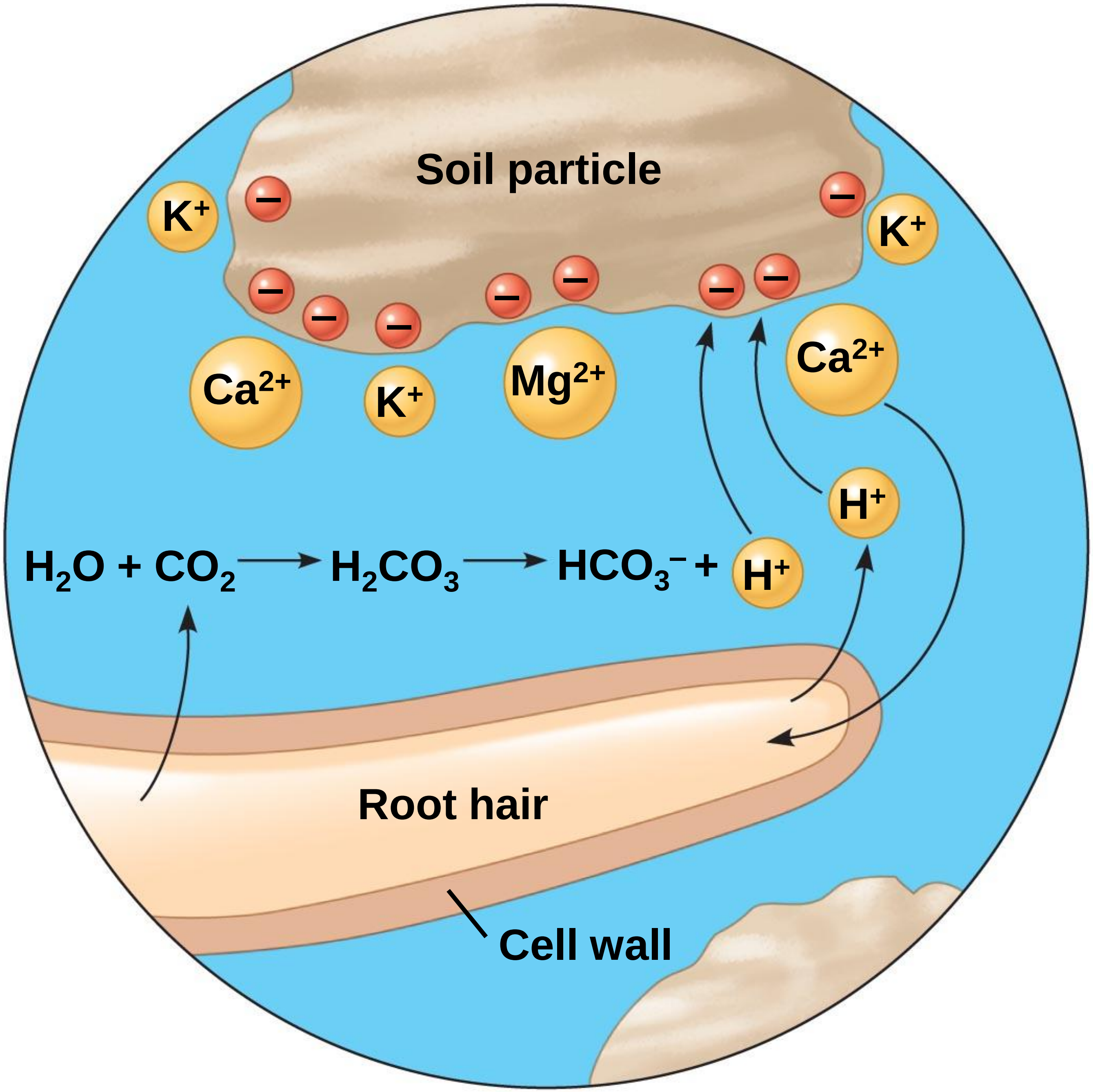

Soil particle
K+
K+
Ca2+
K+
Mg2+
Ca2+
H+
H2O + CO2 → H2CO3 → HCO3− + H+
Root hair
Cell wall

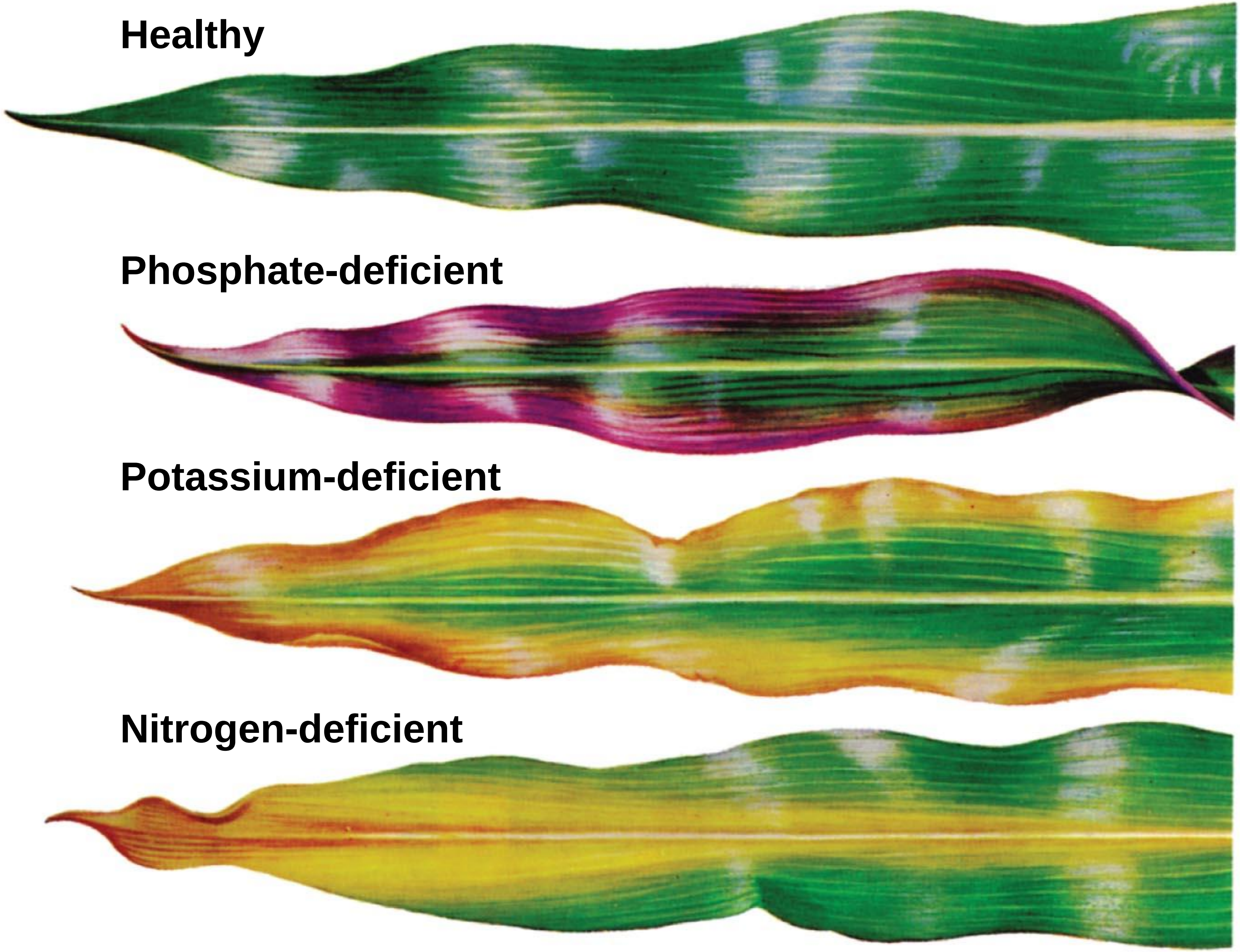
TECHNIQUE

Control: Solution containing all minerals

Experimental: Solution without potassium

Table 37.1 Essential Elements in Plants

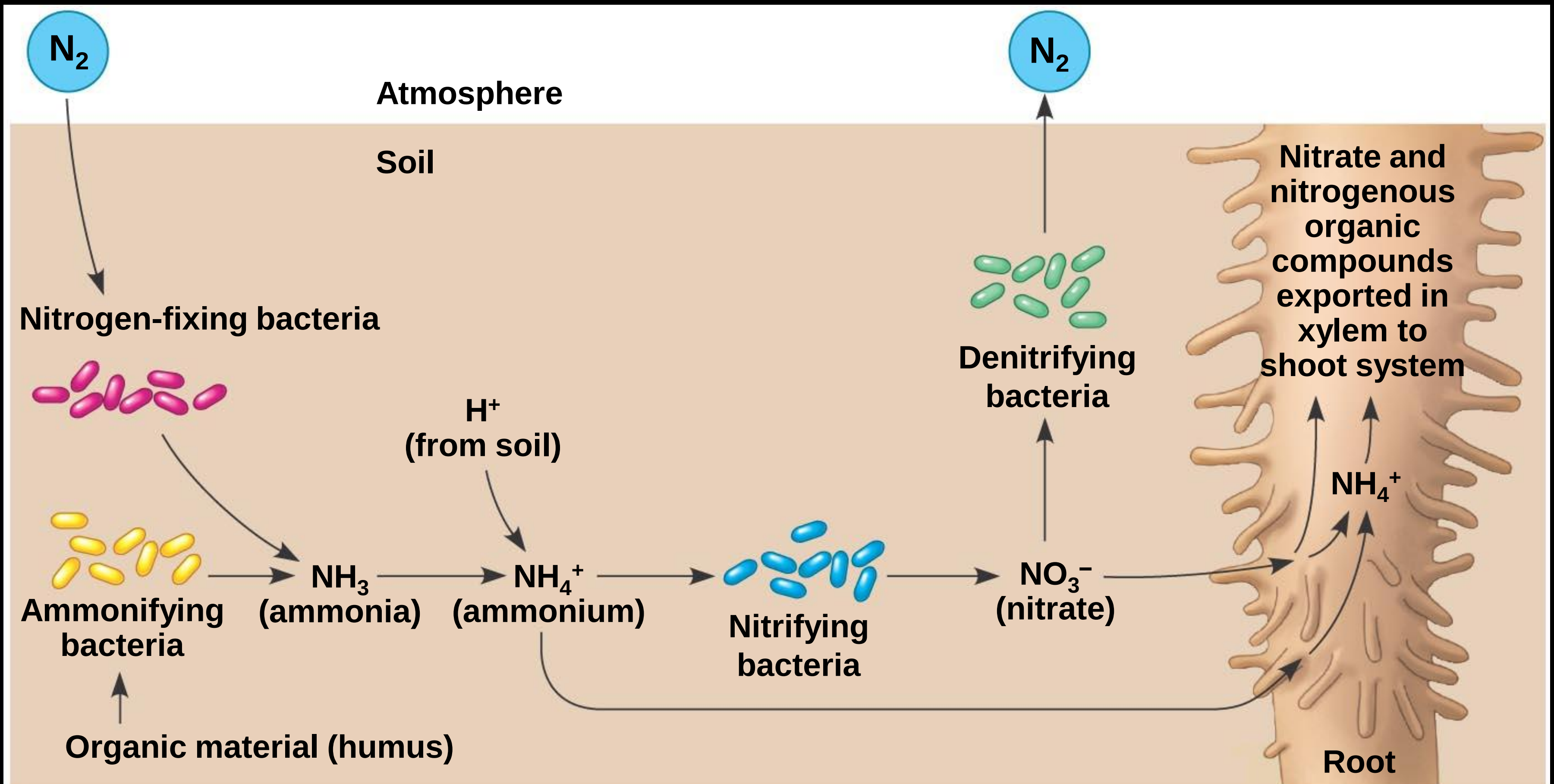
Element	Form Available to Plants	% Mass in Dry Tissue	Major Functions
Macronutrients			
Carbon	CO_2	45%	Major component of plant's organic compounds
Oxygen	CO_2	45%	Major component of plant's organic compounds
Hydrogen	H_2O	6%	Major component of plant's organic compounds
Nitrogen	NO_3^-, NH_4^+	1.5%	Component of nucleic acids, proteins, hormones, chlorophyll, coenzymes
Potassium	K^+	1.0%	Cofactor that functions in protein synthesis; major solute functioning in water balance; operation of stomata
Calcium	Ca^{2+}	0.5%	Important in formation and stability of cell walls and in maintenance of membrane structure and permeability; activates some enzymes; regulates many responses of cells to stimuli
Magnesium	Mg^{2+}	0.2%	Component of chlorophyll; activates many enzymes
Phosphorus	$H_2PO_4^-$, HPO_4^{2-}	0.2%	Component of nucleic acids, phospholipids, ATP, several coenzymes
Sulfur	SO_4^{2-}	0.1%	Component of proteins, coenzymes
Micronutrients			
Chlorine	Cl^-	0.01%	Required for water-splitting step of photosynthesis; functions in water balance
Iron	Fe^{3+}, Fe^{2+}	0.01%	Component of cytochromes; activates some enzymes
Manganese	Mn^{2+}	0.005%	Active in formation of amino acids; activates some enzymes; required for water-splitting step of photosynthesis
Boron	$H_2BO_3^-$	0.002%	Cofactor in chlorophyll synthesis; may be involved in carbohydrate transport and nucleic acid synthesis; role in cell wall function
Zinc	Zn^{2+}	0.002%	Active in formation of chlorophyll; activates some enzymes
Copper	Cu^+, Cu^{2+}	0.001%	Component of many redox and lignin-biosynthetic enzymes
Nickel	Ni^{2+}	0.001%	Cofactor for an enzyme functioning in nitrogen metabolism
Molybdenum	MoO_4^{2-}	0.0001%	Essential for symbiotic relationship with nitrogen-fixing bacteria; cofactor in nitrate reduction


Healthy
Phosphate-deficient
Potassium-deficient
Nitrogen-deficient

No phosphorus deficiency

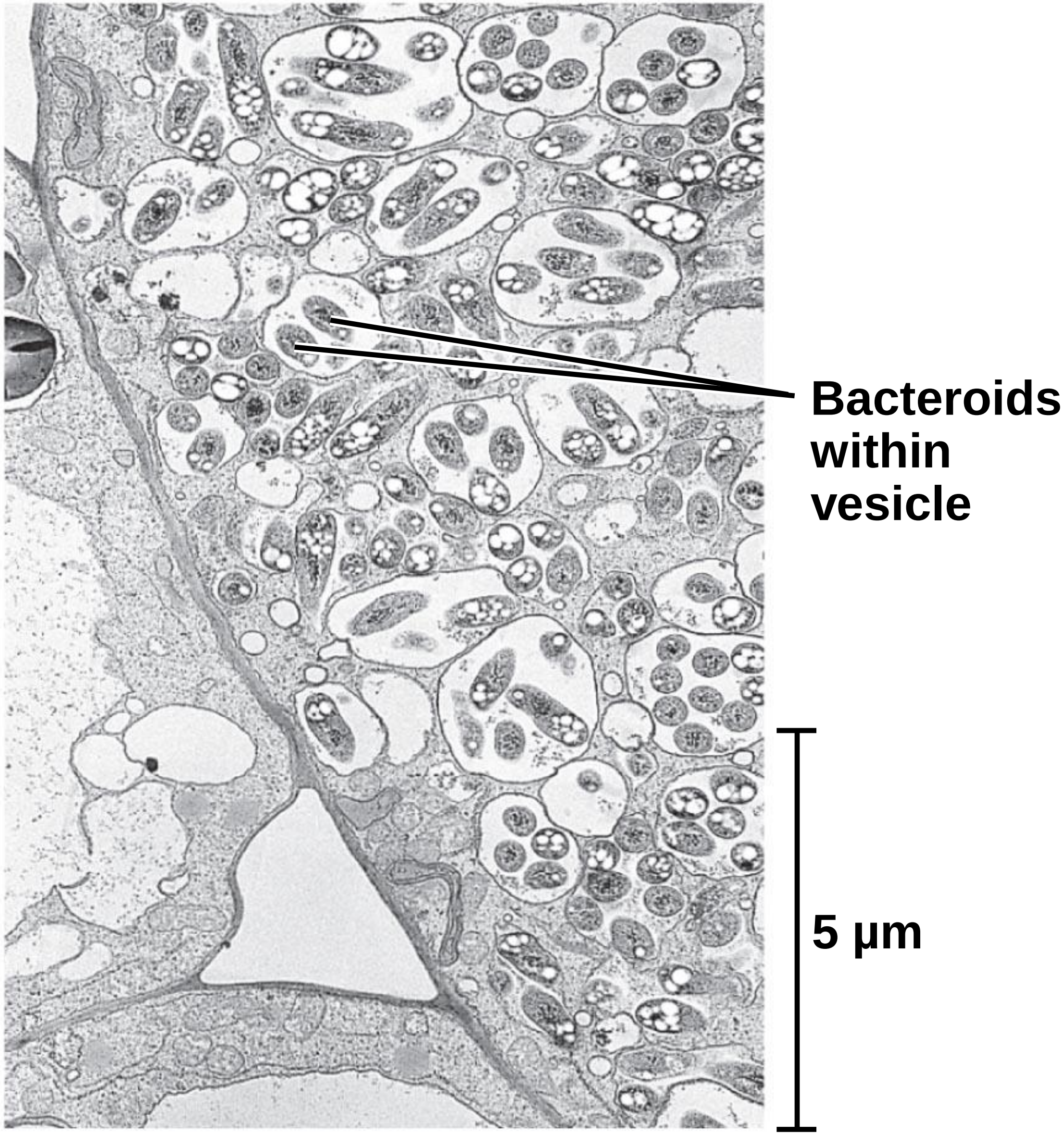
Beginning phosphorus deficiency

Well-developed phosphorus deficiency

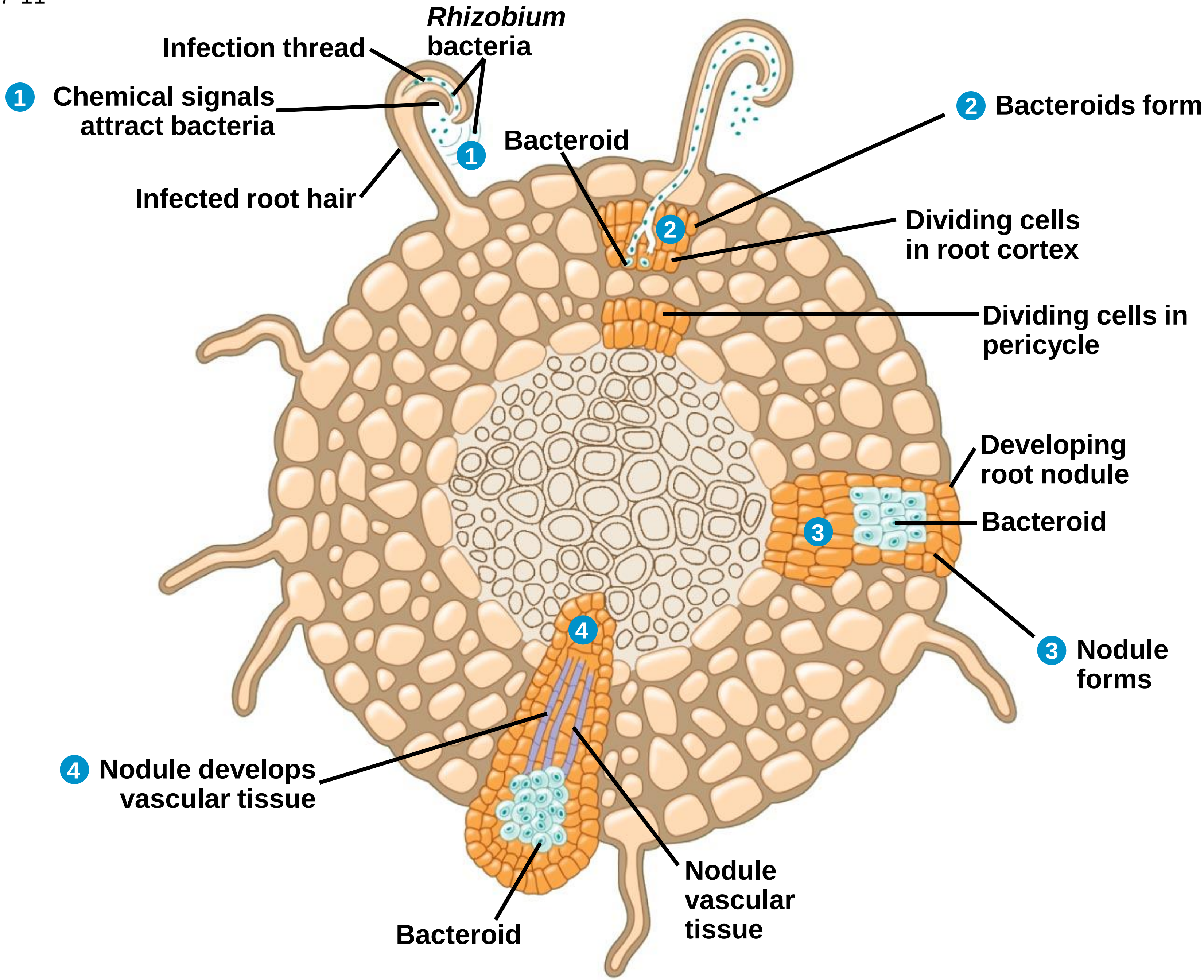


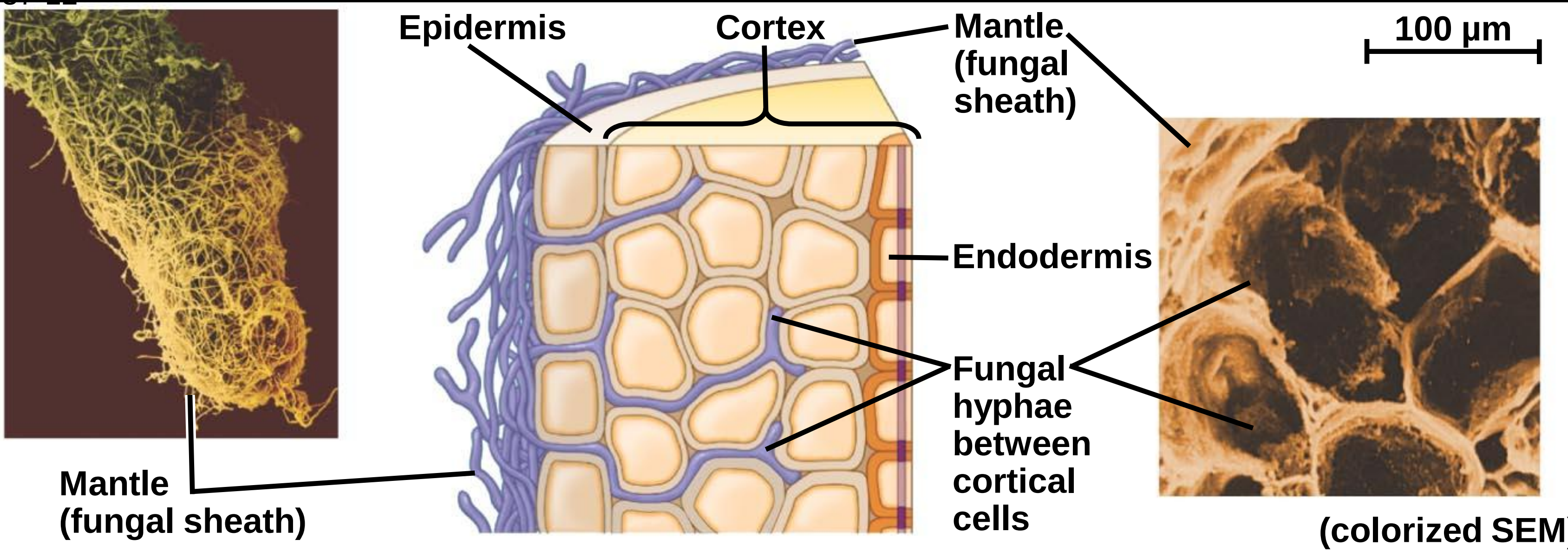
N2
N2
Atmosphere
Soil
Nitrogen-fixing bacteria
Denitrifying bacteria
Nitrate and nitrogenous organic compounds exported in xylem to shoot system
H+ (from soil)
NH4+
Ammonifying bacteria
NH3 (ammonia)
NH4+ (ammonium)
Nitrifying bacteria
NO3– (nitrate)
Organic material (humus)
Root

(a) Pea plant root

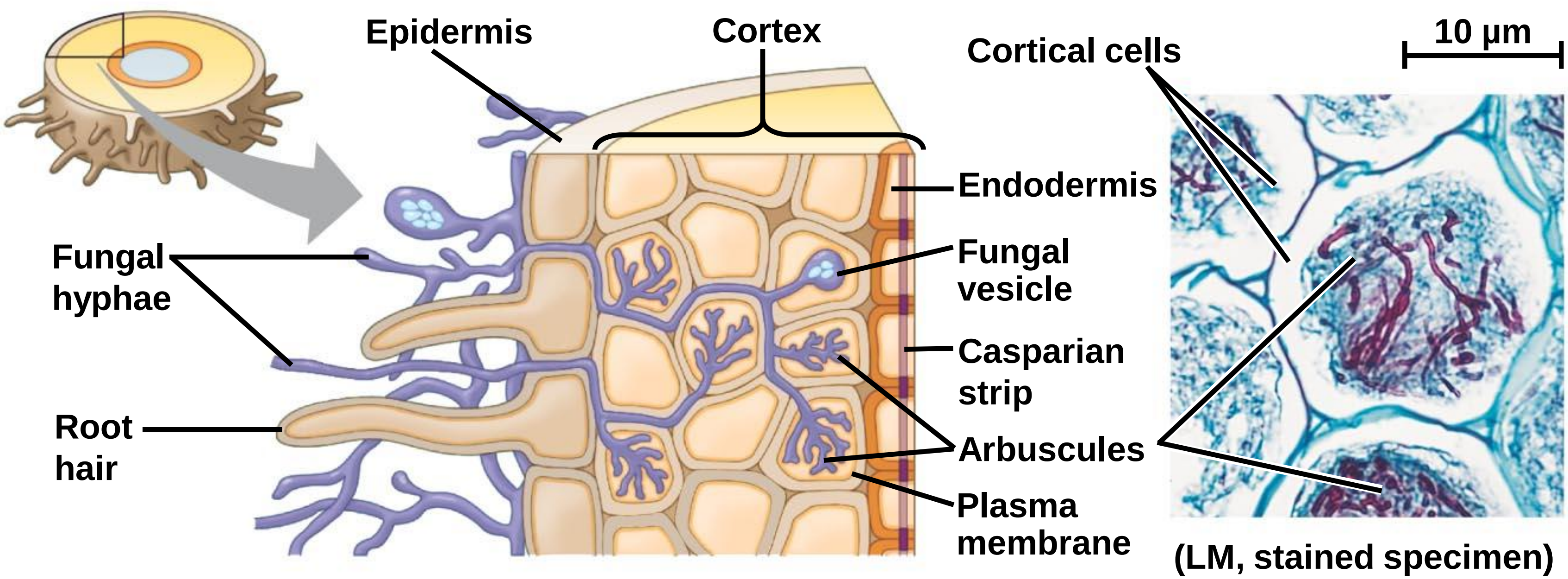


(b) Bacteroids in a soybean root nodule


Rhizobium bacteria
Infection thread
1 Chemical signals attract bacteria
1
Infected root hair
Bacteroid
2 Bacteroids form
2
Dividing cells in root cortex
Dividing cells in pericycle
Developing root nodule
Bacteroid
3
3 Nodule forms
4
4 Nodule develops vascular tissue
Nodule vascular tissue
Bacteroid



