

We will examine each hormones within the context of one of its roles.

Remember that these are merely examples; most hormones affect most processes in one way or another.

Introduction to Phytohormones

Cell signalling in plants!



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What are phytohormones?



Frits Went, 1903-1990

".....characterized by the property of serving as chemical messengers, by which the activity of certain organs is coordinated with that of others".
-*Frits Went and Kenneth Thimann, 1937*



Kenneth Thimann, 1904-1997



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Phytohormones

- Phytohormones regulate cellular activities (division, elongation and differentiation), pattern formation, organogenesis, reproduction, sex determination, and responses to abiotic and biotic stress.



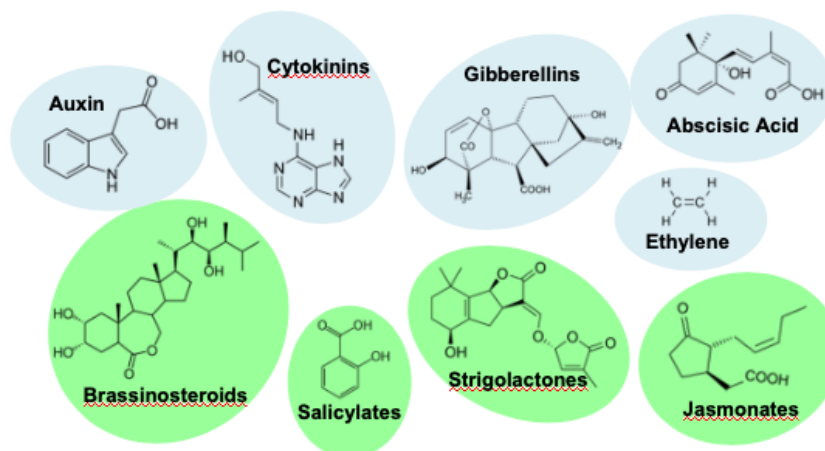
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Phytohormones – some are well studied and other recent discoveries



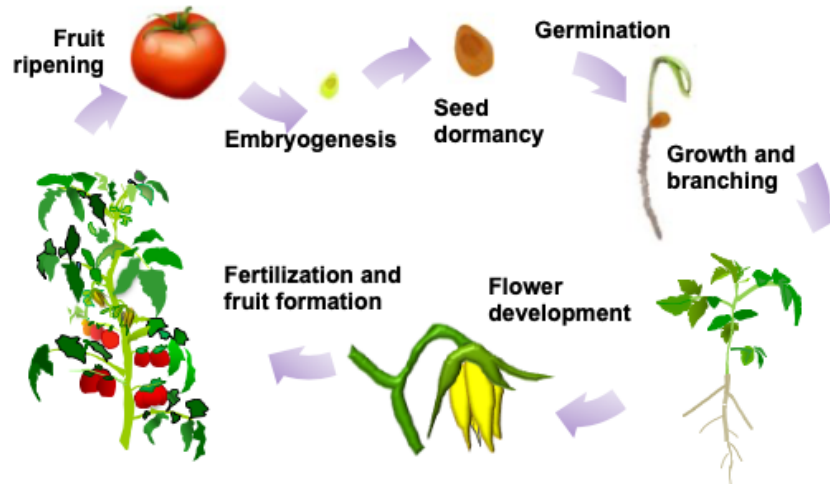
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Phytohormones regulate all stages of the plant life cycle



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Most hormones affect most stages of the plant life cycle



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Hormones play a wide variety of roles throughout the plant life cycle

How hormones work

Hormonal control of vegetative development

- Auxin
- Cytokinins
- Strigolactones (not covered)
- Gibberellins
- Brassinosteroids

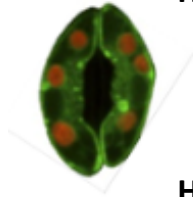
Hormonal control of reproduction

- Ethylene
- Abscissic Acid

Hormonal responses to stress

- Salicylates
- Jasmonates

Cross-regulation of hormonal effects



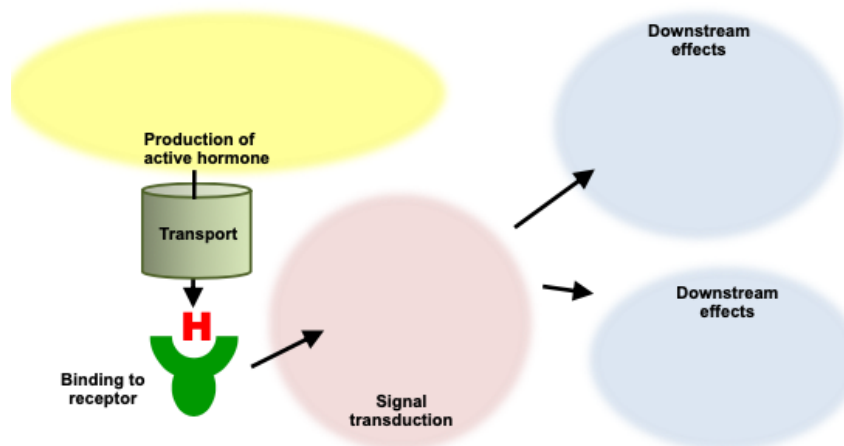
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Hormones: Synthesis, transport, perception, signaling and responses



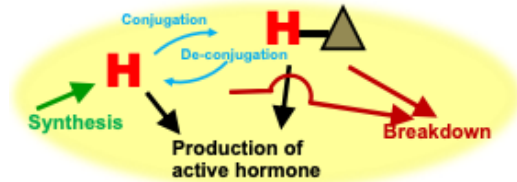
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Synthesis



- Many tightly regulated biochemical pathways contribute to active hormone accumulation. Conjugation can temporarily store a hormone in an inert form, lead to catabolic breakdown, or be the means for producing the active hormone.



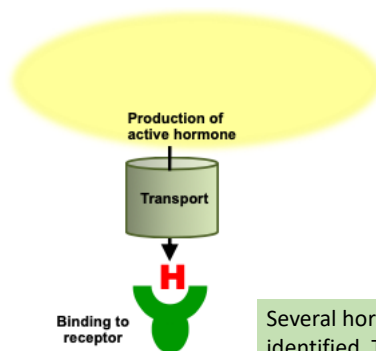
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Transport and perception



Hormones can move:
through the xylem or phloem
across cellular membranes
through regulated transport proteins

Several hormone receptors have recently been identified. They can be membrane bound or soluble



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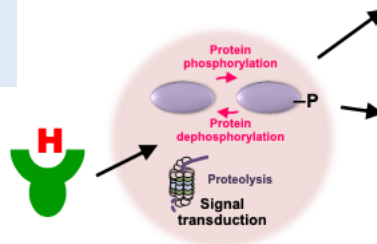
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Signal transduction

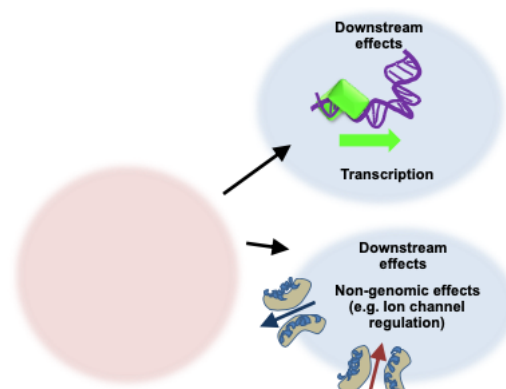
Hormonal signals are transduced in diverse ways. Common methods are reversible protein phosphorylation and targeted proteolysis



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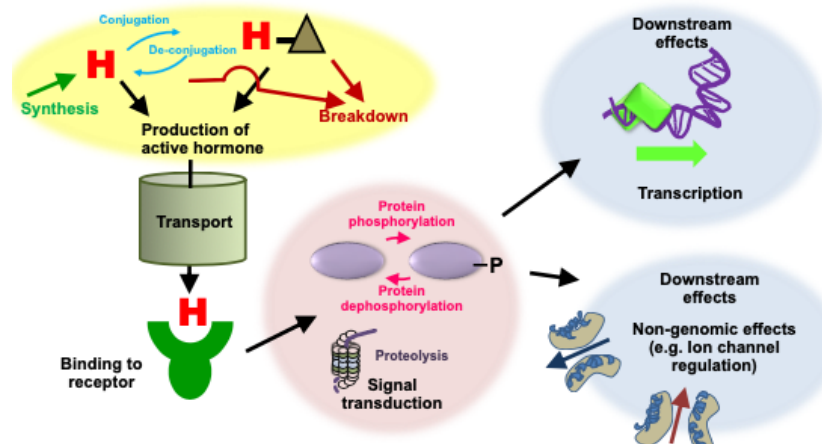
Responses

Downstream effects can involve changes in gene transcription and changes in other cellular activities like ion transport



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Hormones: Synthesis, transport, perception, signaling and responses



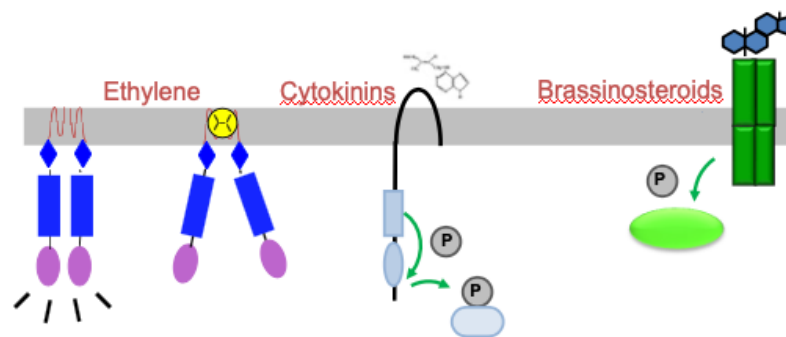
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Receptors can be membrane-bound



Hormone binding initiates an information relay



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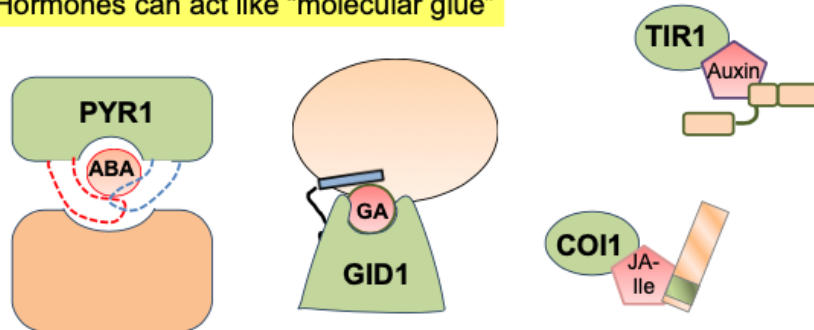
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Soluble receptors can facilitate interactions between proteins

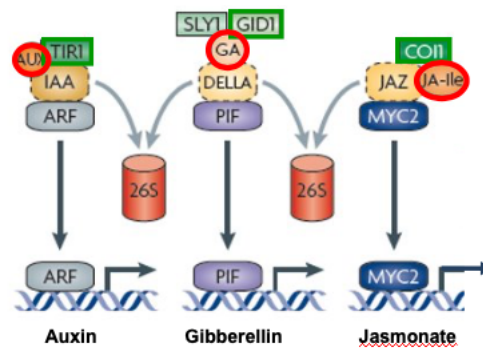
Hormones can act like “molecular glue”



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Some receptors initiate protein proteolysis

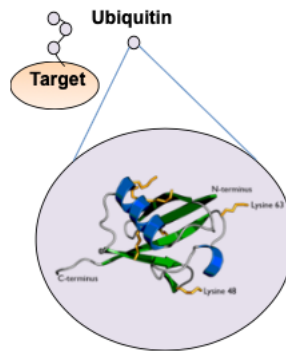
- The hormones (red) bind to receptors (green), initiating proteolysis of repressors (yellow) to activate a transcriptional regulator (blue)



Reprinted by permission from Macmillan Publishers Ltd: NATURE Reviews, 11, and Higgins, G. (2009). Survival of the flexible: Hormonal growth control and adaptation to plant development. Nat. Rev. Genet. 10: 309–317. Copyright 2009.

