit on each axis so that an effective symmetry is achieved in the presentation of the graph. Figure 1 is a frequency histogram of the data from the frequency table, Table 4.

Figure 1: Frequency histogram of heights, in mm, of 48 AstroPlants at Day 10, grouped in class intervals of 10 mm.



The relative frequency (f_i/n) from the frequency table can also be plotted as a *relative frequency histogram*. In this case the x-axis remains the same as in the frequency histogram and the y-axis is arrayed in units of decimal fractions. The appearance of the relative frequency histogram is similar to the frequency histogram, however what is being portrayed is the relative proportion of a class size in relation to the set.

Choosing the proper class interval can be important to the process of analyzing and understanding the information that is codified in the data set of plant height measurements. If the chosen class interval is too small or too large, certain relationships among the individuals within the set will not be evident.

For example if a class interval of i = 25 rather than i = 10 were chosen then the frequency histogram would appear as in Figure 2 or if a class interval of i = 2 were selected the frequency histogram would appear as in Figure 3.

Figure 2: Frequency histogram of heights, in mm, of 48 AstroPlants at Day 10, grouped in class intervals of 25 mm.

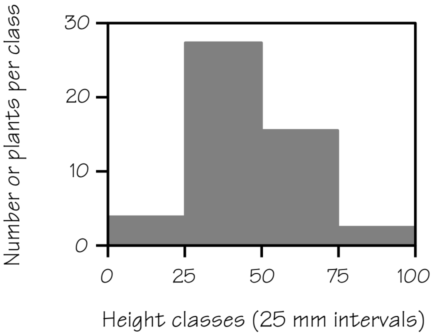
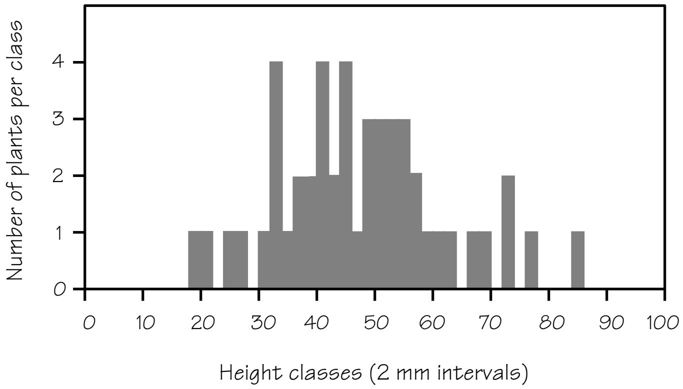


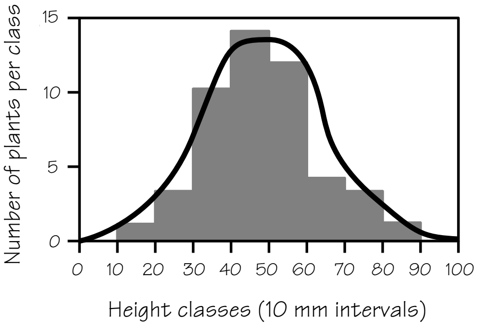
Figure 3: Frequency histogram of heights, in mm, of 48 AstroPlants at Day 10, grouped in class intervals of 2 mm.



The Normal Curve

The outline of a frequency histogram roughly depicts a curve known as a *frequency curve*. Frequency curves can assume various different shapes. Interpretation of the shapes can give insight into underlying phenomena conditioning the expression of the phenotype's contribution to the curve. For instance, the data on plant height recorded in the data chart (Table 2), organized in a frequency table (Table 4), and displayed in the frequency histogram (Figure 4) depicts what is referred to as the *normal distribution curve* or the *normal curve*. A *bell-shaped normal distribution* is commonly observed for many phenomena and is the basis for certain kinds of statistical summarization and interpretation.

Figure 4: Frequency histogram of heights, in mm, of 48 AstroPlants at Day 10, grouped in class intervals of 10 mm.



Organizing and Displaying Data: Numerical Representation

r

Range

There are various ways of describing or summarizing the variation in heights of the 10 day old AstroPlants recorded in Table 2 and displayed in Figure 4. One way is in terms of *range* (r). Range extends from the shortest plant to the tallest plant and is defined as: "r = the difference between the largest and smallest numbers in a set of data." Here again the stem and leaf diagram is useful in identifying the range, r = 84 - 18 = 66 mm. The range identifies the upper and lower limits of a data set and is helpful in determining the limits of the x-axis on a graph. When measuring a population of AstroPlants over several days of growth it is interesting to observe what happens to the range of plant heights. Does the range stay the same, decrease or increase? Why?

Mean, Median and Mode: Measures of Center

Another way to summarize the variation represented in a set is in terms of *averages*. Continuing with our example, the average or *arithmetic mean* (*x*) is the sum of the measurements divided by the total number of measurements, n:

x

$x = \sum i\ {}^{x}i/_{n} = (x_1 + x_2 + x_n)(1/n)$

When phenotypes are distributed normally, the mean can be a useful way of summarizing or representing the set. The mean or average is a way of representing a data set using a single number. In our example the mean is:

$x = (x_1 + x_2 + x_n)(1/n) = (2212)(1/48) = 47.13$

Another way of identifying a central point in the data set is to identify the *median* (md), or middle value of a set. The median is the highest value divided by two, in our example:

md

md = 84/2 = 42

Notice that the median differs from the mean by approximately 5 mm (47 - 42 = 5).