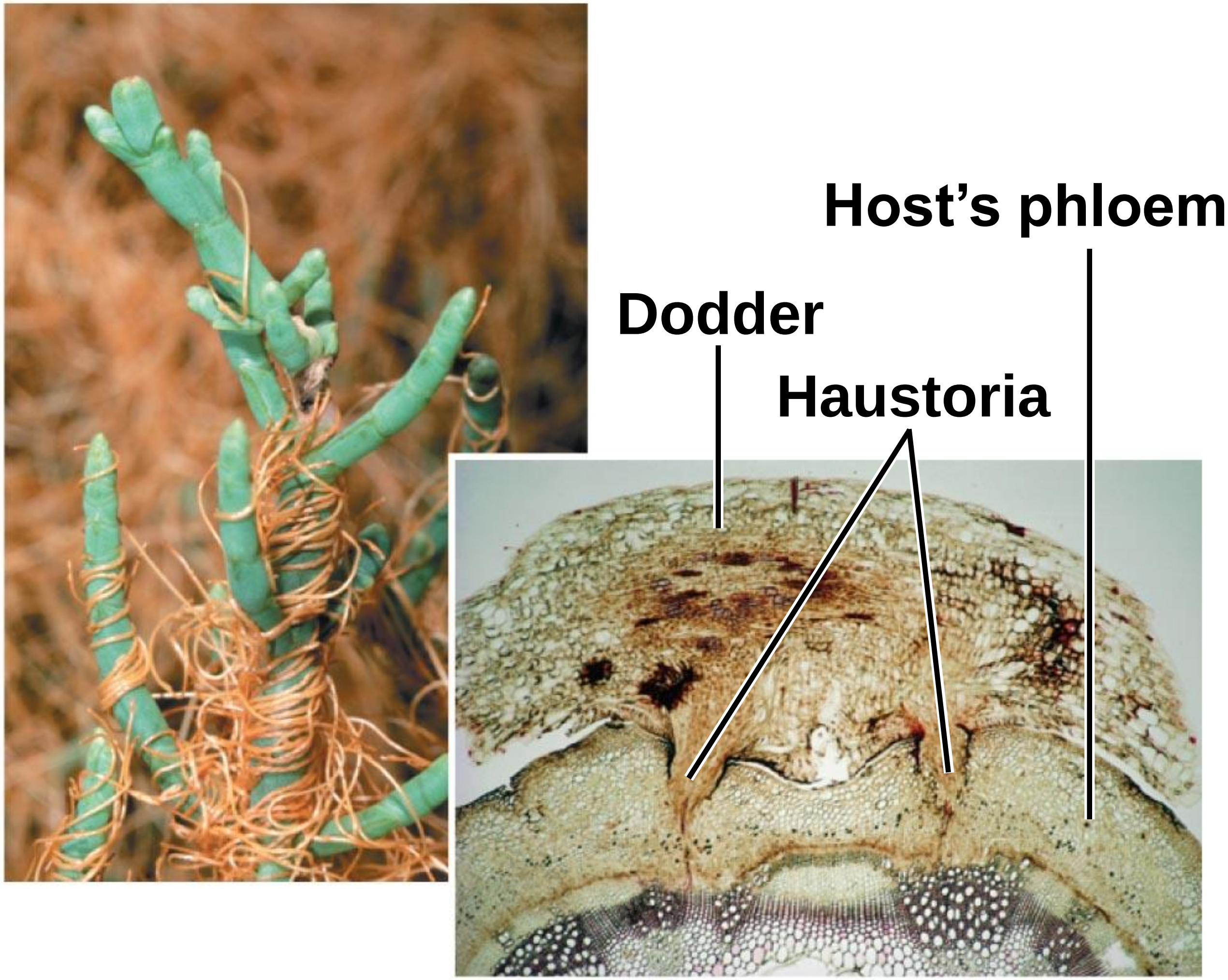
(a) Ectomycorrhizae



(b) Arbuscular mycorrhizae (endomycorrhizae)

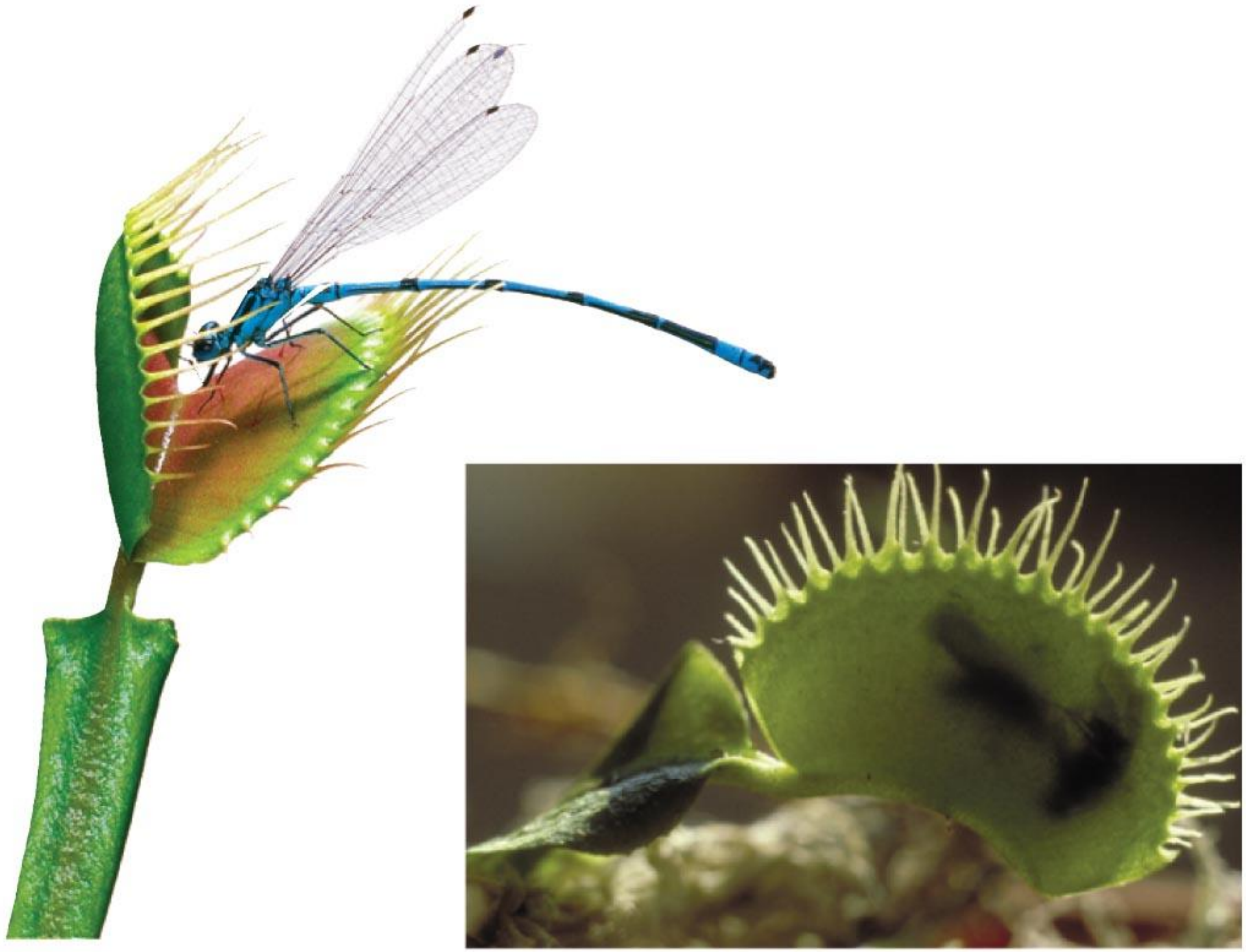
Staghorn fern, an epiphyte

Mistletoe, a photosynthetic parasite

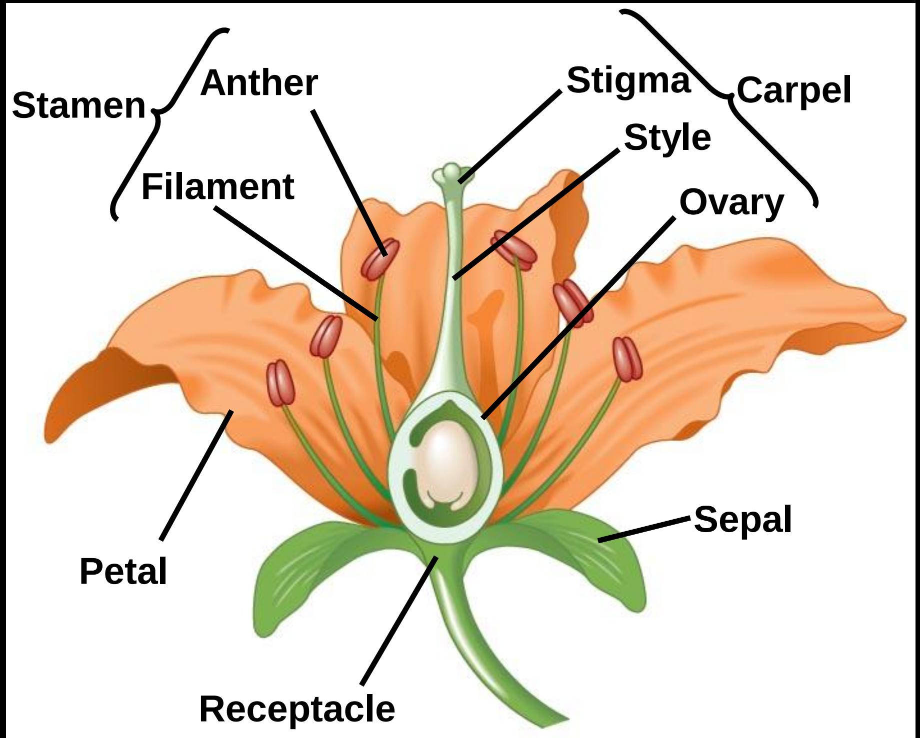


Dodder, a nonphotosynthetic parasite

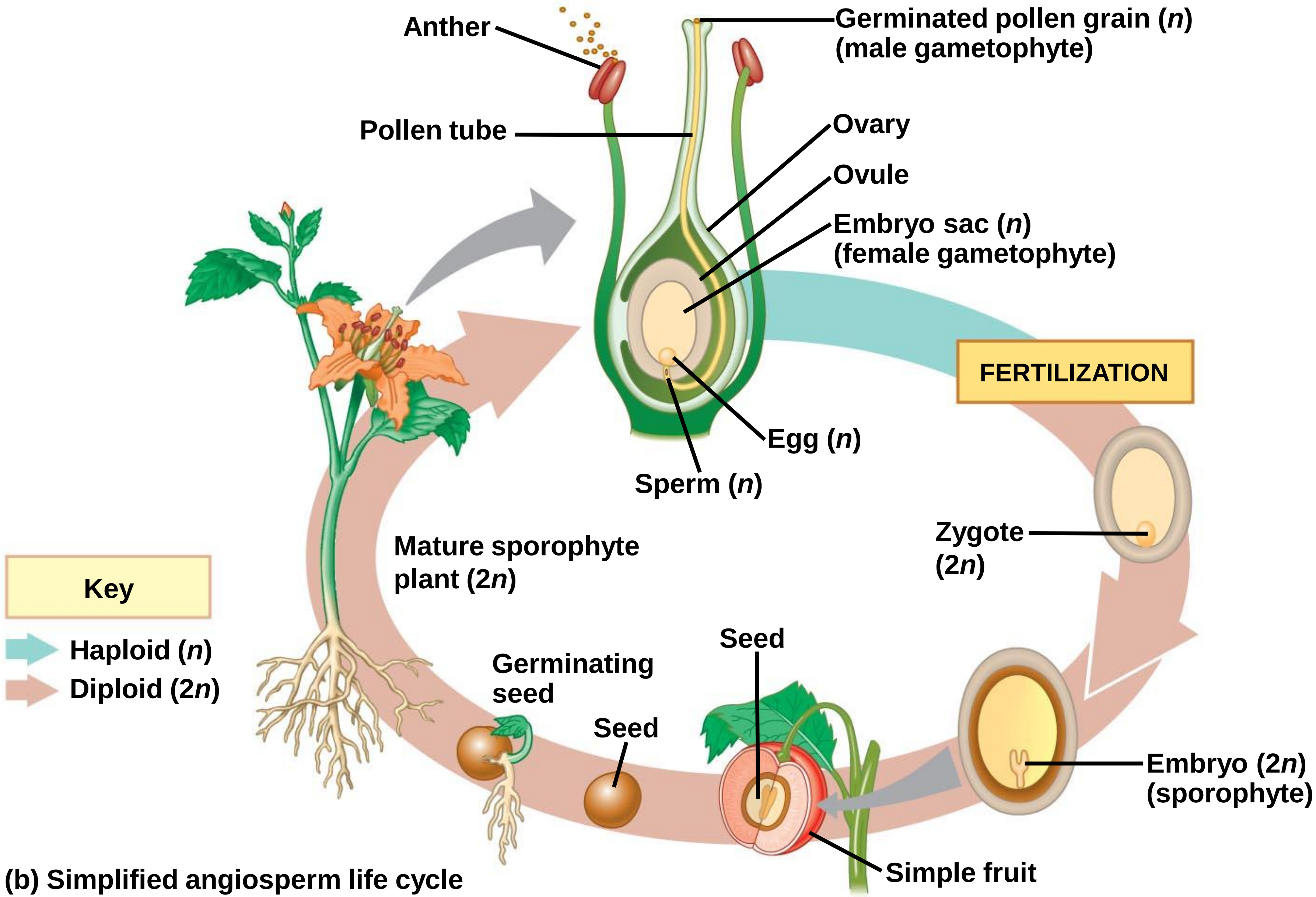
Indian pipe, a nonphotosynthetic parasite



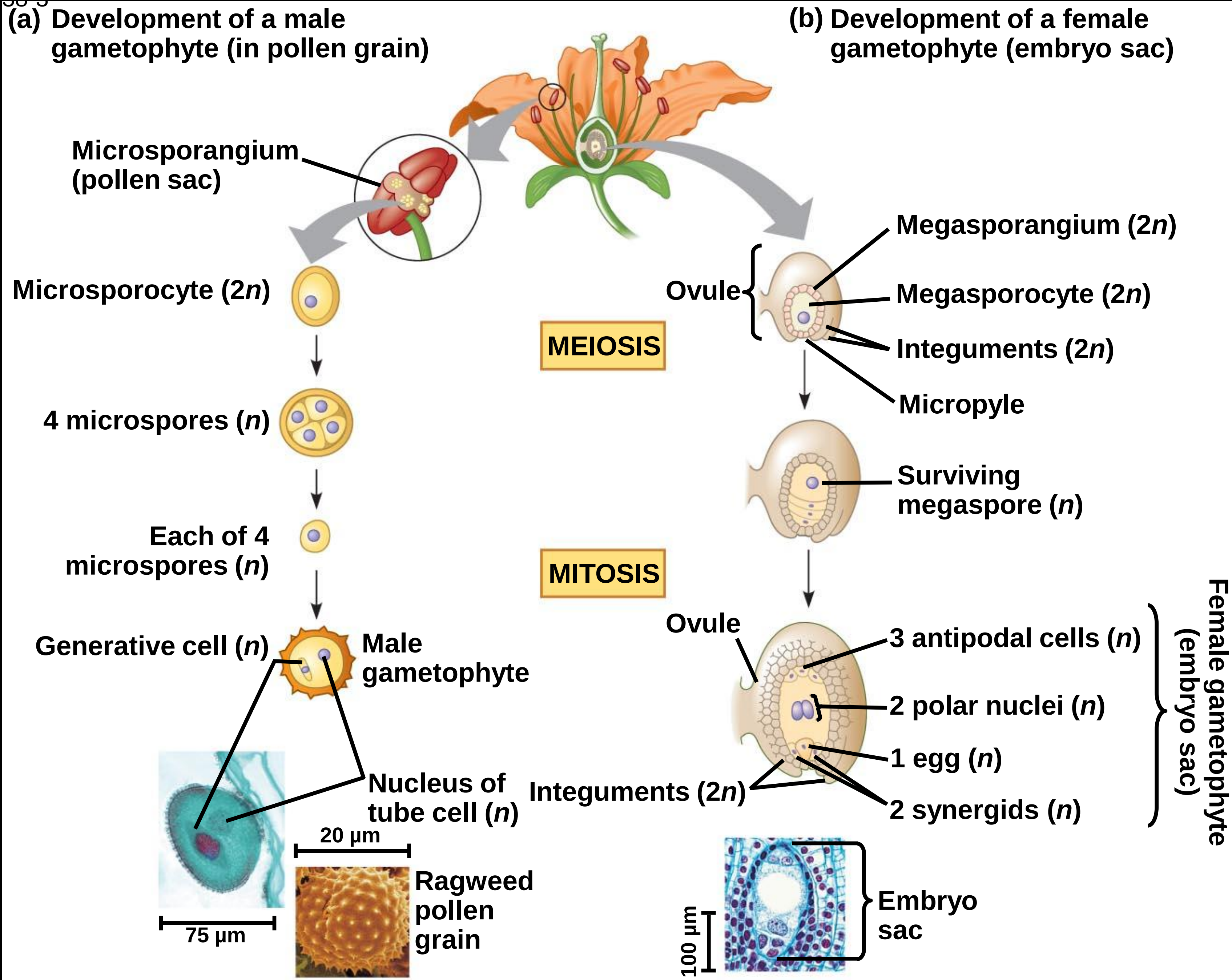
Venus flytrap



(a) Structure of an idealized flower



(b) Simplified angiosperm life cycle


(a) Development of a male gametophyte (in pollen grain)
(b) Development of a female gametophyte (embryo sac)
Microsporangium (pollen sac)
Microsporocyte (2n)
4 microspores (n)
Each of 4 microspores (n)
Generative cell (n)
Male gametophyte
Nucleus of tube cell (n)
75 µm
20 µm
Ragweed pollen grain
MEIOSIS
MITOSIS
Ovule
Megasporangium (2n)
Megasporocyte (2n)
Integuments (2n)
Micropyle
Surviving megaspore (n)
Ovule
3 antipodal cells (n)
2 polar nuclei (n)
1 egg (n)
2 synergids (n)
Integuments (2n)
Female gametophyte (embryo sac)
Embryo sac
100 µm

Abiotic Pollination by Wind

Hazel staminate flowers (stamens only)

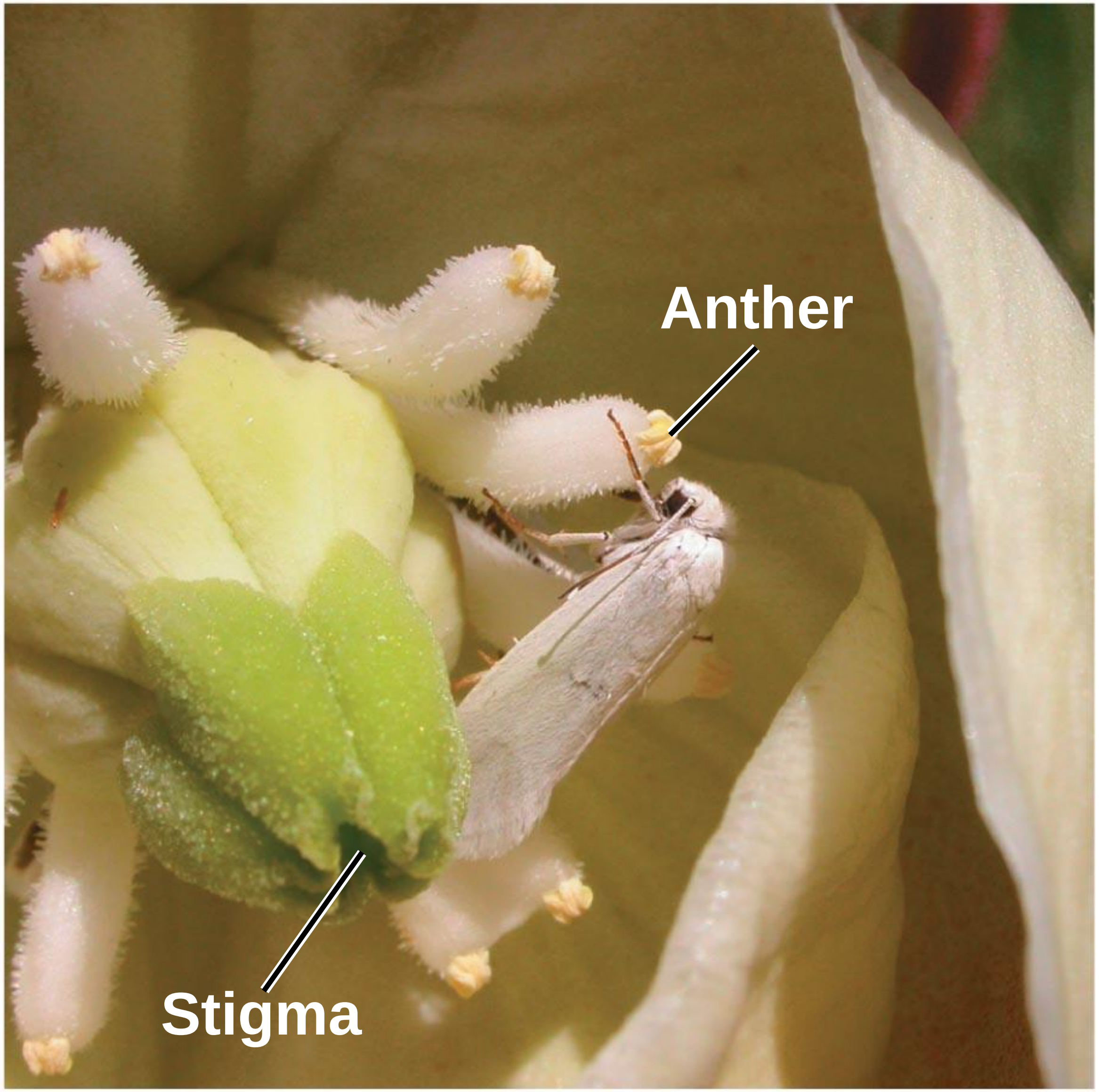
Hazel carpellate flower (carpels only)