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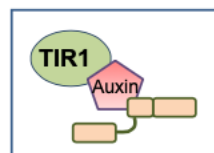
Proteolytic targets are covalently linked to ubiquitin



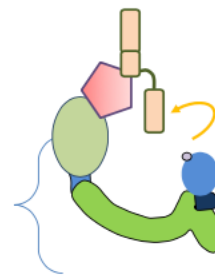
Ubiquitin is a small (76 aa) protein that targets proteins for proteolytic cleavage.

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Ubiquitin ligase complexes ubiquitinate target proteins



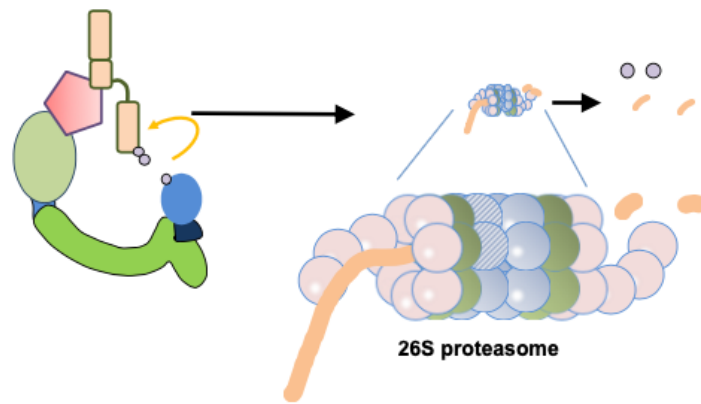
- The auxin and jasmonate receptors are F-box proteins, part of an SCF ubiquitin ligase complex



Ubiquitin is ligated to the target

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Ubiquitinated proteins are targeted for proteolysis



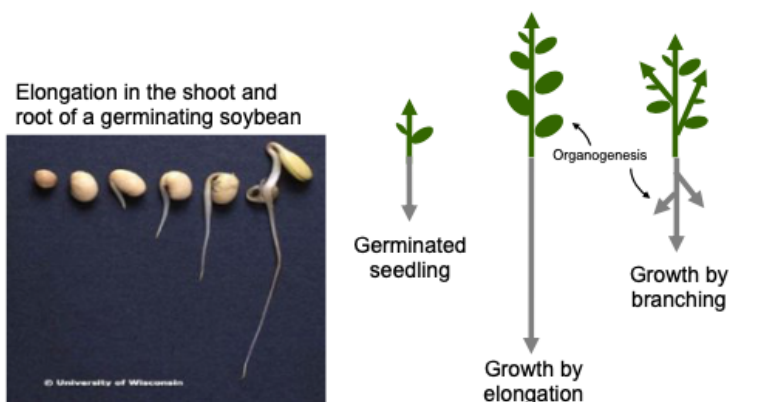
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Hormones affect vegetative growth: elongation, branching and organogenesis



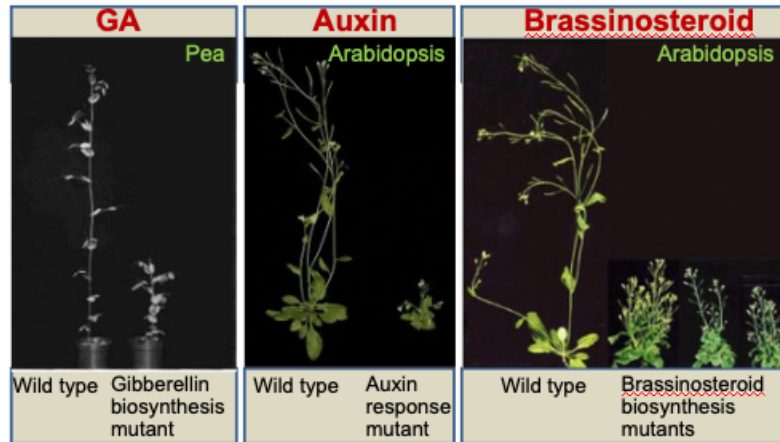
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Disrupting hormone synthesis or response interferes with elongation



Lester, D.R., Ross, J.J., Davies, P.J., and Reid, J.B. (1997) Mendel's stem length gene (*Le*) encodes a gibberellin 3-oxidohydrolase. *Plant Cell* 9: 1435-1443. Gray WM (2004) Hormonal regulation of plant growth and development. *PLoS Biol* 2(9): e131. Cline SD (2002) *Brassinosteroids*. The Arabidopsis Book. Rockville, MD: American Society of Plant Biologists.



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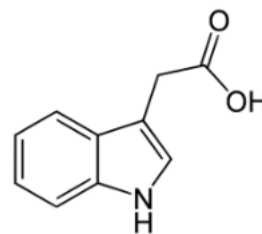
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Auxin

- Growth
- Phototropism and gravitropism
- Branching
- Embryonic patterning
- Stem cell maintenance
- Organ initiation



Indole-3-acetic acid (IAA), the most abundant natural auxin



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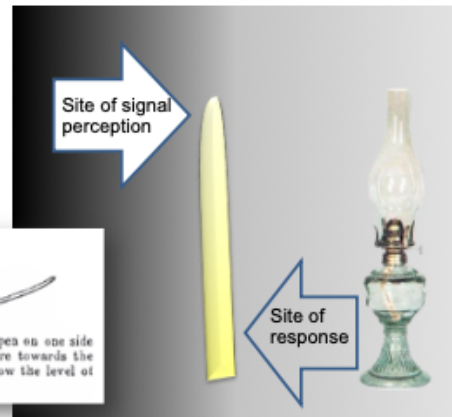
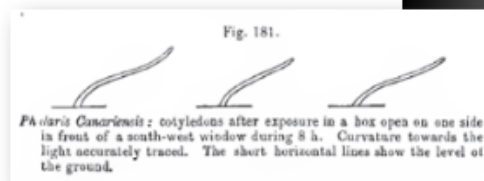
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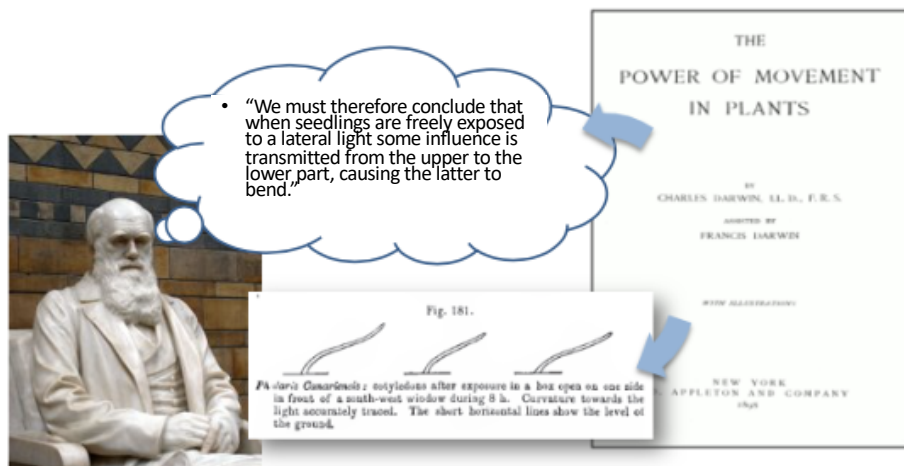
Auxin controls growth

Charles Darwin studied the way seedlings bend towards light, a direct effect of auxin action



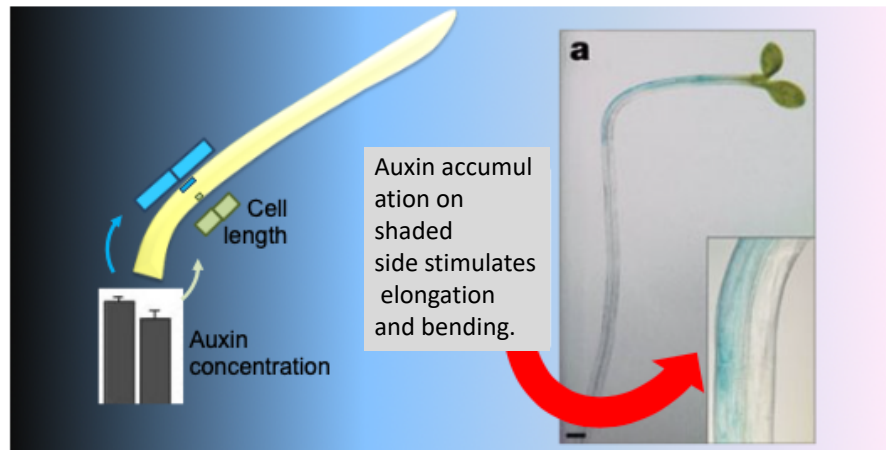
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Darwin concluded that a signal moves through the plant controlling growth



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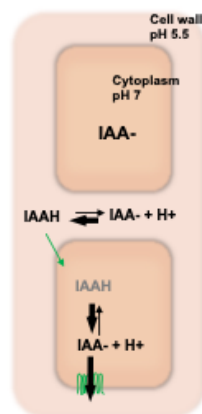
Differential cell growth is a result of auxin movement to the shaded side



Etten, C.A. et al. (2006) A mutant of auxin and auxin-dependent transcription reveals tonic growth responses. *Proc. Natl. Acad. Sci. USA* 103: 236-241.

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Auxin moves in part by a chemiosmotic mechanism

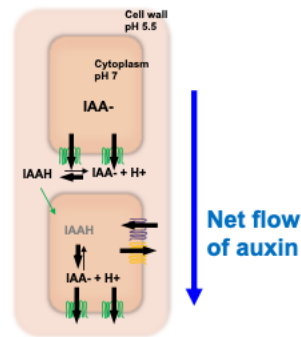


Auxin is a charged anion (IAA^-) in the cytoplasm (pH 7).

In the more acidic cell wall (pH 5.5) some is uncharged (IAAH). The uncharged form crosses the plasma membrane into the cell where it is deprotonated and unable to exit other than through specific transporters.

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Polar auxin transport



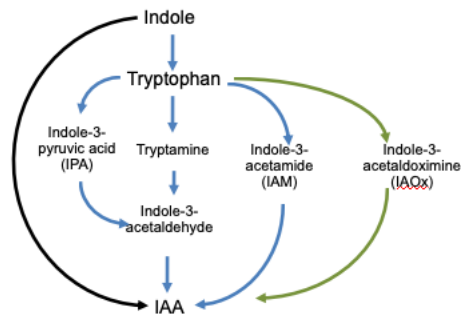
Auxin transport out of cells is controlled by three families of transport proteins that collectively control the directionality of auxin movement. Asymmetric distribution of the transporters controls polar auxin transport.

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Auxin biosynthesis

IAA is produced from tryptophan (Trp) via several semi-independent pathways and one Trp-independent pathway.

Environmental and developmental control of the genes controlling auxin biosynthesis, conjugation and degradation maintain auxin homeostasis.



Adapted from [Glick et al., 2000](#), L.J. Davis, N.W. Smith, J.A. Makenzie, P.P. Zeng, N.D. and Ben, J.J. (2000) Auxin biosynthesis in pea: Characterization of the tryptamine pathway. *Plant Physiol.* 131: 1138-1151.

