

# Bi8940 Developmental Biology

## Lesson 8

### Postembryonic Plant Development

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and

**Functional Genomics and Proteomics of Plants**  
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INVESTICE DO ROZVOJE VZDĚLÁVÁNÍ

Tato prezentace je spolufinancována  
Evropským sociálním fondem  
a státním rozpočtem České republiky



# Outline of Lesson 8

## Postembryonic Plant Development

- The role of plant meristems in the plant postembryonic development
- Shoot apical meristem (SAM)
  - Structure of the SAM
  - SAM establishment and maintenance
- Phyllotaxy
  - Fibonacci series and golden mean in the nature
  - Molecular determinants of phyllotaxy
- Root apical meristem (RAM)
  - RAM structure
  - Positioning of RAM organization centre
  - Radial root patterning
  - RAM size determination
- Lateral root formation
- Vascular tissue formation in shoot and root



# Outline of Lesson 8

## Postembryonic Plant Development

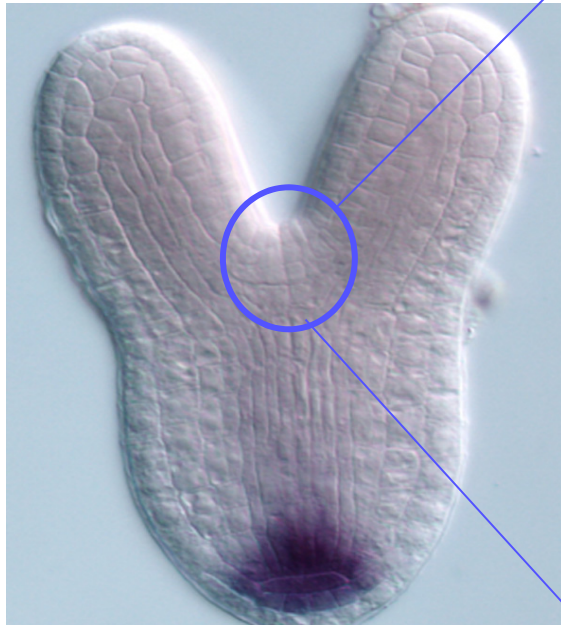
- The role of plant meristems in the plant postembryonic development



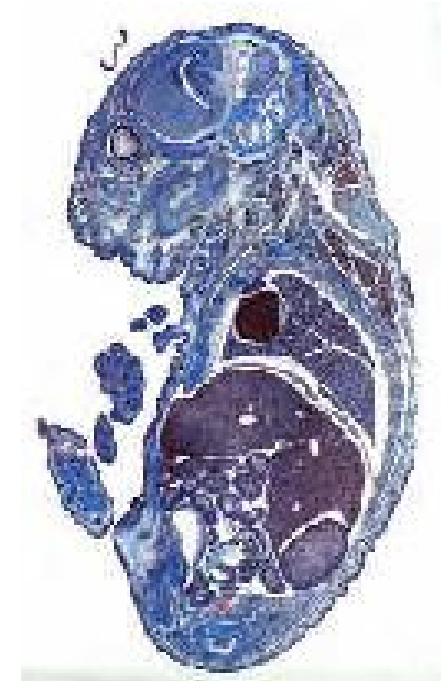
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# What is the principal difference between plants and animals?

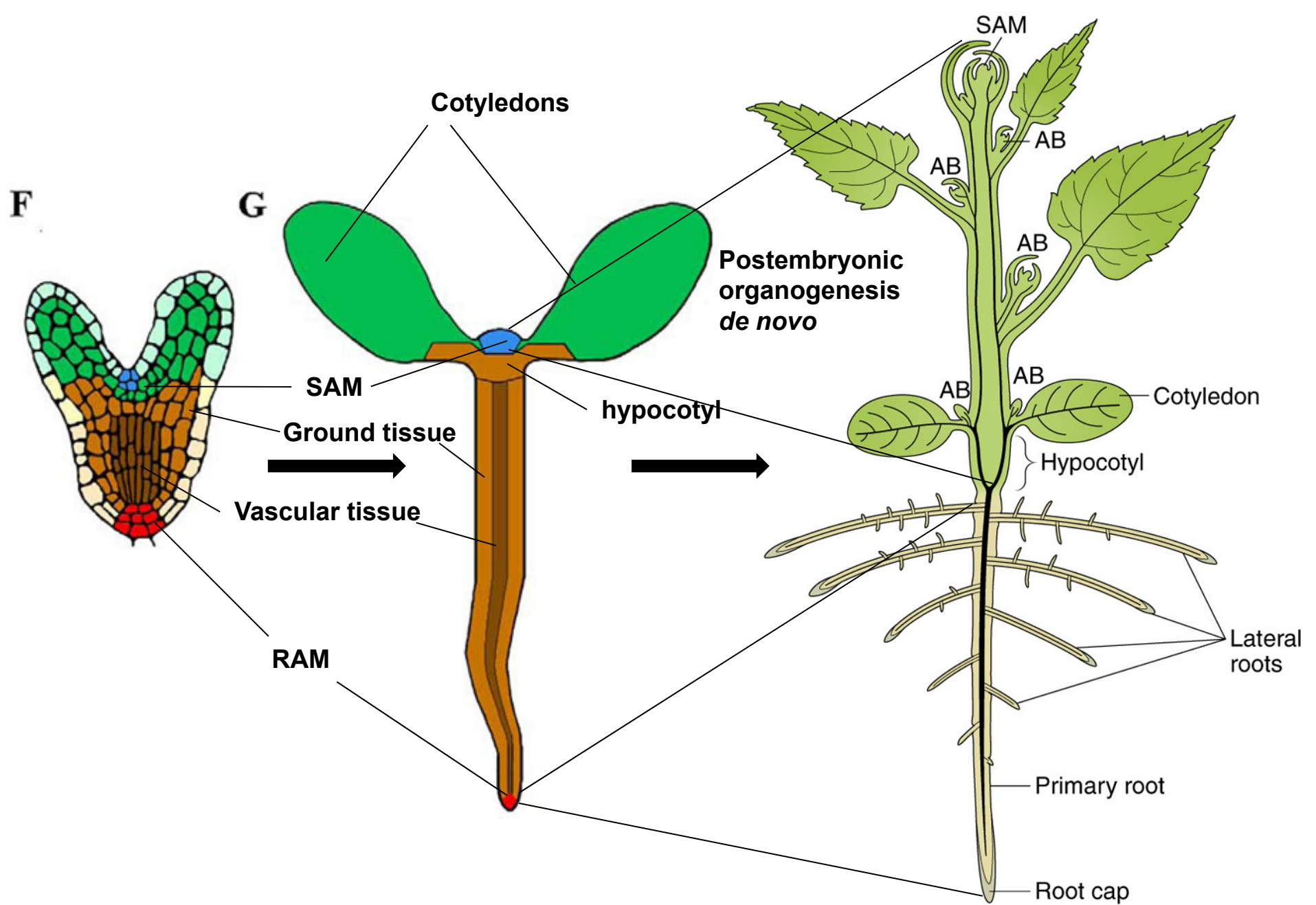


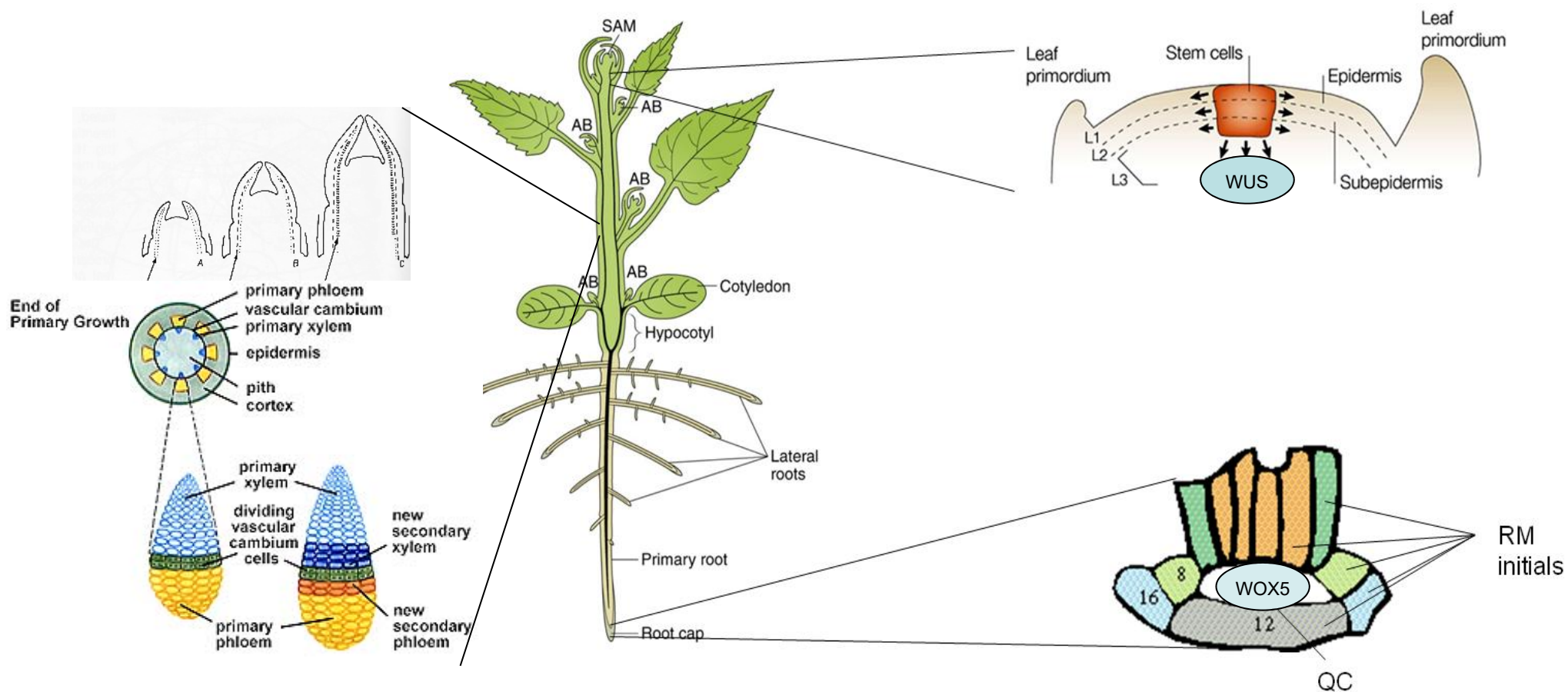
*Arabidopsis thaliana*, embryo at the torpedo stage



*Mus musculus*, embryo, longitudinal section







## Division ↔ Differentiation

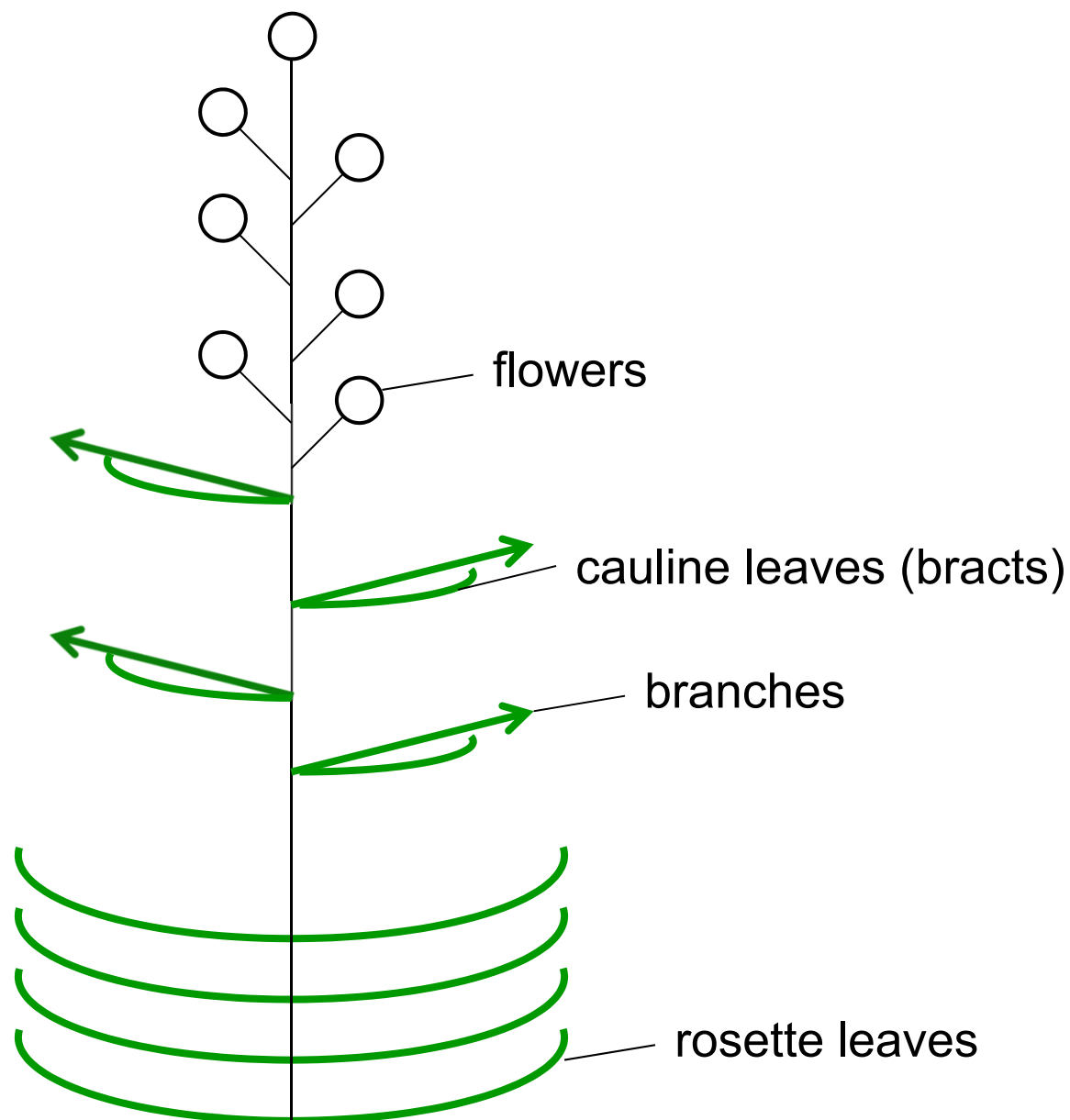


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- The role of plant meristems in the plant postembryonic development
- Shoot apical meristem (SAM)
  - Structure of the SAM