Pollination by Bees

Common dandelion under normal light

Common dandelion under ultraviolet light

Pollination by Moths and Butterflies



Moth on yucca flower

Pollination by Flies

Fly egg

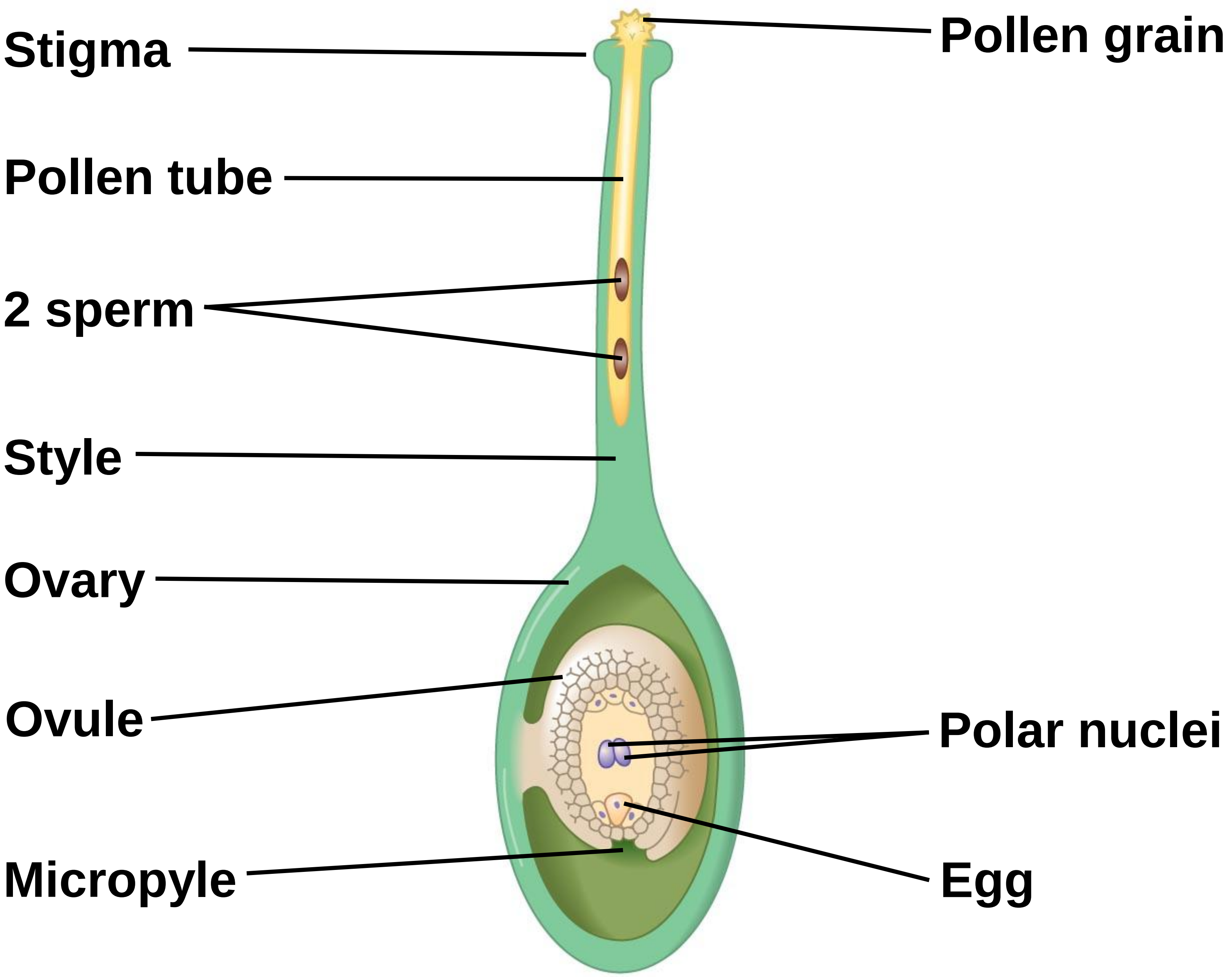
Blowfly on carrion flower

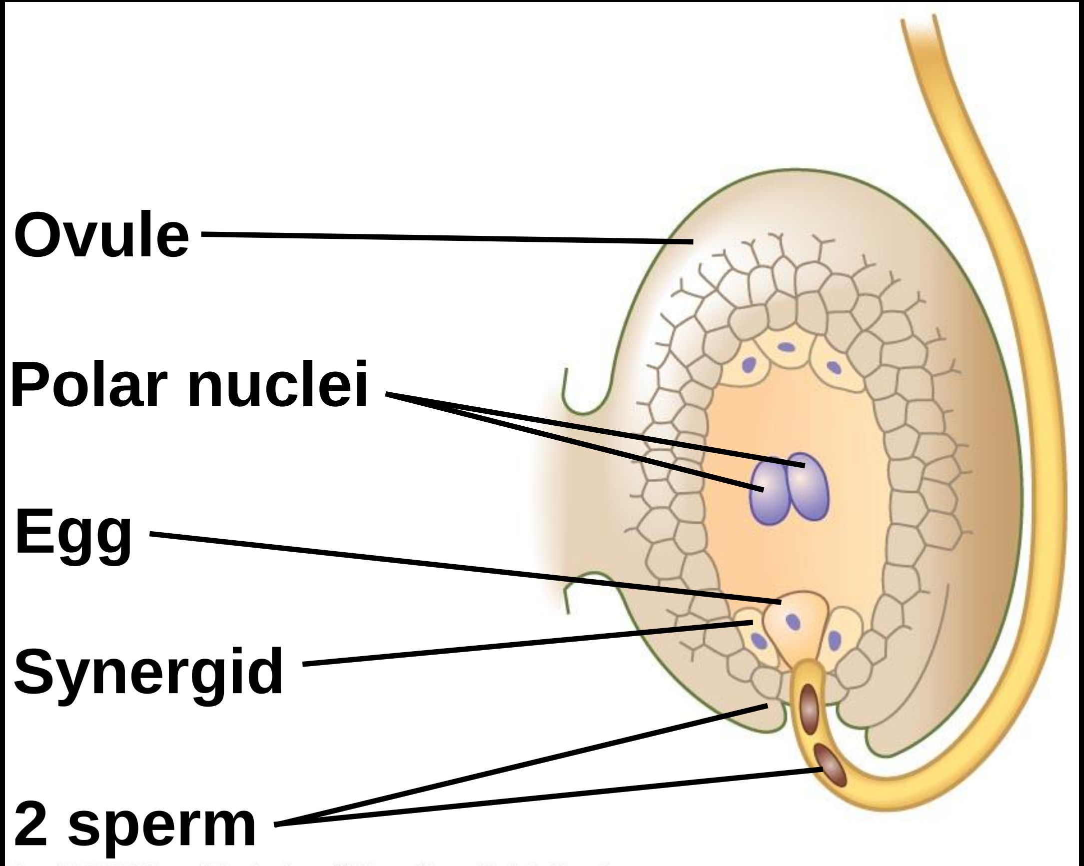
Pollination by Birds

Hummingbird drinking nectar of poro flower

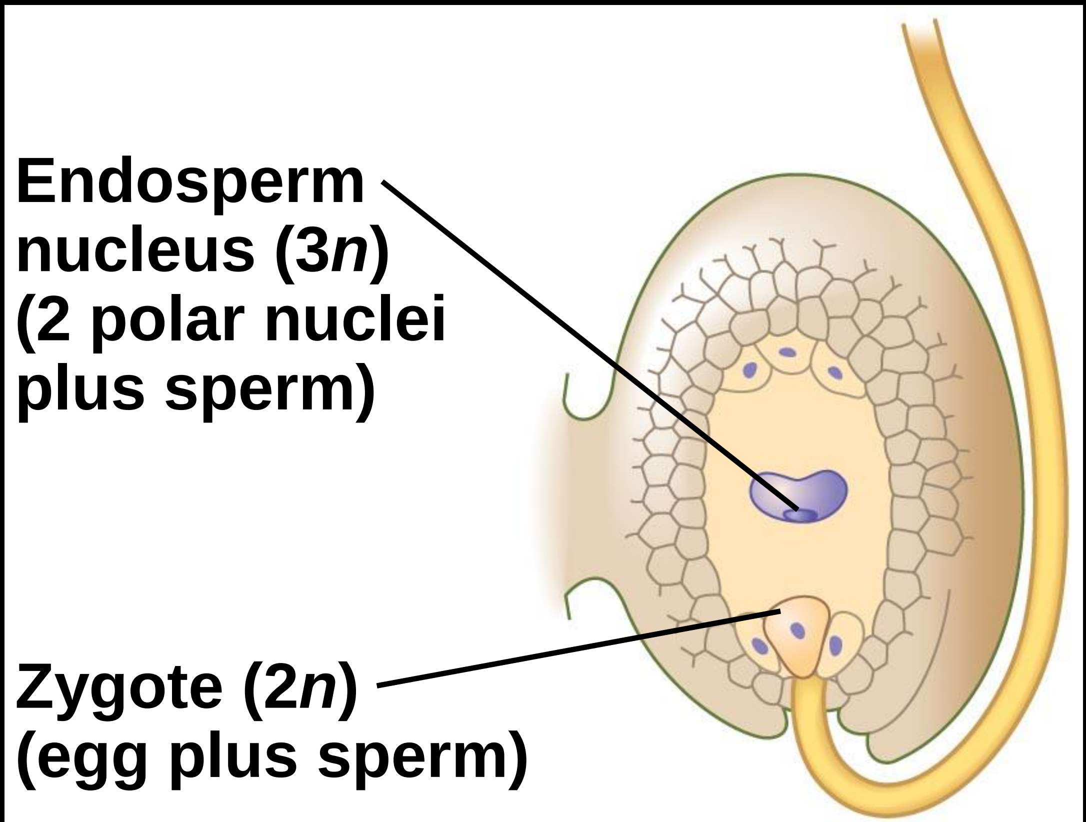
Pollination by Bats

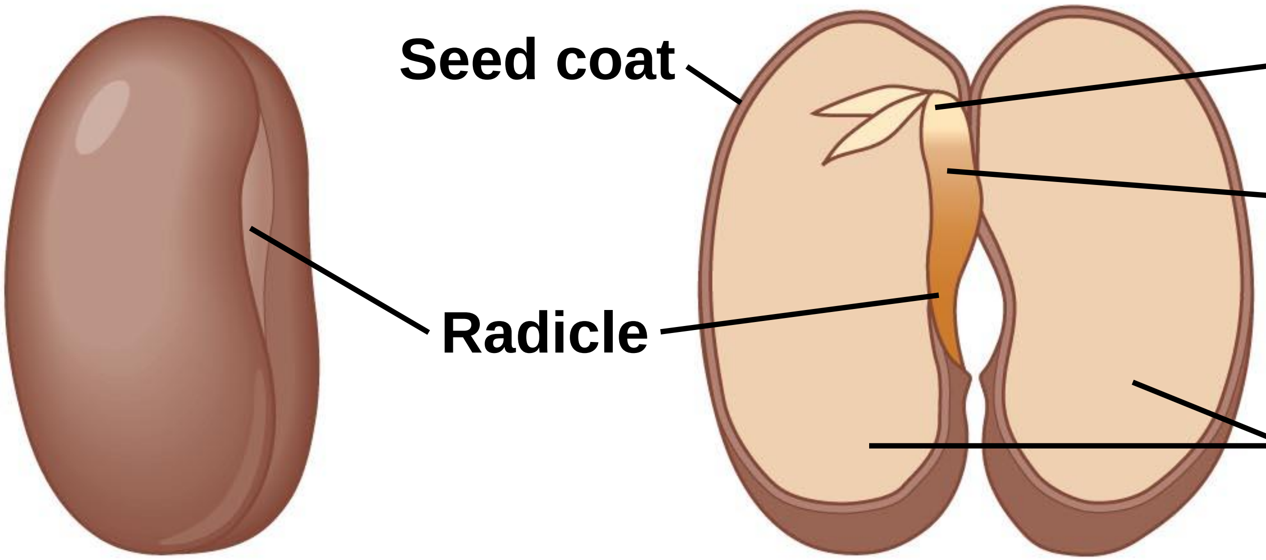
Long-nosed bat feeding on cactus flower at night


Stigma
Pollen grain
Pollen tube
2 sperm
Style
Ovary
Ovule
Polar nuclei
Micropyle
Egg

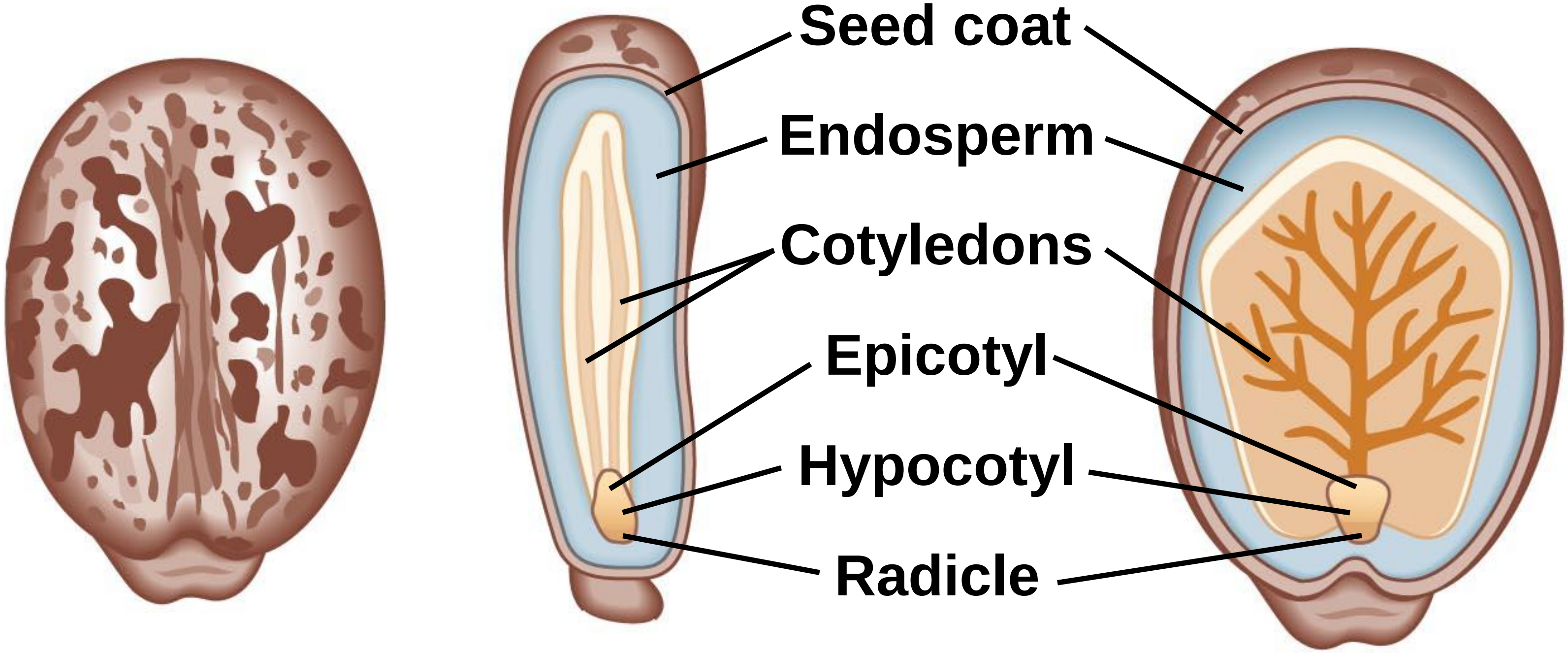


Ovule
Polar nuclei
Egg
Synergid
2 sperm

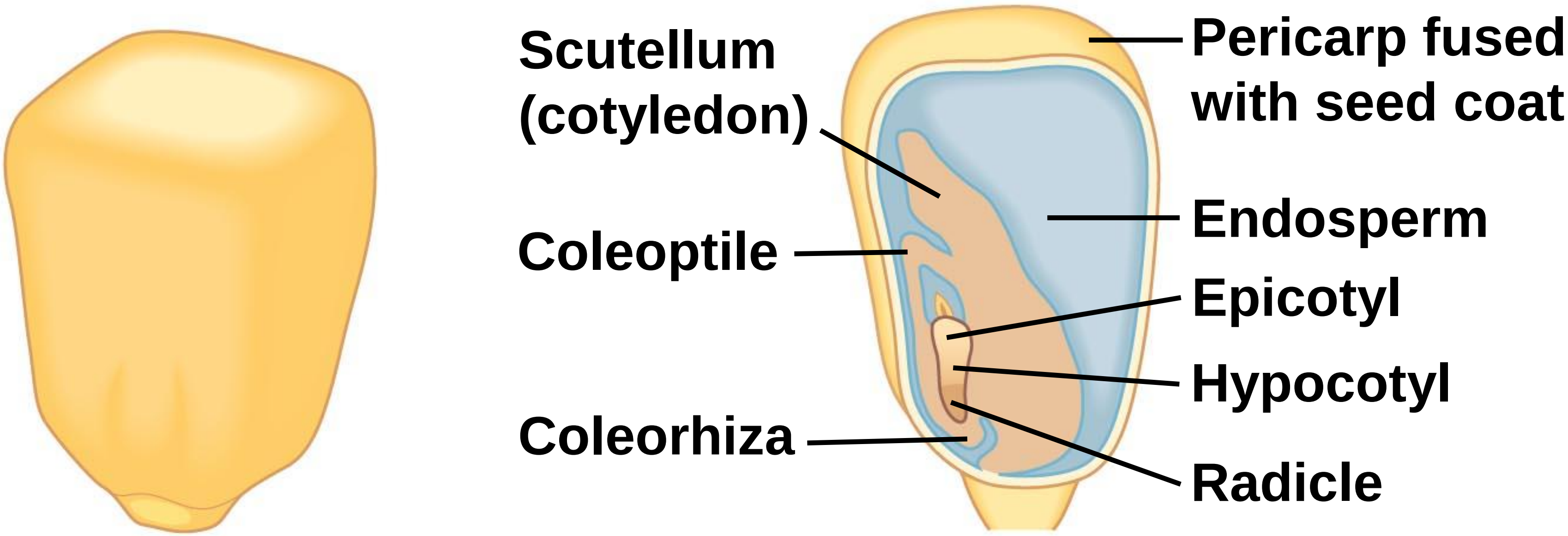

Endosperm nucleus (3*n*) (2 polar nuclei plus sperm)
Zygote (2*n*) (egg plus sperm)



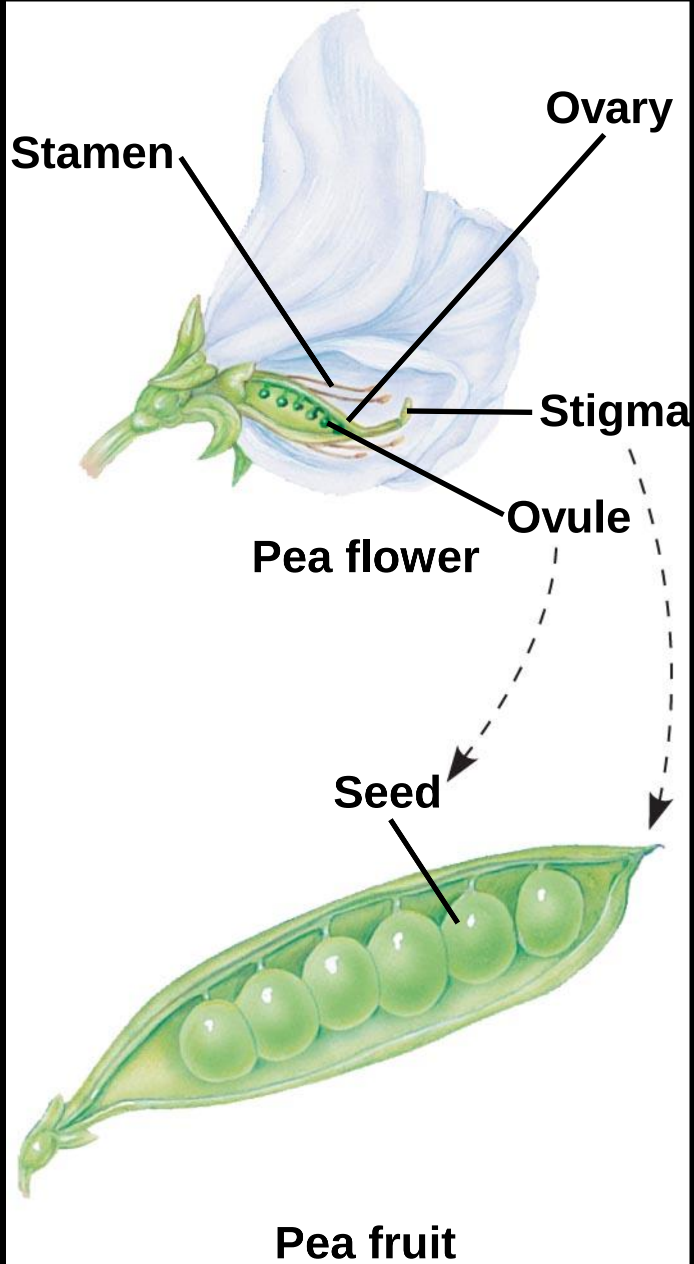
(a) Common garden bean, a eudicot with thick cotyledons



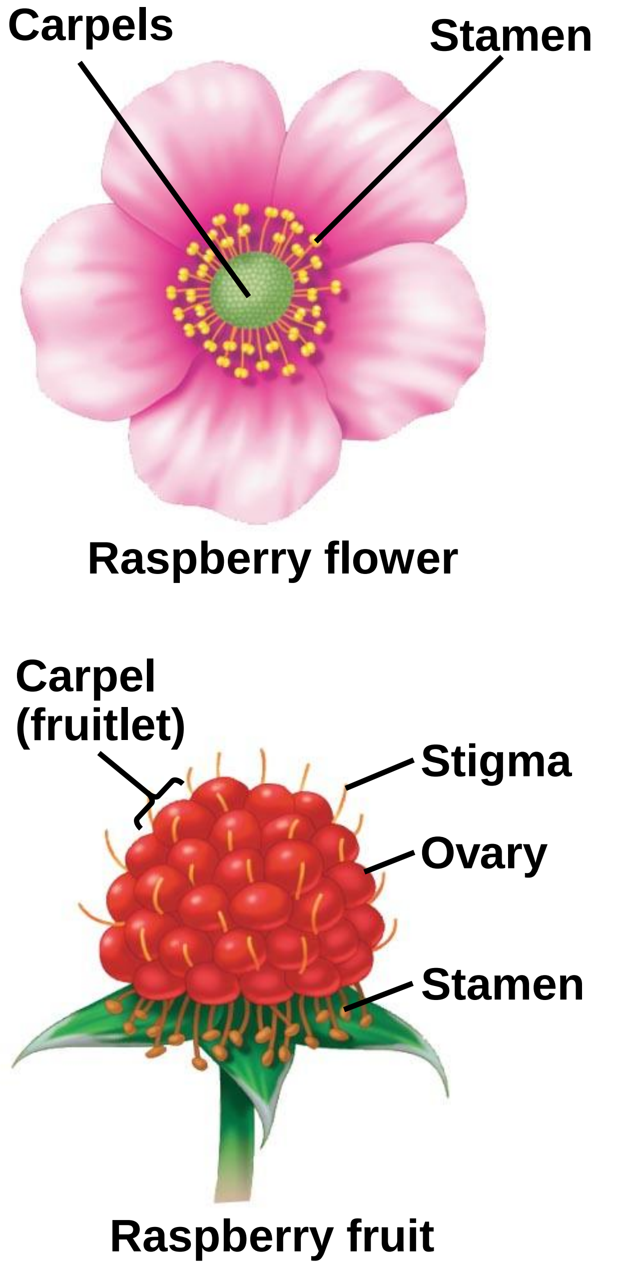
(b) Castor bean, a eudicot with thin cotyledons



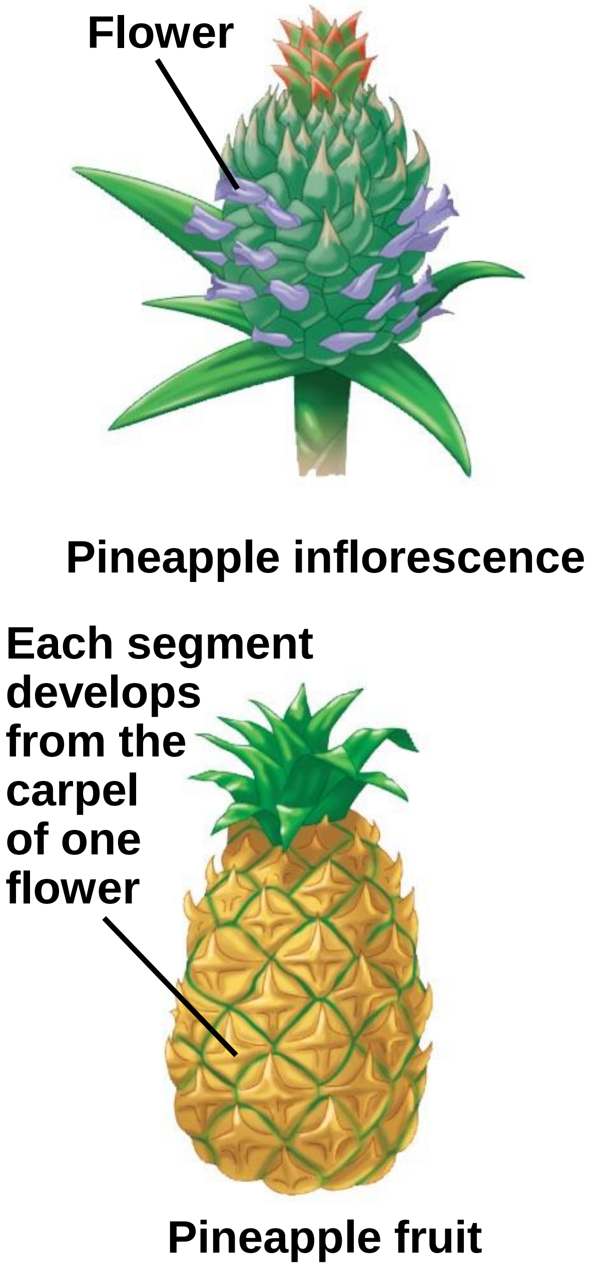
(c) Maize, a monocot



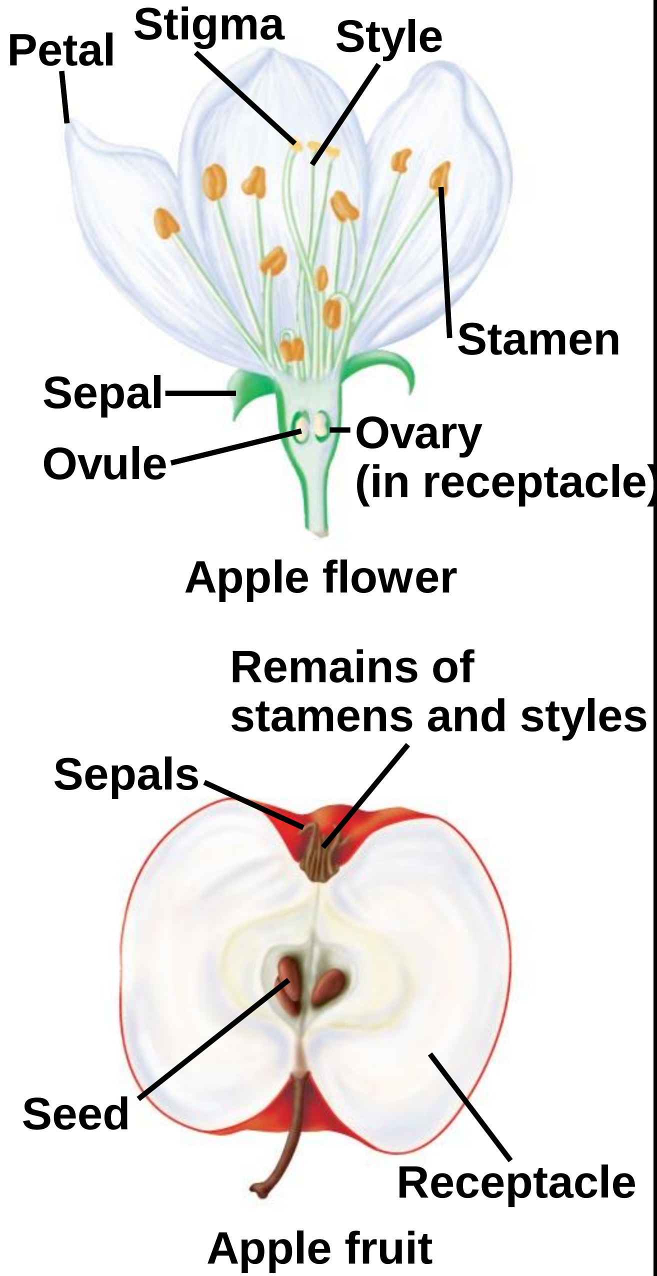
(a) Simple fruit



(b) Aggregate fruit



(c) Multiple fruit



(d) Accessory fruit

Dispersal by Water

Coconut

Dispersal by Wind

Winged seed of Asian climbing gourd

Dandelion "parachute"