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Auxin regulates plant development

Lateral organ initiation at the shoot apical meristem

Inhibit branching in the shoot

Patterning and vascular development

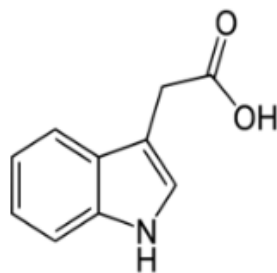
Promote branching in the root

Maintain stem cell fate at the root apical meristem



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Many of auxin's effects are mediated by changes in gene expression



Genes controlling cell growth

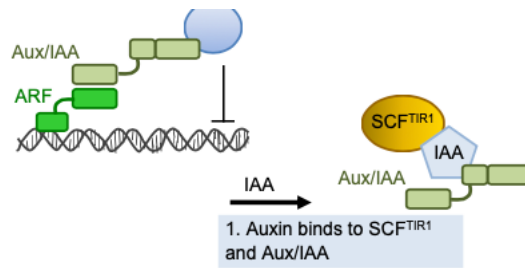
Genes involved in signaling

Genes coordinating other hormone response pathways



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The auxin signaling pathway



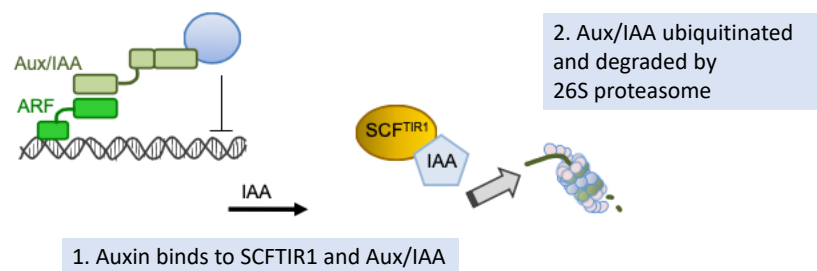
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The auxin signaling pathway



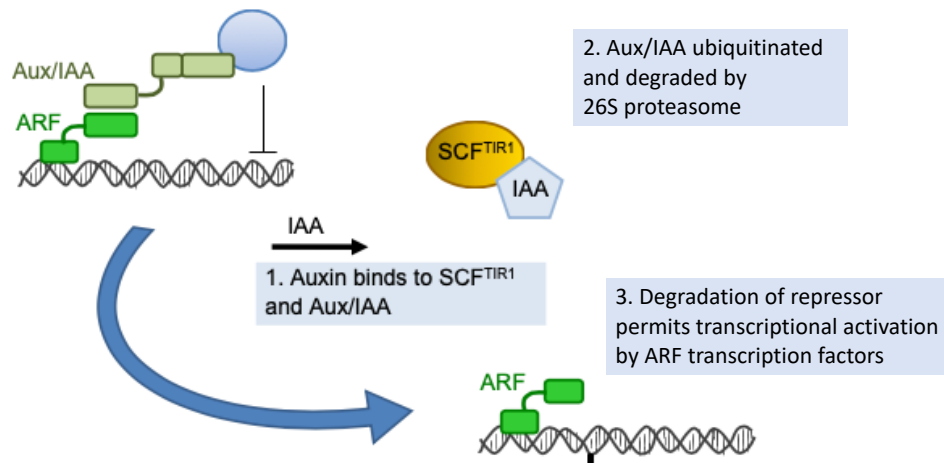
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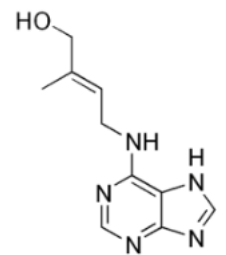
The auxin signaling pathway



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Cytokinins

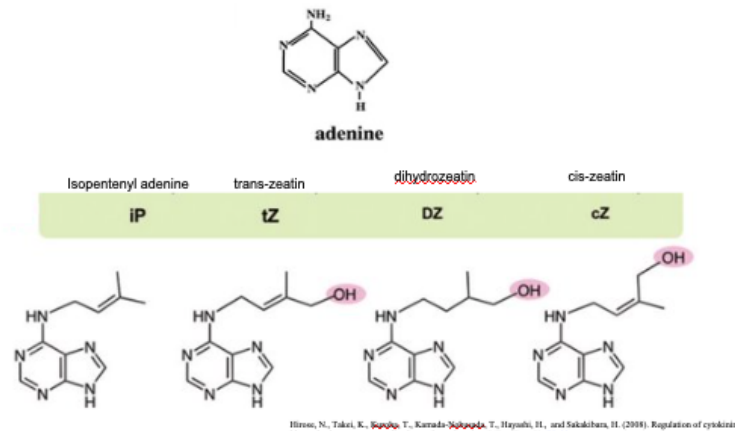
- Cell division
- Control of leaf senescence
- Control of nutrient allocation
- Root nodule development
- Stem cell maintenance
- Regulate auxin action



trans-zeatin, a cytokinin

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Cytokinins are a family of related adenine-like compounds



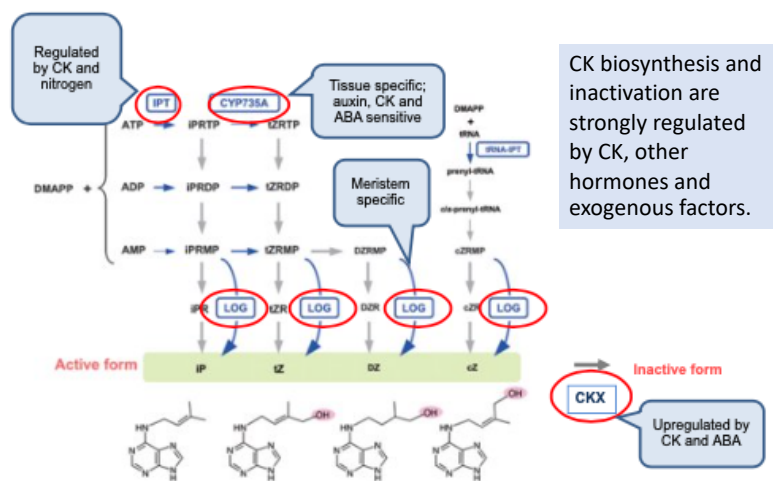
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Cytokinin (CK) biosynthesis



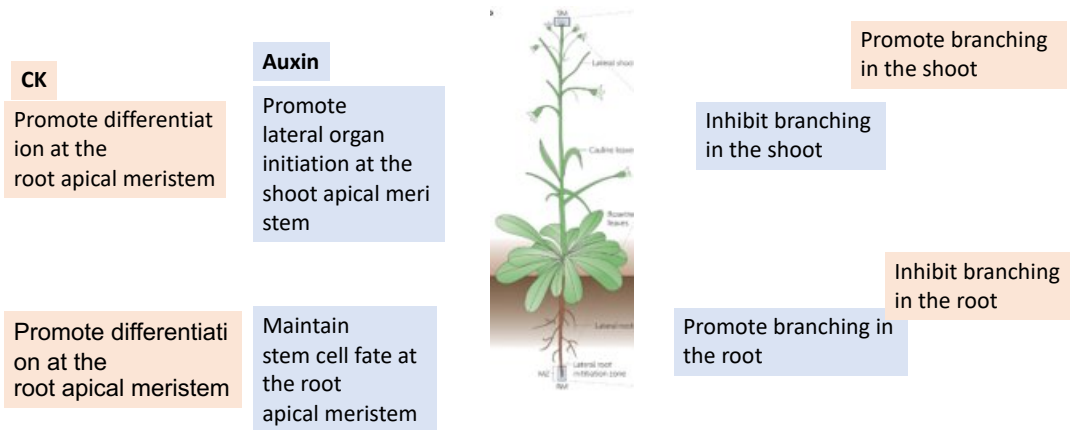
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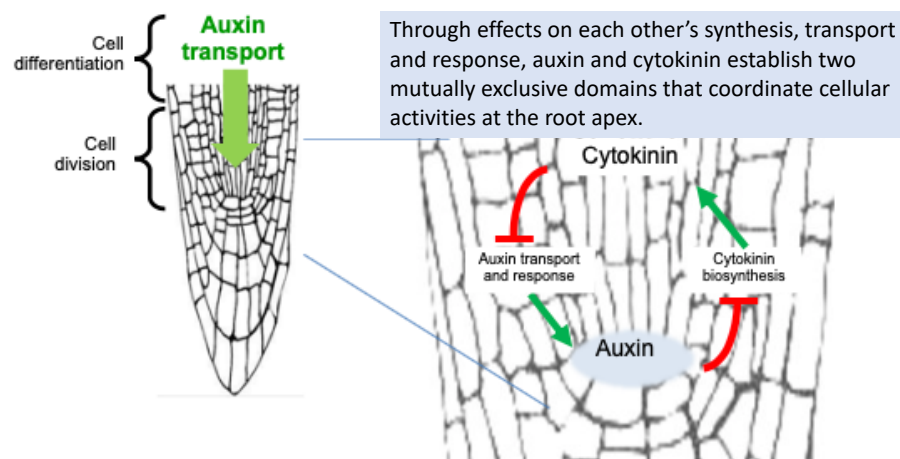
36

Cytokinins act antagonistically to auxins



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Auxin and cytokinin regulate each other's function at the root apex



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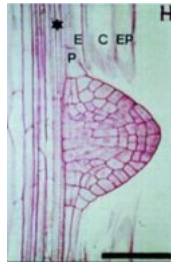
Auxin, cytokinin and strigolactones control branching



Shoot branches are promoted by CK and inhibited by auxin and strigolactones



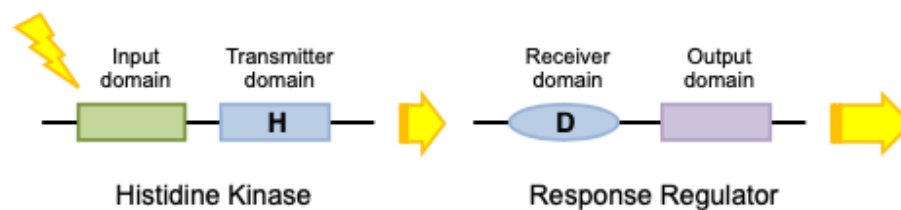
Root branches, called lateral roots, are promoted by auxin and inhibited by CK



Branching controls every aspect of plant productivity from nutrient uptake to crop yields.

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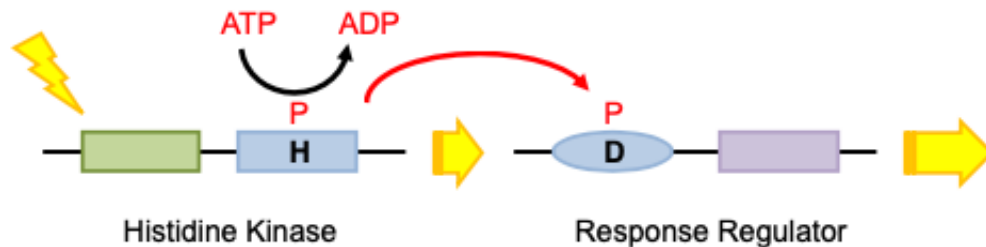
Cytokinin signalling is mediated by a two-component system



A two-component system is a short signaling pathway that moves information from an input to an output. In bacteria it usually consists of two proteins, a histidine kinase (HK) with a conserved histidine residue (H) and a response regulator (RR) with a conserved aspartate residue (D).

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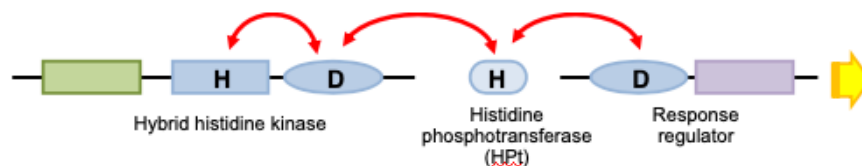
Information and phosphoryl groups are relayed between the components



Stimulation of the input domain activates the kinase activity, phosphorylating the transmitter domain. The phosphoryl group is subsequently relayed to the response regulator.