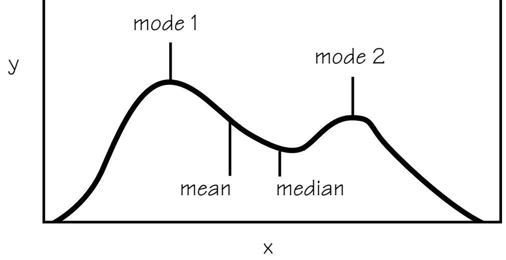
Yet another way of representing the data set with a single number is to use the *mode* (mo). The mode is the measurement with the highest frequency. Again, by scrutinizing each "leaf" of the stem and leaf diagram, you will observe that the number 45 mm appears three times. All others appear less frequently. This would be the mode for our example:

mo

mo = 45.

As is characteristic with normally distributed data, the mean, median and mode tend to be in proximity. With some natural phenomena which are not normally distributed there may be more than one mode, hence the terms *bimodal* and *trimodal* (Figure 5). In other distributions the mode may be widely separated from the mean and median (Figure 6).

Figure 5: Example of a bimodal frequency curve.



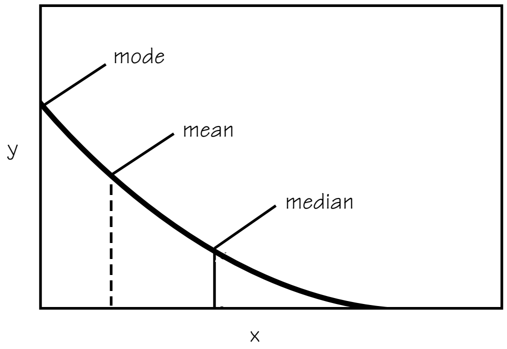


Figure 6: Example of a frequency curve with widely spread mode, mean and median.

Standard Deviation and Variance

Although the mean is probably the most useful value in representing a set of measurements, the mean does not give an indication of the way in which the values of the set are distributed around the mean. In other words, how the shape of the bell in the normal frequency curve appears. The *standard deviation* (s) is a statistical notation that provides an indication of whether the measures of phenotype are widely distributed around the mean. When s is relatively high the normal curve is broad; when s is low the curve is relatively narrow, or tightly distributed around the mean (Figure 7).

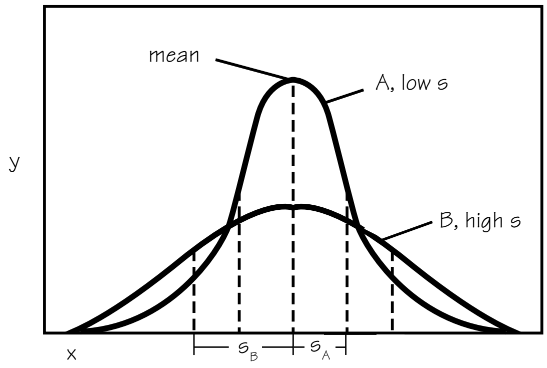
The standard deviation is the square root of the *variance* (s^2), which is the sum of the squared deviations of each value from the mean *x* divided by n-1, the set size minus one.

S

$$s^2 = \frac{\sum i\,(x_1 - x)^2}{n-1}$$

Though the standard deviation is a tedious calculation to make with a pencil and paper, most hand calculators with a statistical capability will have functions that automatically provide the mean (*x*), variance (s^2) and standard deviation (s).

Figure 7: Example of normally distributed frequency curves depicting high A and low B standard deviations.



Statistical Summaries

For our data set of 48 height measures of 10 day old AstroPlants, the summarized statistical data are given in Table 5.

Table 5: Statistical summary of height data of 48 AstroPlants from Table 2.

number in set	n = 48
range	r = 66 mm
mean	*x* = 47.13 mm
standard deviation	s = 14.27 mm

From the statistical summaries and graphical displays of the data sets you and your students will be able to better understand the variation that will become evident in all aspects of the CUE-TSIPS investigations. Throughout, the activities of measuring and recording, organizing and displaying are important. In order to communicate your observations, results and conclusions effectively with others, it is important that you compare the same sorts of data in the same terms of reference. The CUE-TSIPS activities have been designed so that your students will be able to share their data with others and generate discussion of their results.

Data Sheets and Tables

Data sheets or tables need to be organized so as to receive descriptive information in a logical and orderly manner that will minimize the likelihood of entry errors and that will aid in later summarization and analysis. For each activity, examples of student and class data sheets have been provided. With most of the experiments, the data sheets also contain columns for data summation and statistical analyses. Calculators with graphical capabilities may be useful to students in analyzing data.