Winged fruit of maple

Tumbleweed

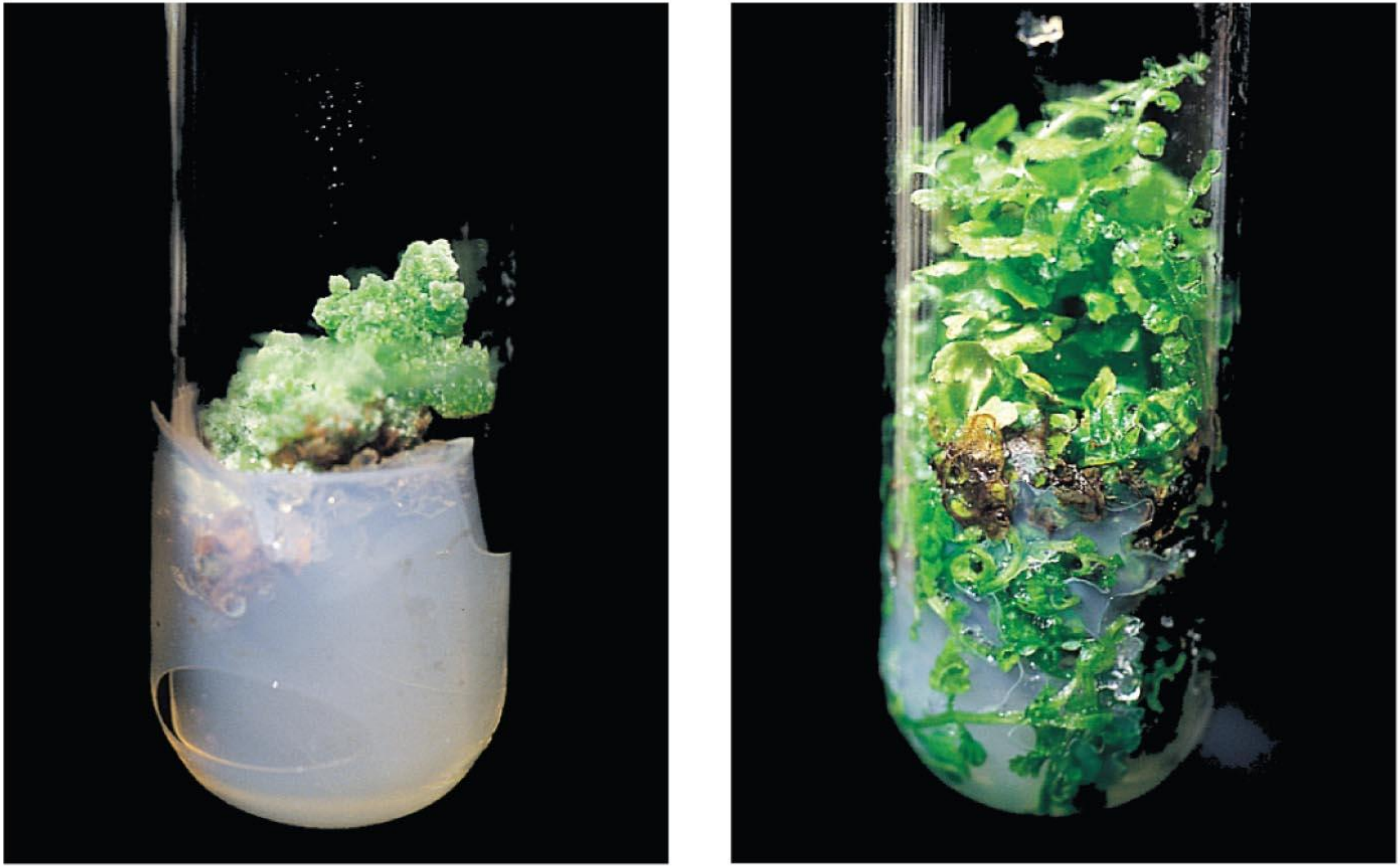
Dispersal by Animals

Barbed fruit

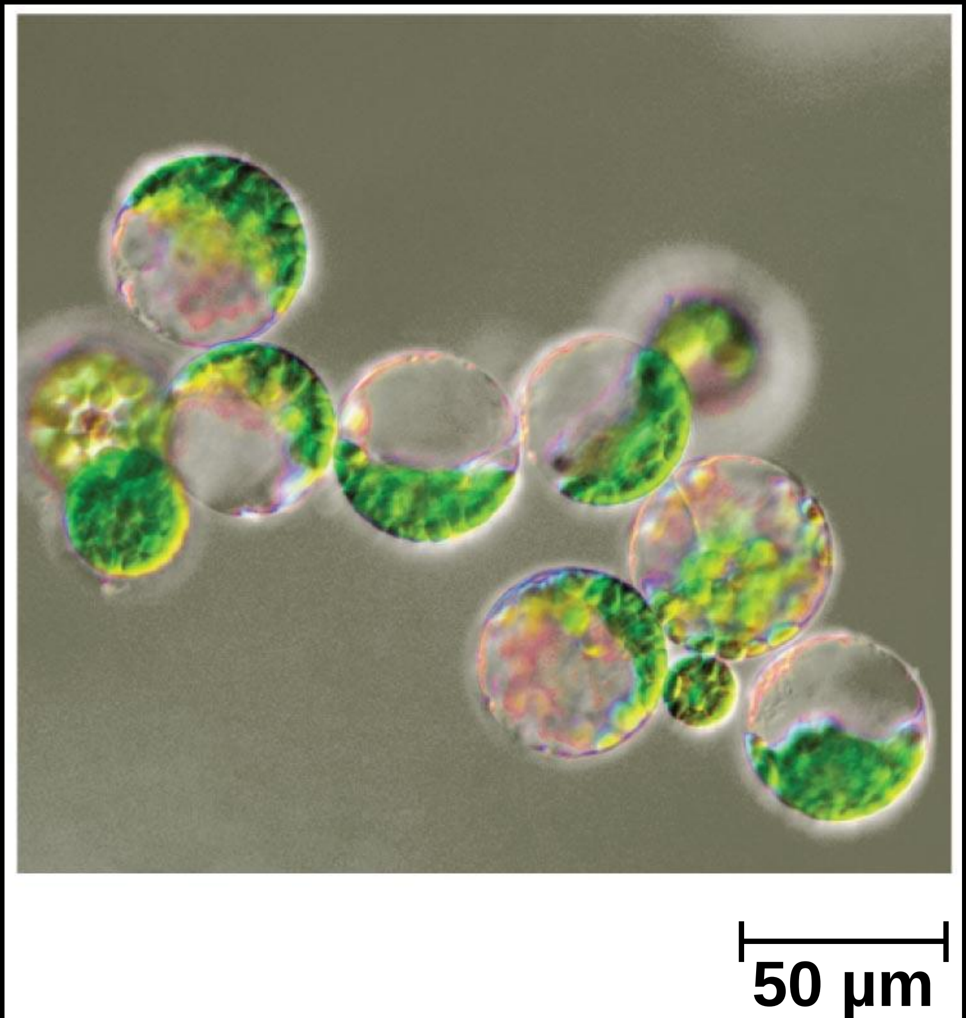
Seeds in feces

Seeds carried to ant nest

Seeds buried in caches



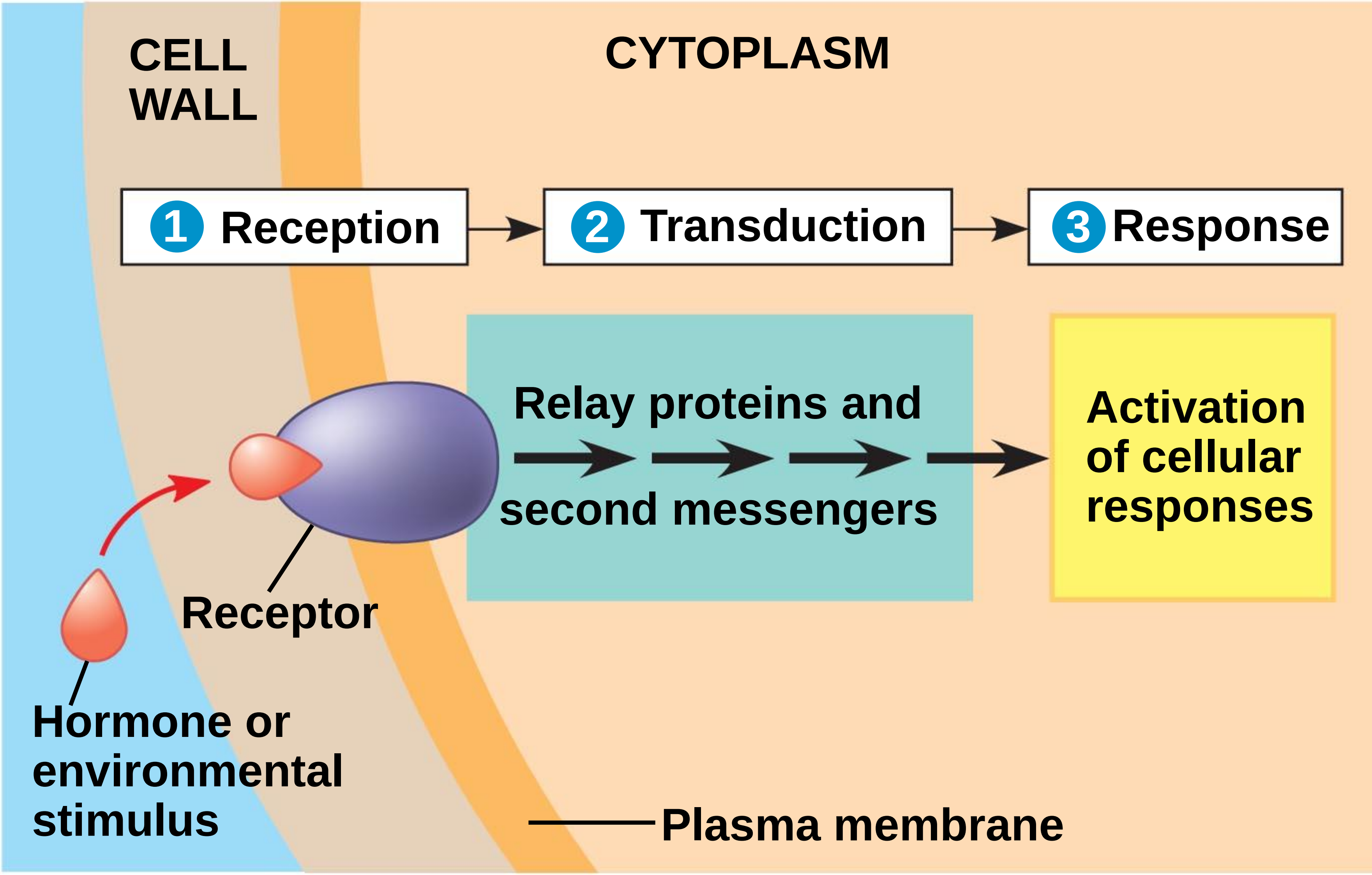
(a) Undifferentiated carrot cells **(b) Differentiation into plant**


50 µm

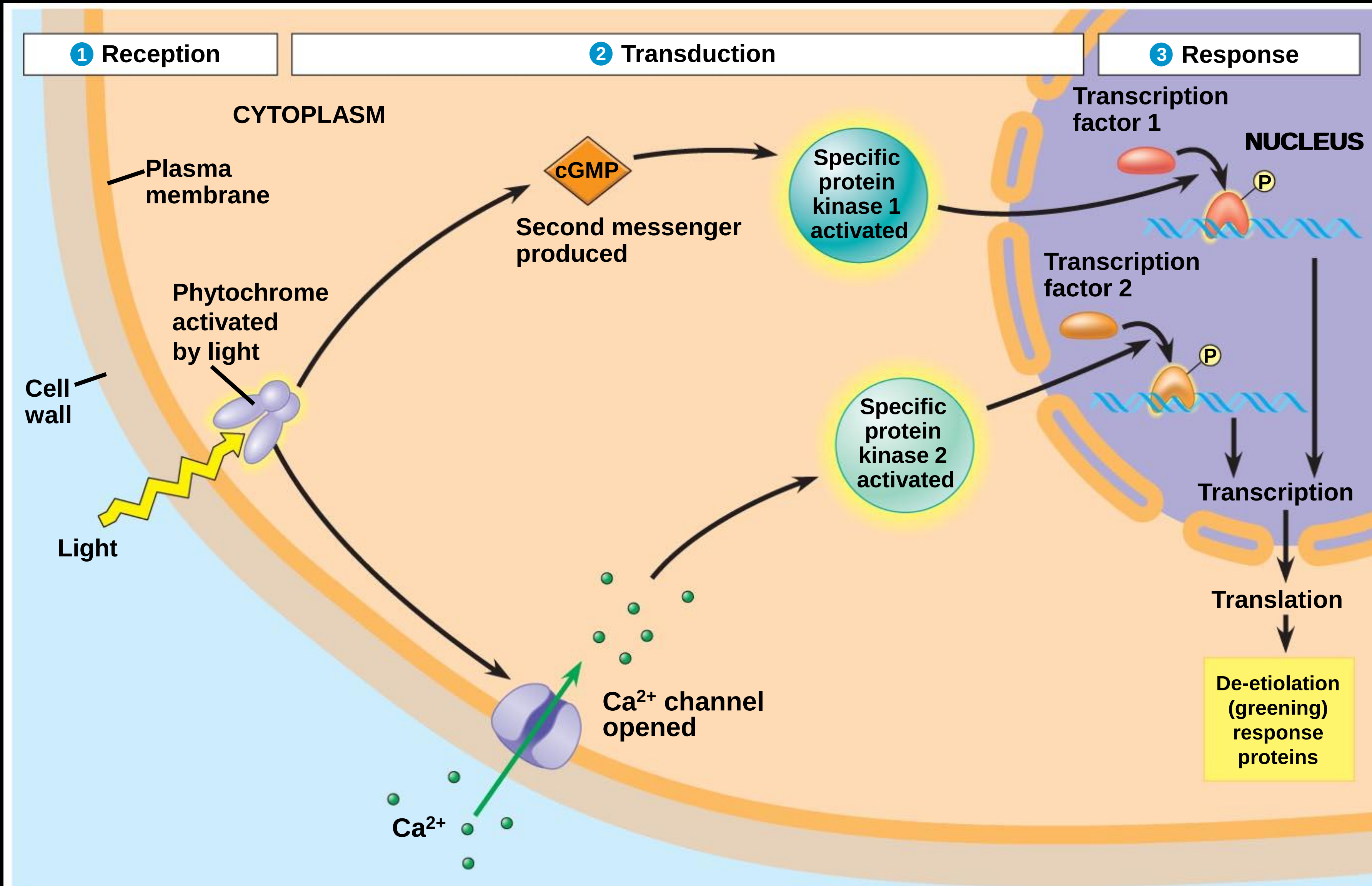

Genetically modified rice
Ordinary rice

(a) Before exposure to light

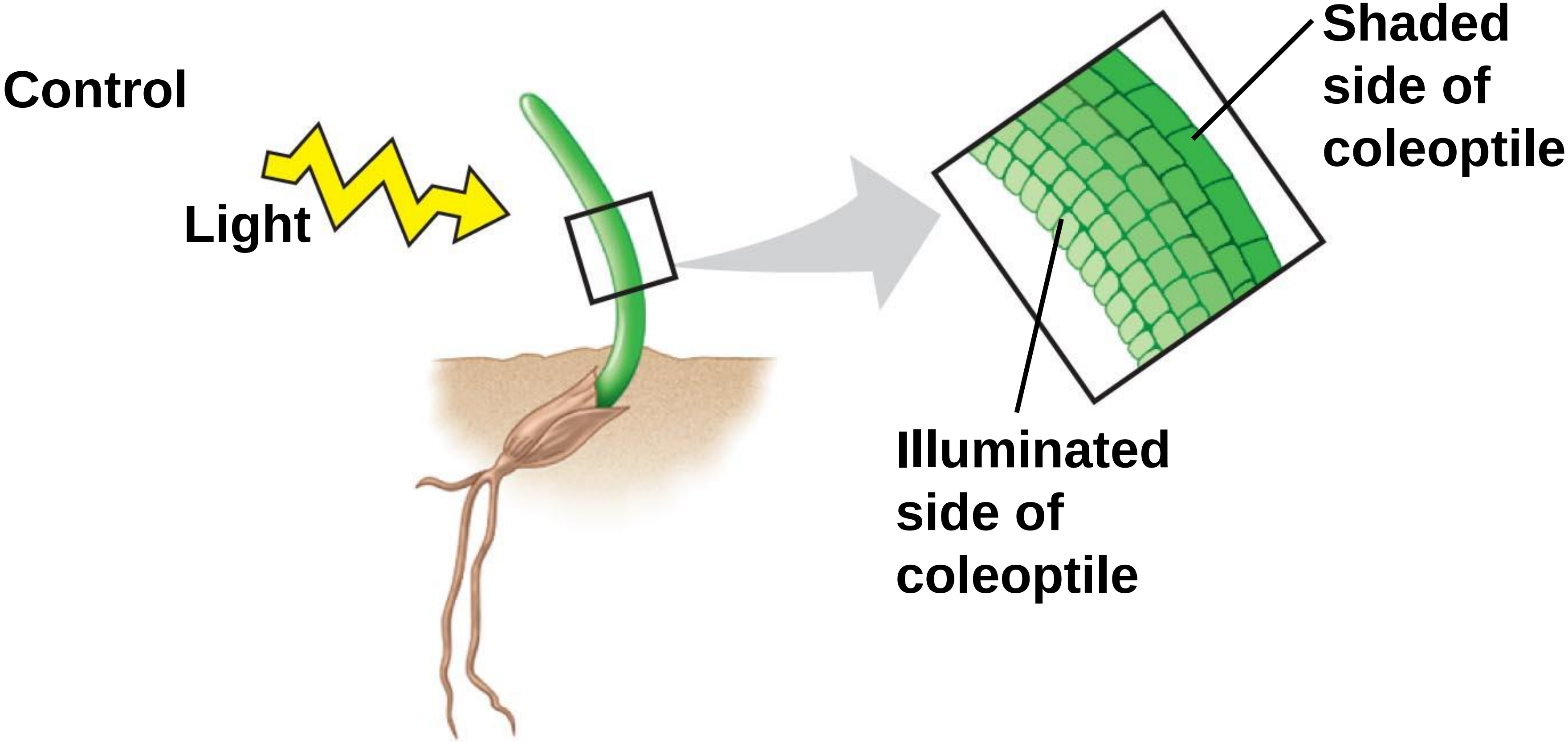
(b) After a week's exposure to natural daylight



CELL WALL
CYTOPLASM
1 Reception
2 Transduction
3 Response
Relay proteins and
second messengers
Activation of cellular responses
Receptor
Hormone or environmental stimulus
Plasma membrane


1 Reception
2 Transduction
3 Response
CYTOPLASM
Plasma membrane
Cell wall
Light
Phytochrome activated by light
cGMP
Second messenger produced
Specific protein kinase 1 activated
Specific protein kinase 2 activated
Ca^{2+} channel opened
Ca^{2+}
Transcription factor 1
Transcription factor 2
NUCLEUS
P
P
Transcription
Translation
De-etiolation (greening) response proteins