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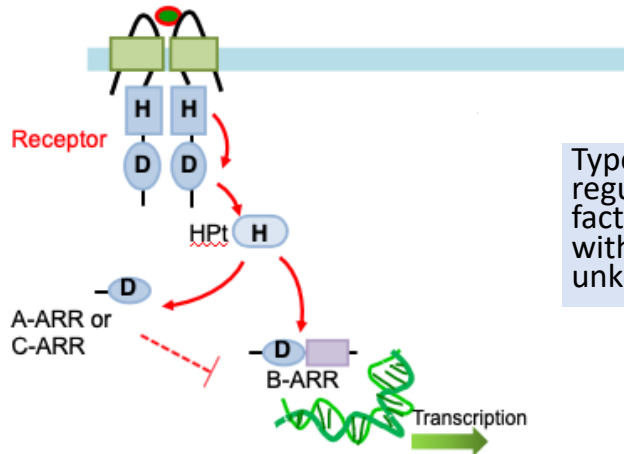
Two component signaling in plants



Most plant HKs are hybrid histidine kinase, which transfer the phosphoryl group to a histidine phosphotransferase. The HPT transfers it to a response regulator.

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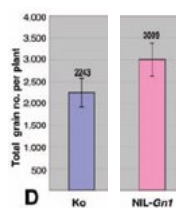
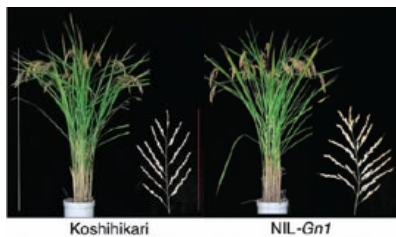
Cytokinin control of gene expression in *Arabidopsis*



Type B *Arabidopsis* response regulators (ARRs) are transcription factors. Type A or C ARR interfere with CK signaling through as yet unknown means.

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Cytokinins affect grain production and drought tolerance



Rice plants that accumulate more CK can produce more grain per plant because of changes in inflorescence architecture.

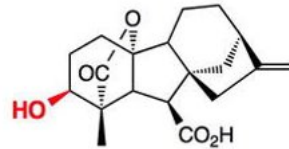
Tobacco plants that produce more CK are more drought tolerant because of the delay in leaf senescence conferred by CK.



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Gibberellins

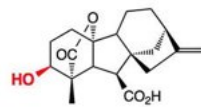
- Growth
- Seed germination
- Promote flowering
- Promote sex determination in some species
- Promote fruit growth



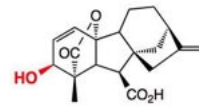
A Gibberellin (GA4)

45

GA4 is the major active GA in Arabidopsis

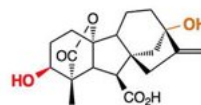


GA₄

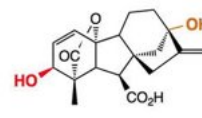


GA₇

Only some GAs are biologically active. The major bioactive gibberellins are shown here.



GA₁



GA₃

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Genes controlling GA synthesis are important “green revolution” genes



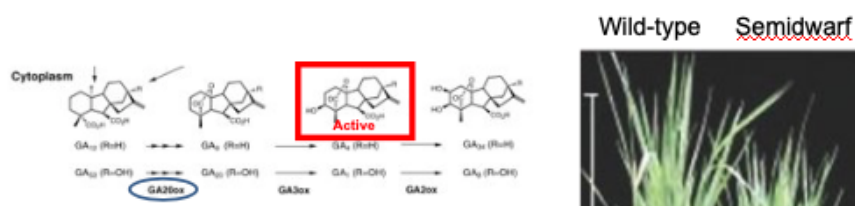
Distinguished plant breeder and Nobel Laureate
[Norman Borlaug 1914-2009](#)

Tremendous increases in crop yields (the Green Revolution) during the 20th century occurred because of increased use of fertilizer and the introduction of semidwarf varieties of grains.

The semidwarf varieties put more energy into seed production than stem growth, and are sturdier and less likely to fall over.

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Several of the green revolution genes affect GA biosynthesis



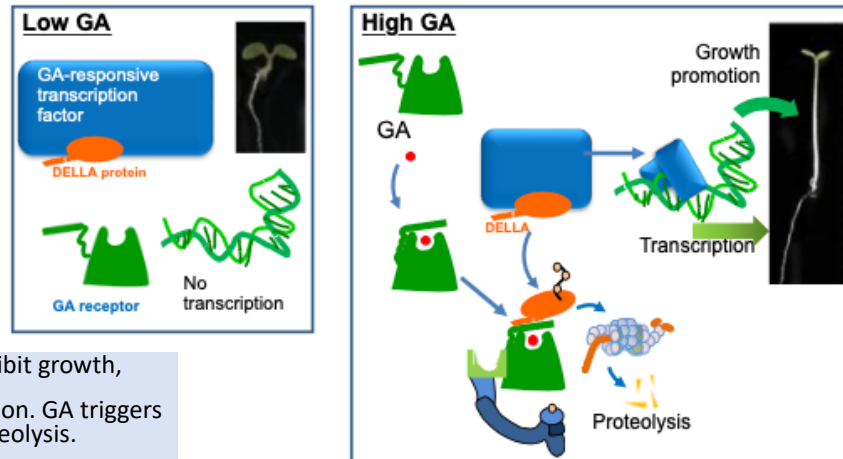
- Semidwarf rice varieties underproduce GA because of a mutation in the GA20 oxidase biosynthetic gene.



Reprinted by permission from Macmillan Publishers, Ltd. (Nature) Sakai, A., et al. (2002) Green revolution: A mutant gibberellin-synthesis gene in rice Nature 416: 701-702, copyright 2002; Oleznicki, N., Sun, X., and Gruber, P. (2002) Gibberellin biosynthesis, catabolism, and response pathways Plant Cell 14: 561-580.

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GA signalling pathway

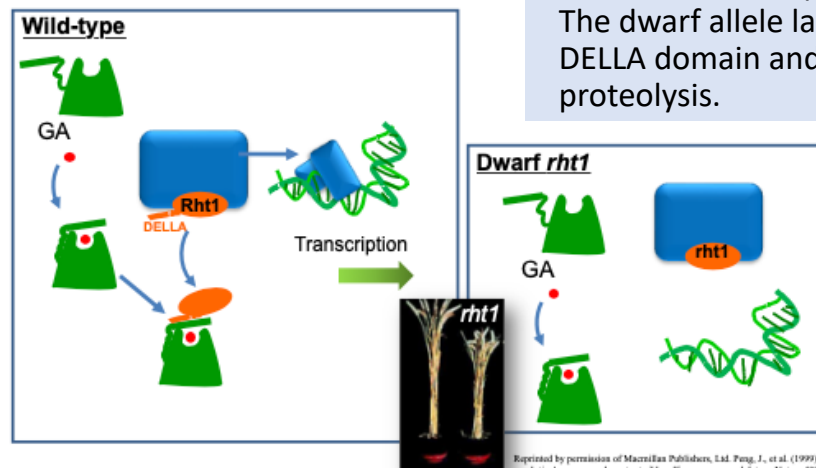


- DELLA proteins inhibit growth, in part through blocking transcription. GA triggers DELLA protein proteolysis.

Reprinted from Dupéix, J.-M., de Lacin, M., and Prat, S. (2008) Transcription factor interaction: a central step in DELLA function. *Curr. Opin. Genet. Dev.* 18.

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A gene affecting DELLA protein stability is a “green revolution” gene



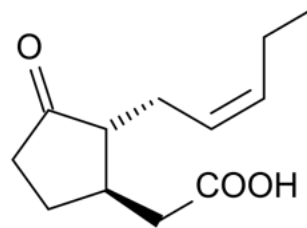
- The wheat *Rht1* locus encodes a DELLA protein. The dwarf allele lacks the DELLA domain and resists proteolysis.

Reprinted by permission of Macmillan Publishers, Ltd. Peng, J., et al. (1999) Green revolution genes encode mutant gibberellin response modulators. *Nature* 400: 256-258.

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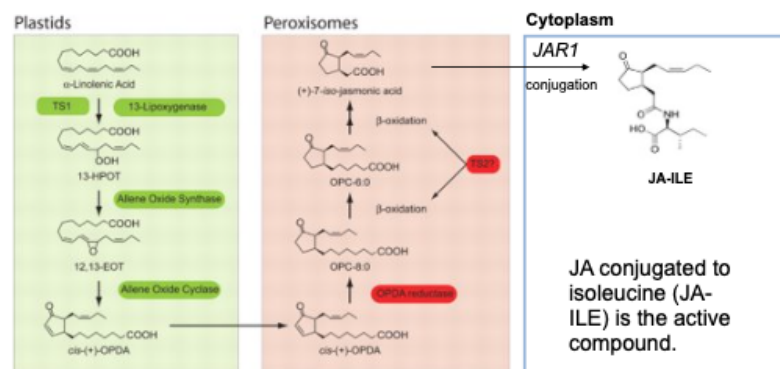
Jasmonates

- Response to necrotrophic pathogens
- Induction of anti-herbivory responses
- Production of herbivore-induced volatiles to prime other tissues and attract predatory insects



53

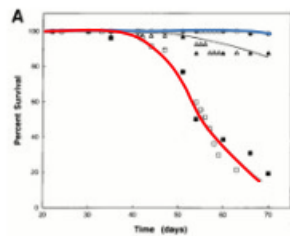
JA biosynthesis



From Acosta, I., et al. (2009) *auxinoid* is a lipoxygenase affecting jasmonic acid signaling in sex determination of

54

Jasmonate signaling contributes to defense against herbivory



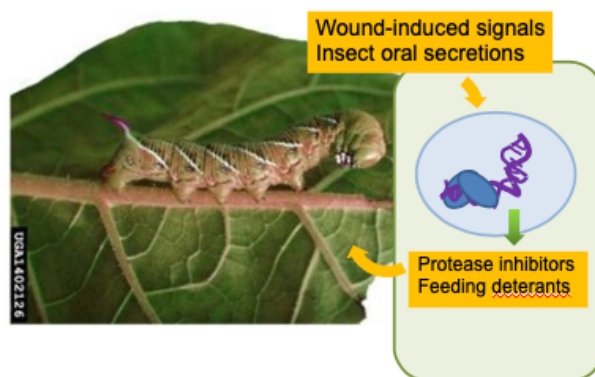
When exposed to hungry fly larvae, plants unable to produce JA have low rates of survival.