inflorescence



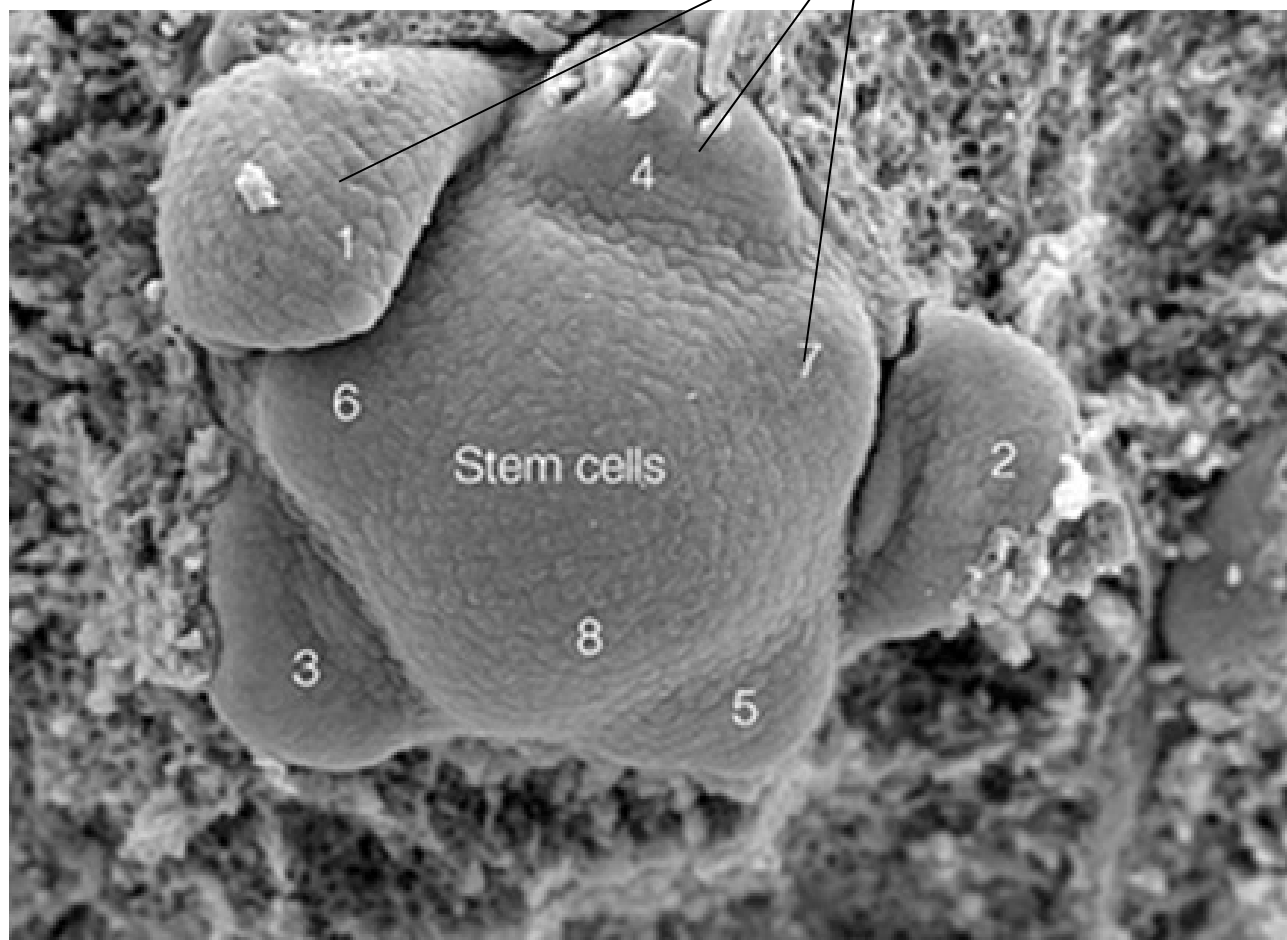
produced by FMs

**generative  
growth phase**

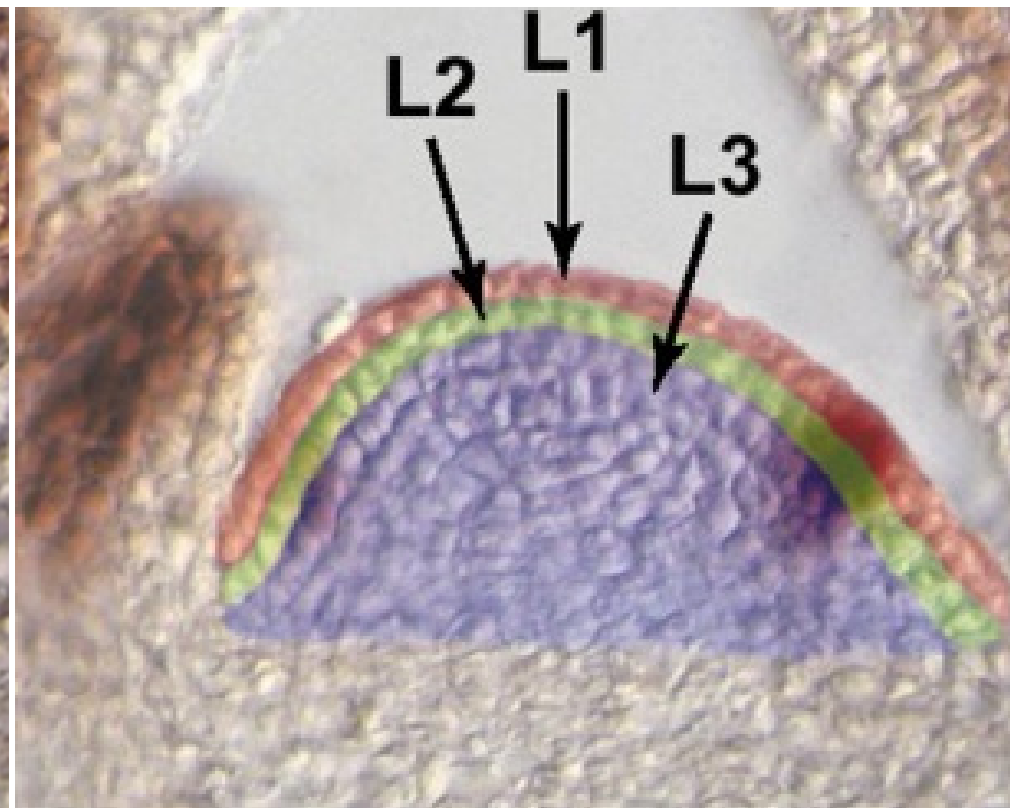
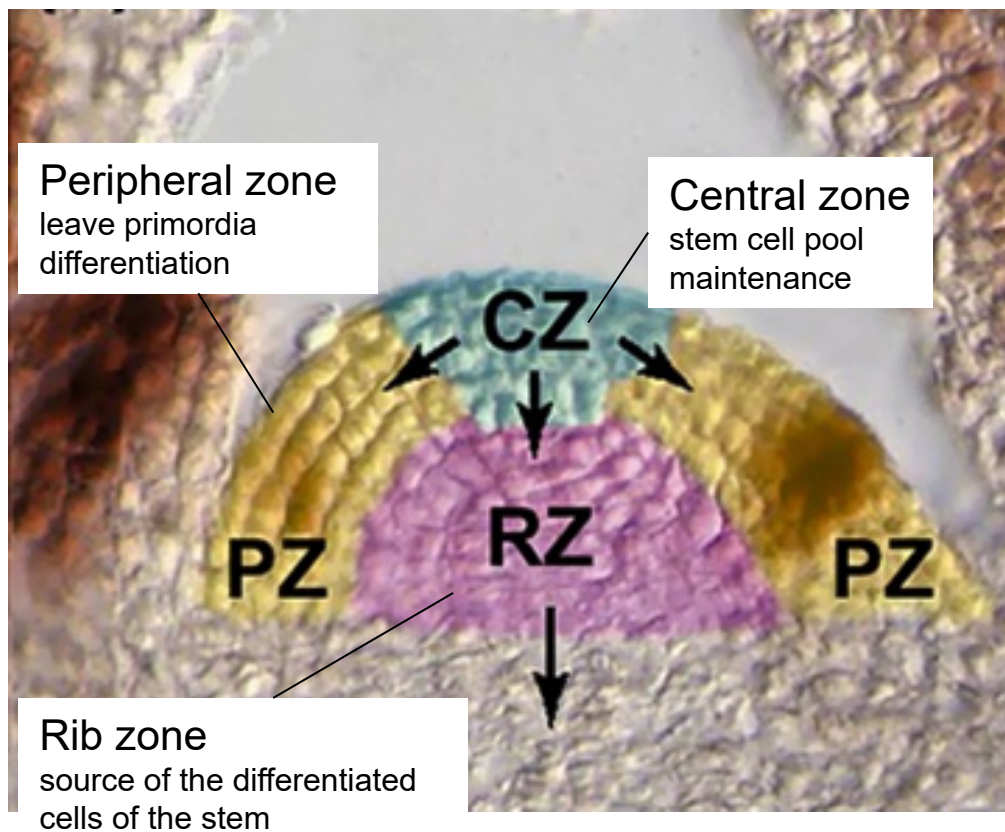
produced by IMs

**vegetative  
growth phase**  
produced by SAM

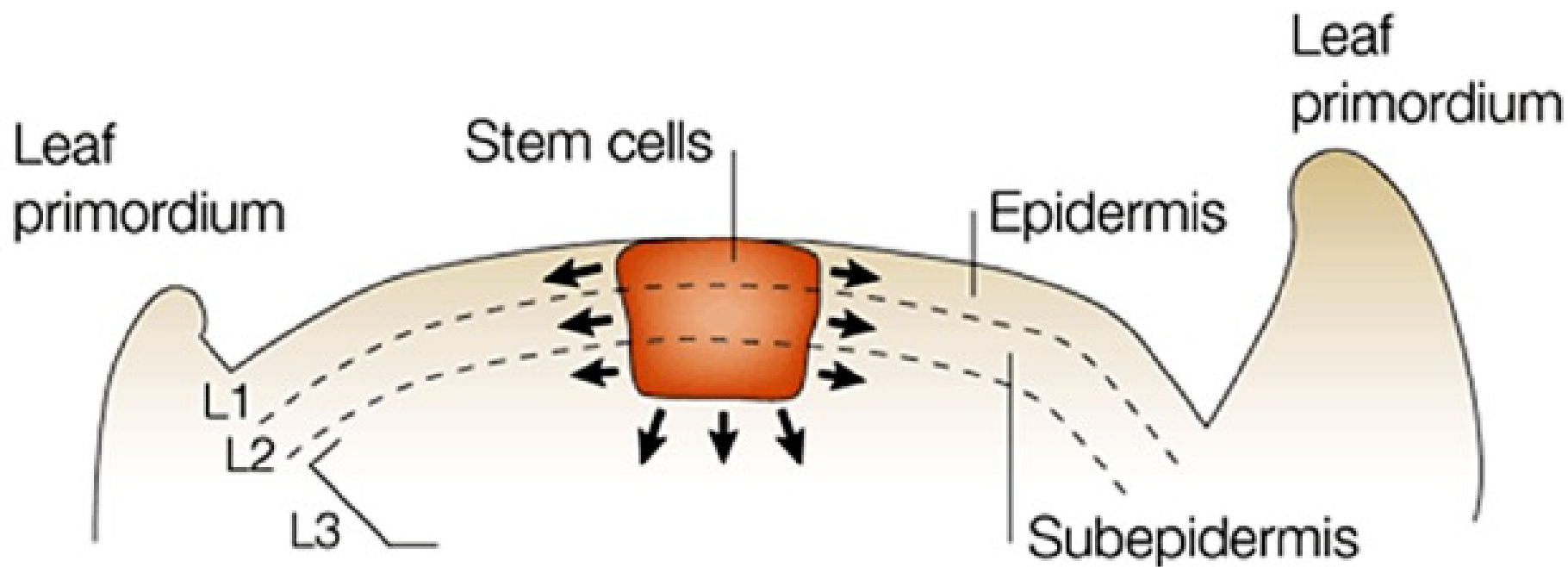
Leave primordia



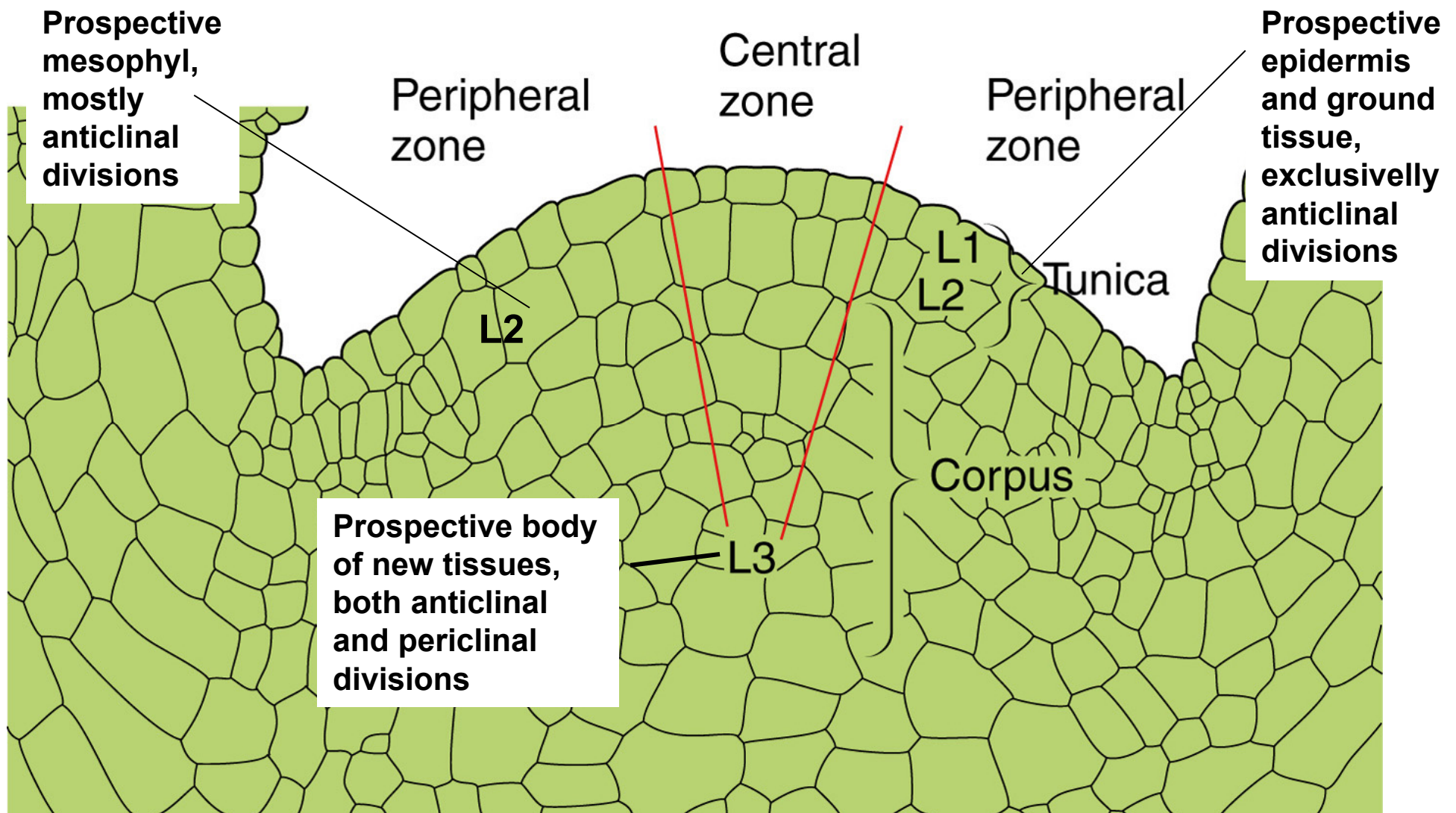




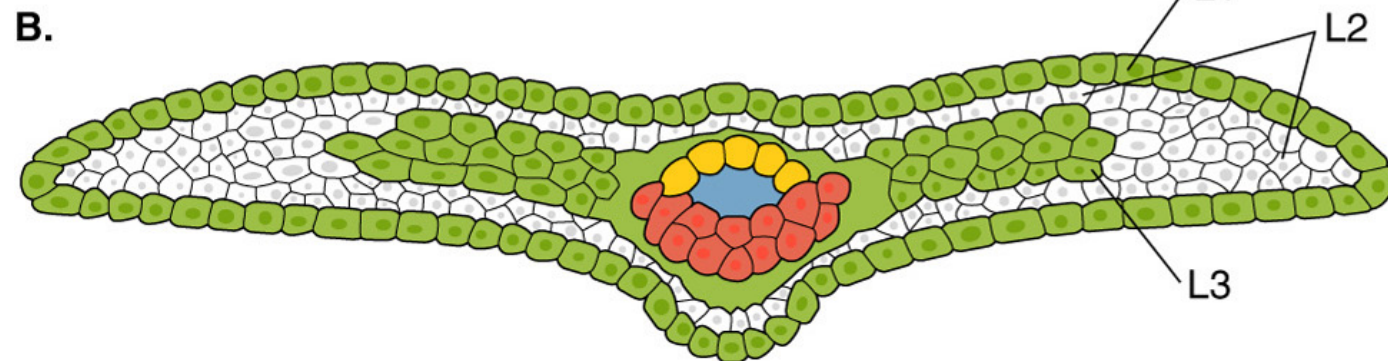
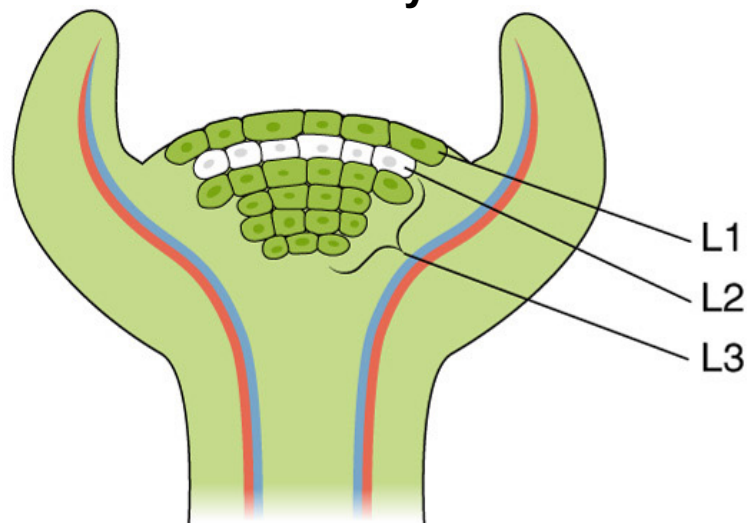
Bowman and Eshed, *Trends Plant Sci* (2000)