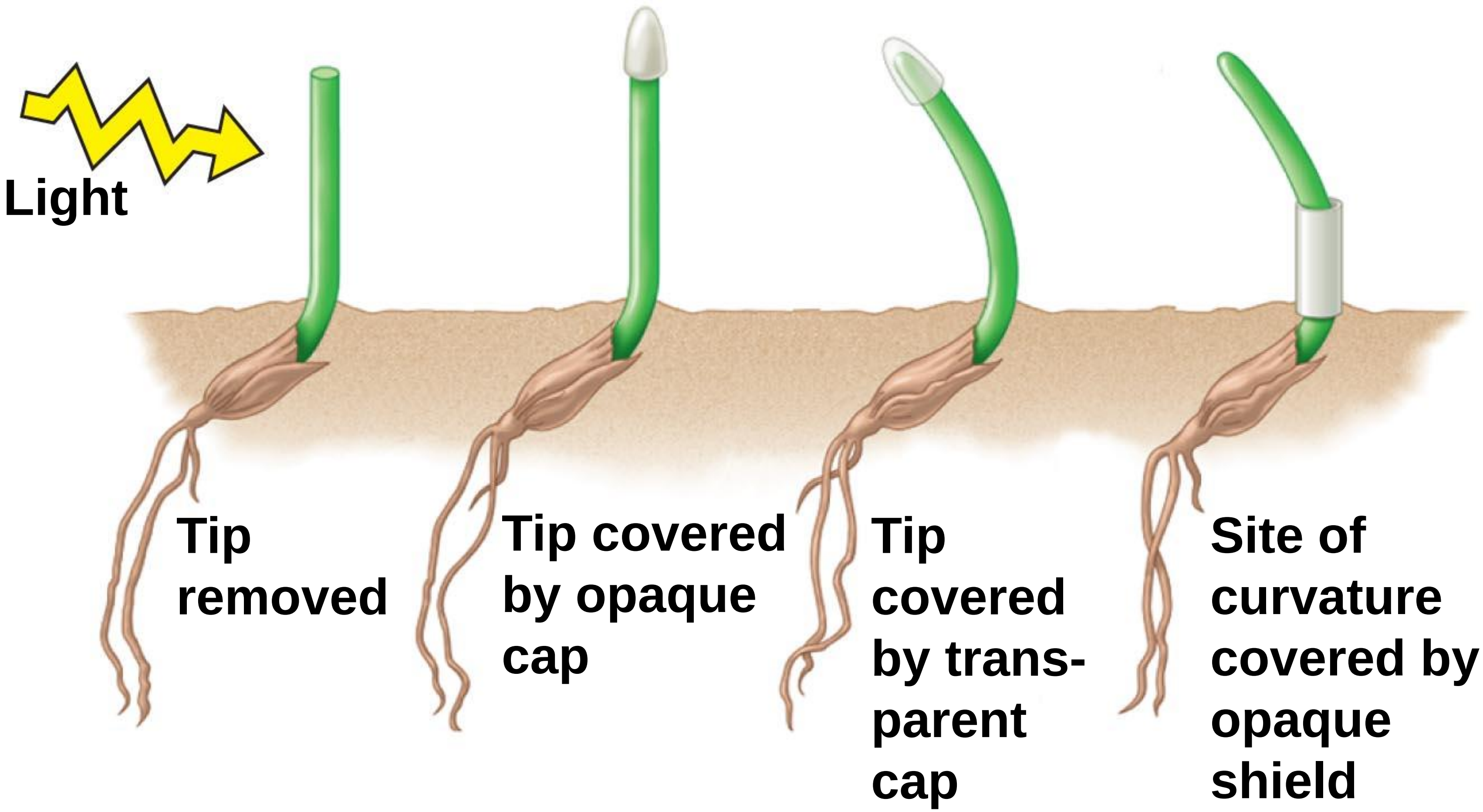
RESULTS



Control
Light
Shaded side of coleoptile
Illuminated side of coleoptile

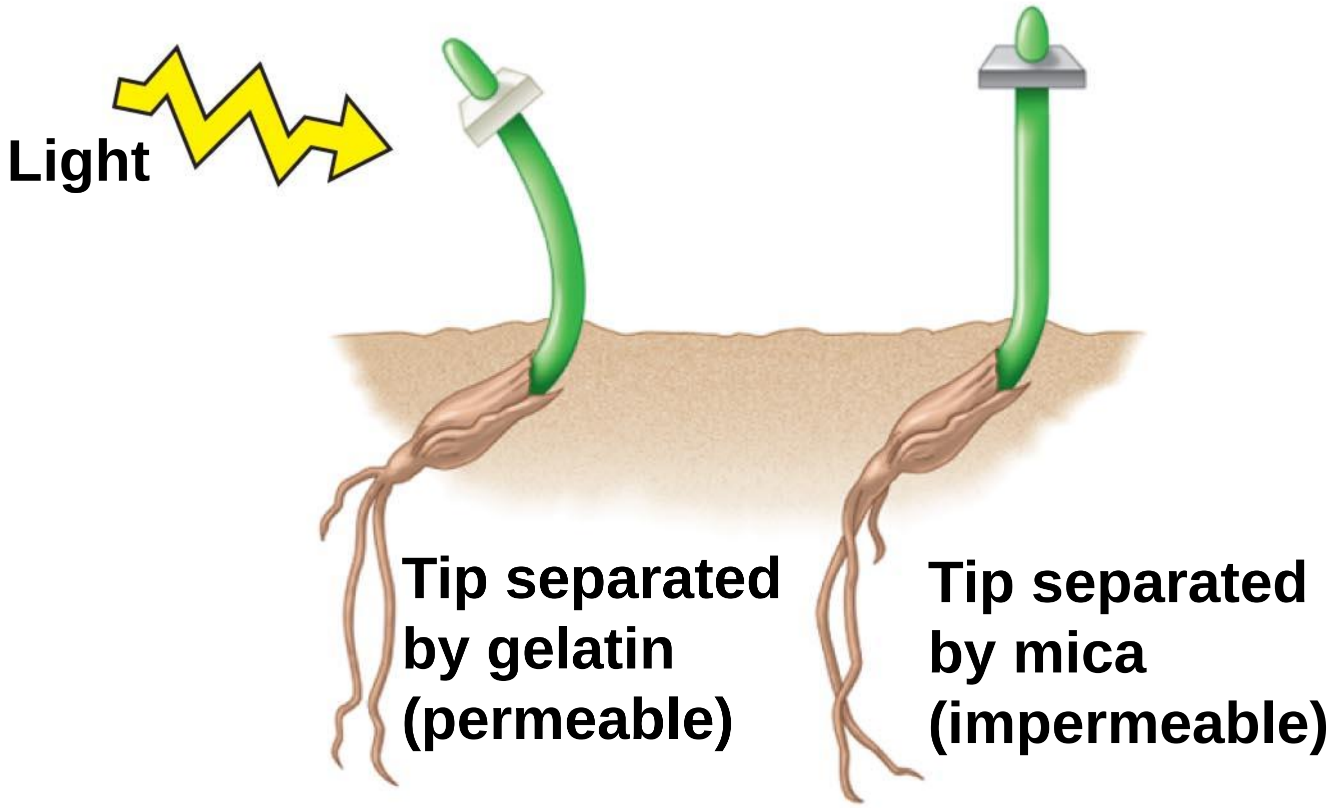
RESULTS

Darwin and Darwin: phototropic response only when tip is illuminated

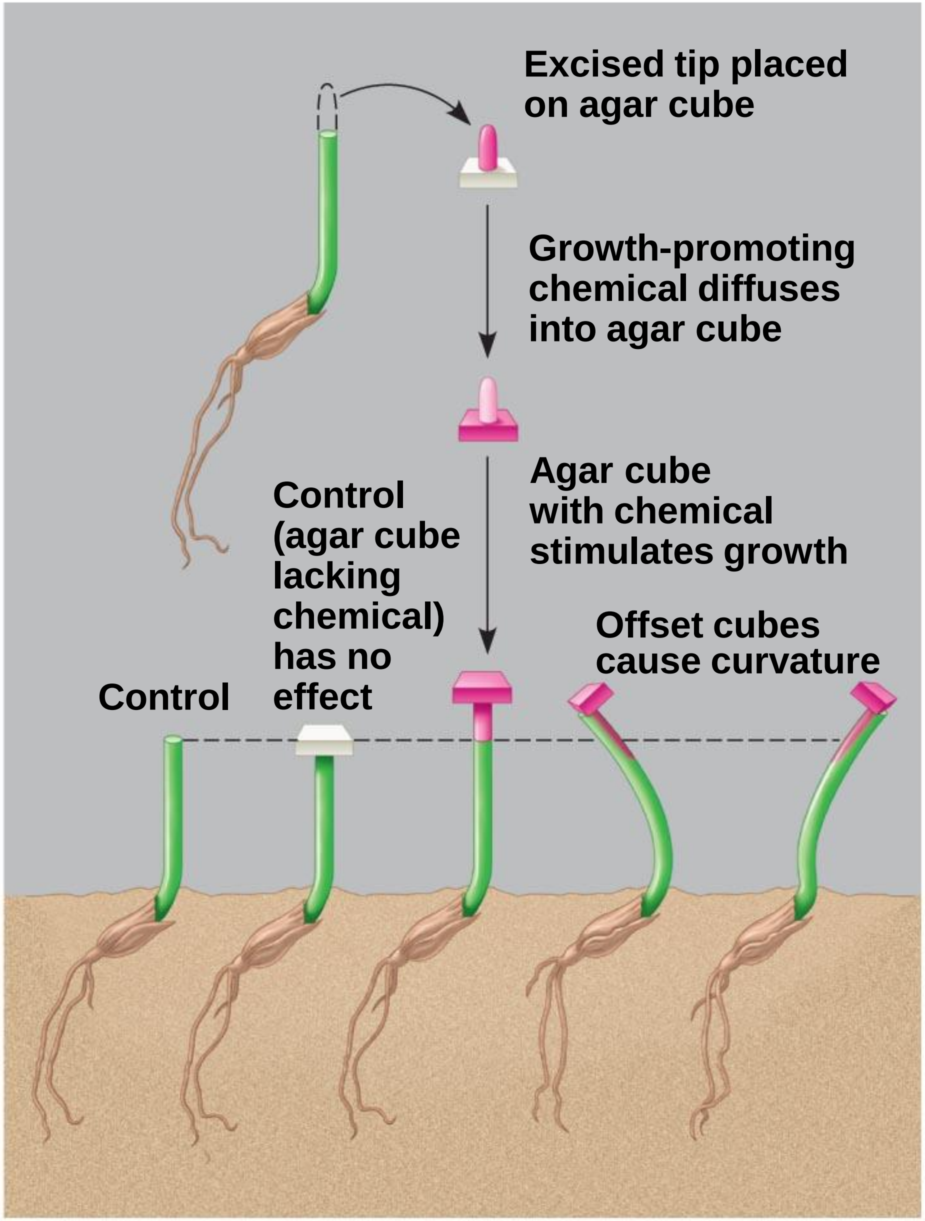


RESULTS

Boysen-Jensen: phototropic response when tip is separated by permeable barrier, but not with impermeable barrier



RESULTS

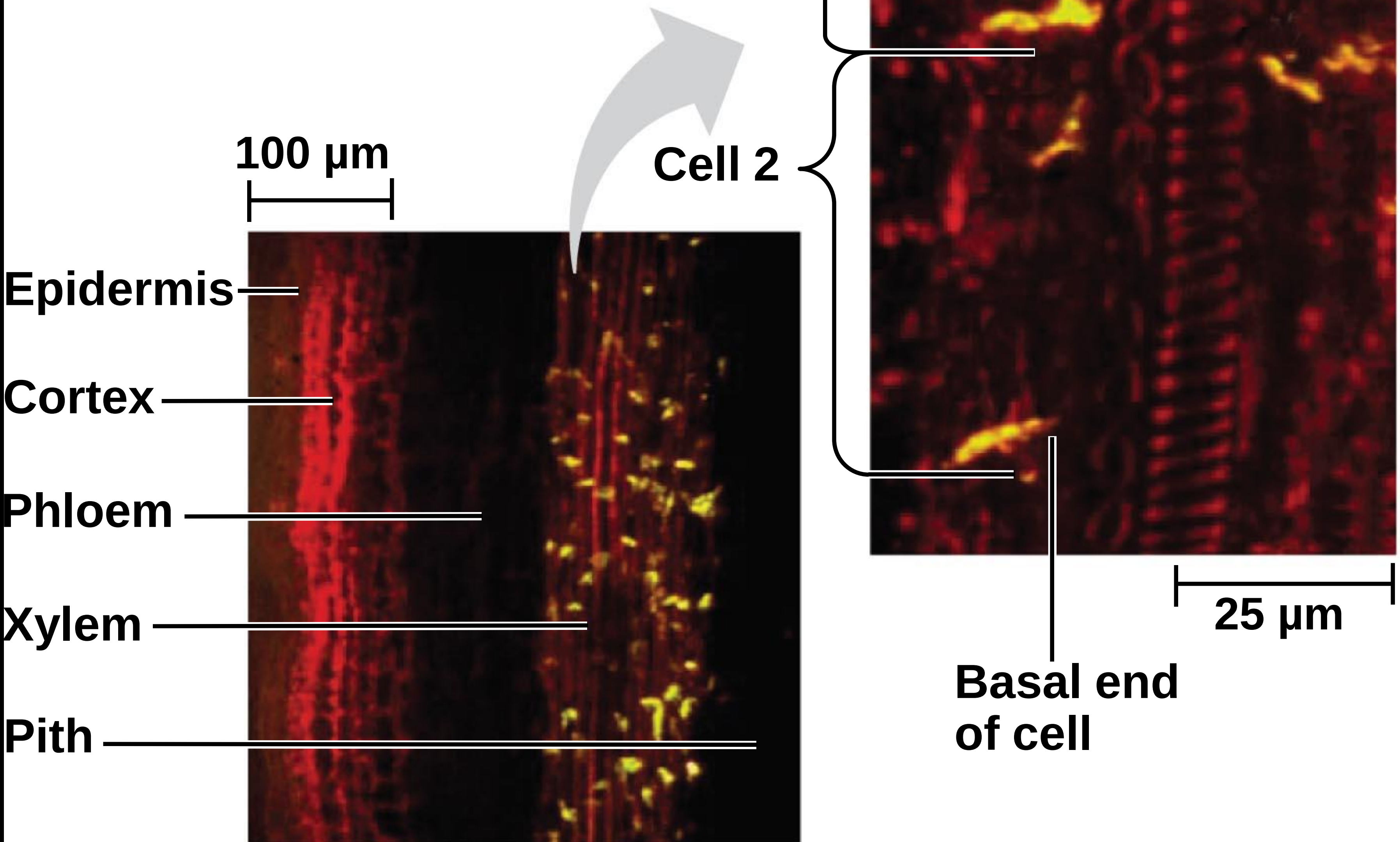


Excised tip placed on agar cube
Growth-promoting chemical diffuses into agar cube
Agar cube with chemical stimulates growth
Control (agar cube lacking chemical) has no effect
Control
Offset cubes cause curvature

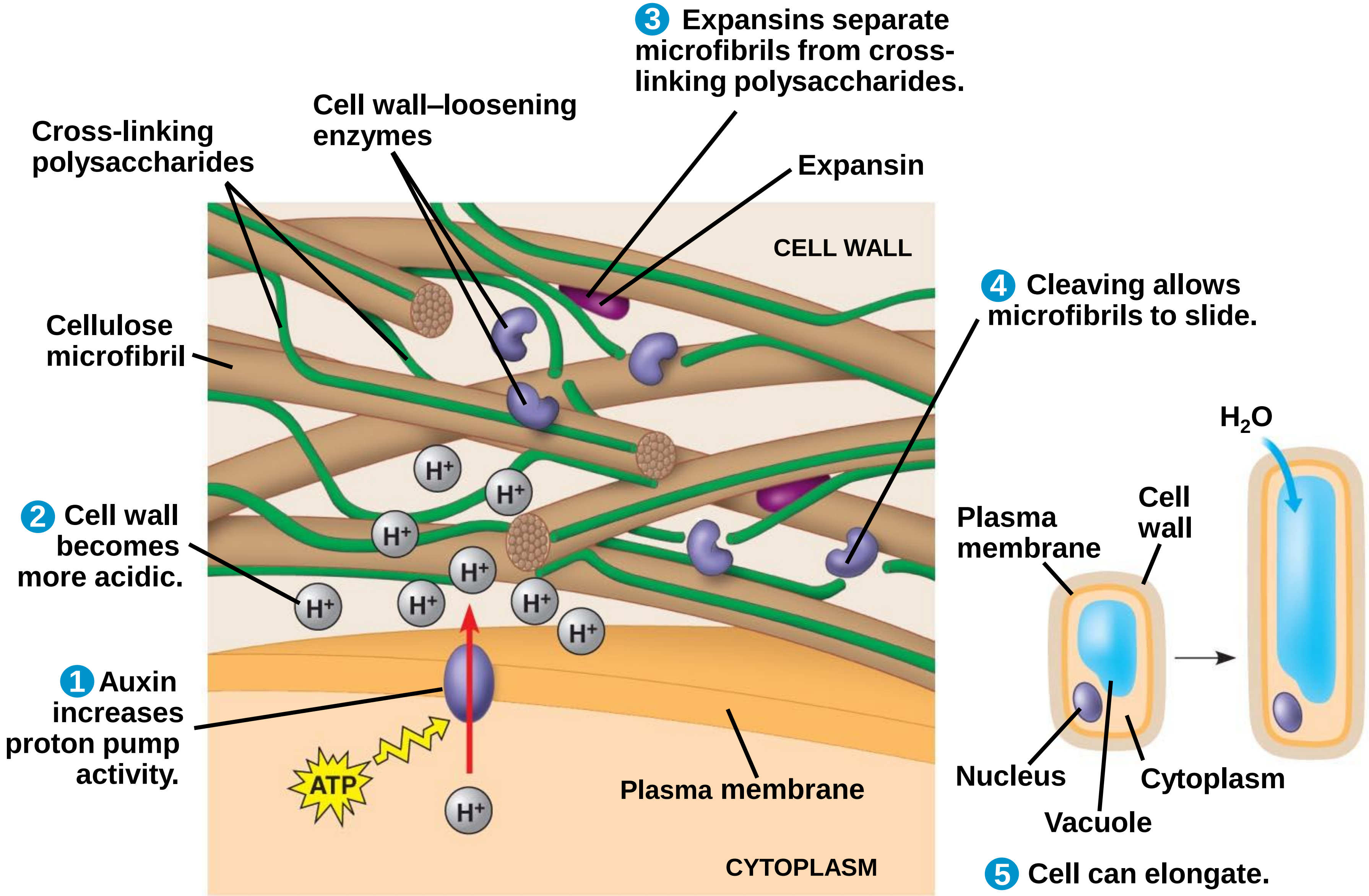
Table 39.1 Overview of Plant Hormones

Hormone	Where Produced or Found in Plant	Major Functions
Auxin (IAA)	Shoot apical meristems and young leaves are the primary sites of auxin synthesis. Root apical meristems also produce auxin, although the root depends on the shoot for much of its auxin. Developing seeds and fruits contain high levels of auxin, but it is unclear whether it is newly synthesized or transported from maternal tissues.	Stimulates stem elongation (low concentration only); promotes the formation of lateral and adventitious roots; regulates development of fruit; enhances apical dominance; functions in phototropism and gravitropism; promotes vascular differentiation; retards leaf abscission.
Cytokinins	These are synthesized primarily in roots and transported to other organs, although there are many minor sites of production as well.	Regulate cell division in shoots and roots; modify apical dominance and promote lateral bud growth; promote movement of nutrients into sink tissues; stimulate seed germination; delay leaf senescence.
Gibberellins	Meristems of apical buds and roots, young leaves, and developing seeds are the primary sites of production.	Stimulate stem elongation, pollen development, pollen tube growth, fruit growth, and seed development and germination; regulate sex determination and the transition from juvenile to adult phases.
Brassinosteroids	These compounds are present in all plant tissues, although different intermediates predominate in different organs. Internally produced brassinosteroids act near the site of synthesis.	Promote cell expansion and cell division in shoots; promote root growth at low concentrations; inhibit root growth at high concentrations; promote xylem differentiation and inhibit phloem differentiation; promote seed germination and pollen tube elongation.
Abscisic acid (ABA)	Almost all plant cells have the ability to synthesize abscisic acid, and its presence has been detected in every major organ and living tissue; may be transported in the phloem or xylem.	Inhibits growth; promotes stomatal closure during drought stress; promotes seed dormancy and inhibits early germination; promotes leaf senescence; promotes desiccation tolerance.
Ethylene	This gaseous hormone can be produced by almost all parts of the plant. It is produced in high concentrations during senescence, leaf abscission, and the ripening of some types of fruits. Synthesis is also stimulated by wounding and stress.	Promotes ripening of many types of fruit, leaf abscission, and the triple response in seedlings (inhibition of stem elongation, promotion of lateral expansion, and horizontal growth); enhances the rate of senescence; promotes root and root hair formation; promotes flowering in the pineapple family.

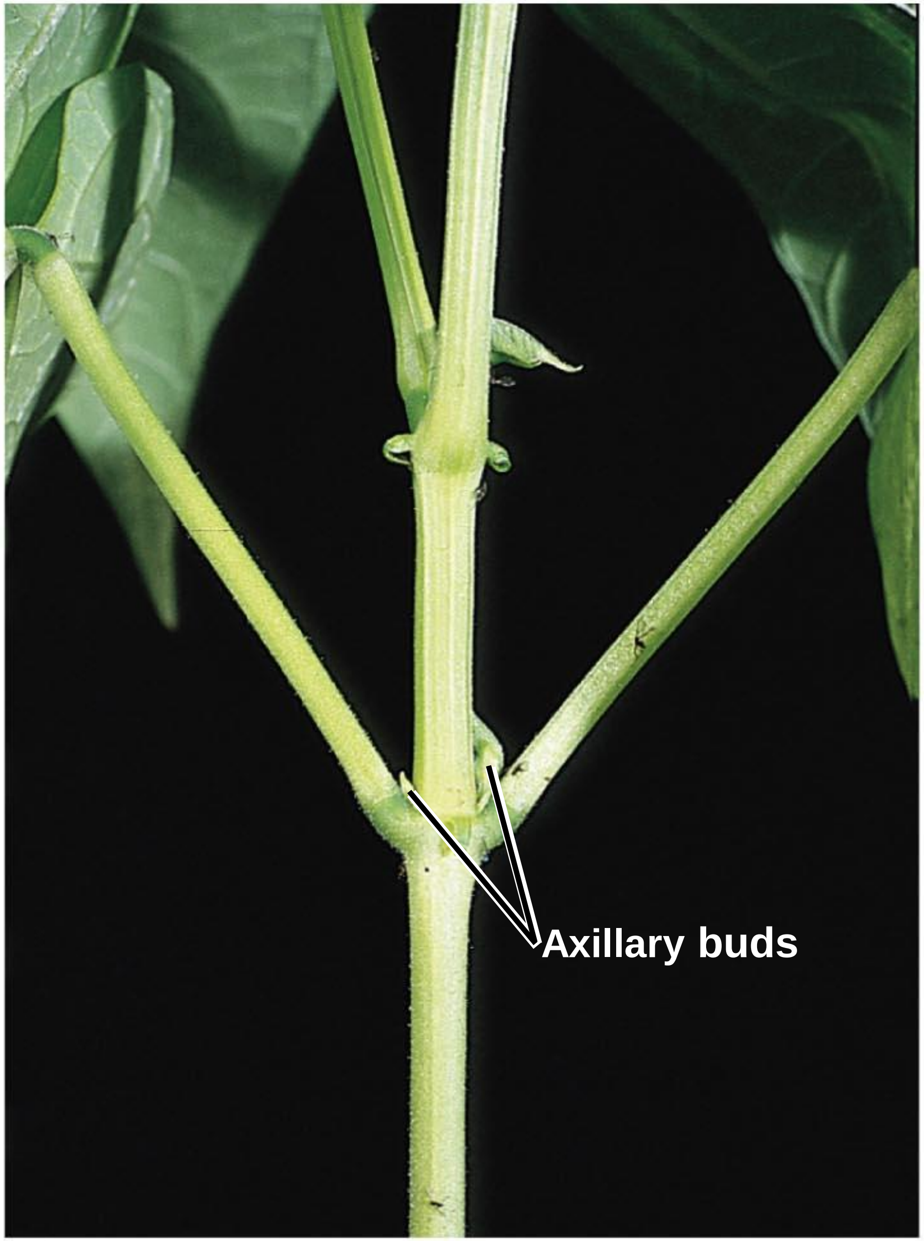
RESULTS



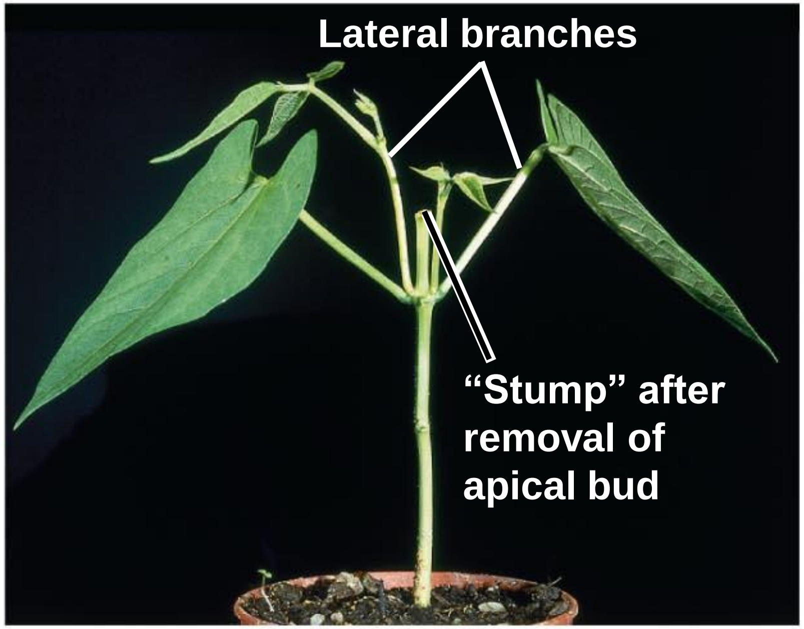
100 µm
Epidermis
Cortex
Phloem
Xylem
Pith
Cell 1
Cell 2
25 µm
Basal end of cell



3 Expansins separate microfibrils from cross-linking polysaccharides.
Cell wall–loosening enzymes
Cross-linking polysaccharides
Expansin
CELL WALL
4 Cleaving allows microfibrils to slide.
Cellulose microfibril
H_2O
H^+
Plasma membrane
Cell wall
2 Cell wall becomes more acidic.
1 Auxin increases proton pump activity.
ATP
Plasma membrane
Nucleus
Cytoplasm
Vacuole
CYTOPLASM
5 Cell can elongate.

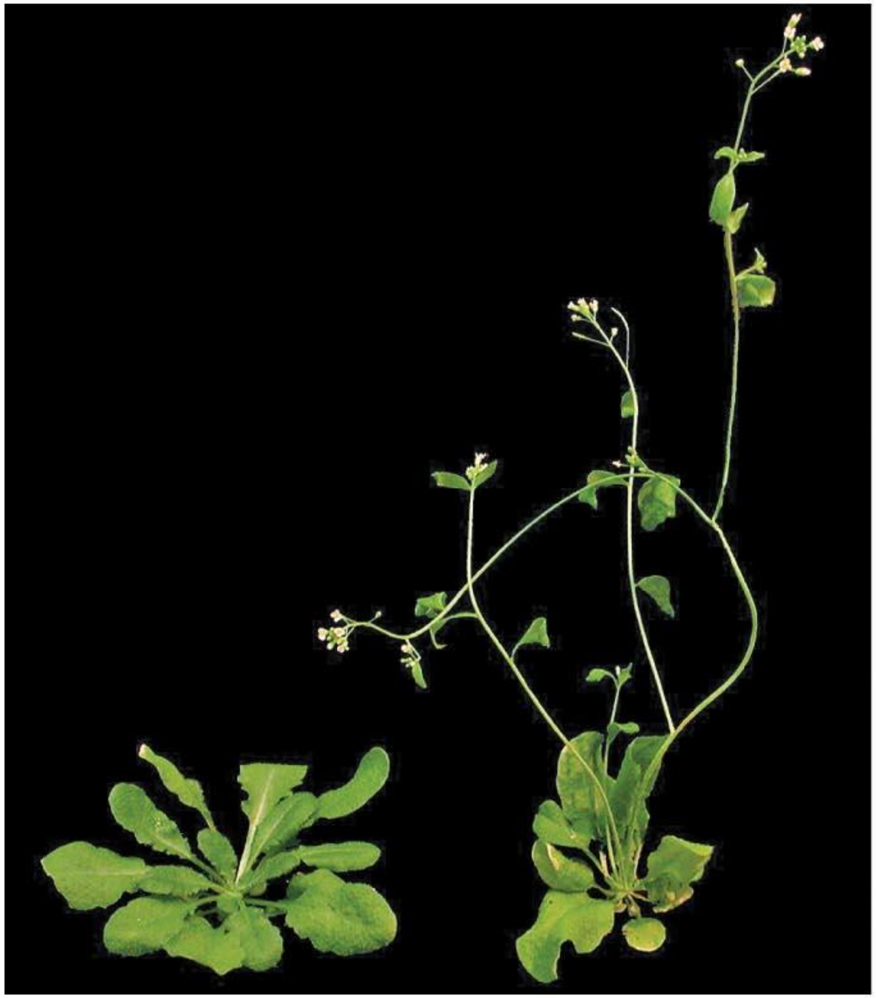


(a) Apical bud intact (not shown in photo)