McPhee M. et al. (2007) Jasmonate is essential for insect defense in Arabidopsis. *Proc. Natl. Acad. Sci. USA* 104: 6271-6277

55

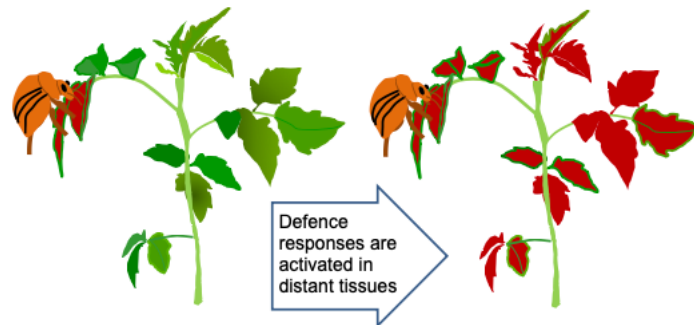
Jasmonates induce the expression of anti-herbivory chemicals



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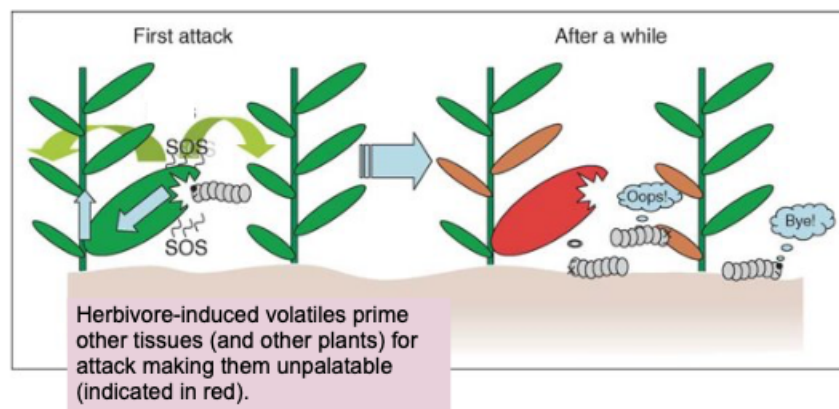
56

Jasmonates contribute to systemic defense responses



57

Jasmonates stimulate production of volatile signaling compounds

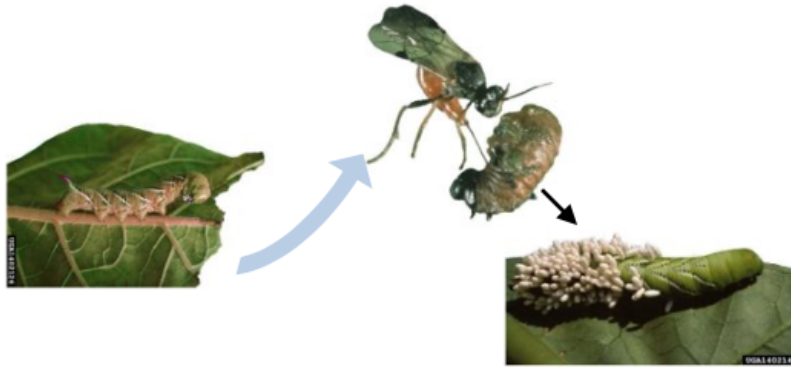


Reprinted from Matsui, K. (2006) Green leaf volatiles: hydroperoxide lyase pathway of

58

Herbivore-induced volatiles are recognized by carnivorous and parasitoid insects

parasitoid insects



The Host Tobacco/Wild Cotton/Brassica and 1 Tobacco/Tobacco/Brassica/Glycine and 2 Tobacco/Tobacco/Brassica/Brassica



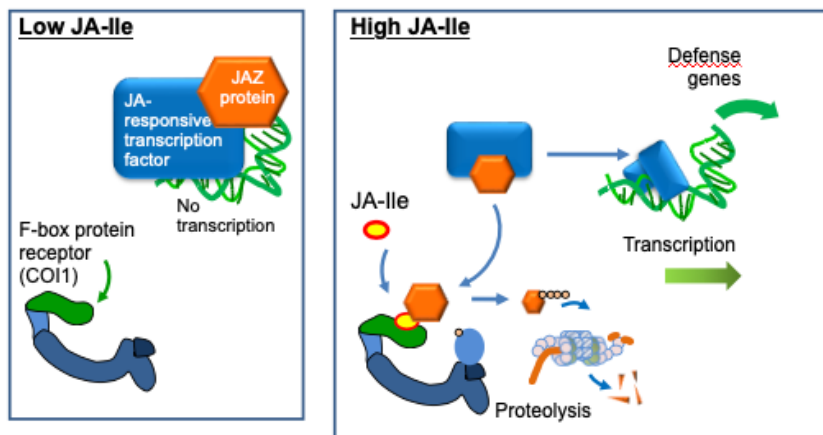
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JA-induced changes in gene expression



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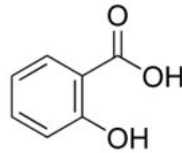
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60

Salicylic Acid – plant hormone and painkiller

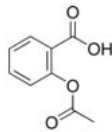
- Response to biotrophic pathogens
- Induced defense response
- Systemic acquired resistance



Salicylic Acid



Salicylic acid is named for the willow *Salix* whose analgesic properties were known long before the chemical was isolated.



Acetylsalicylic Acid - aspirin



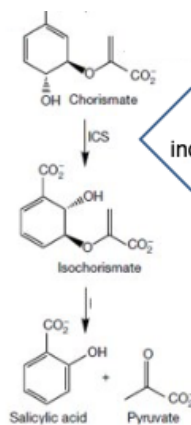
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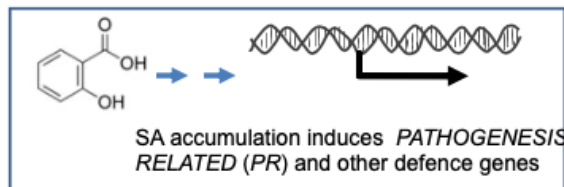
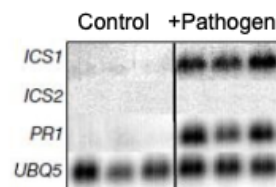
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61

Salicylate synthesis is induced upon pathogen attack



Isochorismate synthase (ICS) is induced by pathogen infection



Reprinted from *Majumdar, J.P. (2002) Recent breakthroughs in the study of salicylic acid biosynthesis. Trends Plant Sci. 7: 332-334*, with permission from Elsevier. Reprinted by permission from Macmillan Publishers Ltd. Wildermuth, M.C., Dandekar, J., Wu, G., and Asszel, F.M. (2001). *Ischorismate synthase is required to synthesize salicylic acid for plant defense. Nature 414: 562-565* copyright 2001.



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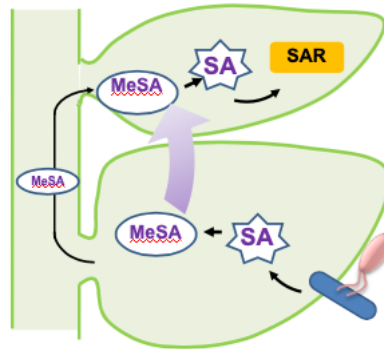
www.plantcell.org/cgi/doi/10.1105/tpc.110.00310
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62

Salicylates contribute to systemic acquired resistance

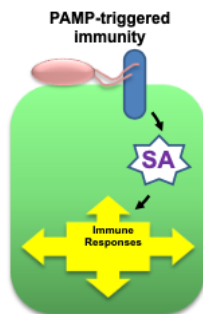
SA is necessary in systemic tissue for SAR, but the nature of the mobile signal(s) is still up in the air

It is likely that multiple signals contribute to SAR



63

Plants recognize PAMPS (pathogen-associated molecular patterns)



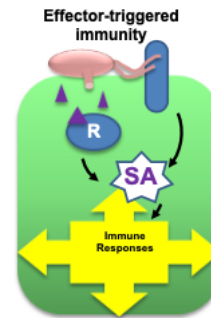
Flagellin is a conserved bacterial protein recognized by plants, also known as a pathogen-associated molecular pattern (PAMP).

Recognition of PAMPs by a plant cell triggers a set of immune responses that are mediated by salicylic acid.

64

Some pathogens elicit a stronger defense response

- Many plants express resistance genes that recognize the effects of bacterial proteins effector proteins.
-
- The interaction of an R protein with an effector protein promotes a stronger immune response, including the hypersensitive response.



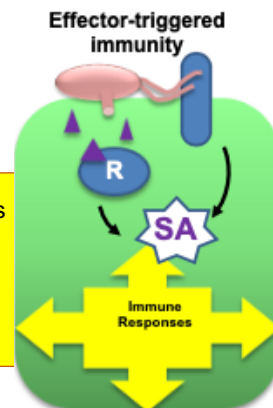
Adapted from: *Plant Cell*, 2011, 23(10):1005-1010

65

The hypersensitive response involves cell death



Pathogen Response (PR) genes
Antimicrobial compounds
Strengthening of plant cell walls
Programmed cell death
Hypersensitive response (HR)



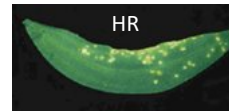
From Cawley, J., Cole, A.B., Kiraly, L., Qiu, W., and Schoelz, J.E. (2009) The plant gene *CTD2* selectively blocks cell death during the hypersensitive response to cauliflower mosaic virus infection. *MPLB* 18: 211-222. Retrieved from <https://doi.org/10.1101/000000>.
(2009) *Nat. Chem. Biol.* 5: 316-316.

66

The hypersensitive response seals the pathogen in a tomb of dead cells



The HR kills the infected cells and cells surrounding them and prevents the pathogen from spreading.

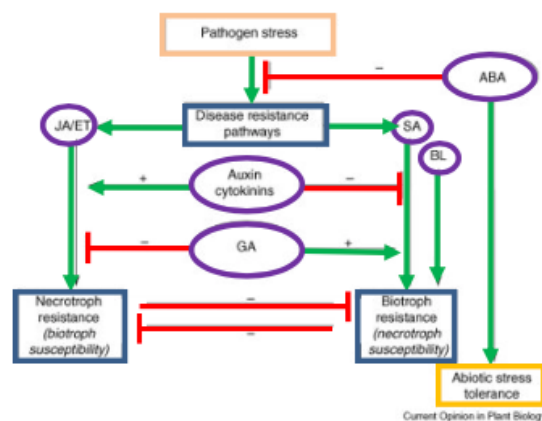


Without a hypersensitive response, the pathogen can multiply.

Drawing credit Credit: [Nicole Rager Fuller](#), National Science Foundation; Photo reprinted by permission of Macmillan Publishers Ltd. Pruitt, R.E., Bowman, J.L., and Grossniklaus, U. (2003) Plant genetics: a decade of integration. Nat. Genet. 33: 294–304.

67

Other hormones affect defense response signaling



As part of their immune responses, plants modulate synthesis and response to other hormones. Some pathogens exploit the connections between growth hormones and pathogen-response hormones to their own advantage, by producing “phytohormones” or interfering with hormone signaling.

Reprinted from Robert-Scallan, A., Navarro, L., Bari, R., and Jones, J.D.G. (2007). Pathological hormone imbalances. Curr. Opin. Plant Biol. 10: 372–379, with permission from Elsevier.

68

Hormonal control of reproductive development



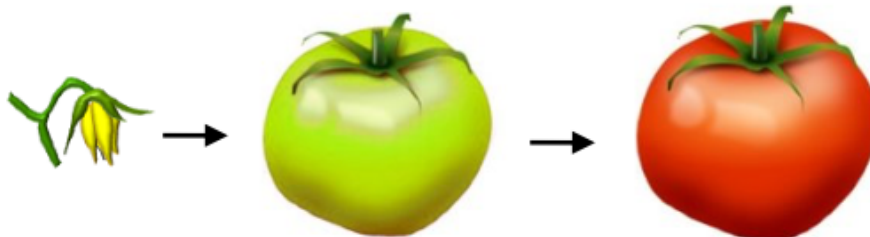
In angiosperms:

- transition from vegetative to reproductive growth
- flower development,
- fruit development and ripening
- seed development, maturation and germination

Photo courtesy of [Tom Ronald](#)

69

Fruit development and ripening are under hormonal control



Pollination initiates petal senescence, cell division and expansion in the ovary to produce a fruit, and fruit ripening.



70

Auxin and GA promote cell division and growth of the fruit

- Seedless varieties of grapes and other fruits require exogenous application of GA for fruit development. Strawberry receptacles respond to auxin.