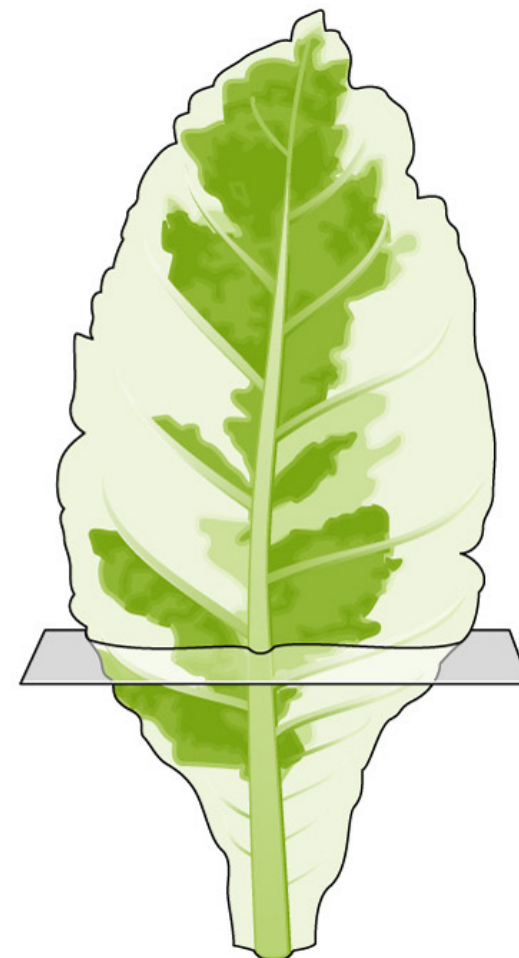




**A. Chimera with albino L2 layer**



**C.**



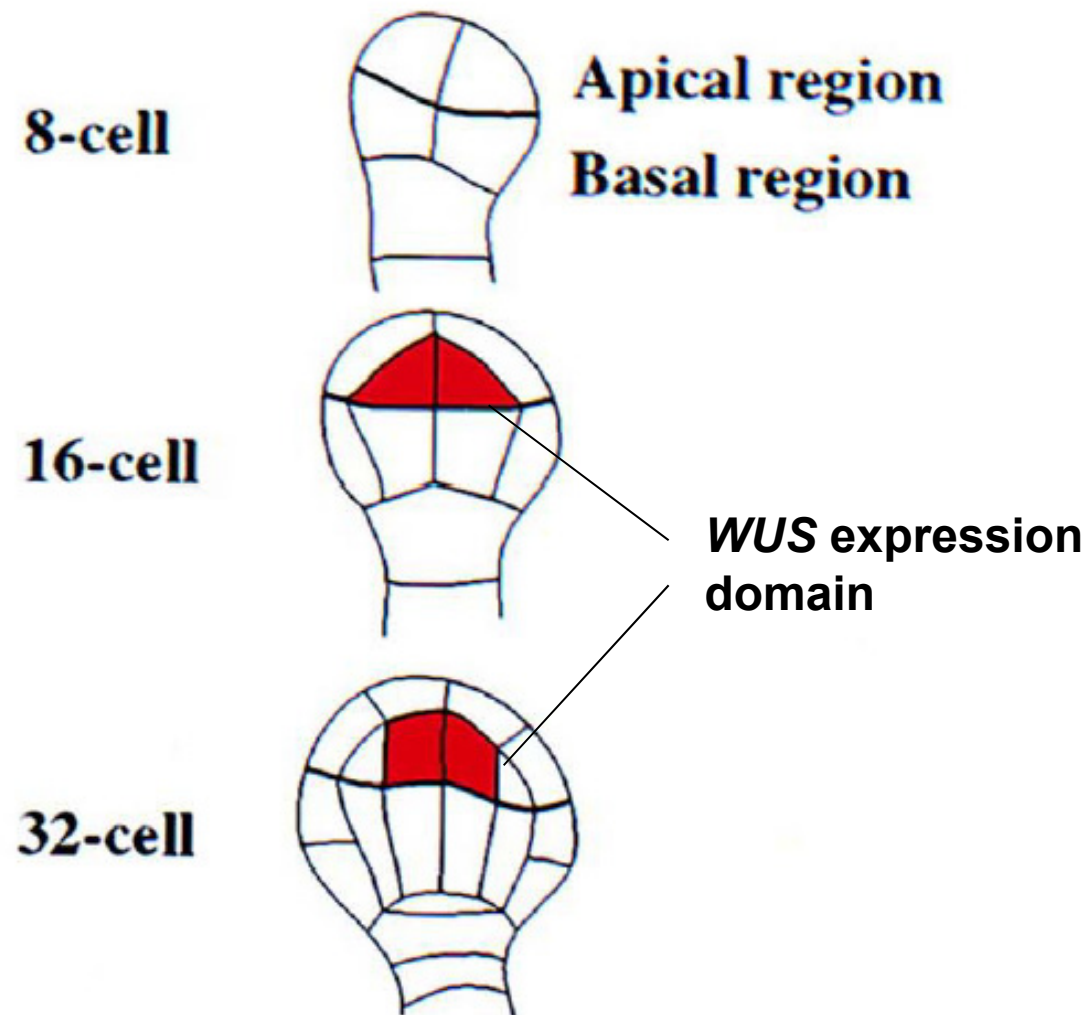


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## Postembryonic Plant Development

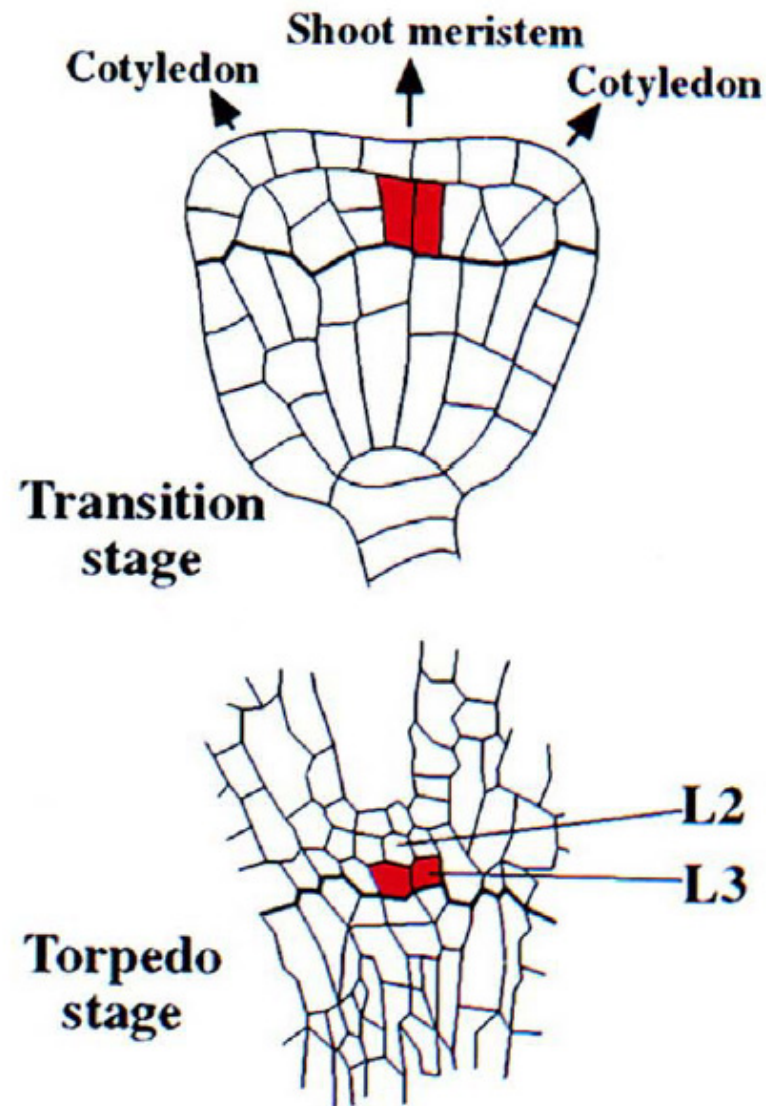
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- Shoot apical meristem (SAM)
  - Structure of the SAM
  - SAM establishment and maintenance

# SAM specification

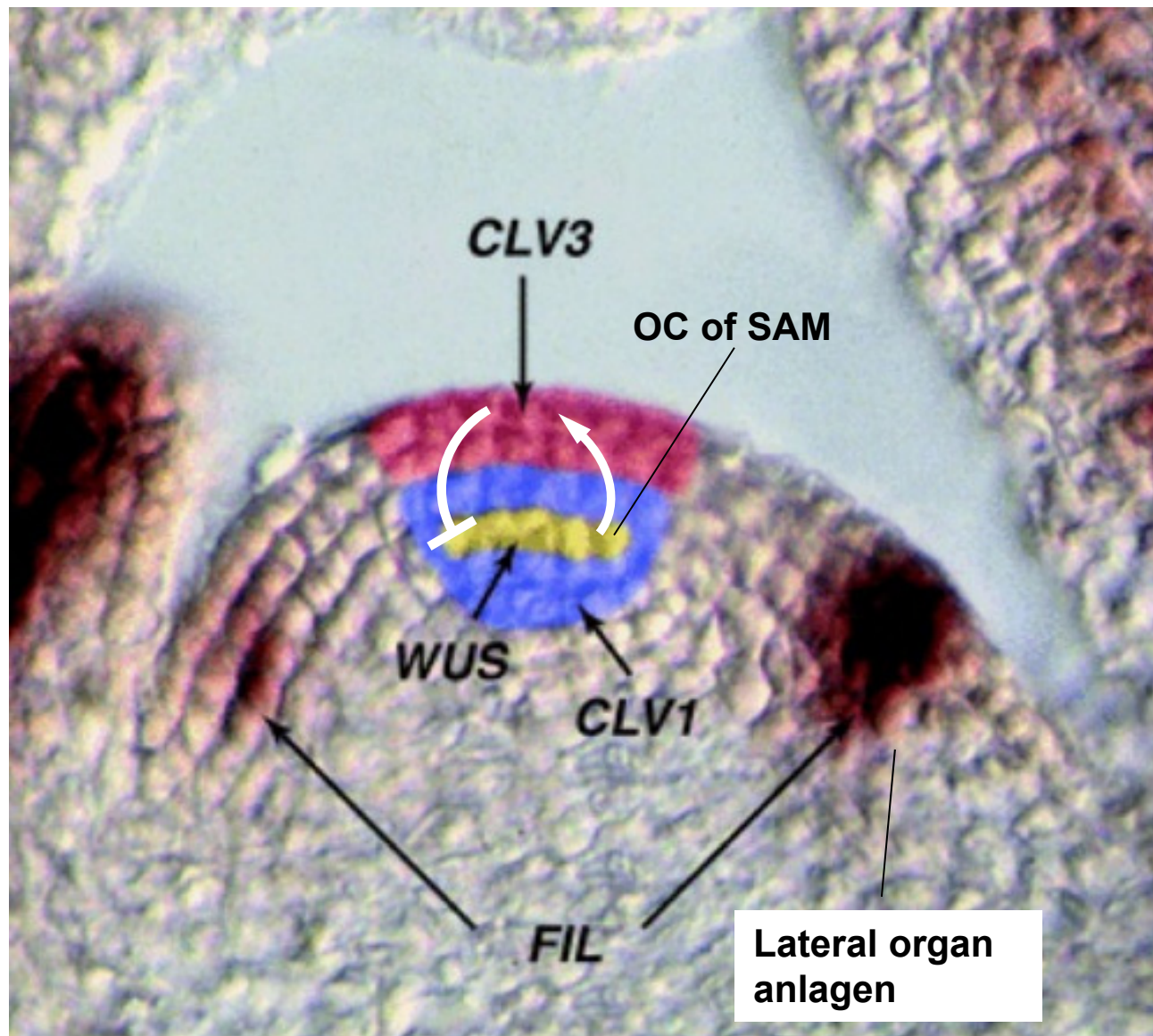


Capron et al., *Arabidopsis Book* (2009)

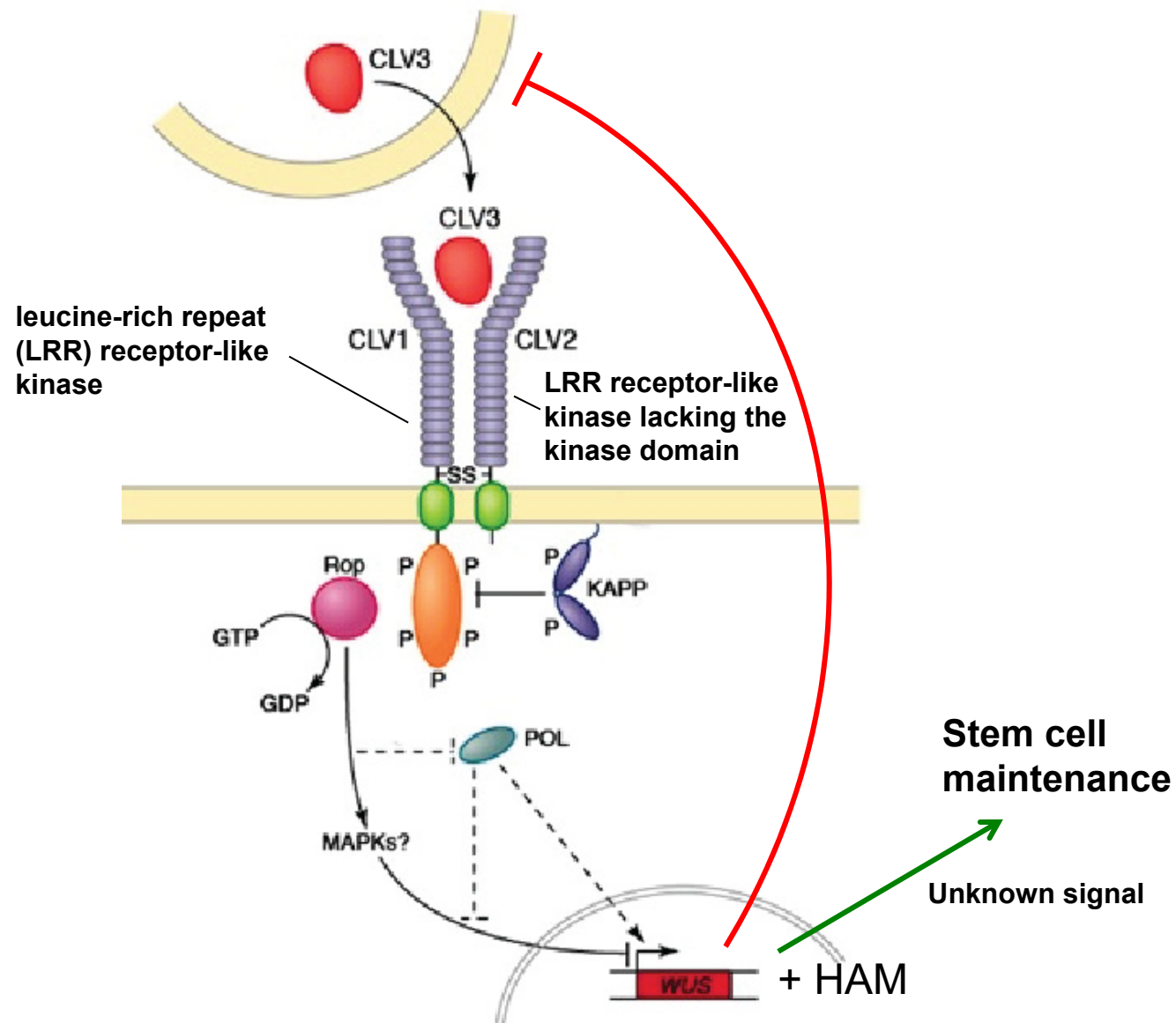




Capron et al., *Arabidopsis Book* (2009)