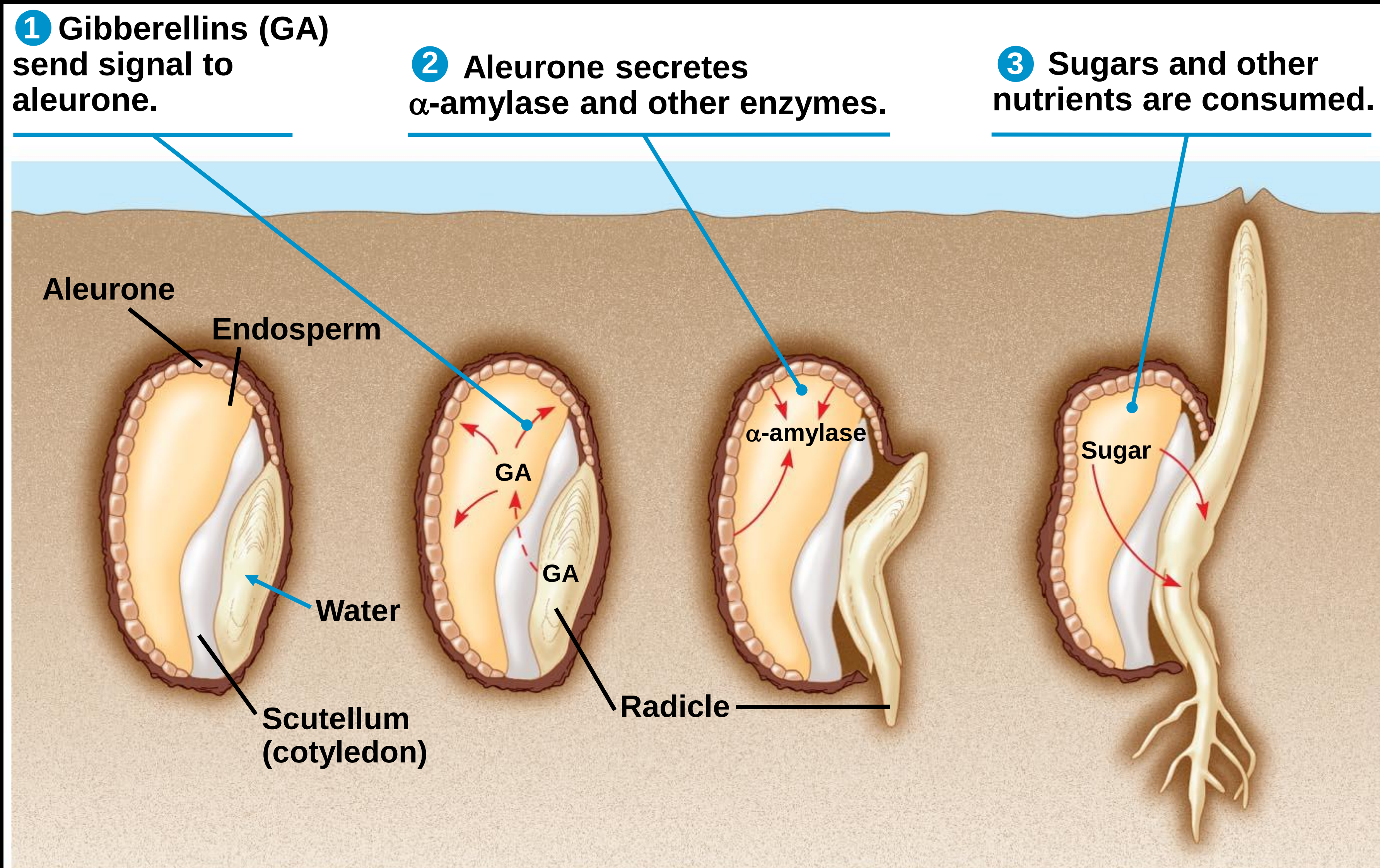
(b) Apical bud removed

(c) Auxin added to decapitated stem

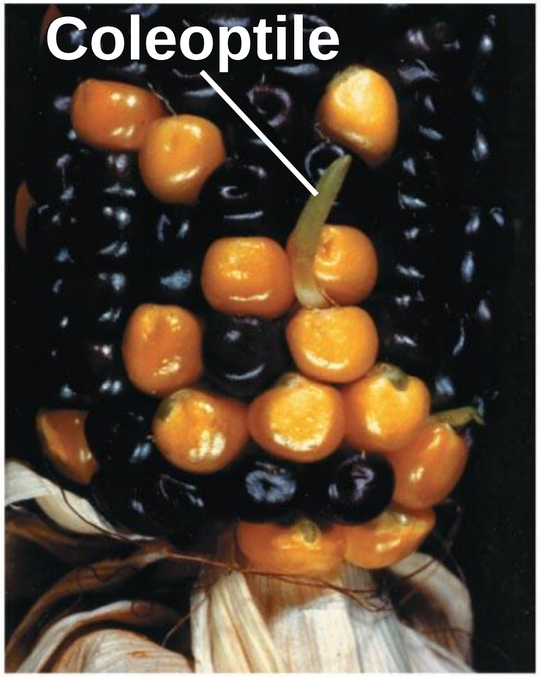


(a) Gibberellin-induced stem growth

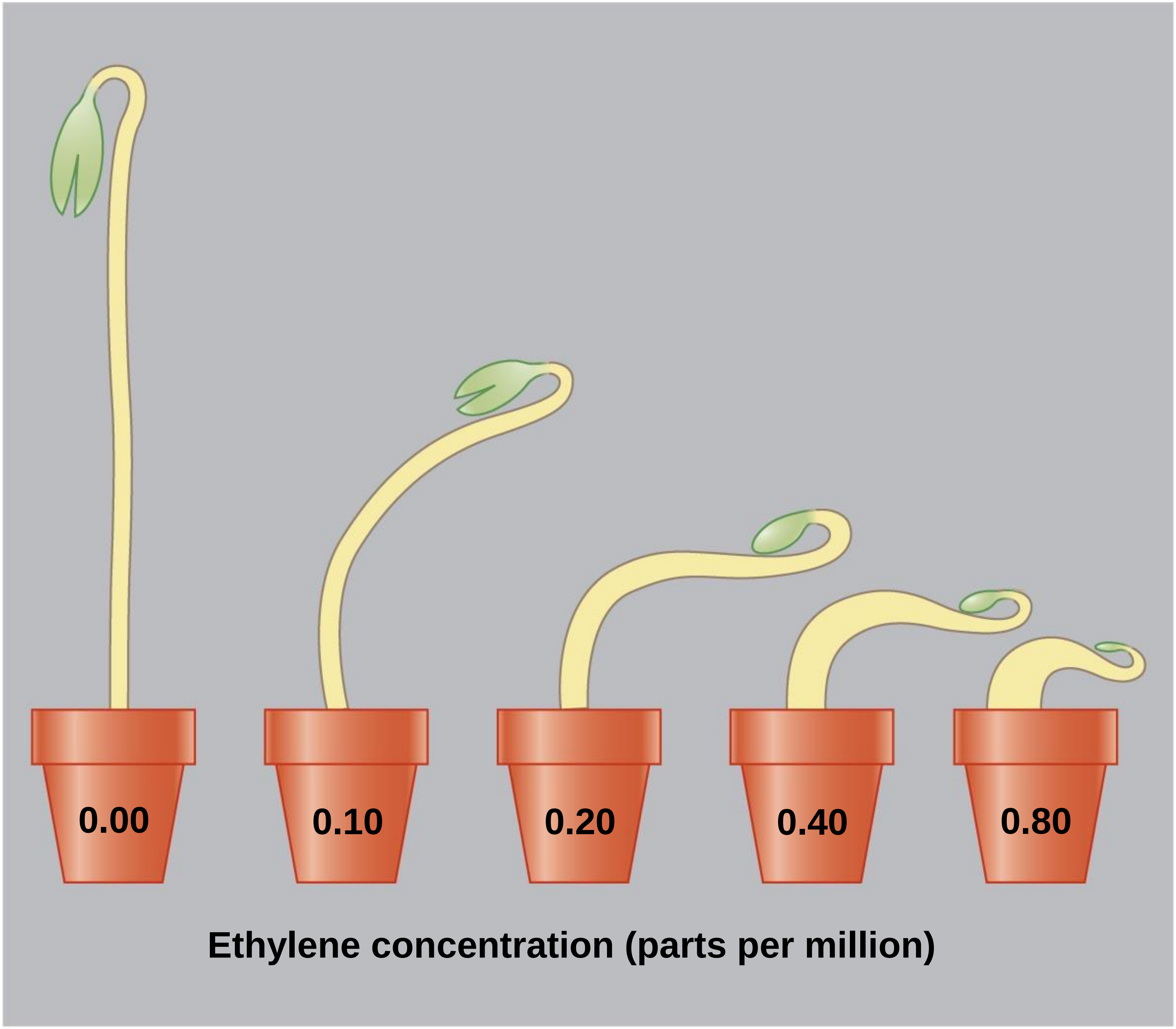
(b) Gibberellin-induced fruit growth

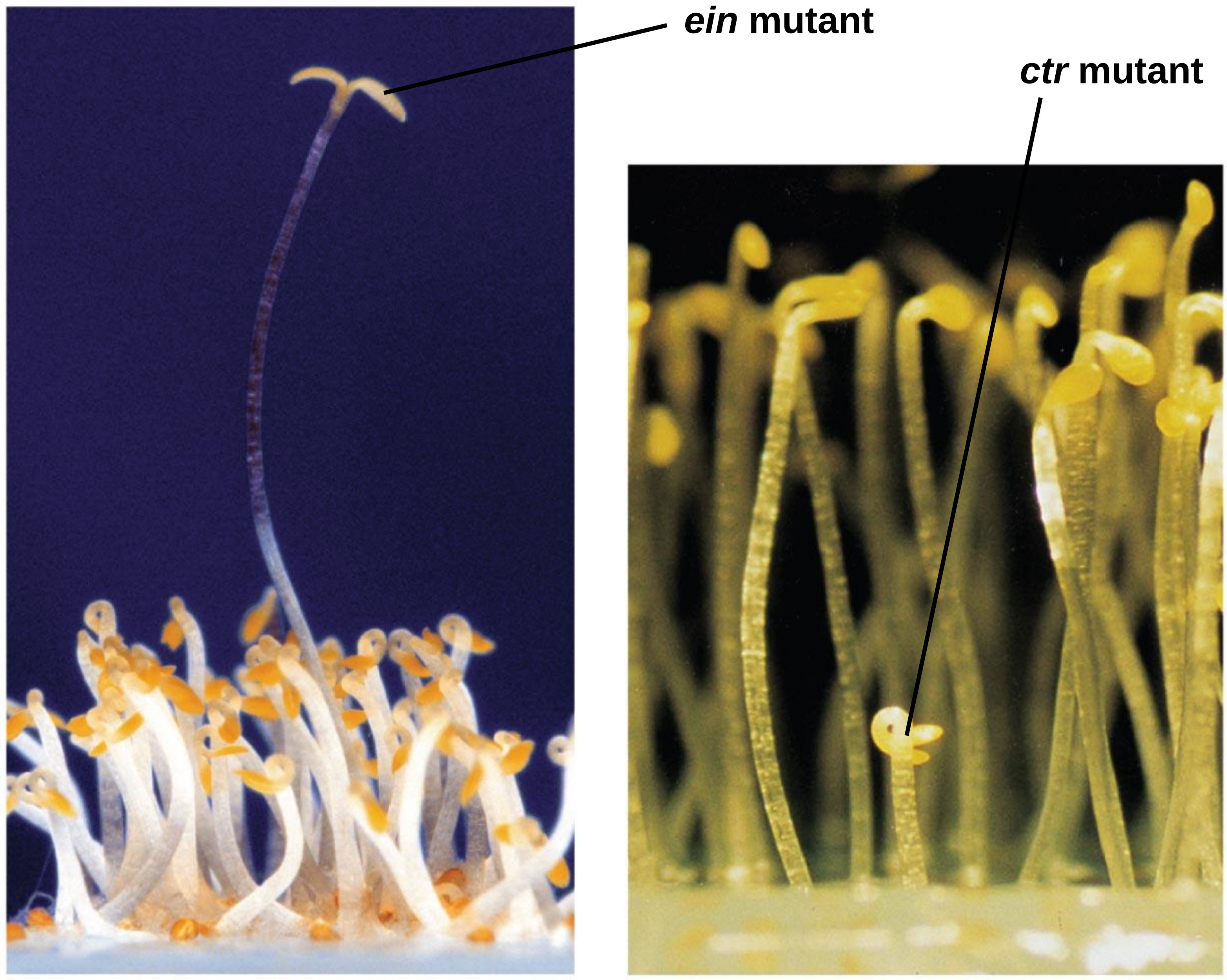

1 Gibberellins (GA) send signal to aleurone.
2 Aleurone secretes α-amylase and other enzymes.
3 Sugars and other nutrients are consumed.
Aleurone
Endosperm
Water
Scutellum (cotyledon)
GA
GA
Radicle
α-amylase
Sugar

◀ Early germination in red mangrove

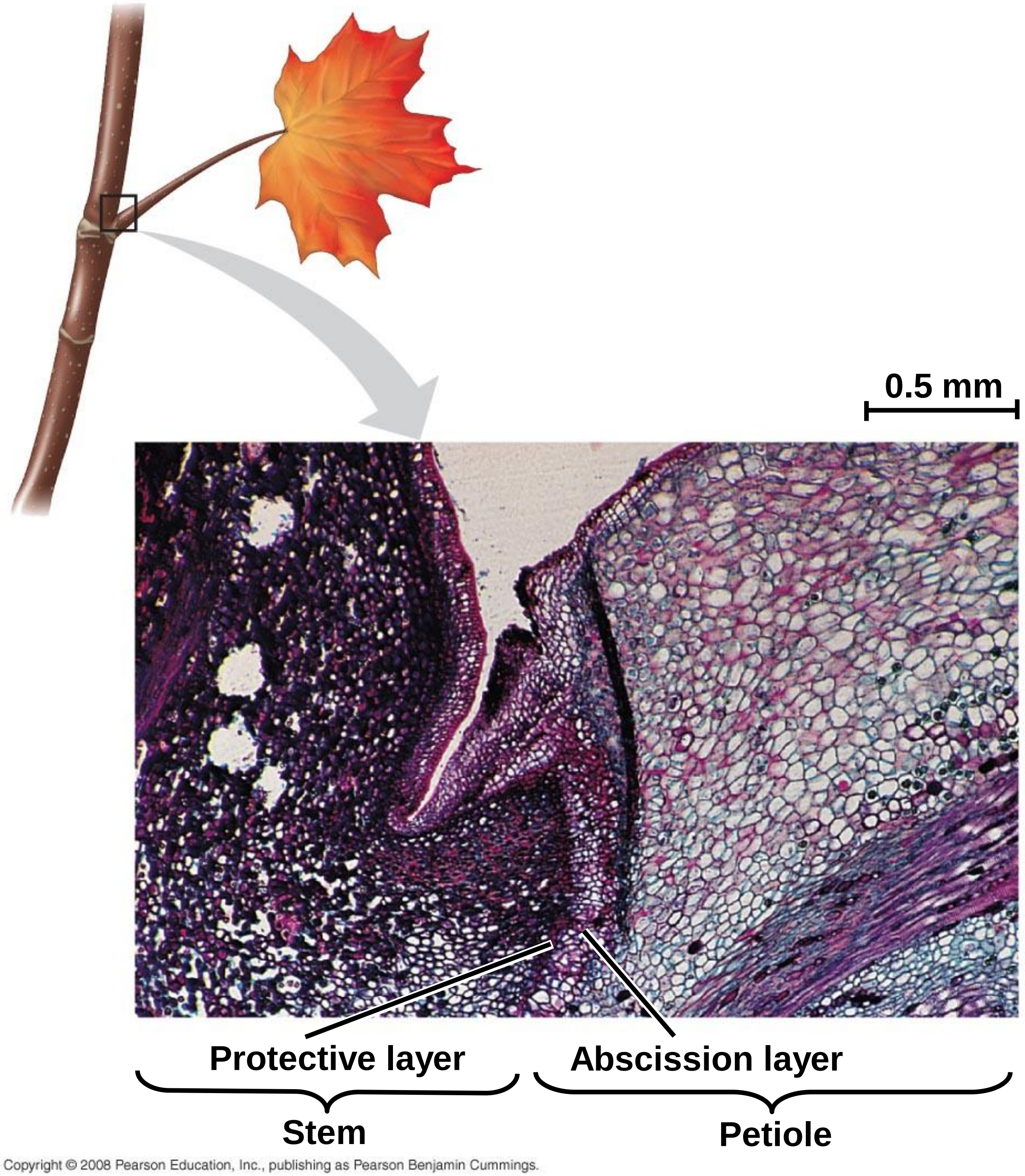


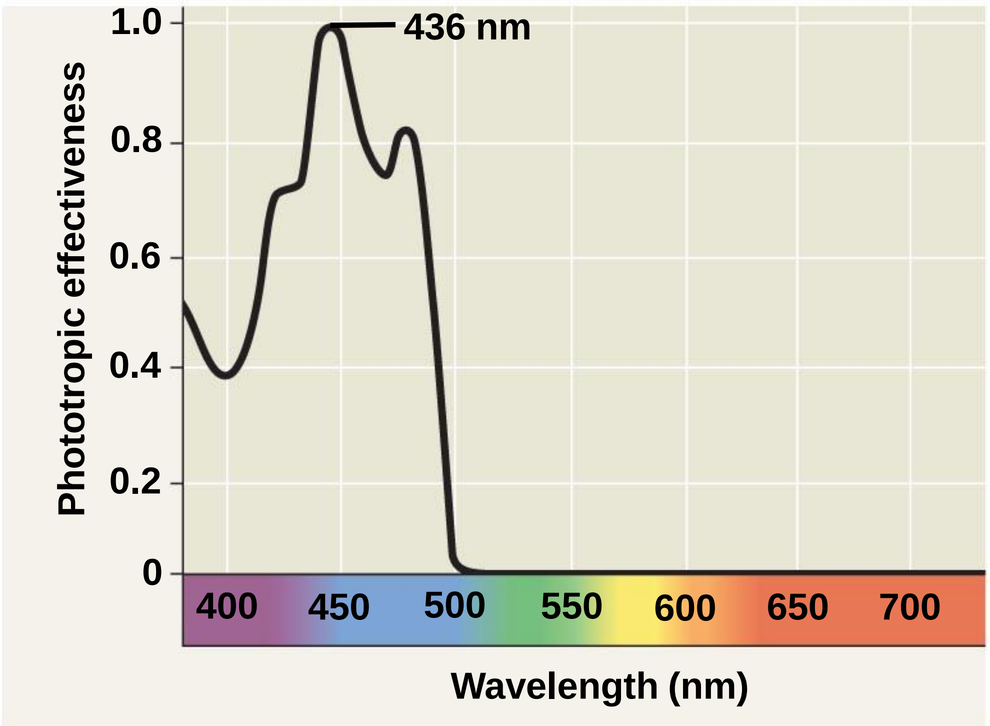
▲ Early germination in maize mutant


0.00
0.10
0.20
0.40
0.80
Ethylene concentration (parts per million)

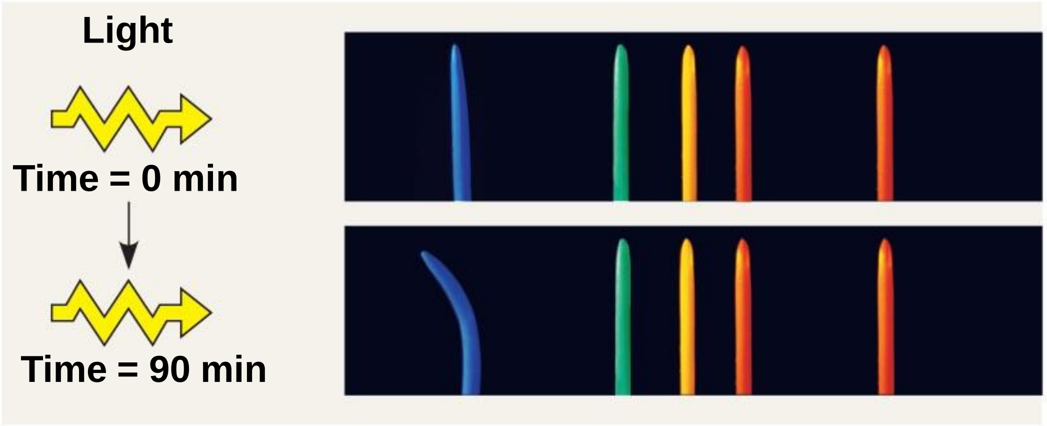


(a) *ein* mutant **(b) *ctr* mutant**

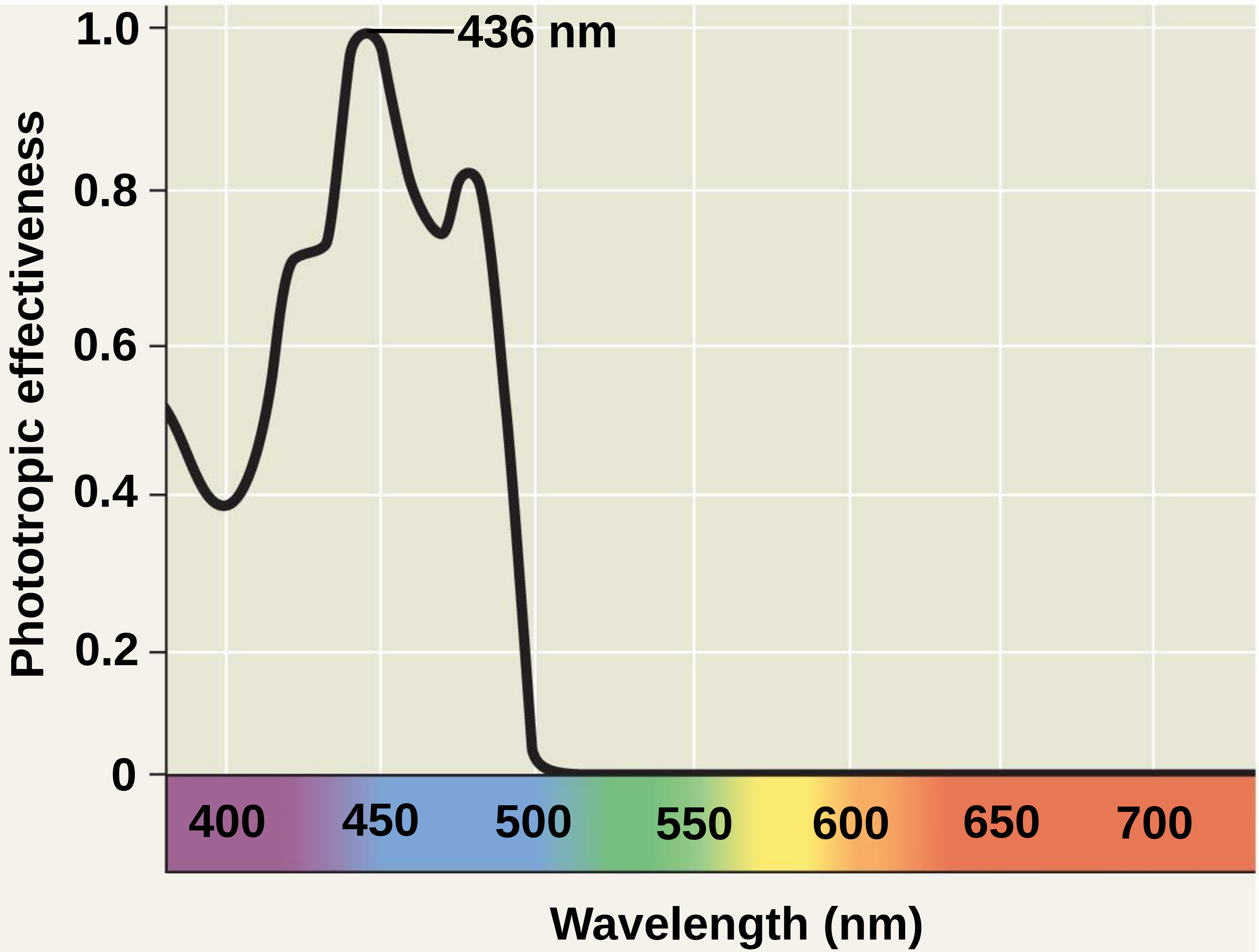

0.5 mm
Protective layer
Abscission layer
Stem
Petiole



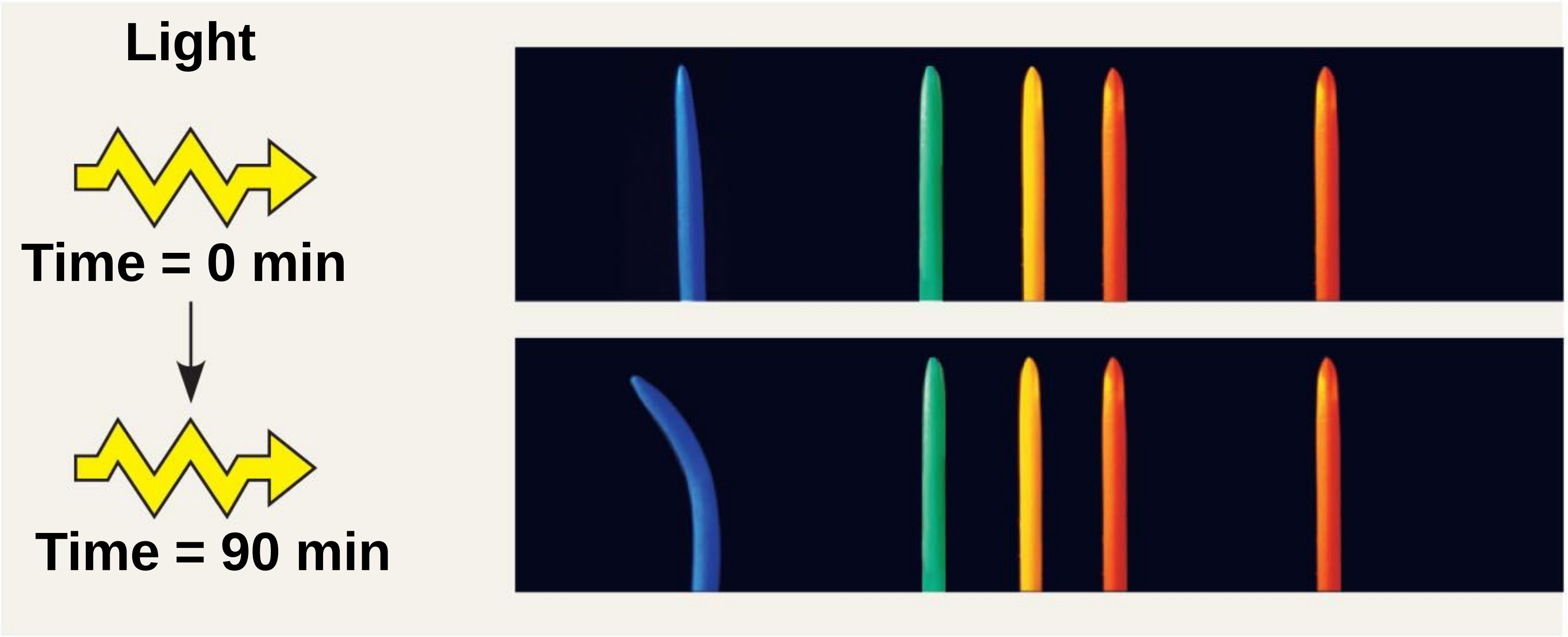
(a) Action spectrum for blue-light phototropism