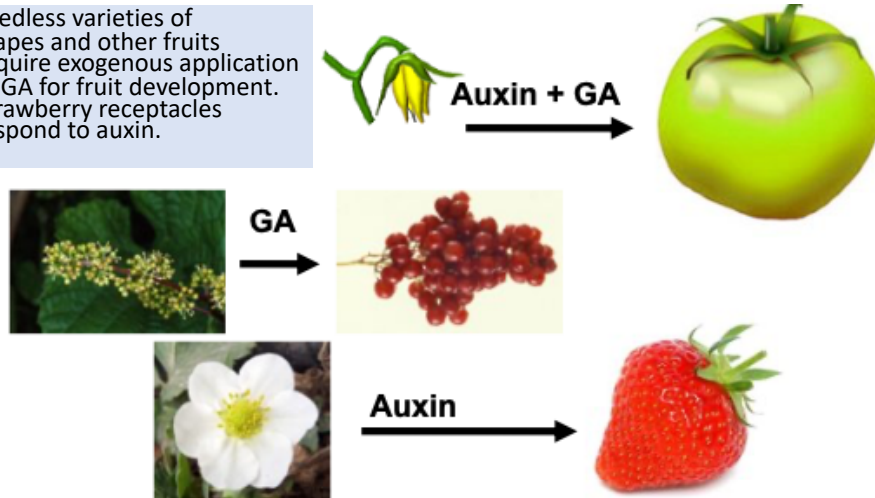


Photo credits: Grape flowers by [Bruce Reichy](#), Strawberry flower by [Shihao](#)



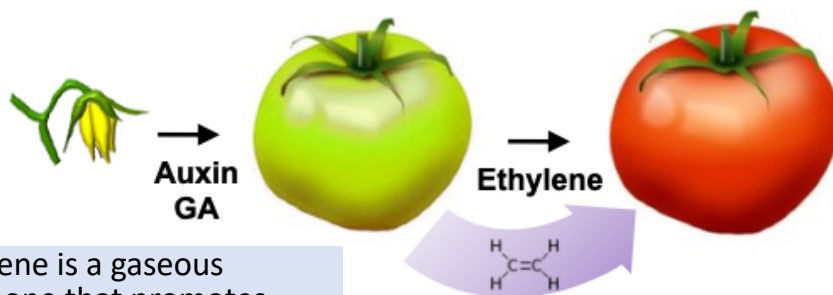
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Fruit ripening is induced by ethylene



- Ethylene is a gaseous hormone that promotes fruit softening and flavor and color development



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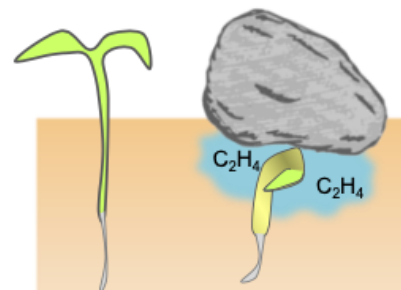
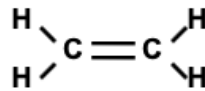
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Ethylene

- Control of fruit ripening
- Control of leaf and petal senescence
- Control of cell division and cell elongation
- Sex determination in some plants
- Control of root growth
- Stress responses



Ethylene induces the triple response:

- reduced elongation,
- hypocotyl swelling,
- apical hook exaggeration.



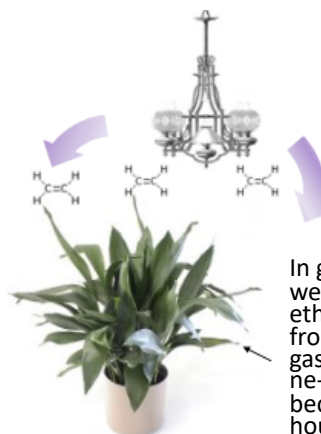
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73

Ethylene promotes senescence of leaves and petals



In gas-lit houses, plants were harmed by the ethylene produced from burning gas. *Aspidistra* is ethylene-resistant and so became popular houseplant.

Bayer, Jr., E.M. (1976) A potent inhibitor of ethylene action in plants. *Plant Physiol.* 58: 268-27



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www.plantcell.org/cgi/content/full/19/3/105/figs 110.00-510
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74

Ethylene shortens the longevity of cut flowers and fruits



Ethylene levels can be managed to maintain fruit freshness, commercially and at home.



Strategies to limit ethylene effects

Limit production - high CO₂ or low O₂

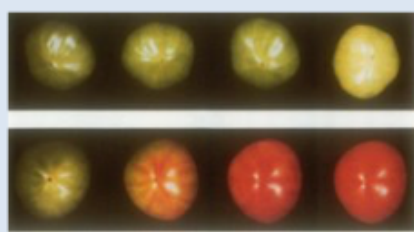
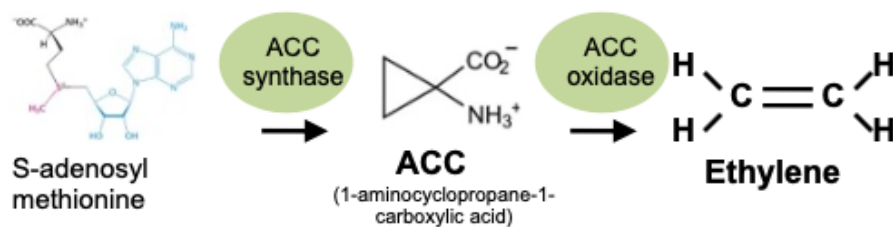
Removal from the air - KMnO₄ reaction, zeolite absorption

Interfere with ethylene binding to receptor - sodium thiosulfate (STS), diazocyclopentadiene (DACP), others

Reprinted from Serek, M., Woltering, E.J., Sisler, E.C., Frello, S., and Sriskandarajah, S. (2006) Controlling ethylene responses in flowers at the receptor level. Biotech. Adv. 24: 388-391 with permission from Elsevier.

75

Molecular genetic approaches can limit ethylene synthesis



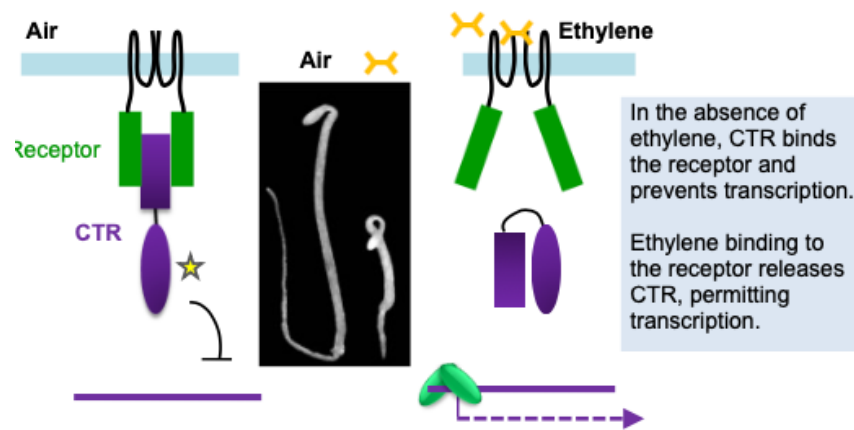
Antisense
ACC synthase

Control

Introduction of antisense constructs to interfere with expression of biosynthesis enzymes is an effective way to control ethylene production.

76

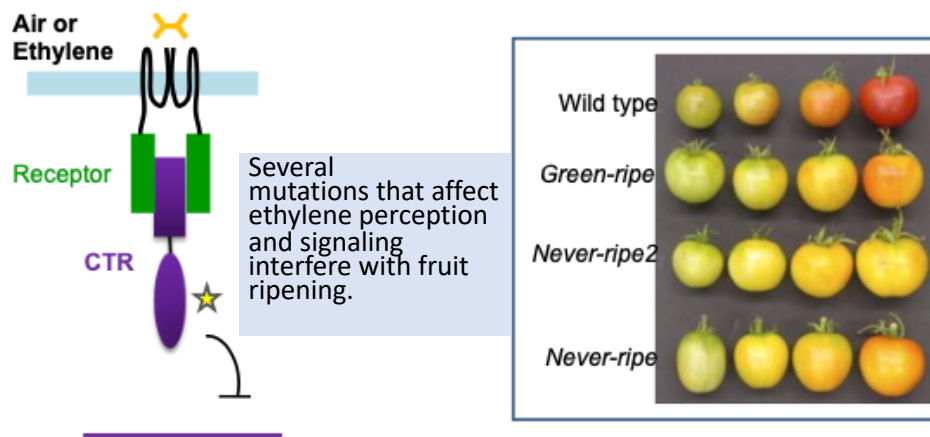
Ethylene-regulated gene expression is negatively regulated



Benavente, L.M., and Alonso, J.M. (2004) Molecular mechanisms of ethylene signaling in Arabidopsis. *Mol. Biotech.* 2: 165-172. Reproduced by permission of The Royal Society of Chemistry (RSC) for the European Society for Plant Biology, the European Photochemistry Association, and the RSC. Diagram adapted from Guo, H., and Ecker, J.R. (2004) The ethylene signaling pathway: new insights. *Cur. Opin. Plant Biol.* 7: 40-49.

77

Ethylene perception mutants interfere with ripening

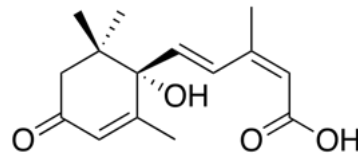


Barr, C. C. et al. (2004) Ethylene insensitivity conferred by the *Green-ripe* and *Never-ripe2* mutations of tomato. *Plant Physiol.* 136: 767-776.

78

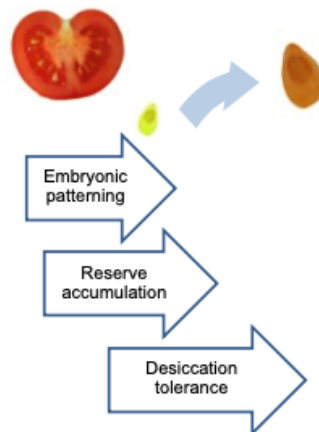
Absciscic acid

- Seed maturation and dormancy
- Desiccation tolerance
- Stress response
- Control of stomatal aperture



79

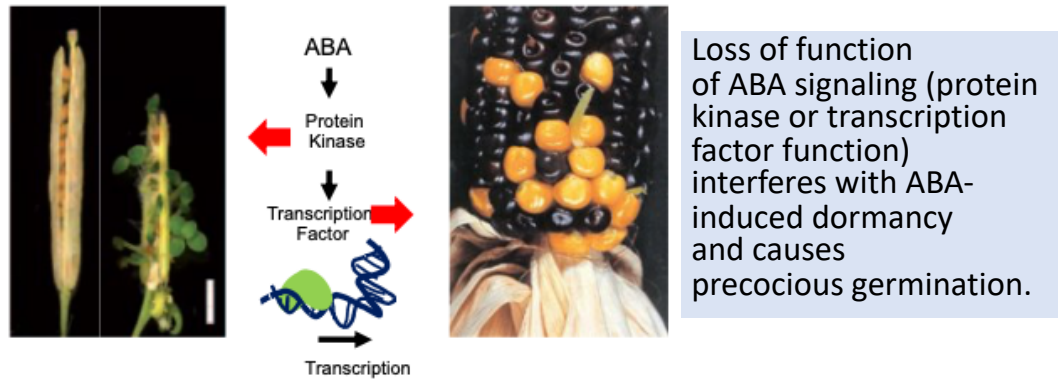
ABA accumulates in maturing seeds



Seed maturation requires ABA synthesis and accumulation of specific proteins to confer desiccation tolerance to the seed.

80

ABA synthesis and signaling is required for seed dormancy



Nakashima, K., et al. (2009) Three Arabidopsis SnRK2 protein kinases, SRK2D/SnRK2.2, SRK2E/SnRK2.6/OST1 and SRK2I/SnRK2.3, involved in ABA signaling are essential for the control of seed development and Dormancy. *Plant Cell Physiol.* 50: 1345-1363. Copyright (c) 2009 by the Japanese Society of Plant Physiologists with permission from Oxford University Press. McCarty, D.R., Carson, C.B., Stinard, P.S., and Robertson, D.S. (1989) Molecular analysis of viviparous-1: An abscisic acid-insensitive mutant of maize. *Plant Cell* 1: 523-537.