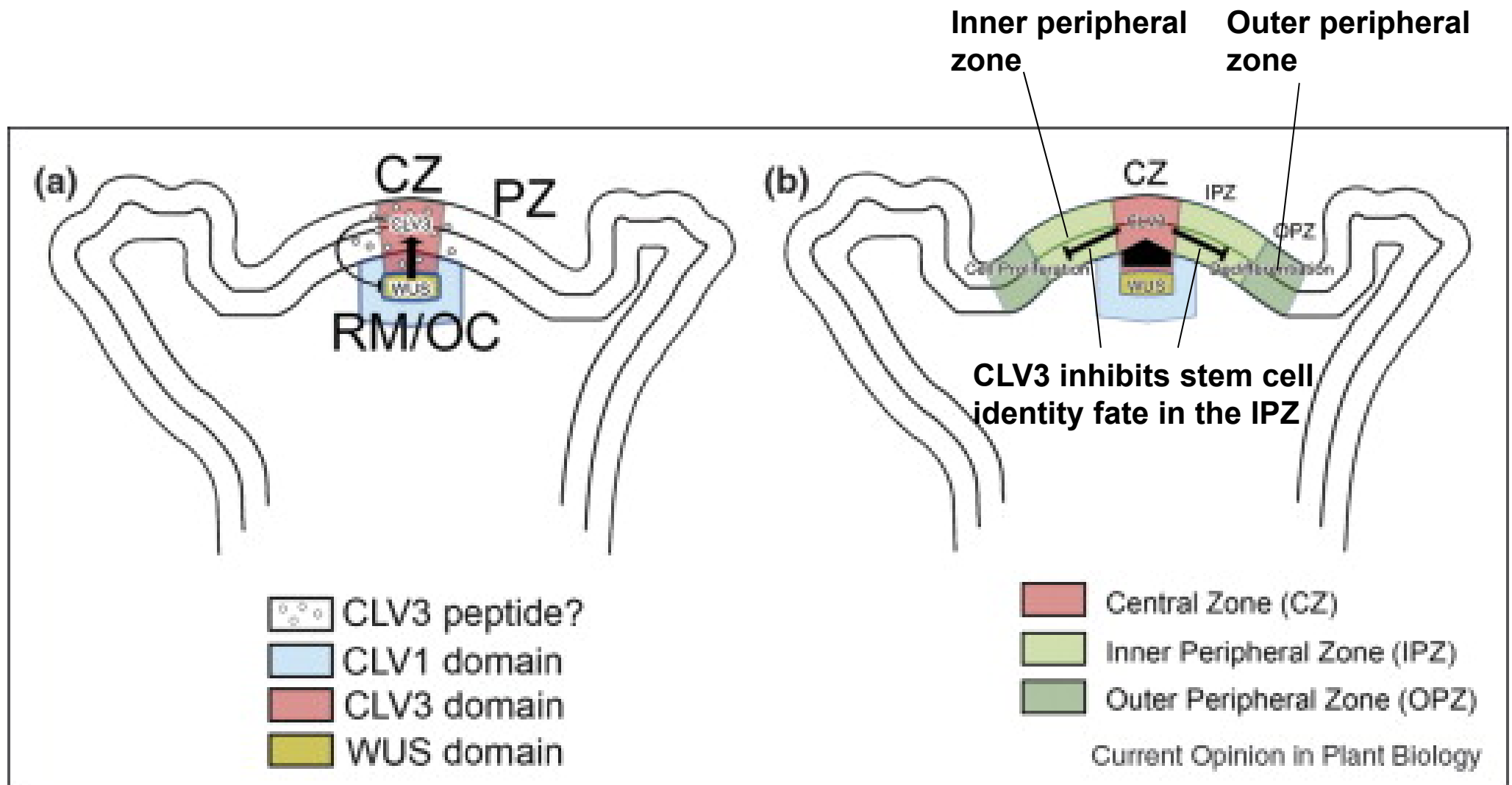


Bowman and Eshed, *Trends Plant Sci* (2000)



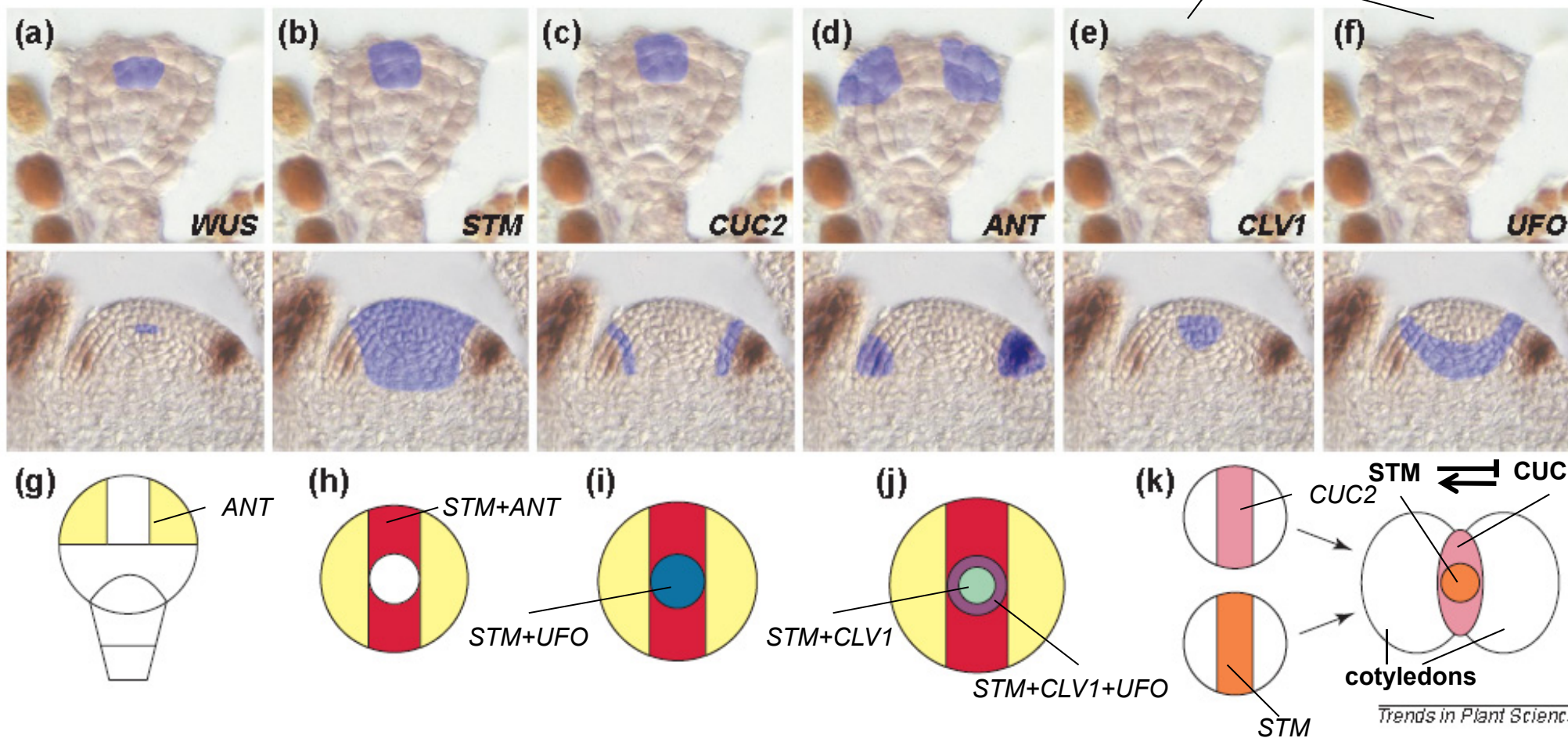
Carles et al., *Trends Plant Sci* (2003)





Reddy, *Current Opinion Plant Biol* (2000)

Expression in the later  
(heart) stage



Bowman and Eshed, *Trends Plant Sci* (2000)



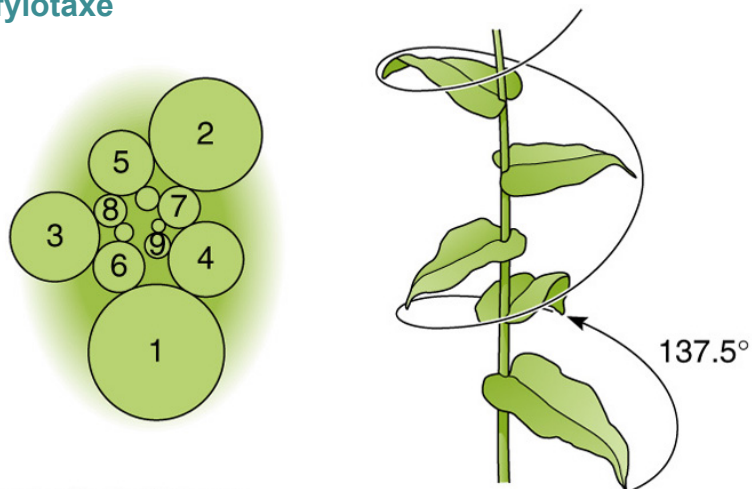
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- Phyllotaxy
  - Fibonacci series and golden mean in the nature

## A. Spiral phyllotaxy

Spirální (vřetenovitá) fylotaxe



## B. Whorled phyllotaxy

Přeslenitá (kruhová) fylotaxe



**distichous**  
**distichie** 1 leaf

**decussate**  
**dvojčetný** 2 leaves  
**přeslen**

**tricussate**  
**trojčetný** 3 leaves  
**přeslen**



<code>i	ai	abs err	Pi	Qi	Pi/Qi
0	1	6.2E-01	1 /	1 =	1.0000000000000000
1	1	-3.8E-01	2 /	1 =	2.0000000000000000
2	1	1.2E-01	3 /	2 =	1.5000000000000000
3	1	-4.9E-02	5 /	3 =	1.6666666666666667
4	1	1.8E-02	8 /	5 =	1.6000000000000000
5	1	-7.0E-03	13 /	8 =	1.6250000000000000
6	1	2.6E-03	21 /	13 =	1.615384615384615
7	1	-1.0E-03	34 /	21 =	1.619047619047619
8	1	3.9E-04	55 /	34 =	1.617647058823529
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11	1	-2.2E-05	233 /	144 =	1.6180555555555556
12	1	8.2E-06	377 /	233 =	1.618025751072961
13	1	-3.1E-06	610 /	377 =	1.618037135278515
14	1	1.2E-06	987 /	610 =	1.618032786885246
15	1	-4.6E-07	1597 /	987 =	1.618034447821682
16	1	1.8E-07	2584 /	1597 =	1.618033813400125
17	1	-6.7E-08	4181 /	2584 =	1.618034055727554
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19	1	-9.8E-09	10946 /	6765 =	1.618033998521803
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22	1	5.4E-10	46368 /	28657 =	1.618033988205325
23	1	-2.1E-10	75025 /	46368 =	1.618033988957902
24	1	7.9E-11	121393 /	75025 =	1.618033988670443
25	1	-3.0E-11	196418 /	121393 =	1.618033988780243
26	1	1.2E-11	317811 /	196418 =	1.618033988738303
27	1	-4.4E-12	514229 /	317811 =	1.618033988754322
28	1	1.7E-12	832040 /	514229 =	1.618033988748204
29	1	-6.5E-13	1346269 /	832040 =	1.618033988750541
30	1	2.5E-13	2178309 /	1346269 =	1.618033988749648

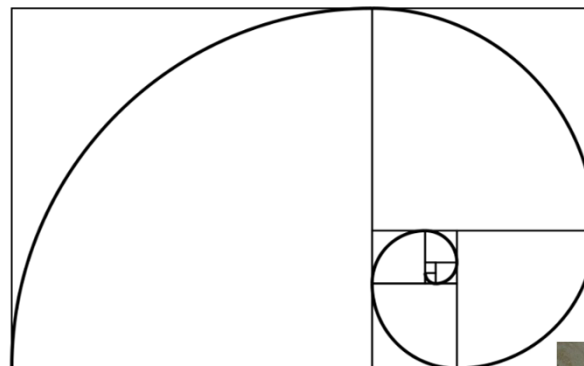
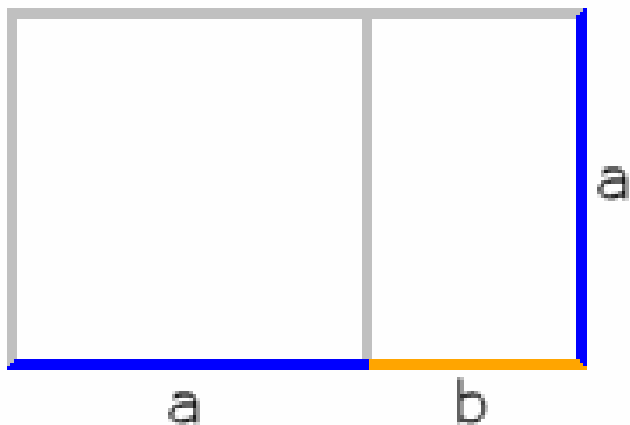


Leonardo Fibonacci (1180-1250)

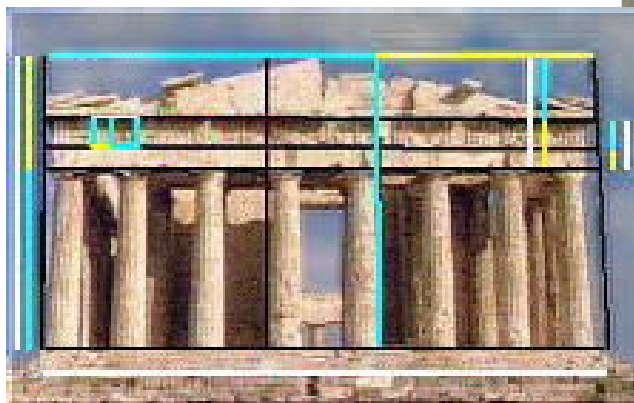
Fibonacci series: 0, 1, 1, 2, 3, 5, 8, 13, 21...

$$\varphi = \frac{1 + \sqrt{5}}{2} \approx 1,618\ 033\ 988\ 749\ 894\ 848\ \dots$$

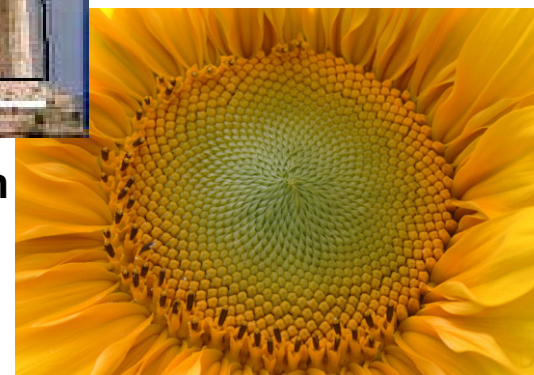
Wikipedia



$a + b / a = a/b = 1.618$   
 “golden mean” or “divine ratio”  
 “zlatý řez”



$1.618 = \Phi$ , according to “Fidios”, the creator of Pantheon

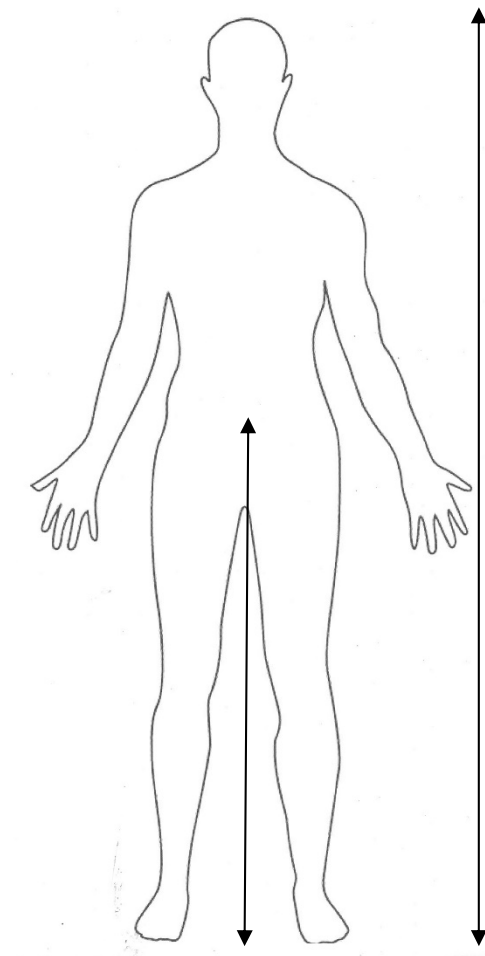


# Fibonacci series – the beauty of math

TED lecture by Arthur Benjamin, <https://youtu.be/SjSHVDfXHQ4>)