(b) Coleoptile response to light colors

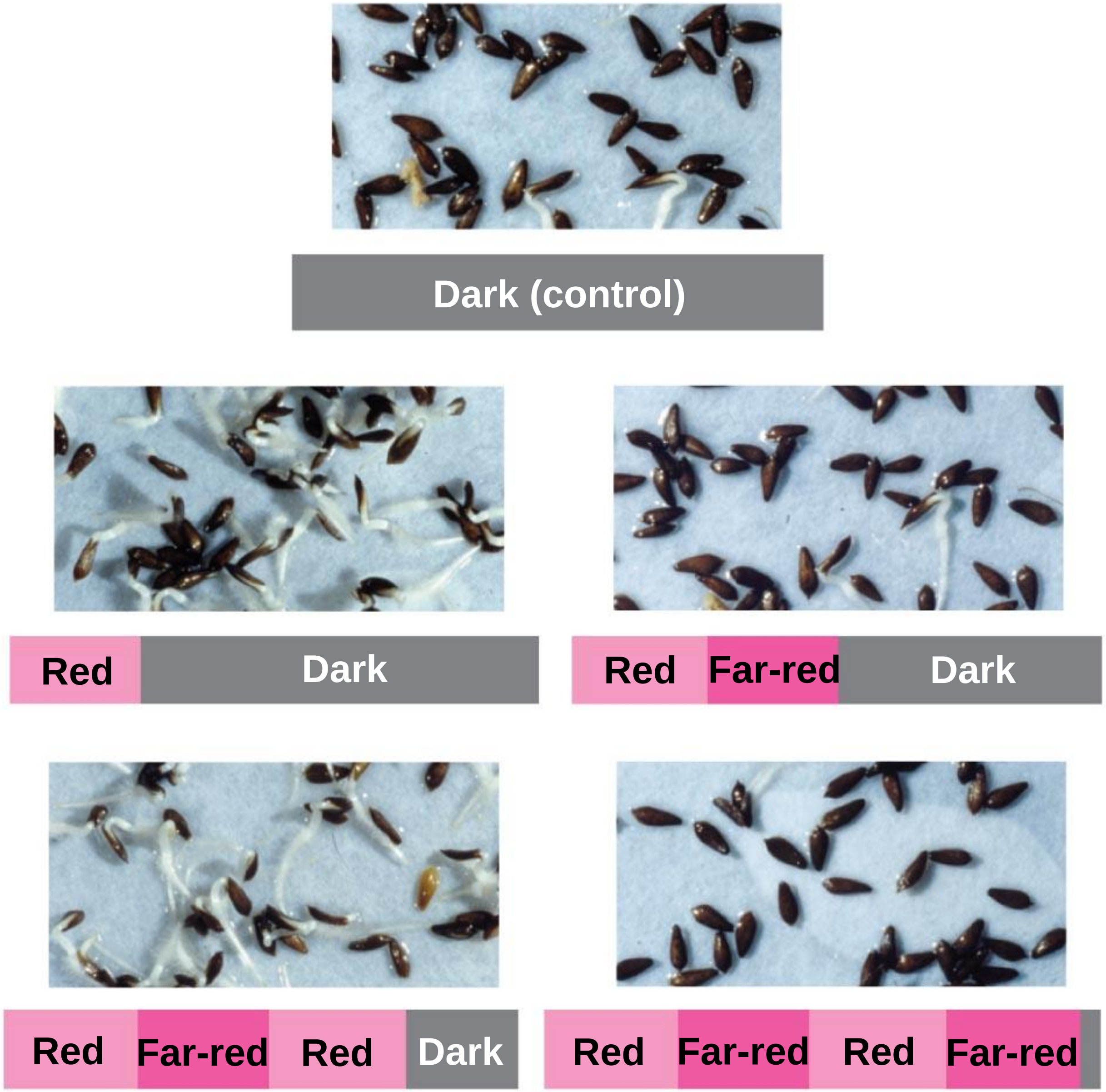


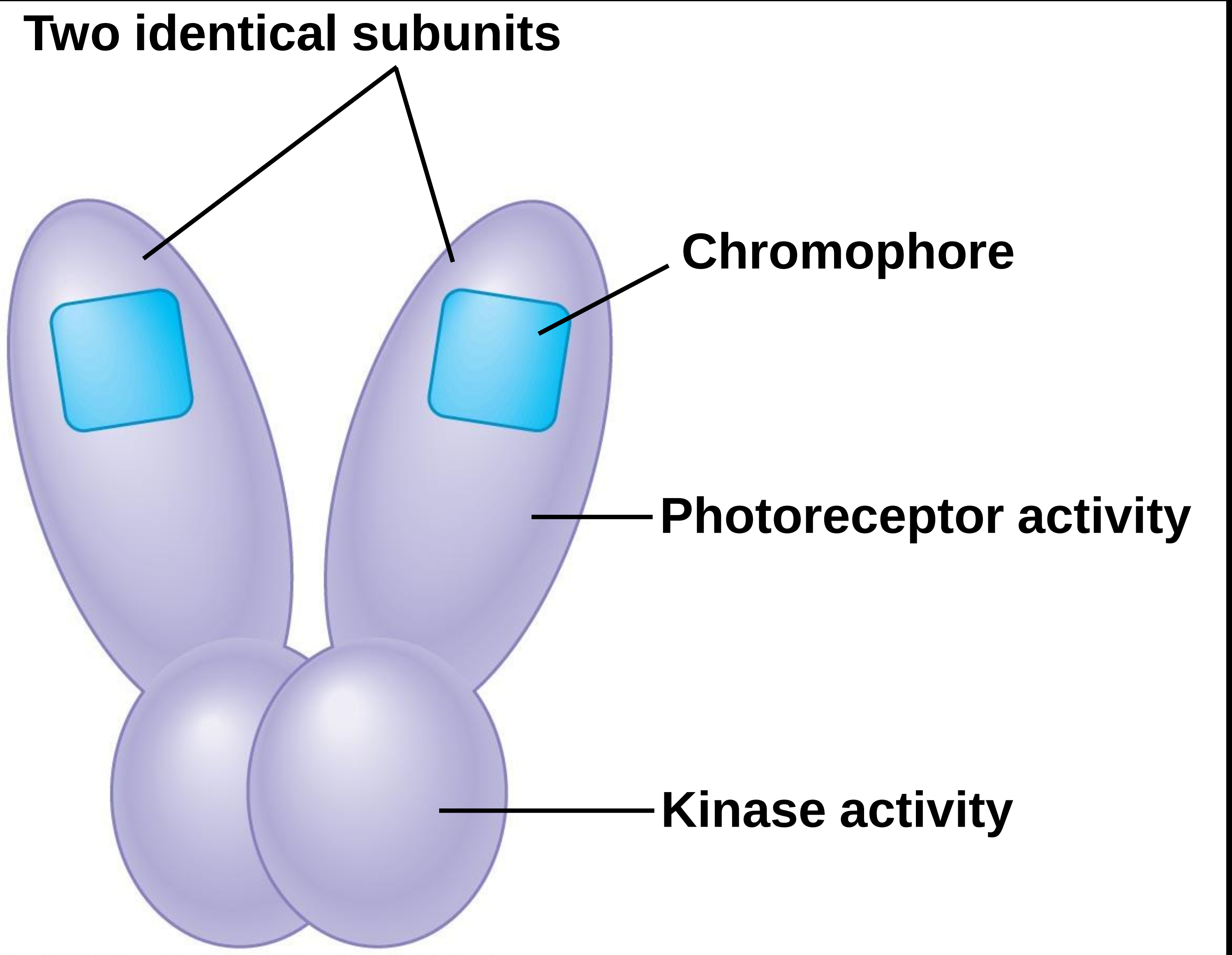
(a) Action spectrum for blue-light phototropism

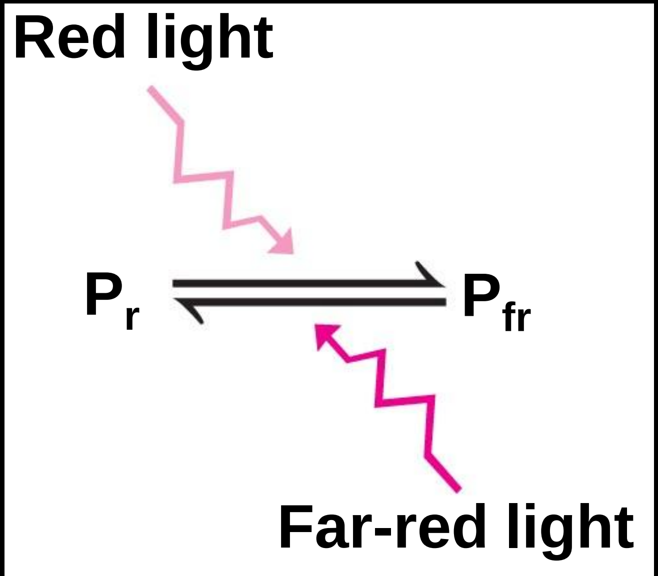


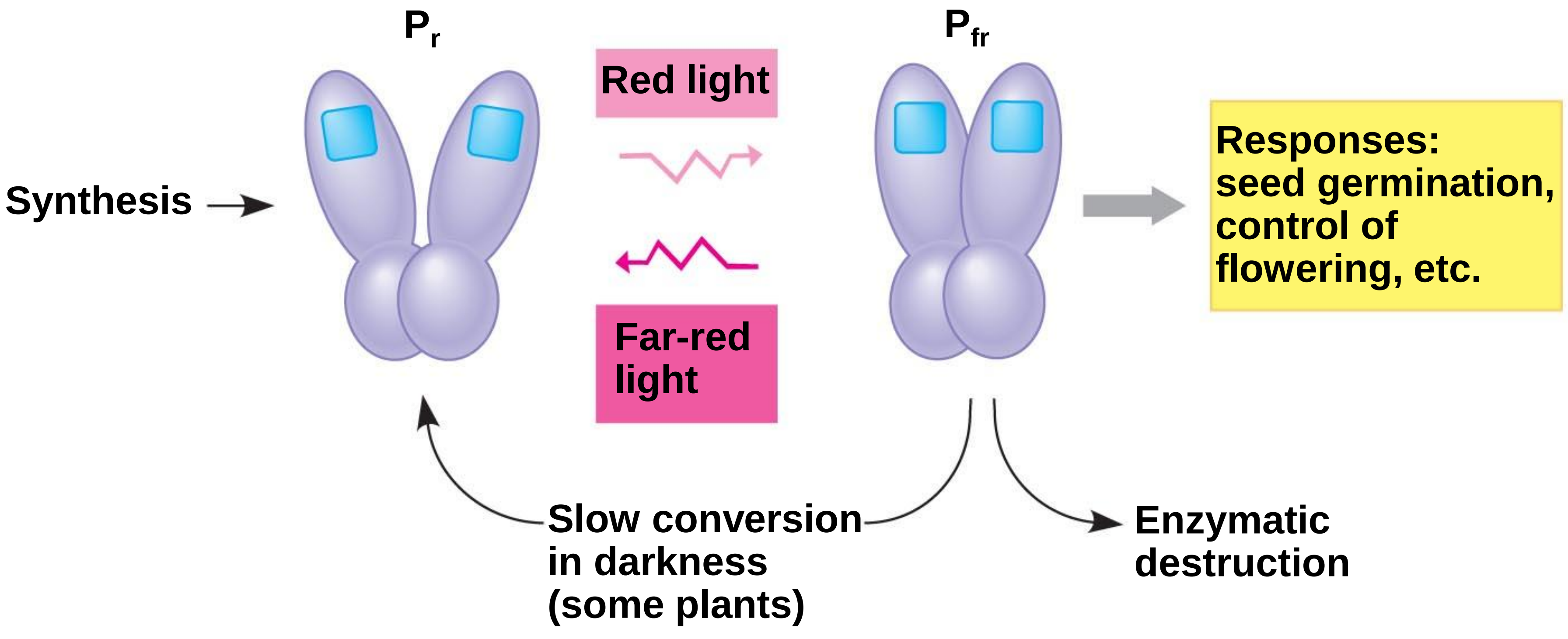
(b) Coleoptile response to light colors

RESULTS


Dark (control)
Red
Dark
Red
Far-red
Dark
Red
Far-red
Red
Dark
Red
Far-red
Red
Far-red

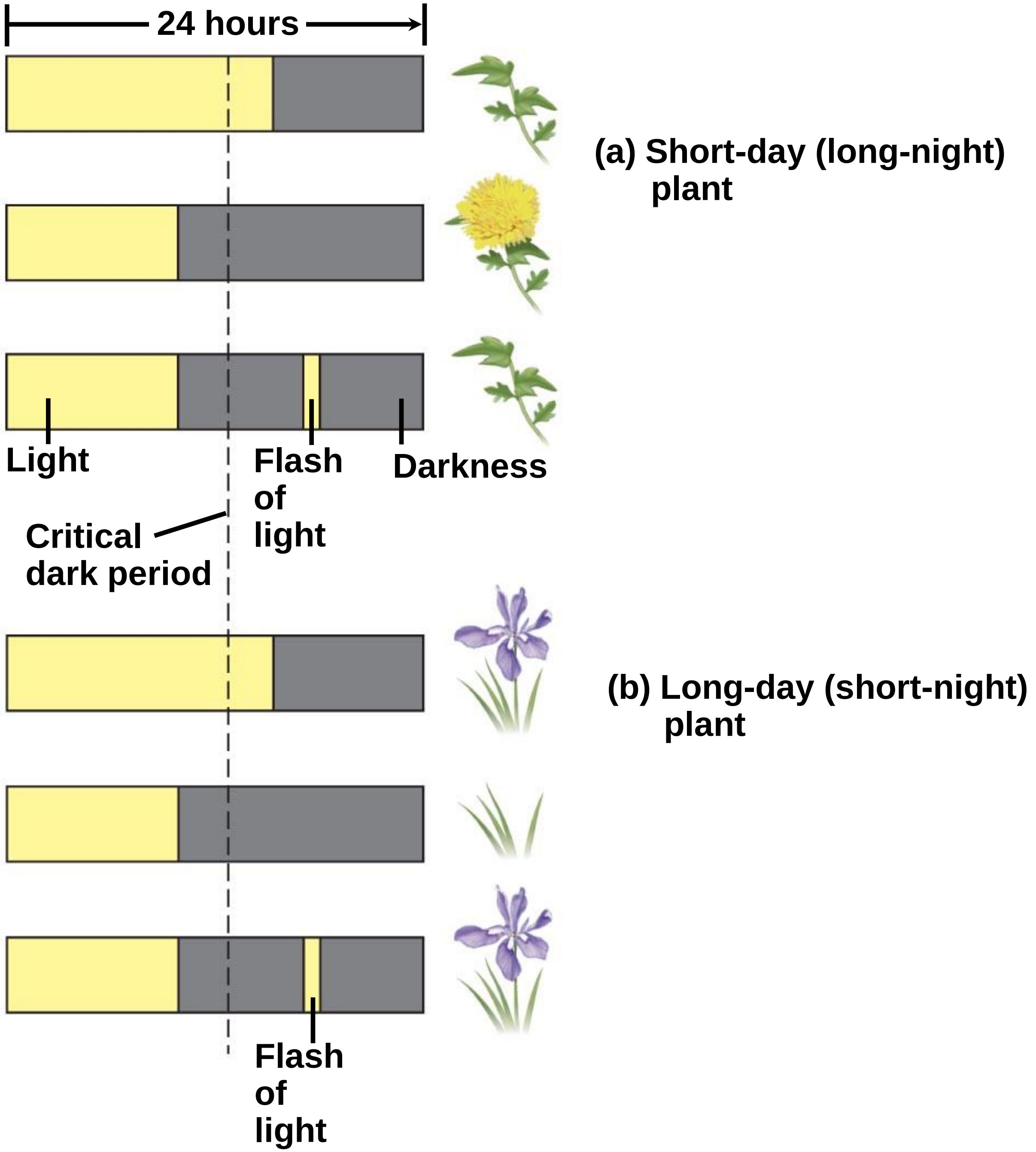

Two identical subunits
Chromophore
Photoreceptor activity
Kinase activity

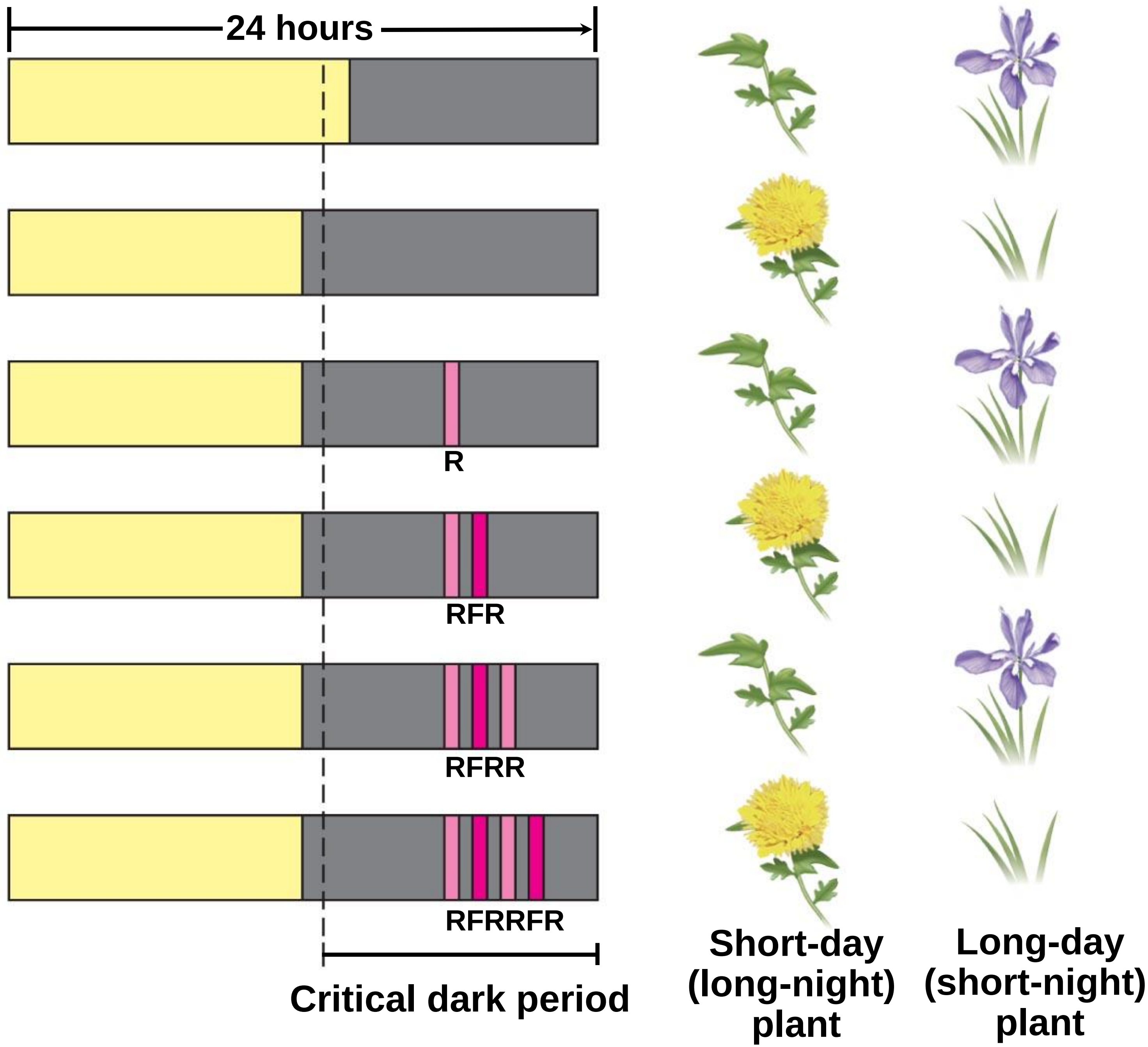

Red light
P_r
P_{fr}
Far-red light

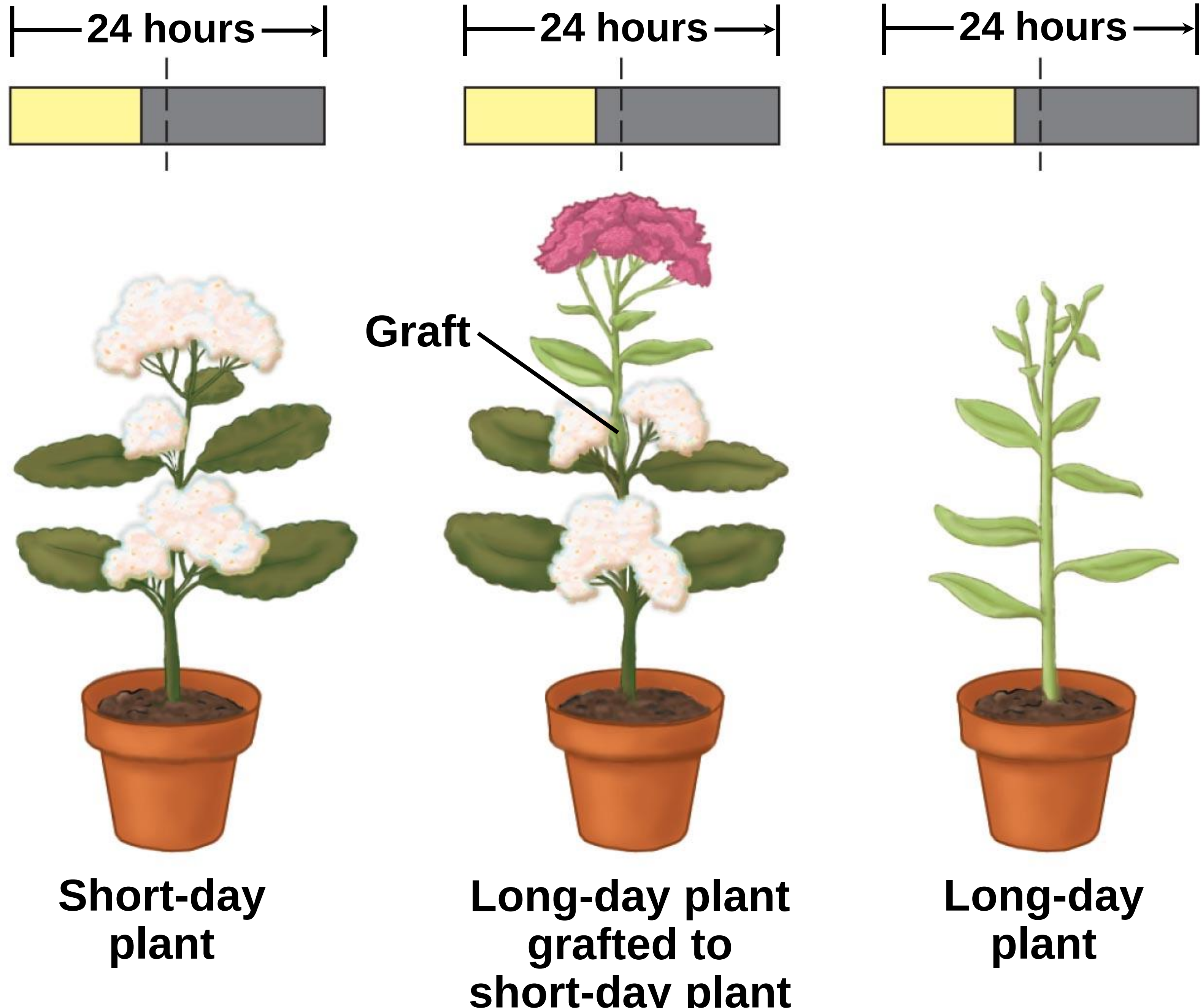

P$_r$
P$_{fr}$
Red light
Far-red light
Synthesis
Responses: seed germination, control of flowering, etc.
Slow conversion in darkness (some plants)
Enzymatic destruction

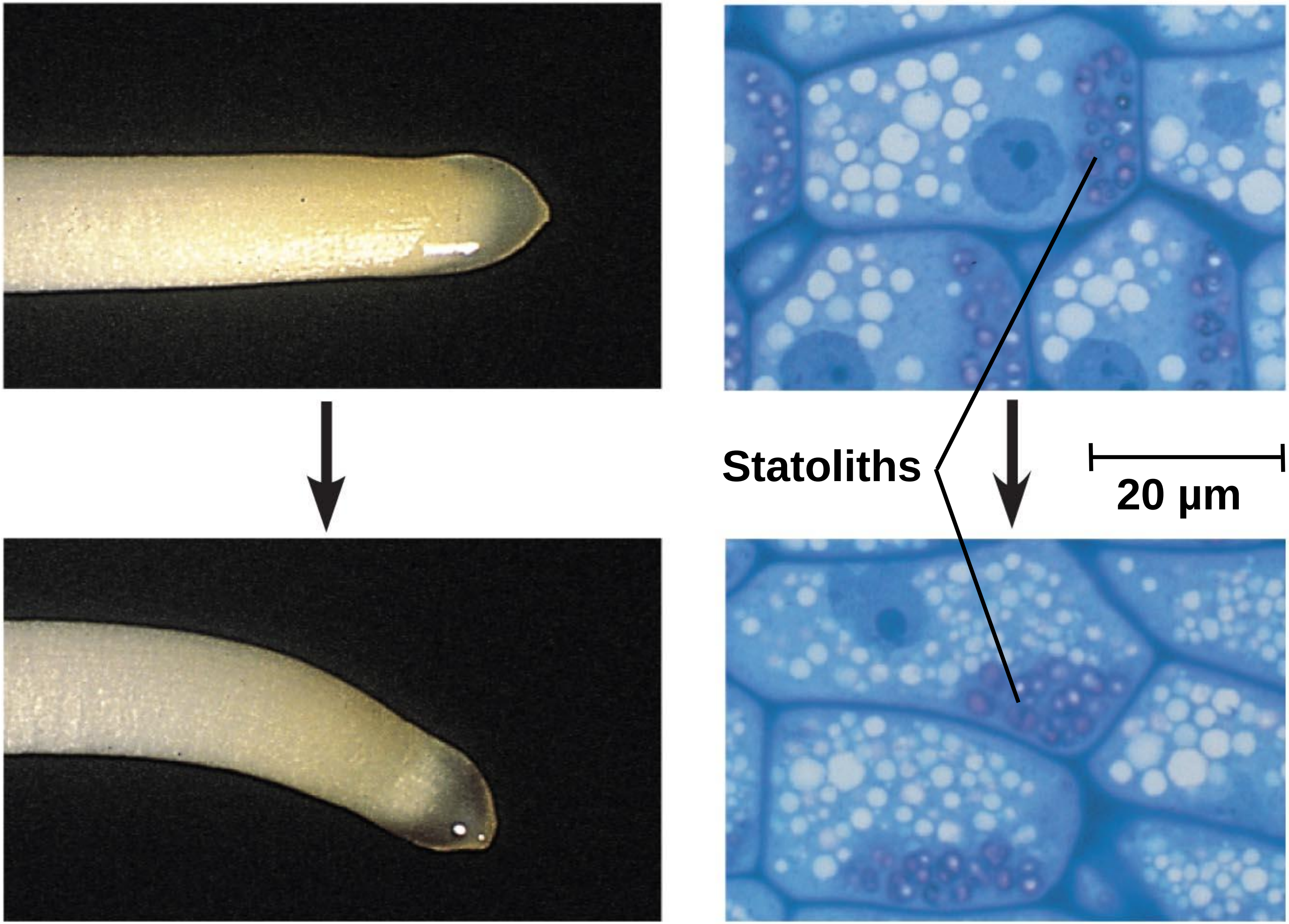
Noon

Midnight


24 hours
Light
Flash of light
Darkness
Critical dark period
(a) Short-day (long-night) plant
(b) Long-day (short-night) plant
Flash of light