81

Once dormant and dry, seeds can remain viable for very long times

These date palm seeds are nearly 2000 years old, but still viable and capable of germination. Five-hundred year old lotus seeds have also been successfully germinated. Having a thick seed coat may help these super seeds retain viability.



Date palm growing from 2000 year old seed.

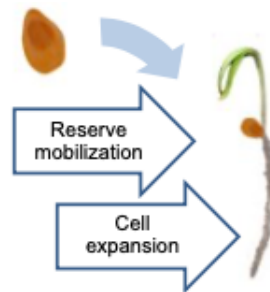


From Sallon, S., et al. (2008). Germination, genetics, and growth of an ancient date seed. *Science* 320: 1464, with permission from AAAS Lotus picture by [Perinthus](#)

82

GA is required for seed germination

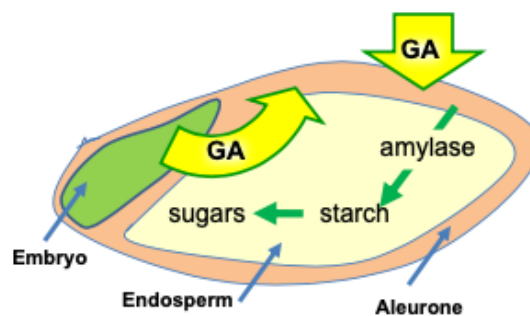
Seed germination requires elimination of ABA and production of GA to promote growth and breakdown of seed storage products.



83

GA is used by brewers to promote barley germination

Breakdown of starch in the endosperm is initiated by GA produced by the endosperm or added during the malting process.



84

Summary – hormonal regulation of reproductive development

GA and ethylene promote flowering in some plants.

Fruit growth, maturation and ripening are regulated by auxin, GA and ethylene.

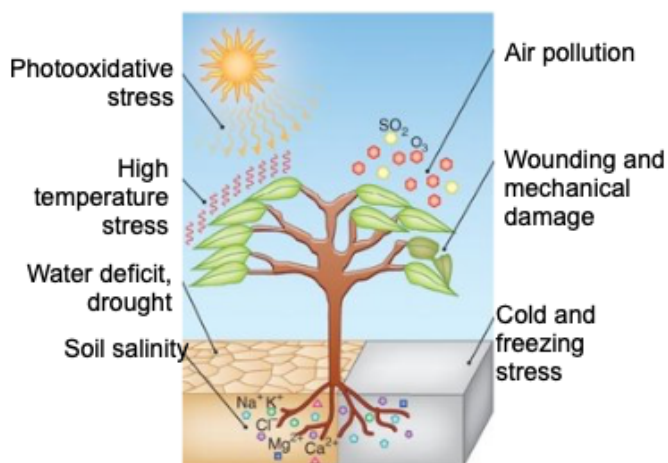
Seed maturation and germination are regulated by ABA and GA.

Understanding the roles of hormones in plant reproduction is important for food production, because most of our caloric intake is derived from seeds.



85

Hormonal responses to abiotic stress

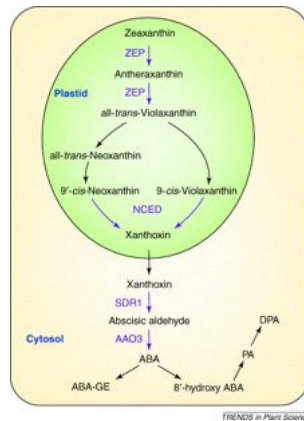


Plants' lives are very stressful.....

ABA and ethylene help plants respond to stress.

86

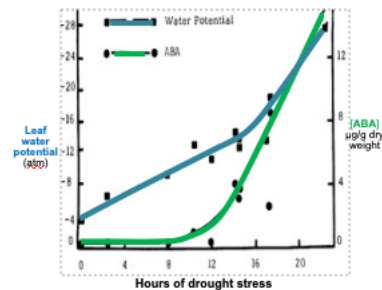
ABA biosynthesis is strongly regulated



ABA levels are tightly controlled. Critical steps in ABA biosynthesis (circled in red) are encoded by multiple tightly regulated genes to ensure rapid and precise control.

87

ABA synthesis is strongly induced in response to stress

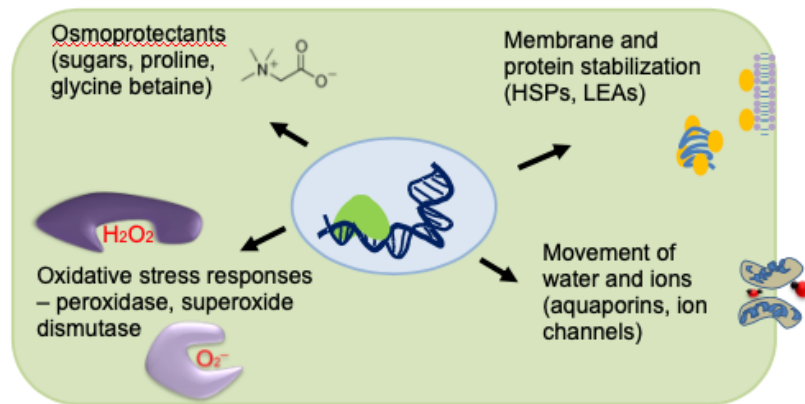


ABA levels rise during drought stress due in part to increased biosynthesis

R.L. Croissant, Bugwood.org www.forestryimages.org; Zabedel, T.J. (1974) A water potential threshold for the increase of abscisic acid in leaves. Plant Physiol. (1974) 53: 125-127.

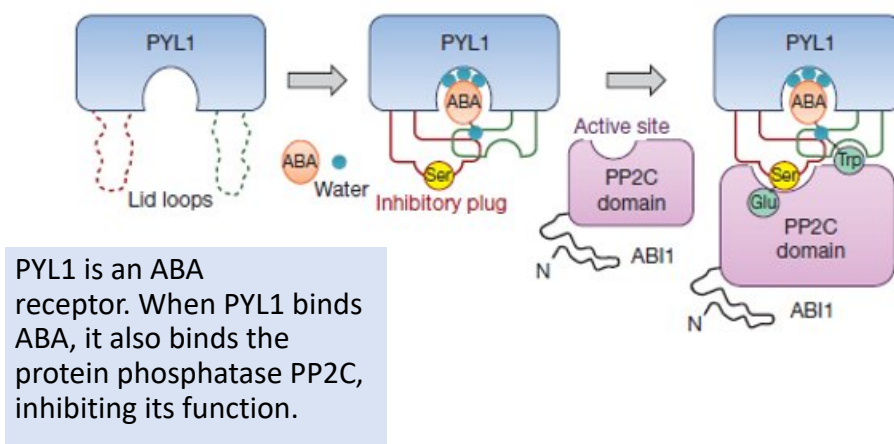
88

ABA induces stress-responsive genes



89

ABA binding to an intracellular receptor initiates transcriptional responses

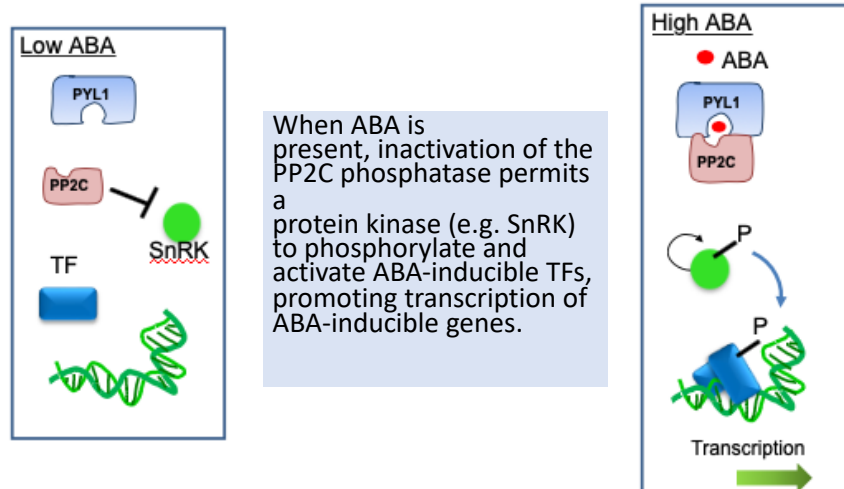


PYL1 is an ABA receptor. When PYL1 binds ABA, it also binds the protein phosphatase PP2C, inhibiting its function.

Reprinted by permission of Macmillan Publishers Ltd. Miyazono, K., et al. (2009) Structural basis of abscisic acid signalling. *Nature* 462: 603-614.

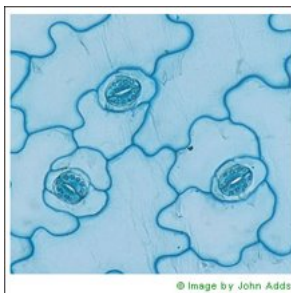
90

ABA signal transduction affects gene expression

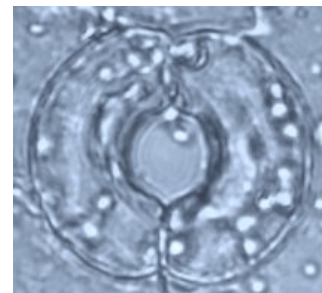


91

ABA regulates stomatal aperture by changing the volume of guard cells



Pairs of guard cells surround the openings of plant pores called stomata.

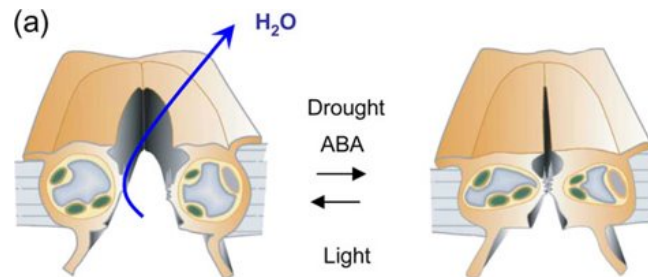


Guard cells control the opening and closing of stomata to regulate gas exchange: a fine balance is required to allow CO₂ in for photosynthesis and prevent excessive water loss.

Guard cell image © John Addis, obtained through the [SAPS Plant Science Image Database](http://SAPS.Plant.Science.Image.Database).

92

ABA controls stomatal aperture by changing the volume of guard cells

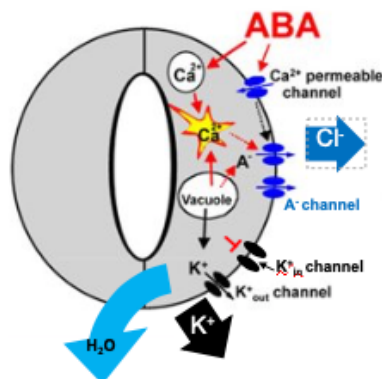


When stomata are open, plants lose water through transpiration. ABA induced by drought causes the guard cells to close and prevents their reopening, conserving water.

Sirichandra, C., Wasilewska, A., Vlad, F., Valon, C., and Leung, J. (2009) The guard cell as a single-cell model towards understanding drought tolerance and abscisic acid action. *Journal of Experimental Botany* 2009 60: 1439-1453. © The Author (2009). Published by Oxford University Press on behalf of the Society for Experimental Biology.

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ABA-induced stomatal closure is extremely rapid and involves changes in ion channel activities



ABA triggers an increase in cytosolic calcium (Ca^{2+}), which activates anion channels (A^-) allowing Cl^- to leave the cell. ABA activates channels that move potassium out of the cell (K^+ out) and inhibits channels that move potassium into the cell (K^+ in). The net result is a large movement of ions out of the cell.

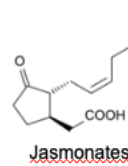
As ions leave the cell, so does water (by osmosis), causing the cells to lose volume and close over the pore.