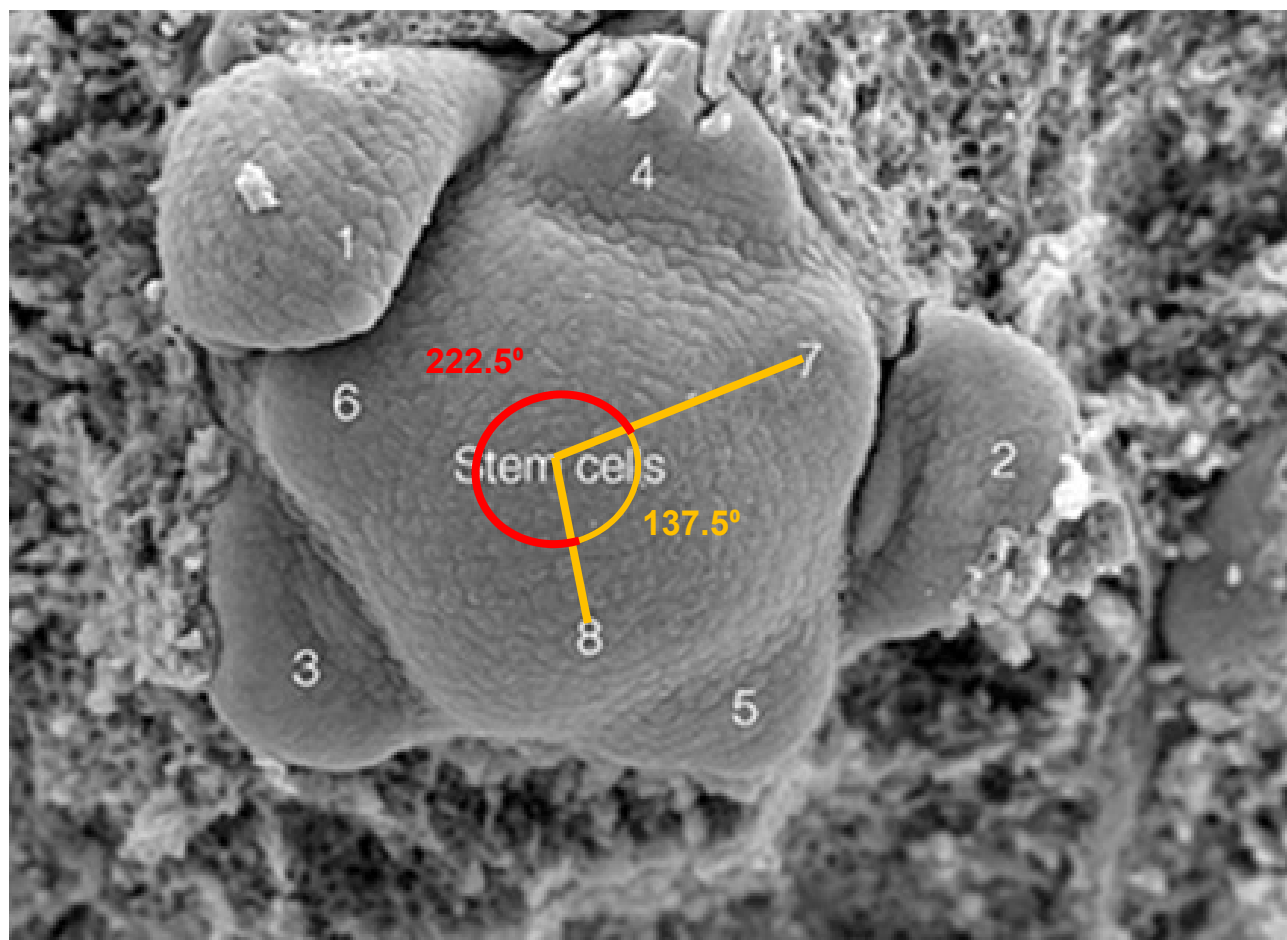




# Golden mean in nature

<https://youtu.be/nt2OIMAJj6o>





$$222.5/137.5 = 1.618$$



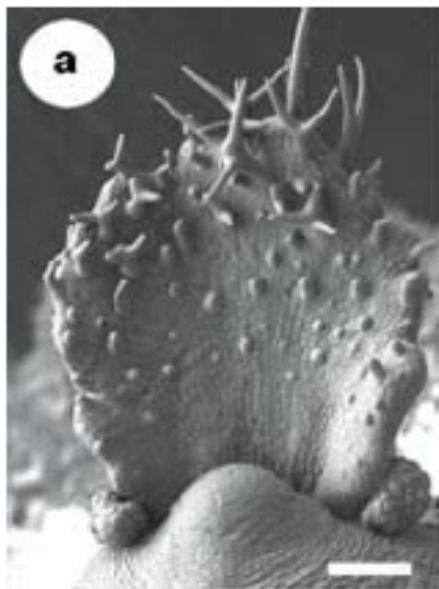
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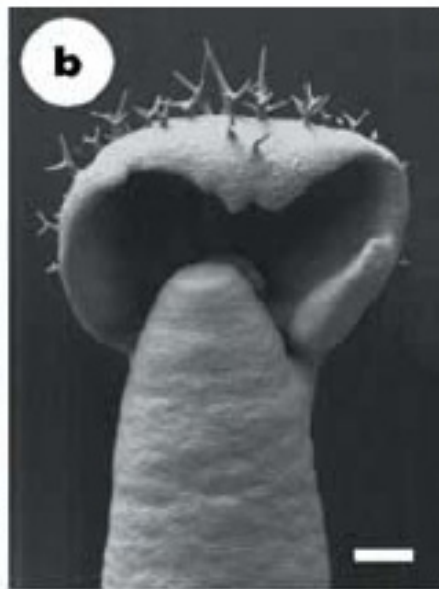
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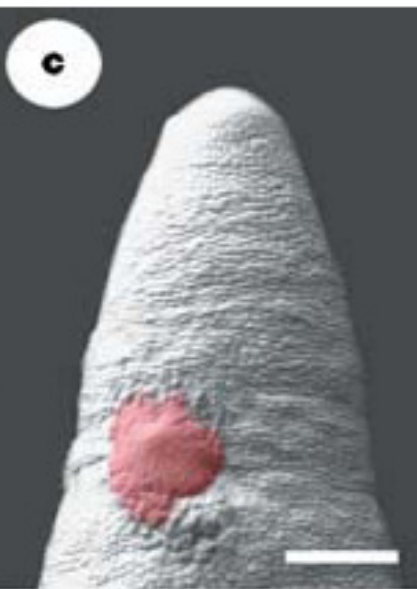
*pin1* + IAA (SAM)



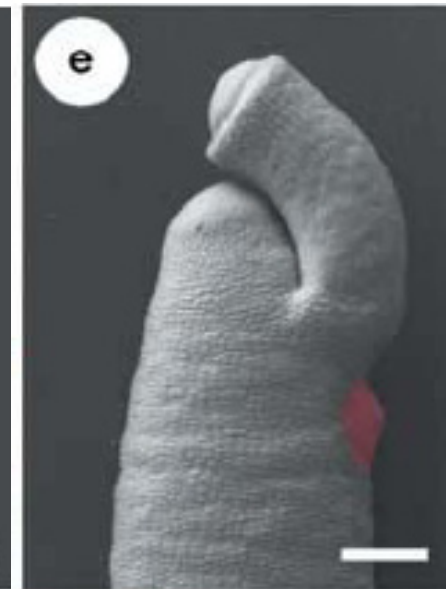
*pin1, lfy* + IAA (IM)



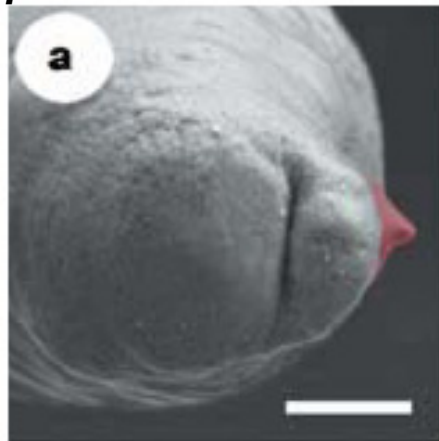
*mp* + IAA



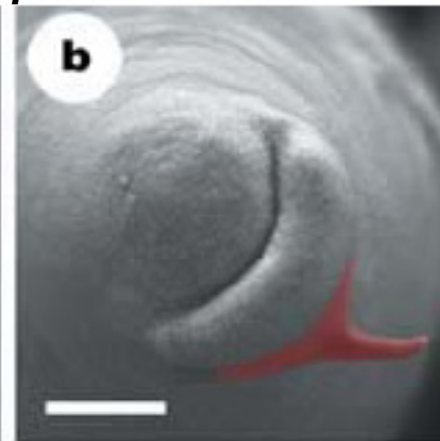
*pid1* + IAA



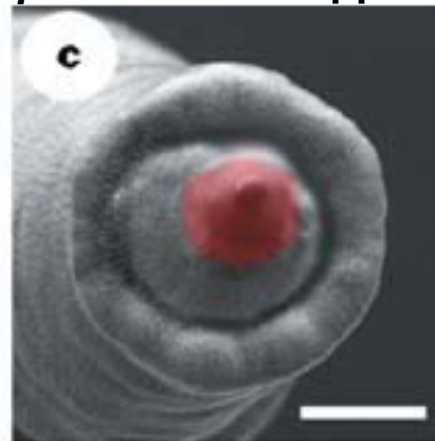
*pin1* + IAA



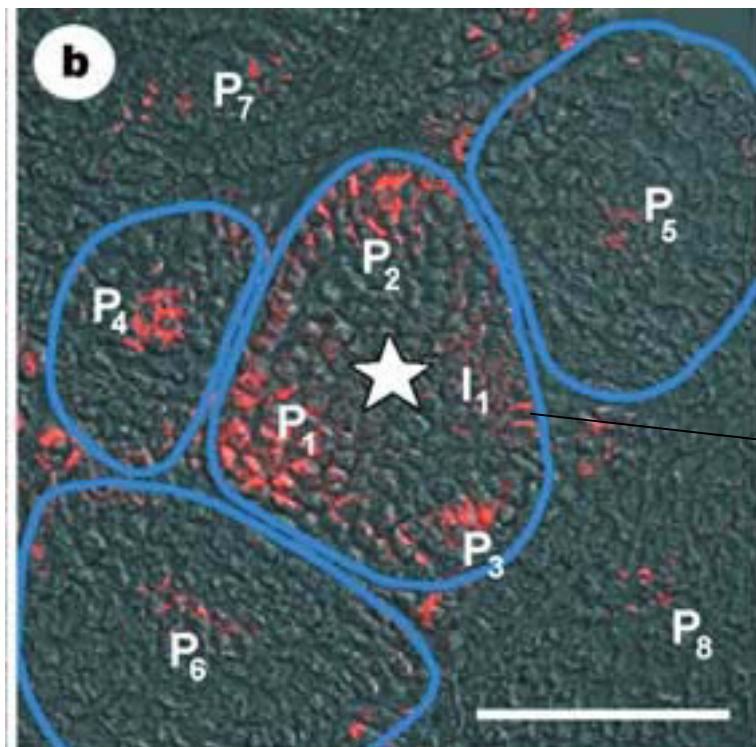
*pin1* + more IAA



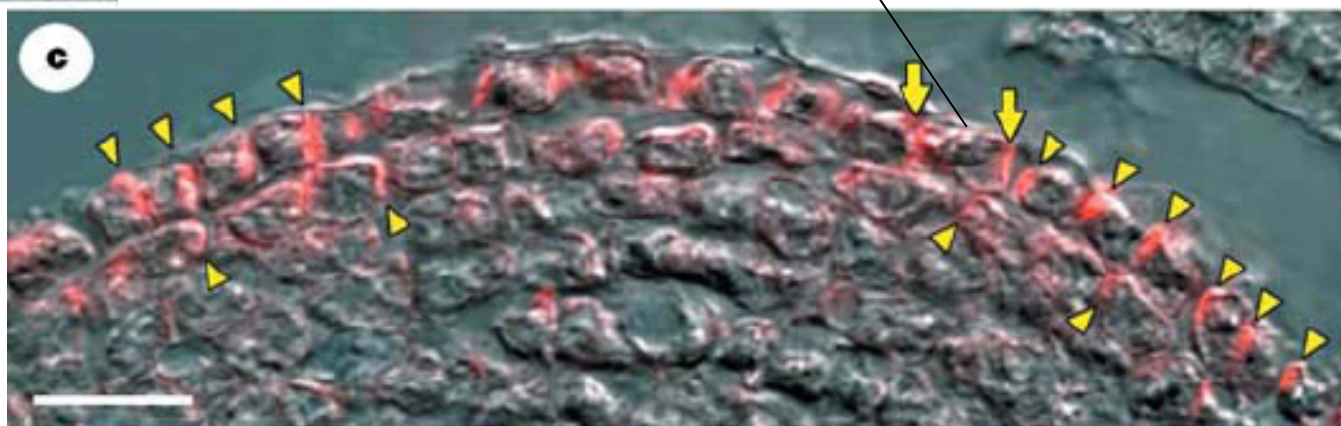
*pin1* + central applied IAA



Reinhardt et al., *Nature* (2005)

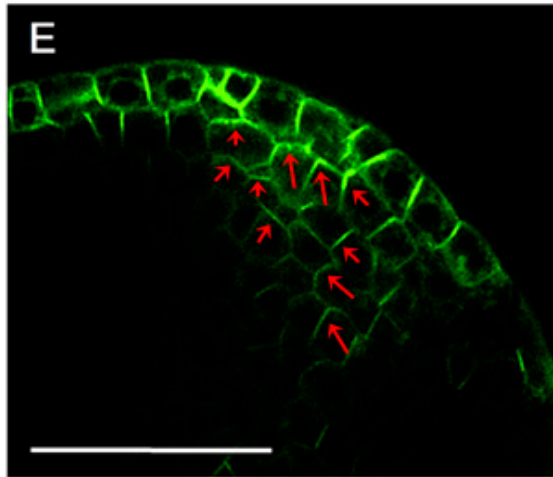


Position of incipient  
primordium



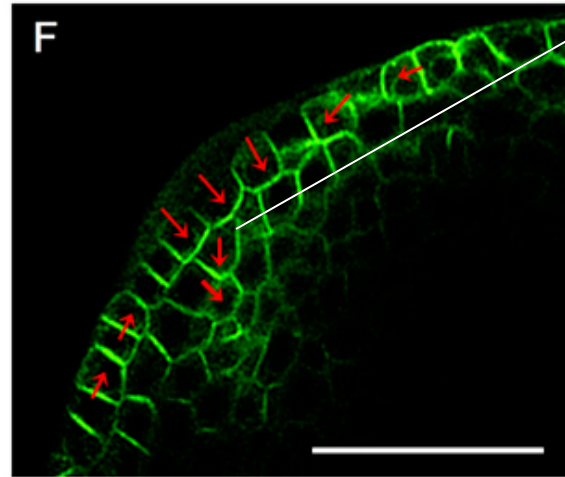
Reinhardt et al., *Nature* (2005)

10 h after IAA application



*ProPIN1:PIN1-GFP*

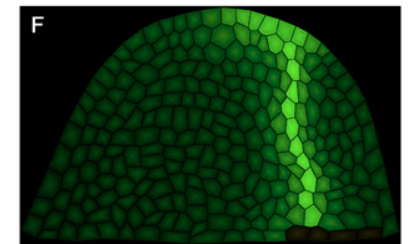
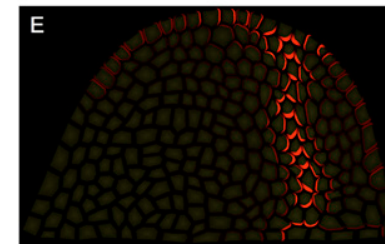
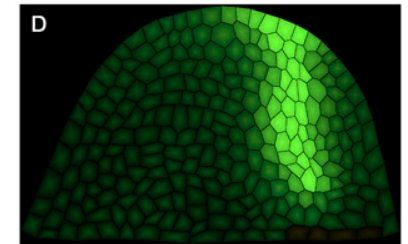
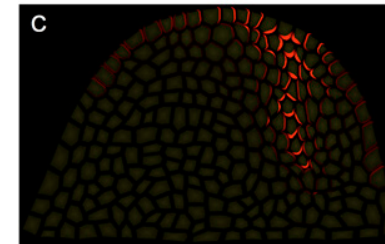
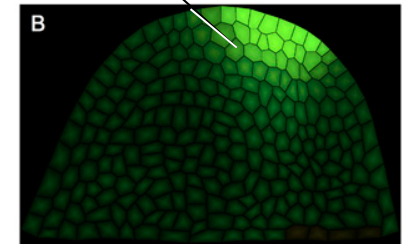
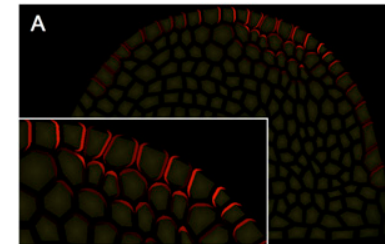
20 h after IAA application