24 hours
R
RFR
RFRR
RFRRFR
Critical dark period
Short-day (long-night) plant
Long-day (short-night) plant


24 hours
24 hours
24 hours
Graft
Short-day plant
Long-day plant grafted to short-day plant
Long-day plant

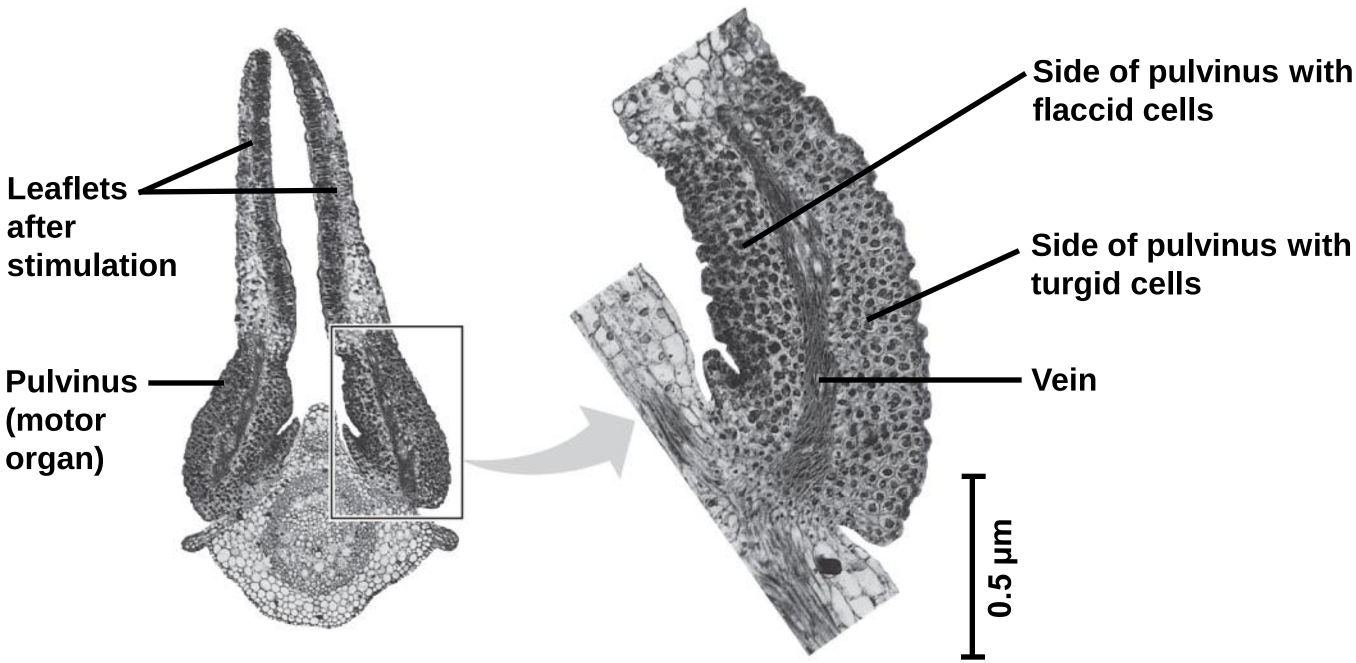


(a) Root gravitropic bending

(b) Statoliths settling

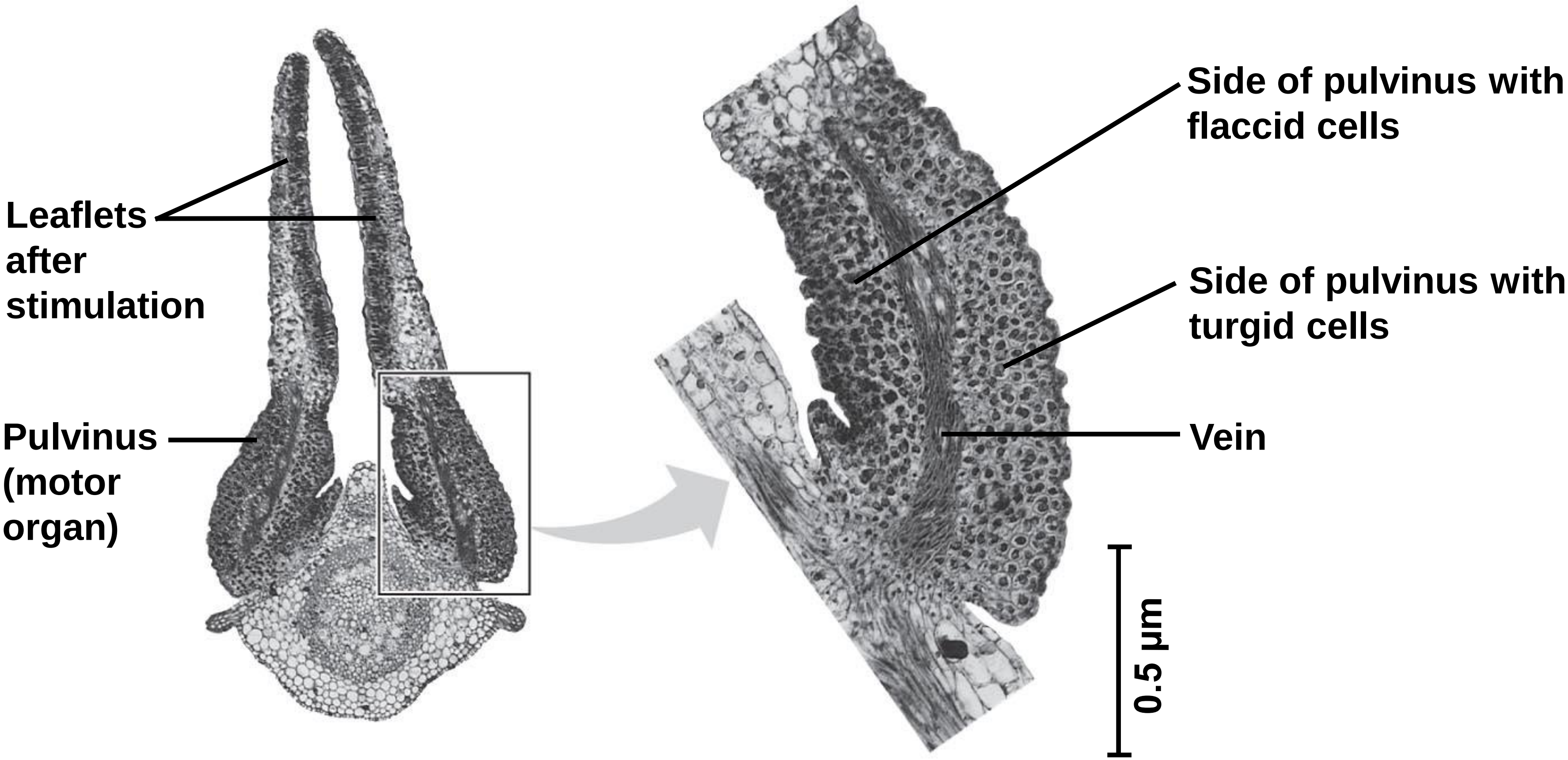
(a) Unstimulated state

(b) Stimulated state

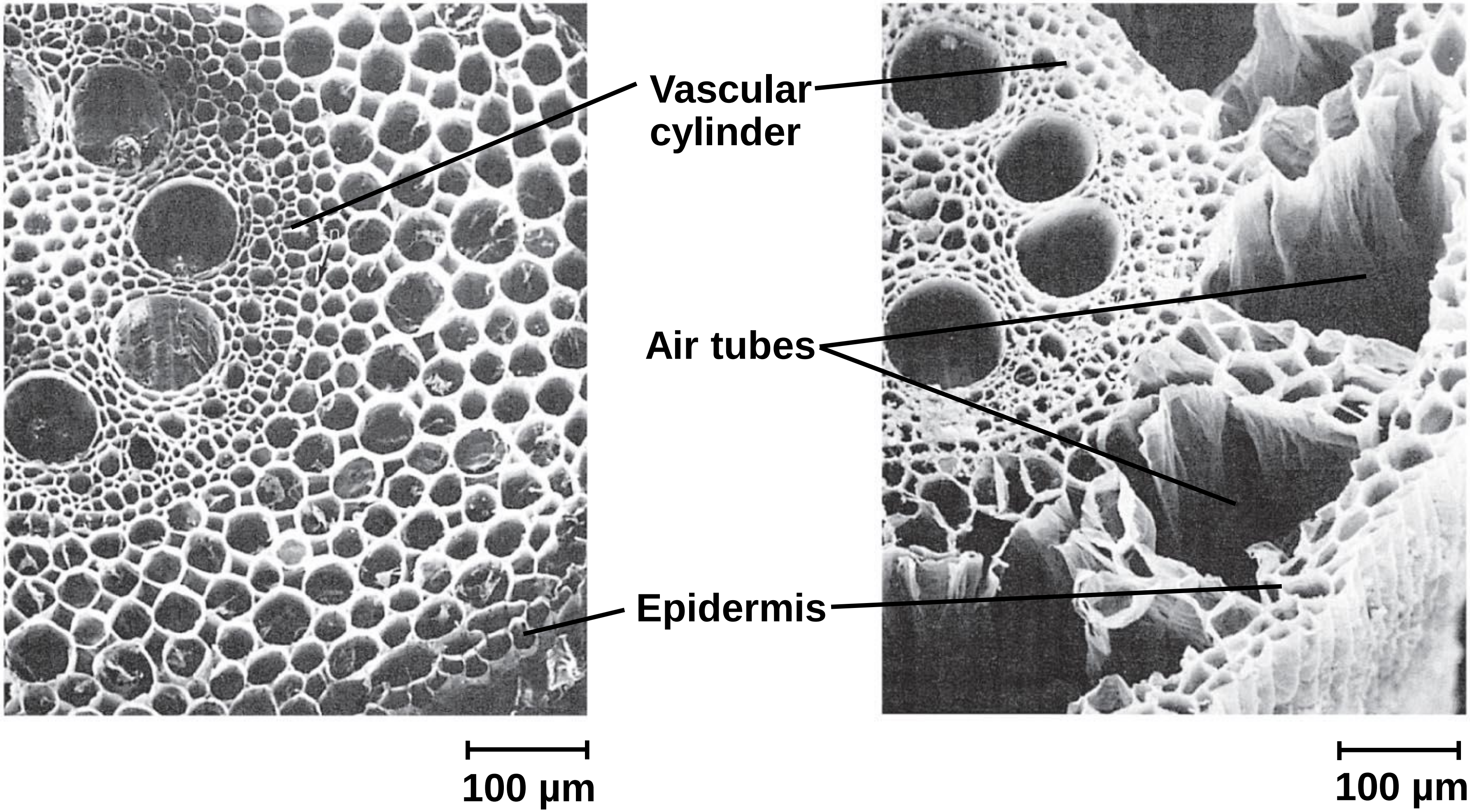


(c) Cross section of a leaflet pair in the stimulated state (LM)

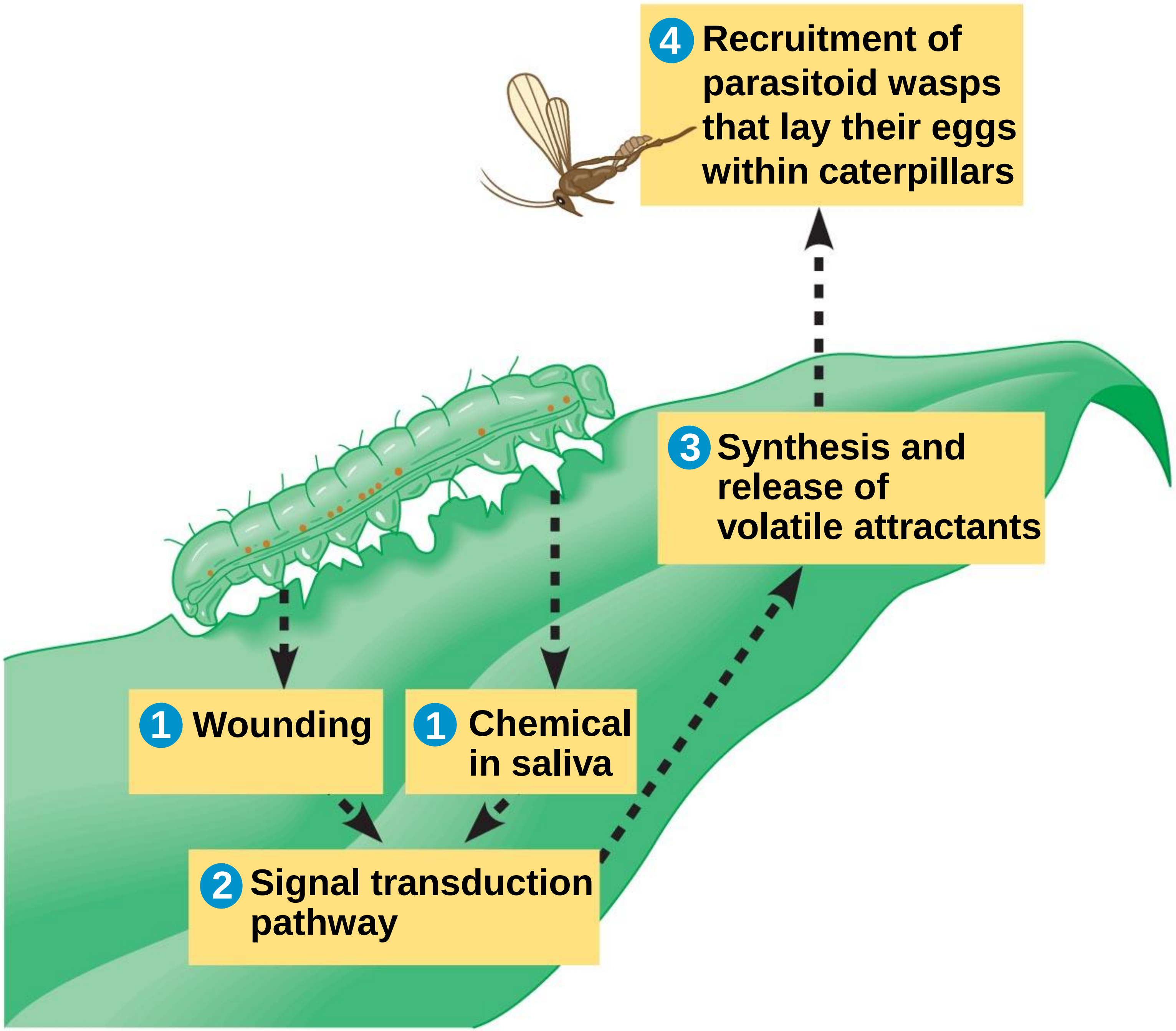
(a) Unstimulated state **(b) Stimulated state**

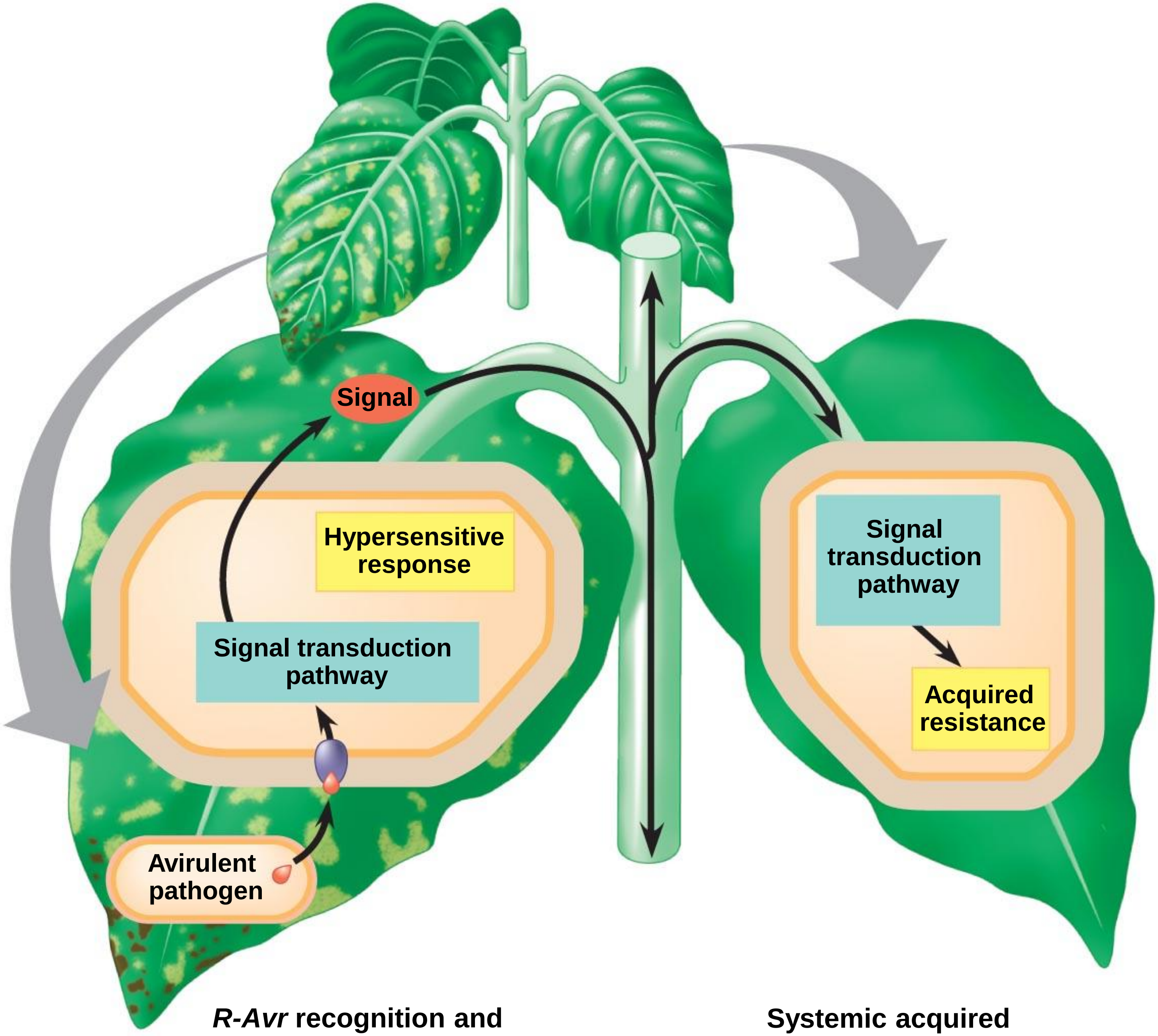


(c) Cross section of a leaflet pair in the stimulated state (LM)



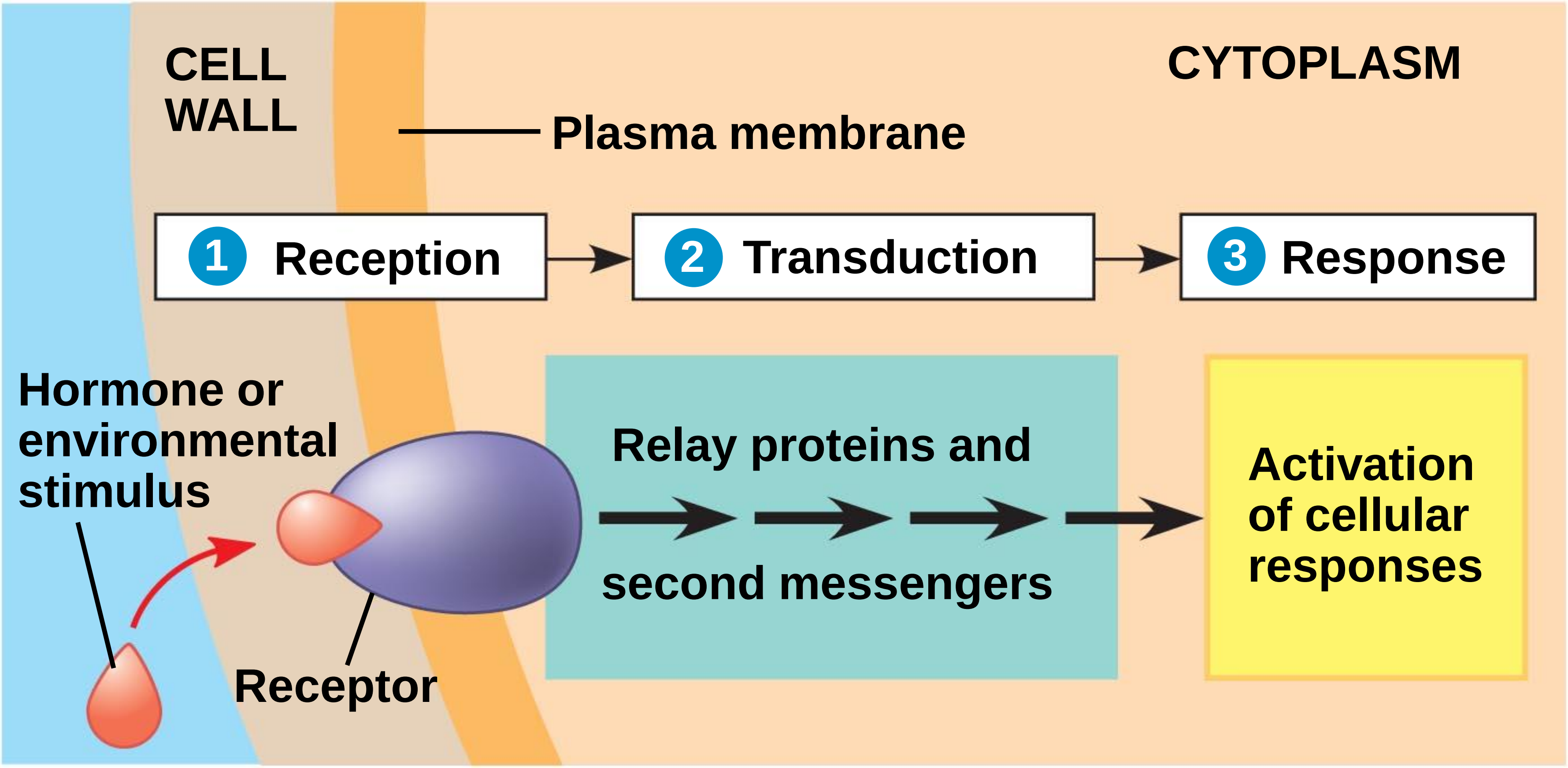
(a) Control root (aerated) (b) Experimental root (nonaerated

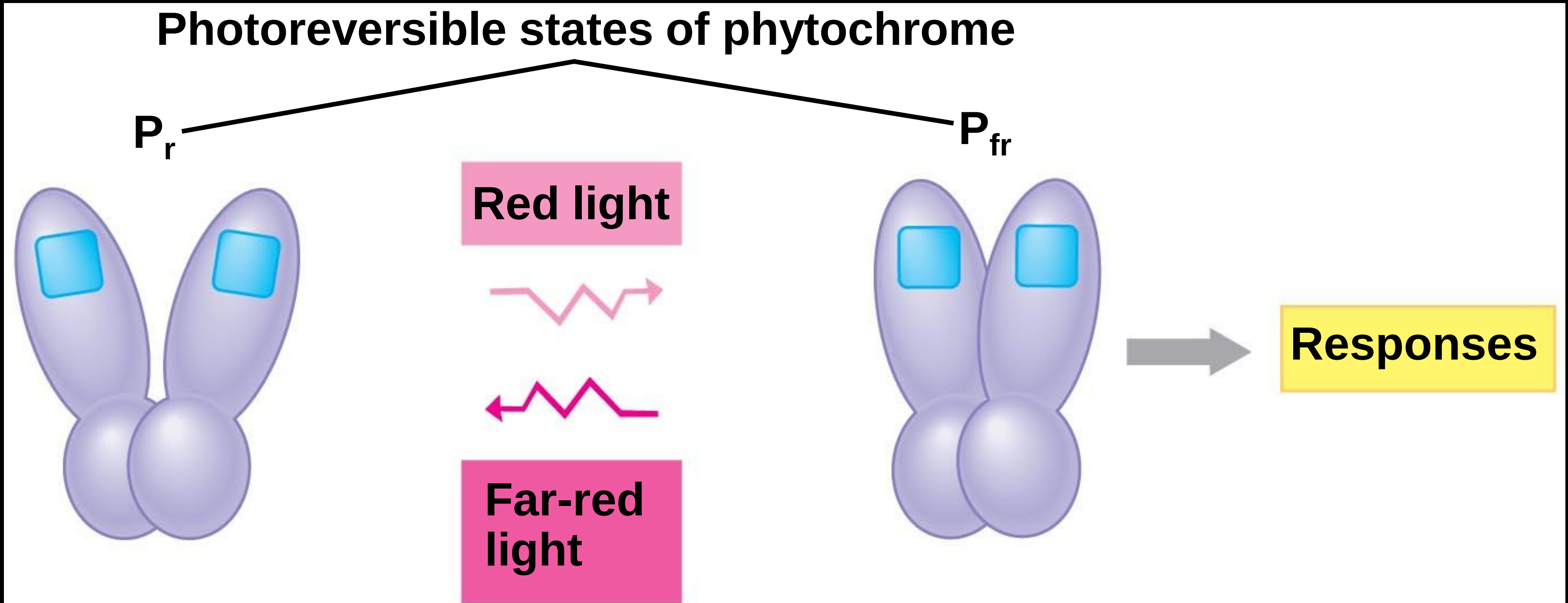

4 Recruitment of parasitoid wasps that lay their eggs within caterpillars
3 Synthesis and release of volatile attractants
1 Wounding
1 Chemical in saliva
2 Signal transduction pathway



R-Avr recognition and hypersensitive response

Systemic acquired resistance


CELL
WALL
CYTOPLASM
Plasma membrane
1 Reception
2 Transduction
3 Response
Hormone or
environmental
stimulus
Relay proteins and
second messengers
Activation
of cellular
responses
Receptor


Photoreversible states of phytochrome
P_r
P_{fr}
Red light
Far-red light
Responses