Adapted from Kwak JM, Mäser P, Schroeder JJ (2008) The clickable guard cell, version II: Interactive model of guard cell signal transduction mechanisms and pathways. *The Arabidopsis Book*, ASPB. doi:10.1199/ab.0114

94

Hormonal responses to biotic stress

Bacteria, fungi, viruses –
Biotrophic organisms

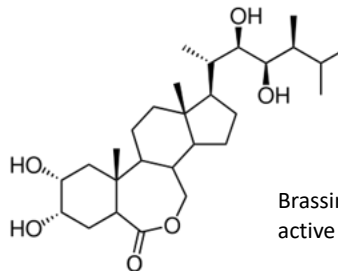


Herbivores – insects,
other animals, fungi –
Necrotrophic organisms

95

Brassinosteroids

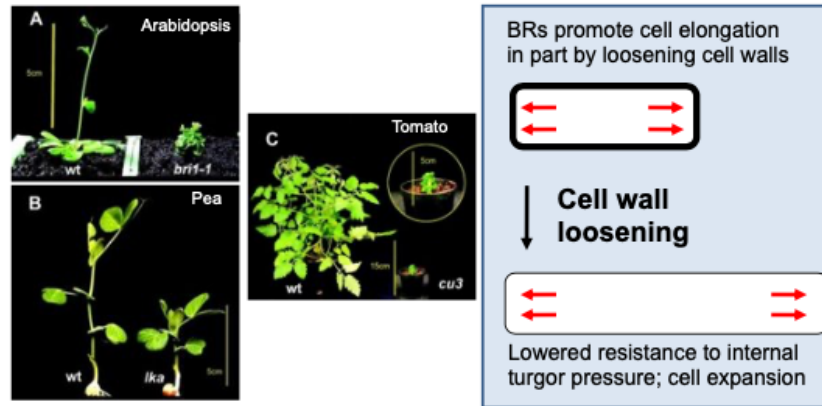
- Cell elongation
- Pollen tube growth
- Seed germination
- Differentiation of vascular tissues and root hairs
- Stress tolerance



Brassinolide, the most
active brassinosteroid

96

Brassinosteroid (BR) mutants are dwarfed



Bishop, G. J., and Koncz, C. Brassinosteroids and plant steroid hormone signaling. (2002) Plant Cell 14: 997-1110.



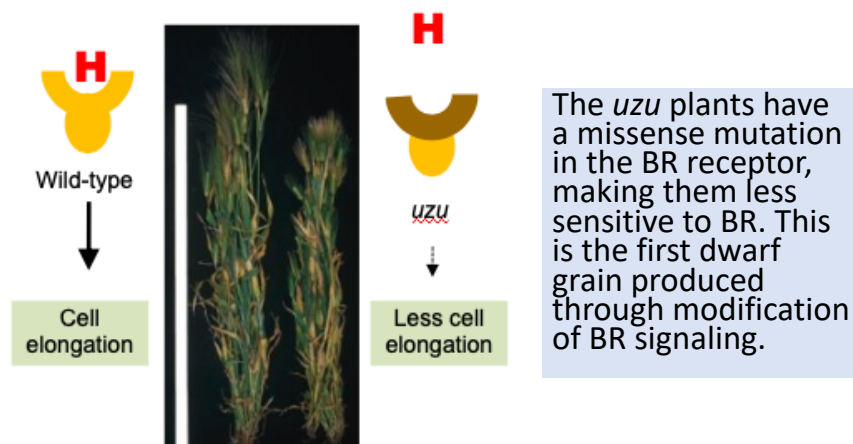
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Reducing BR signalling produces dwarf barley



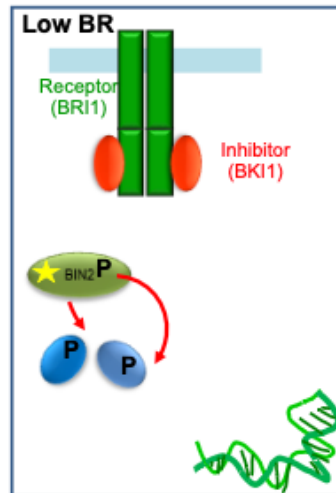
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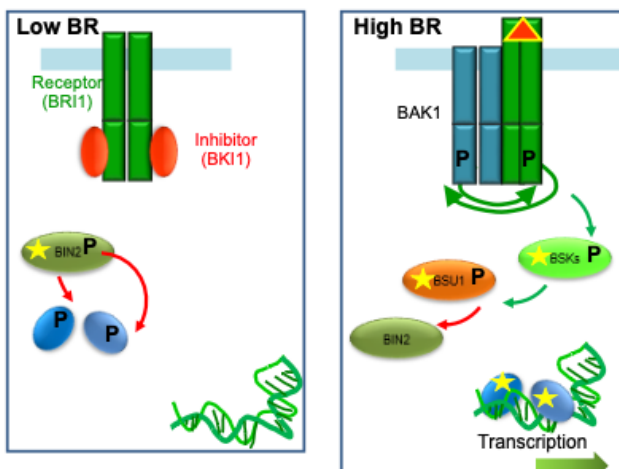
BR signalling



Without BR, the receptor (BRI1) is bound to an inhibitor (BK11). The active BIN2 kinase phosphorylates and inactivates transcription factors.

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BR signalling



BR-binding causes BAK1 and the BRI1 receptor to phosphorylate each other and BSKs. BSKs phosphorylate and activate BSU1 phosphatase, which inactivates BIN2. When BIN2 is inactive, its target transcription factors are dephosphorylated and active.

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Summary – hormonal control of vegetative growth



Plant hormones have diverse effects on plant growth.

Auxin, gibberellins and brassinosteroids contribute to elongation growth.

Auxin, cytokinins and strigolactones regulate branching patterns.

Growth and branching profoundly affect crop yields.

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Summary – stress responses

Hormonal signaling is critical for plant defenses against abiotic and biotic stresses.

ABA and ethylene are produced in stressed plants and critical for activating their defense pathways.

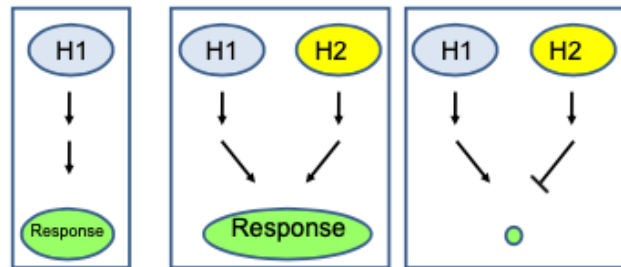
JA and SA contribute to local and systemic defenses against pathogens.

Understanding plant hormonal responses to stress is needed to improving agricultural yields. Abiotic and biotic stresses are major causes of crop losses and reduced yields and which must be minimized.



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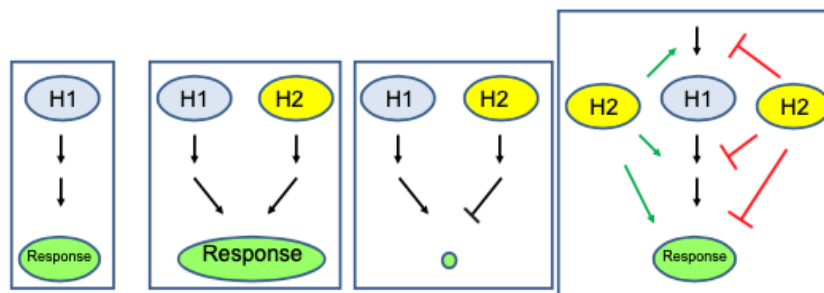
Crosstalk between hormone signaling pathways



Crosstalk (or cross-regulation) occurs when two pathways are not independent. It can be positive and additive or synergistic, or negative.

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Crosstalk between hormone signaling pathways

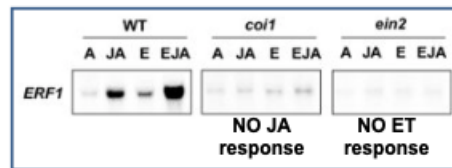


Crosstalk (or cross-regulation) occurs when two pathways are not independent. It can be positive and additive or synergistic, or negative.

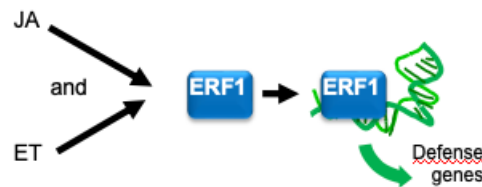
Crosstalk can affect the synthesis, transport or signaling pathway of another hormone.

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Synergistic requirement for JA and ET signaling in defense response



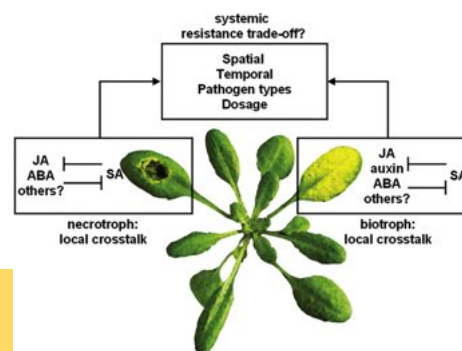
JA and ET signaling are both required for high-level expression of ERF1, a TF that induces defense gene expression



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Negative interaction between JA and SA in defense responses

In defense signaling, the JA and SA pathways are mutually antagonistic (locally), and both are antagonized by ABA.



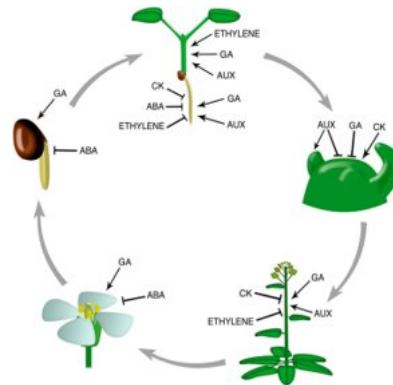
Why does ABA reduce SA and JA signaling?
Perhaps a plant that is already stressed and producing high levels of ABA may be better off temporarily restricting its responses to pathogens.

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GA and DELLAs interact extensively with other signaling pathways

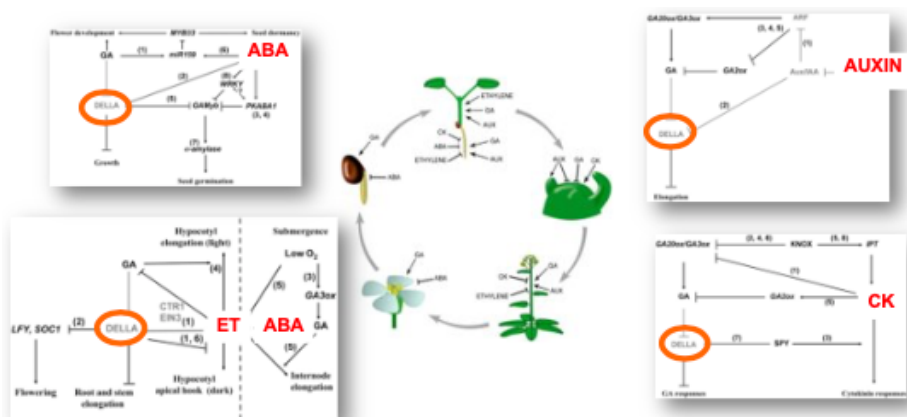
Just about every stage of the plants life is coordinated by GA and its effects on the other hormone signaling pathways.

Although it is clear that GA's effects on DELLA proteins are very important, we don't yet understand what these proteins do.



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GA and DELLAs interact extensively with other signaling pathways



Weiss, D., and Ori, N. (2007) Mechanisms of cross talk between gibberellin and other hormones. *Plant Physiol.* 144: 1240-1245.

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