*ProPIN1:PIN1-GFP*

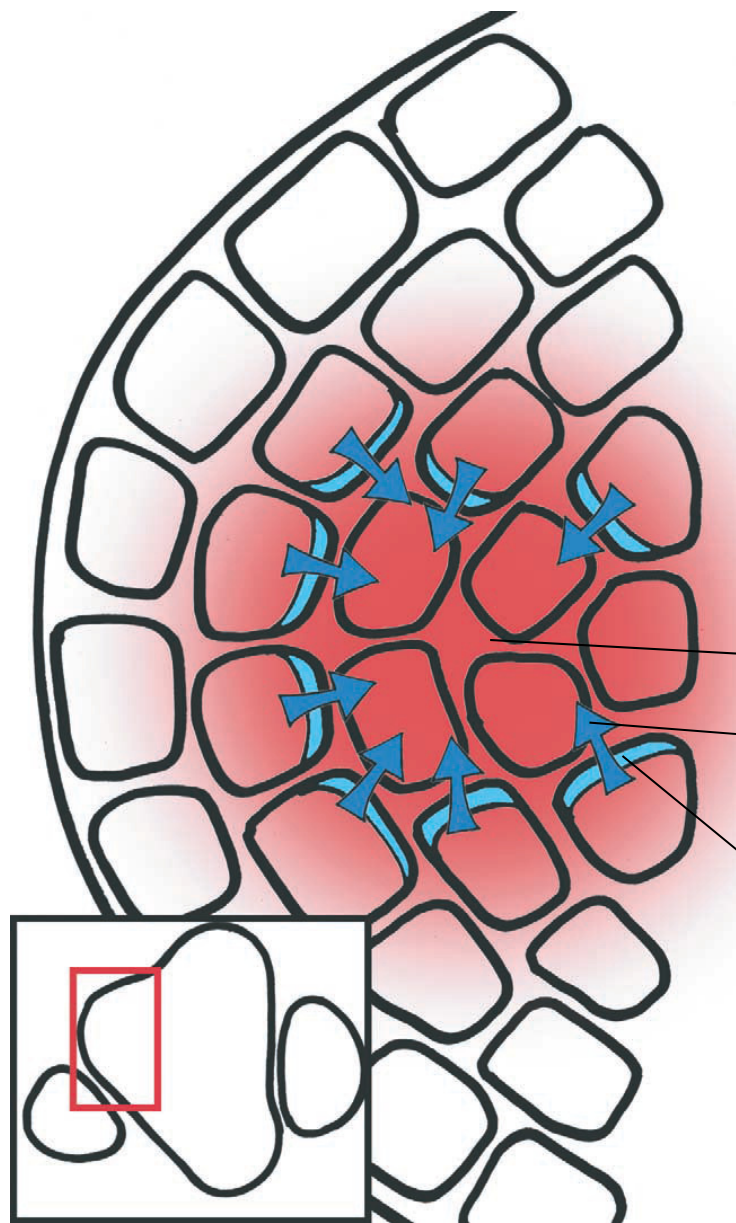
PIN1 relocalization

Auxin accumulation



Bayer et al., *Gene Dev* (2009)

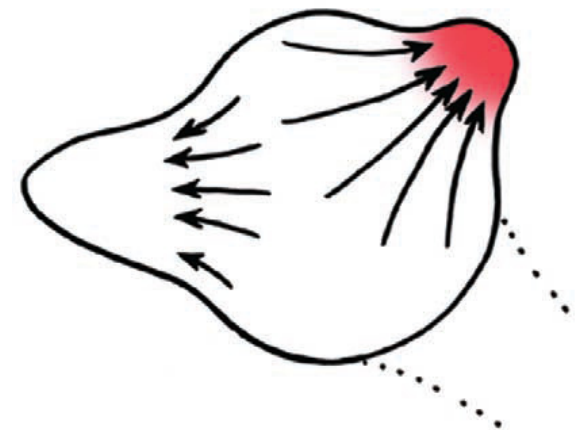
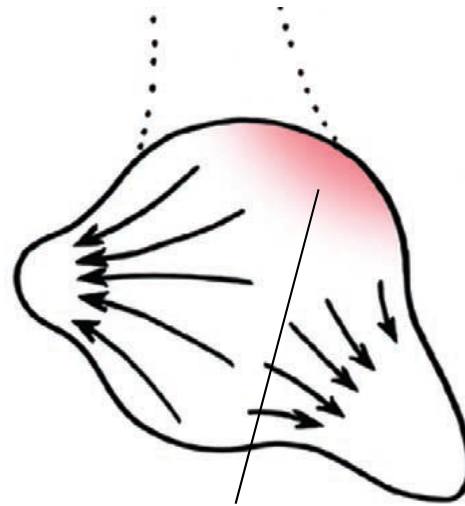




auxin concentration maxima

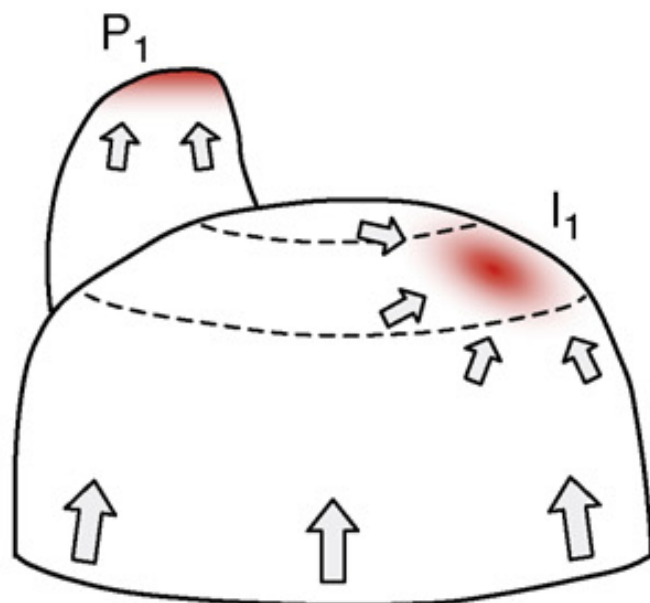
direction of the auxin flow

PIN1

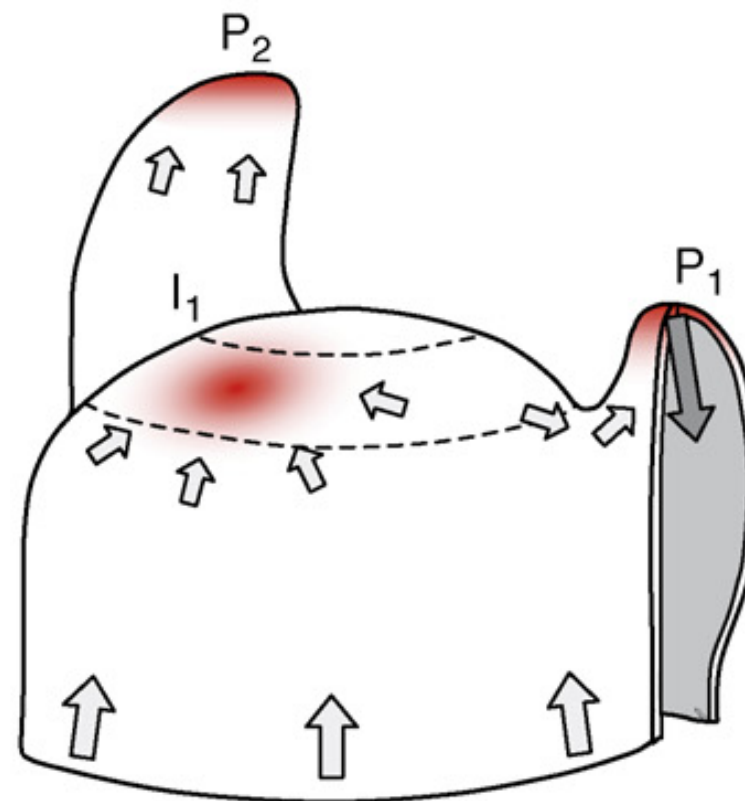


Reinhardt, *Current Opinion Plant Biol* (2005)

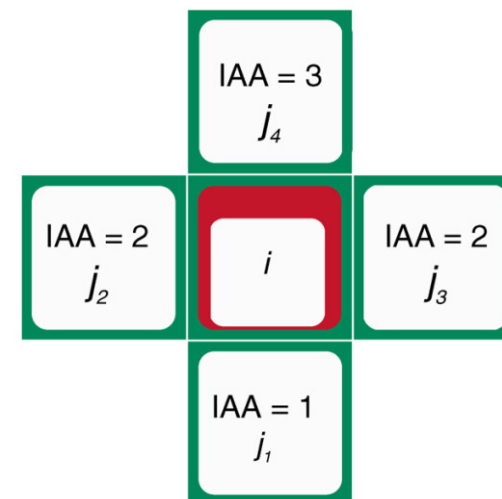
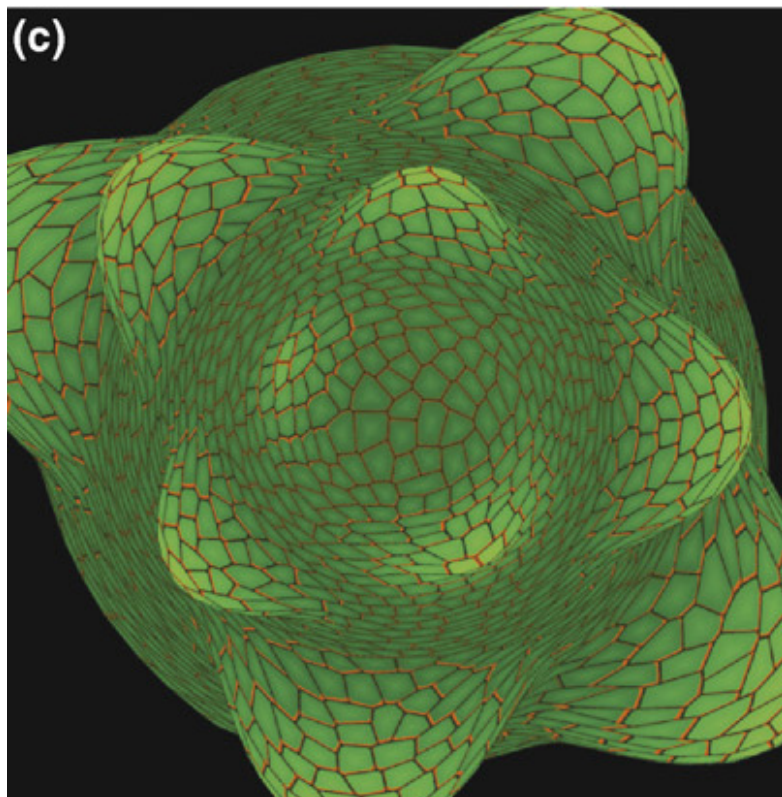
(a)



(b)

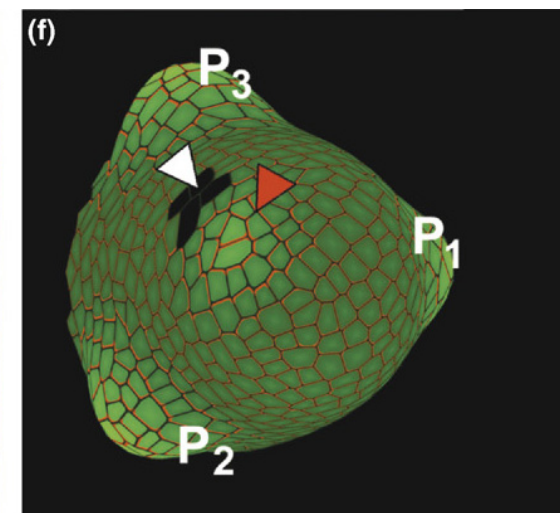
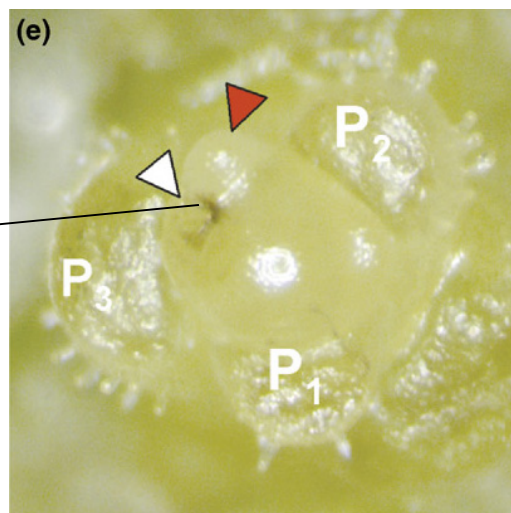


Kuhlermaier, *Trends Plant Sci* (2007)



TRENDS in Plant Science

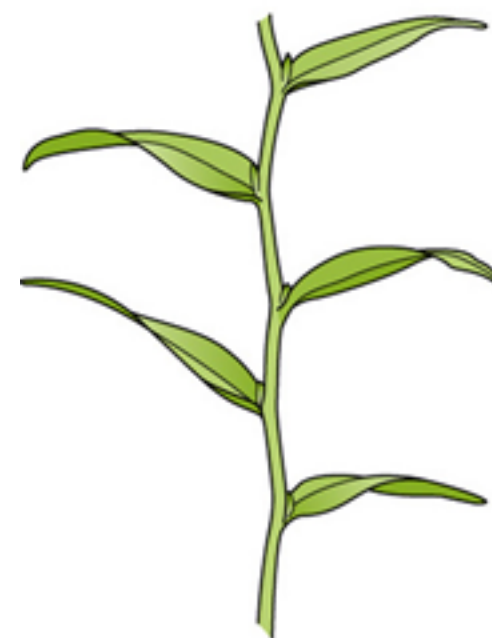
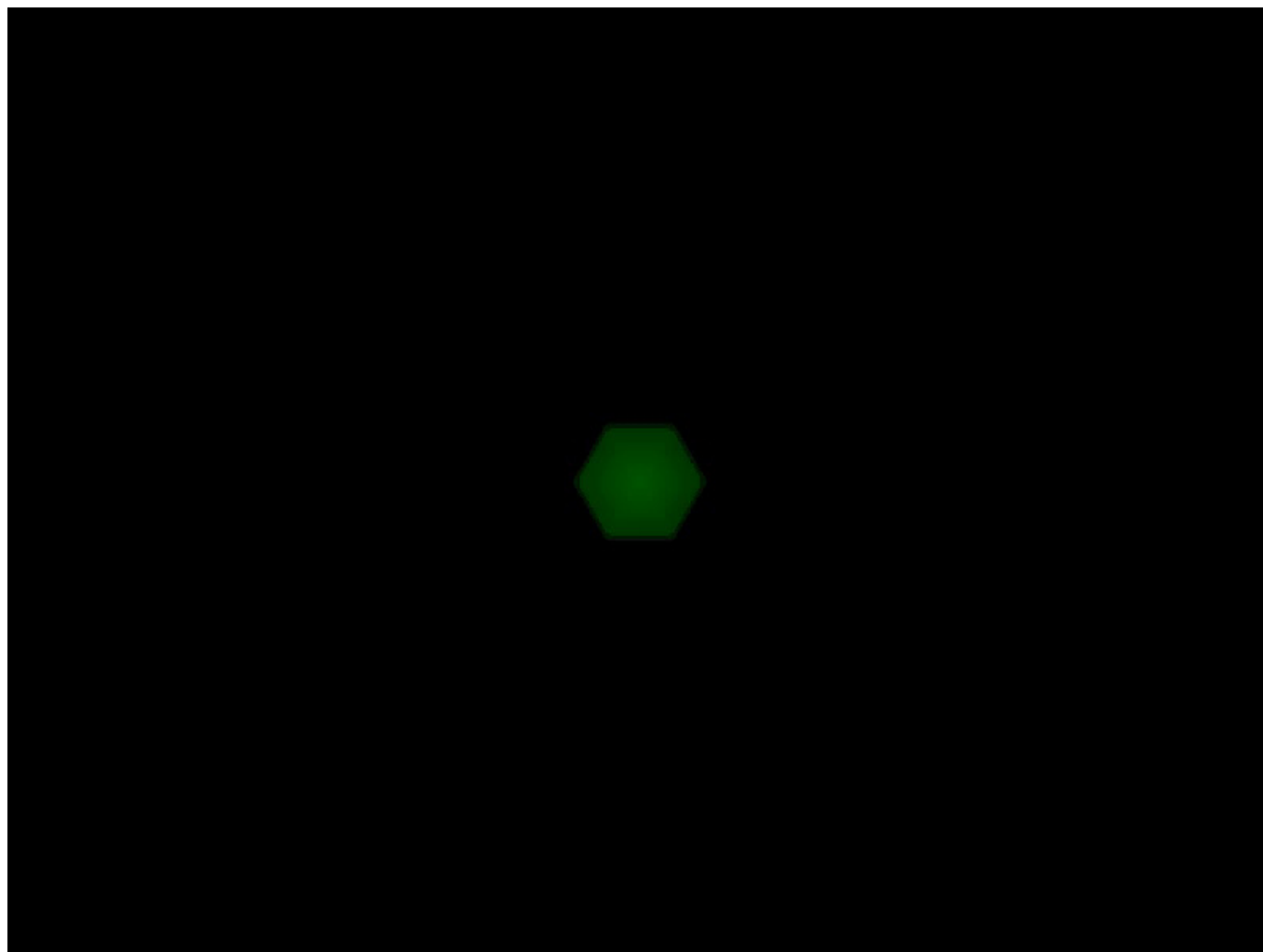
Laser ablation of incipient primordium



Kuhlermaier, *Trends Plant Sci* (2007)



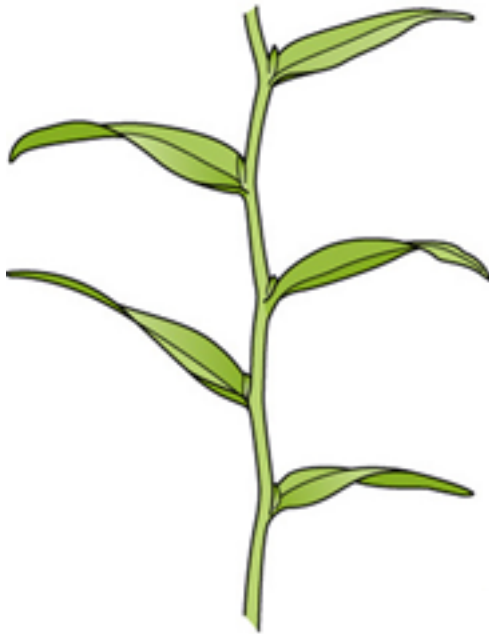
## Distichous Distichie



1 leaf



## Distichous Distichie

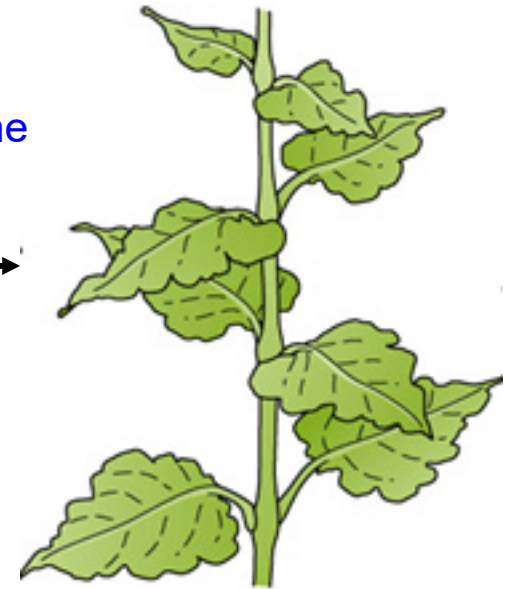


1 leaf

- increasing IAA production
- decreasing the width of the peripheral zone
- increasing the size of the central zone



## Decussate Dvojčetný přeslen



2 leaves

## Decussate Dvojčetný přeslen



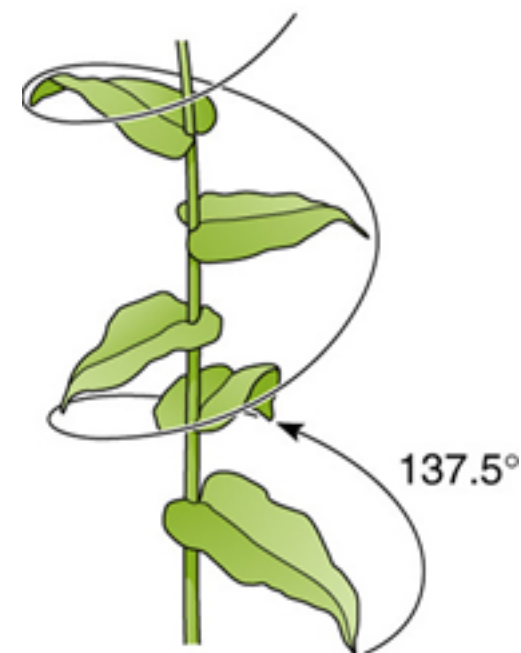
2 leaves

## Tricussate Trojčetný přeslen



3 leaves

## Spiral Spirálovitá fylotaxe



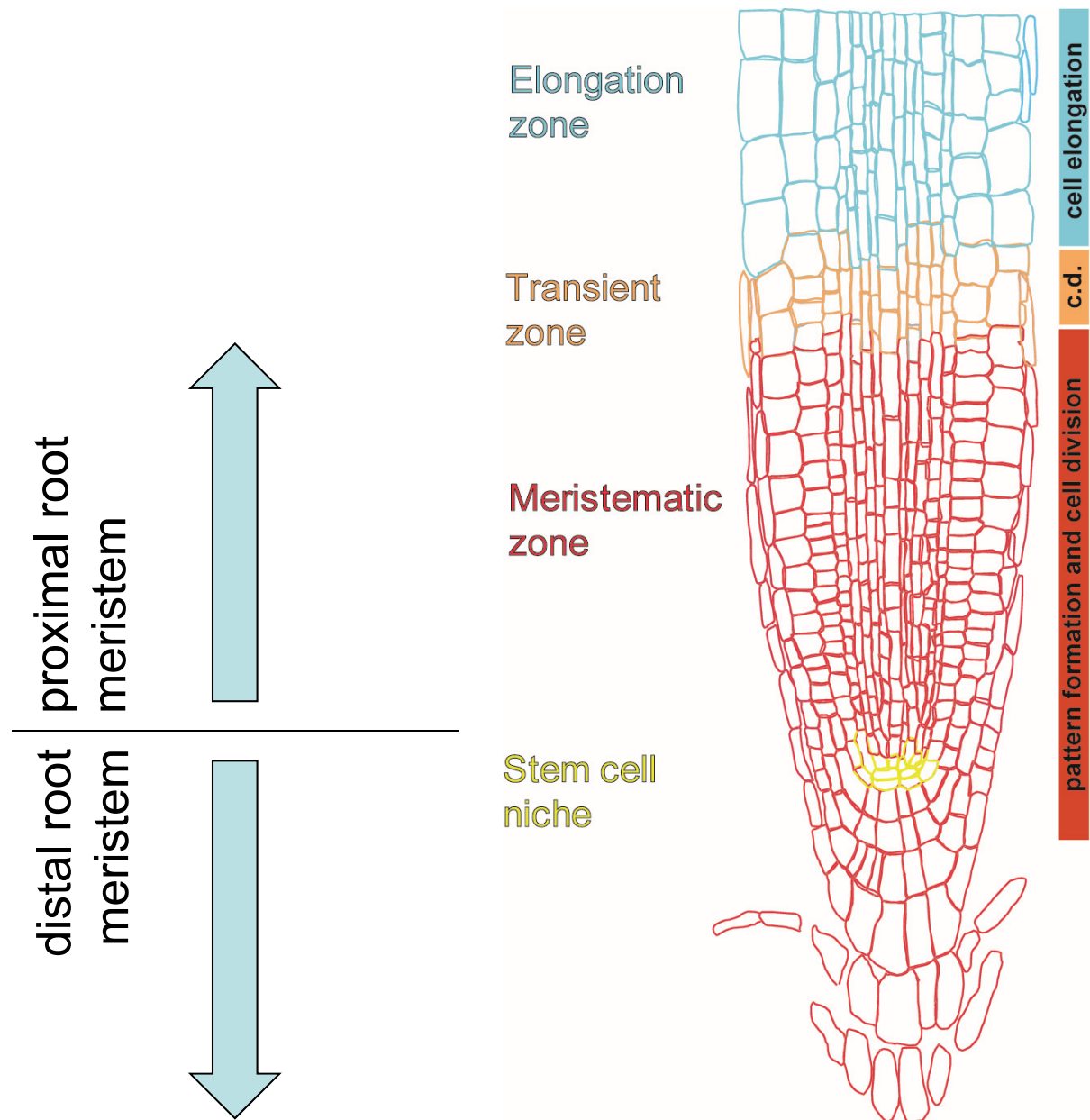




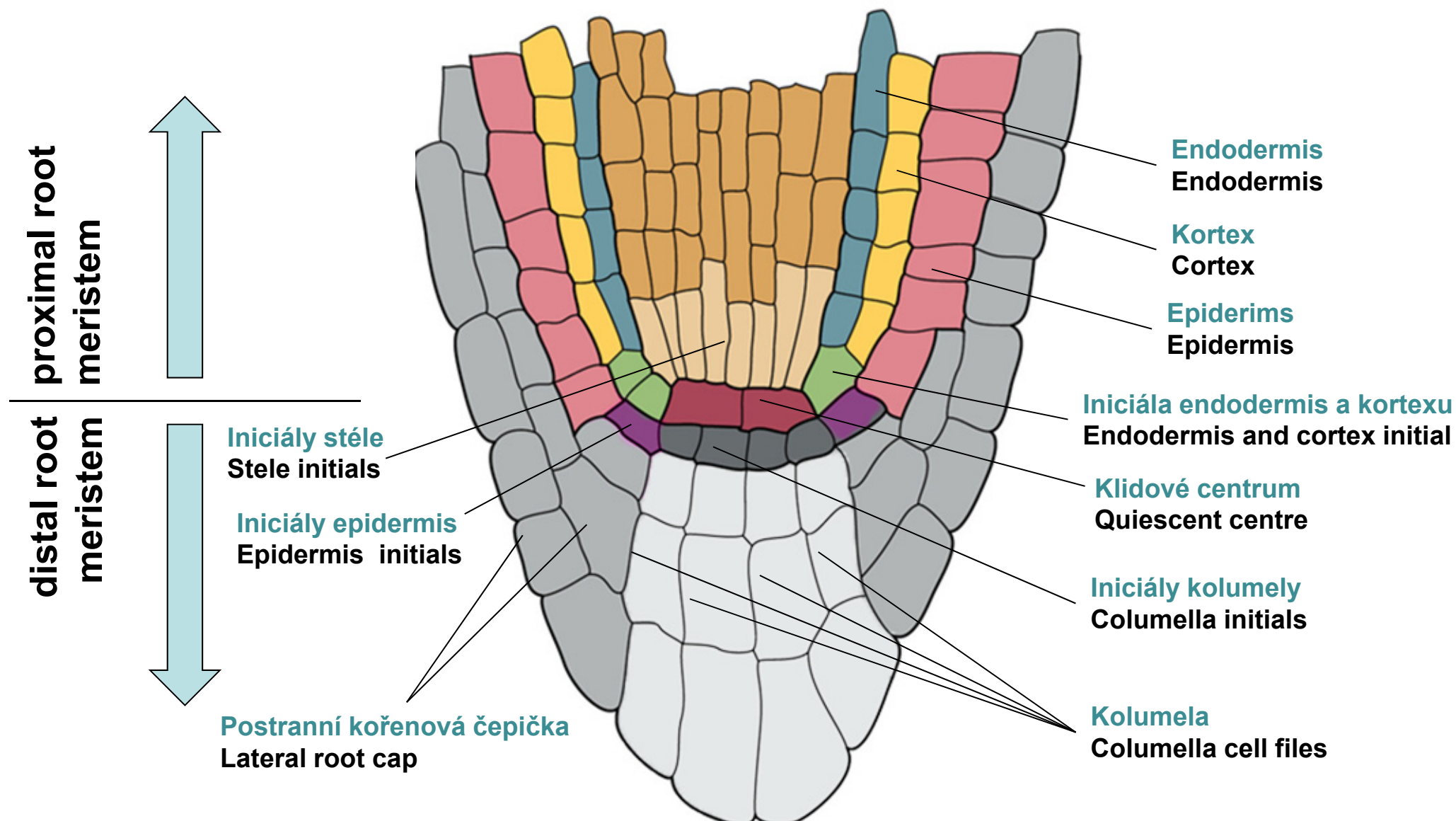
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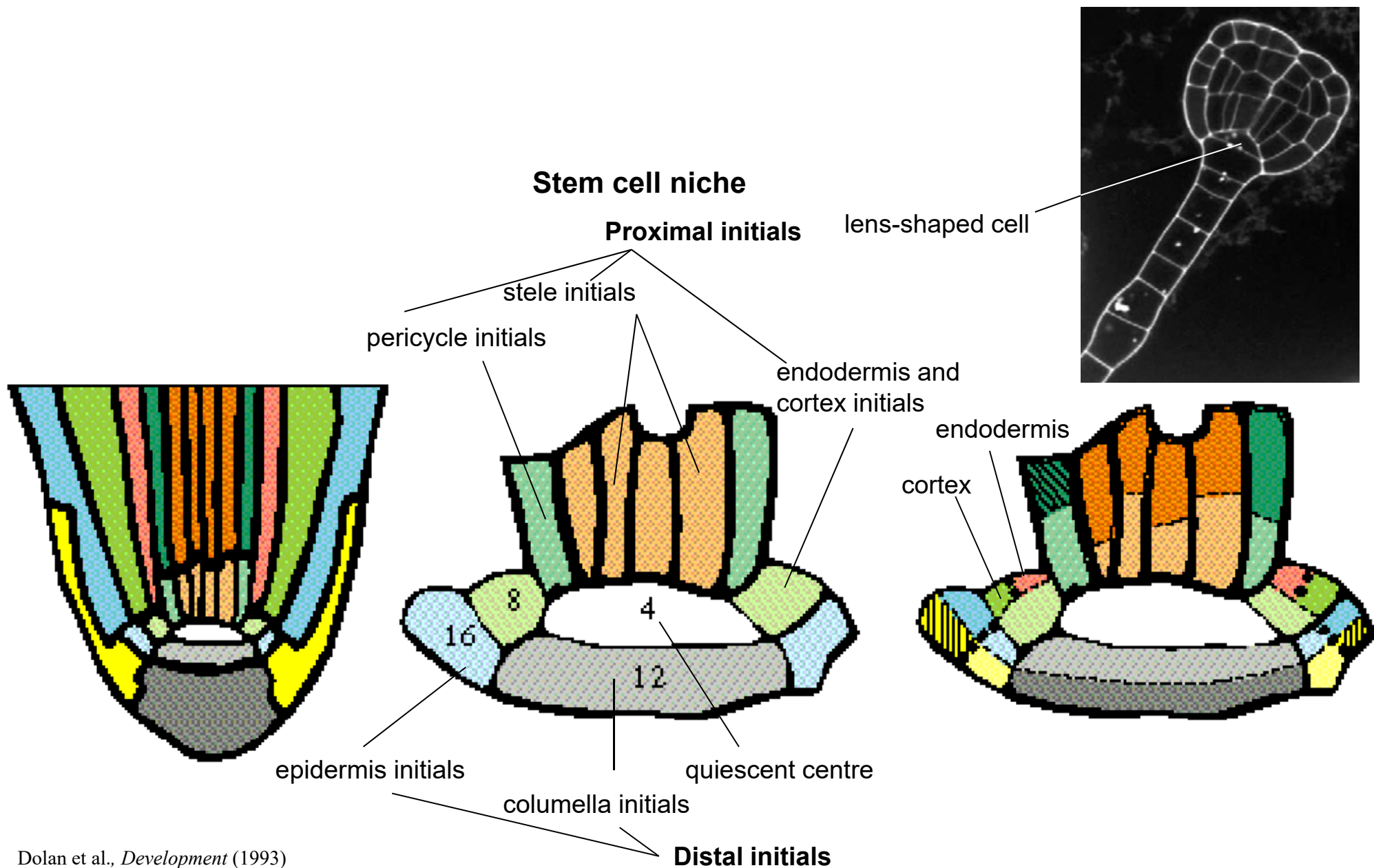
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- Phyllotaxy
  - Fibonacci series and golden mean in the nature
  - Molecular determinants of phyllotaxy
- Root apical meristem (RAM)
  - RAM structure



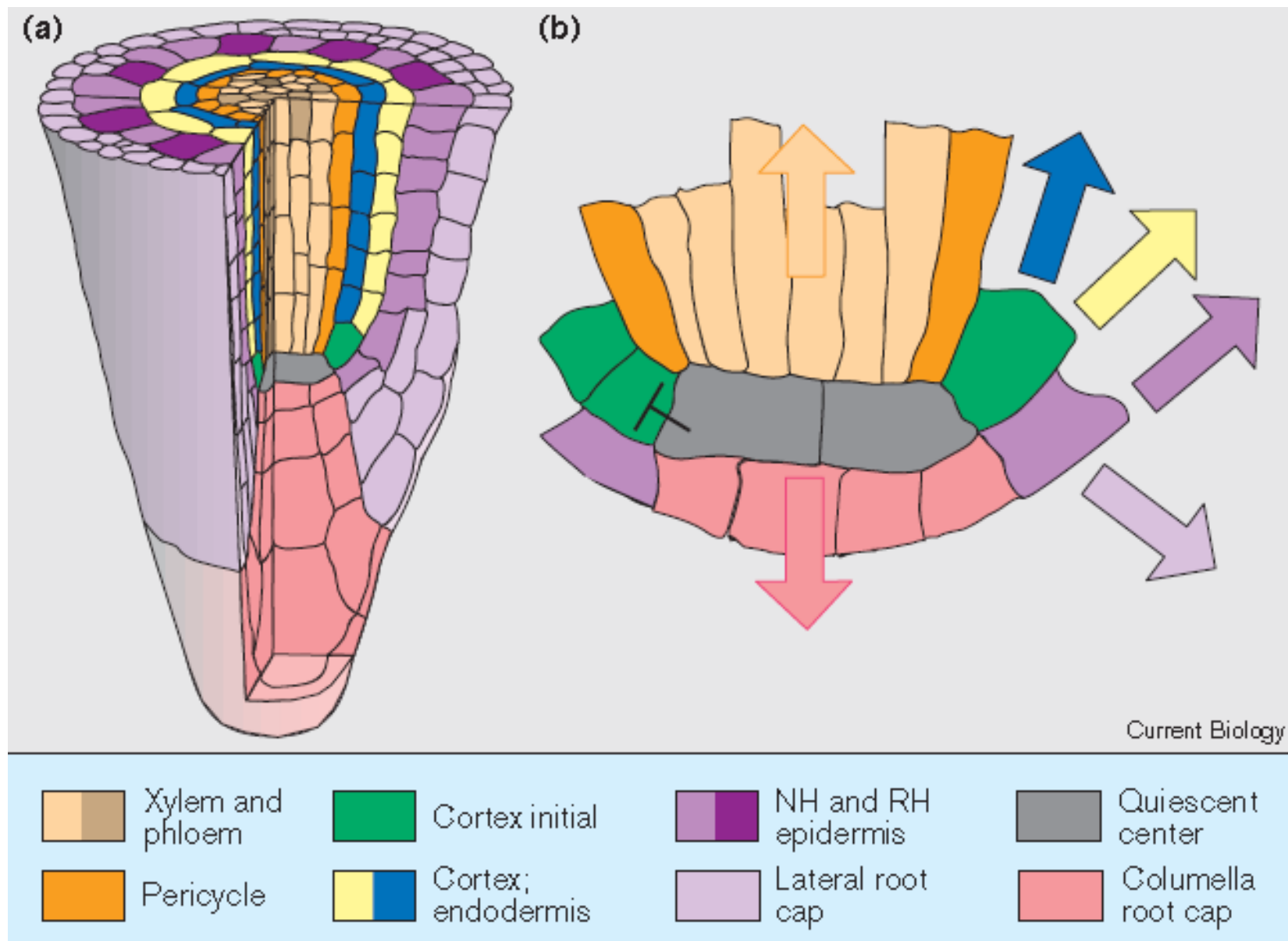
Benkova and Hejatko, *Plant Mol Biol* (2008)





Dolan et al., *Development* (1993)





Benfey and Scheres, *Current Biol* (2000)



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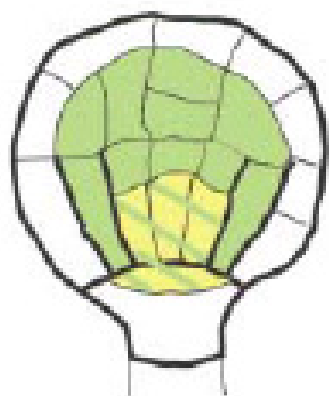
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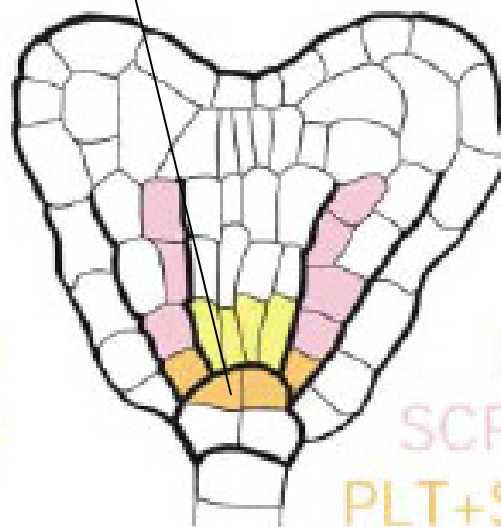
Auxin gradient → PLT

Overlap of expression of *PLT* and *SHR/SCR* provides the positional information for QC positioning

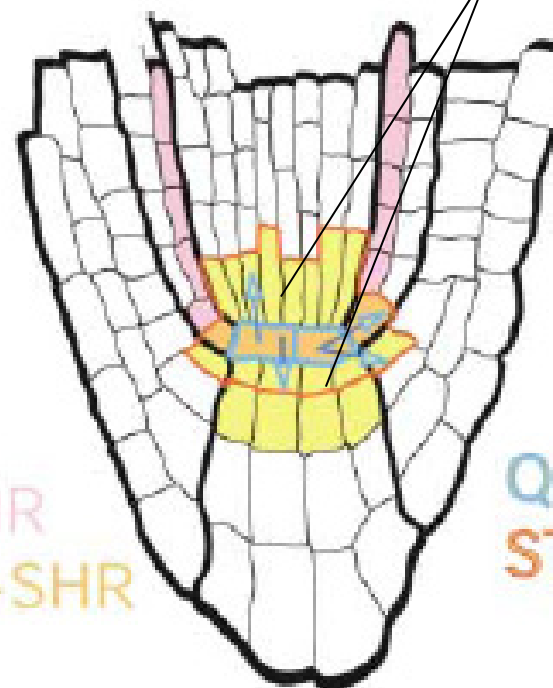
QC-mediated stem cell identity specification



MP  
PLT



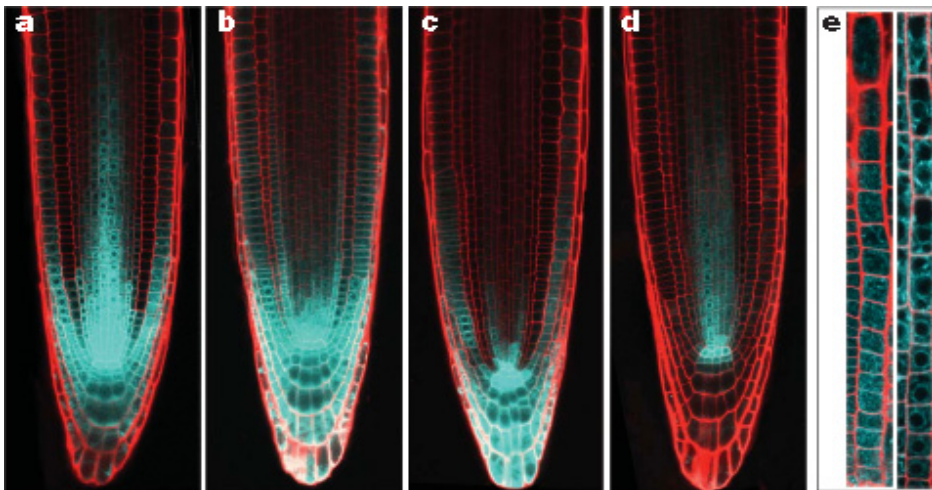
PLT  
SCR+SHR  
PLT+SCR+SHR



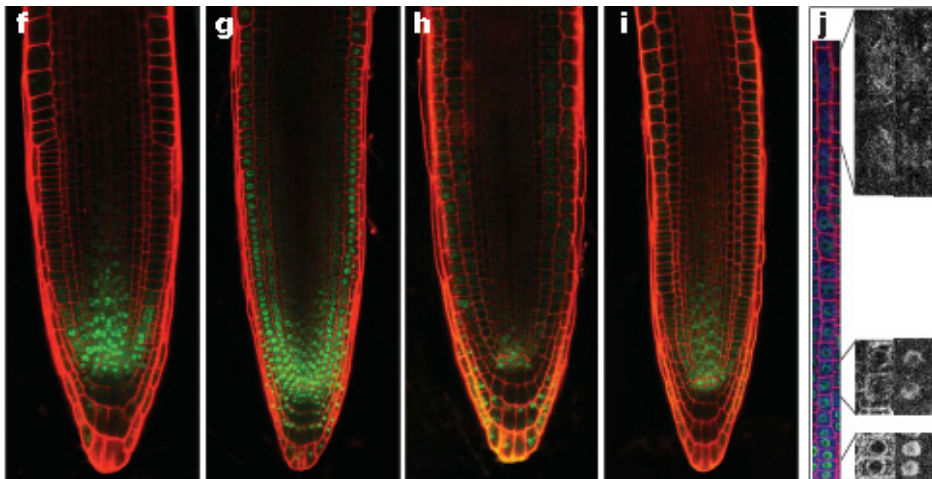
QC  
STEM CELLS

Aida et al., *Cell* (2004)

ProPLT1:CFP ProPLT2:CFP ProPLT3:CFP ProBBM:CFP



ProPLT1:PLT1-CFP ProPLT2:PLT2-CFP ProPLT3:PLT3-CFP ProBBM:BBM-CFP



PLT1, 2, BBM  
gradient

Differentiated  
cells

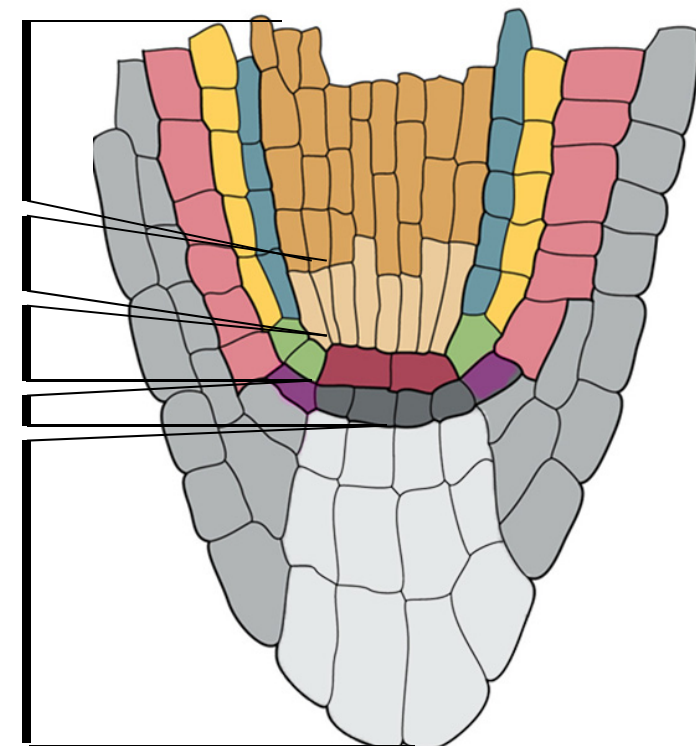
Proximal  
initials

QC

Distal  
initials

Differentiated  
cells

PLT2,3  
gradient

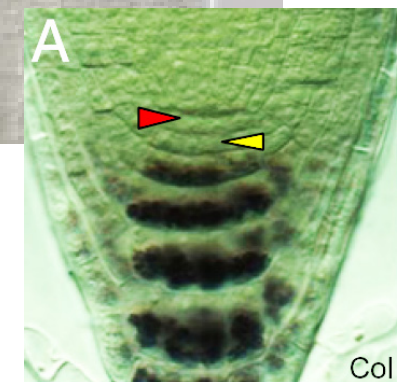
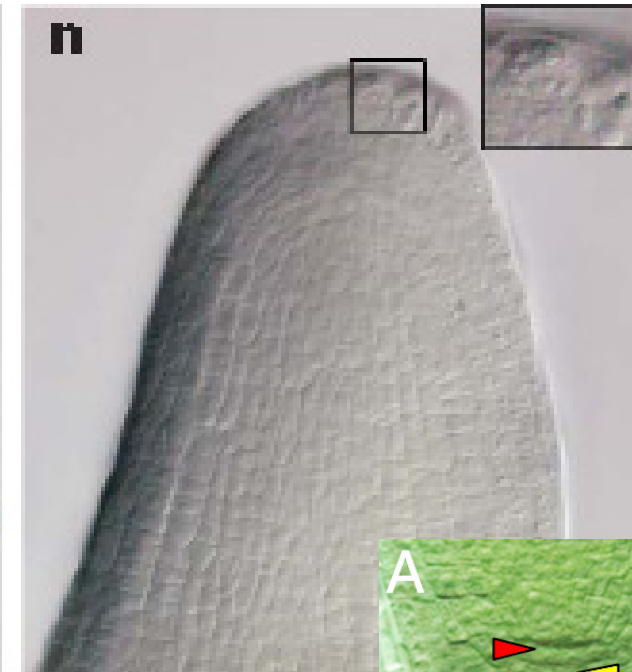


Galinha et al., *Nature* (2007)



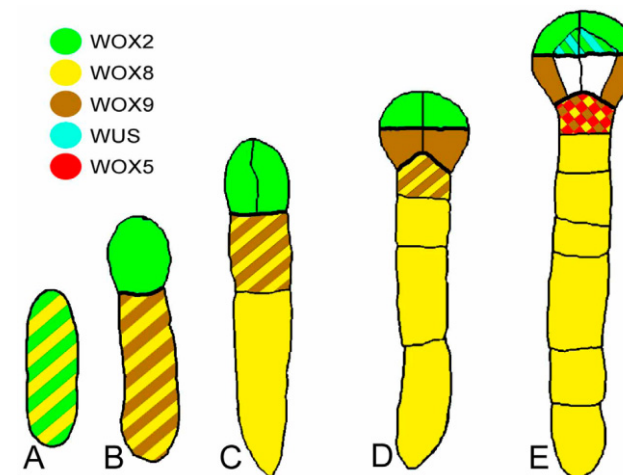
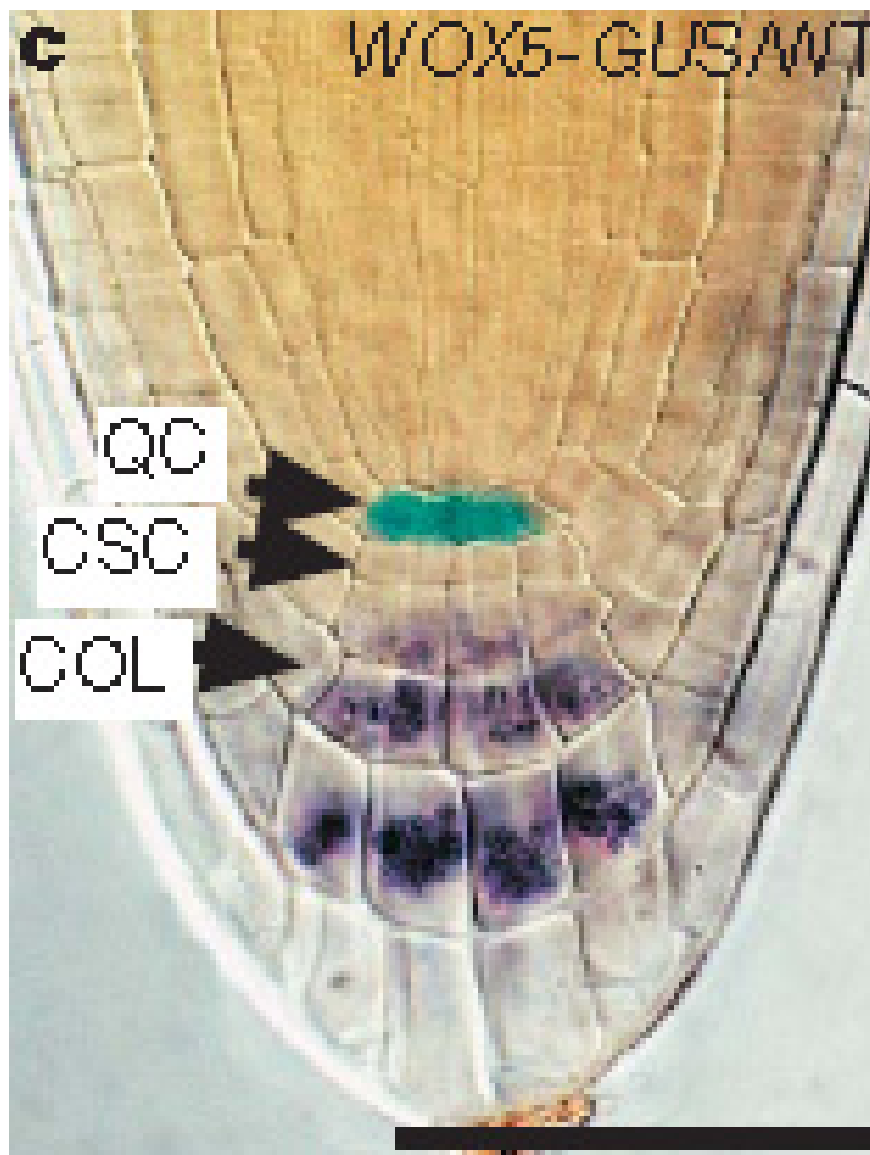
# ***PLTs* are master regulatory genes**

## ***Pro35S-PLT2-GR***

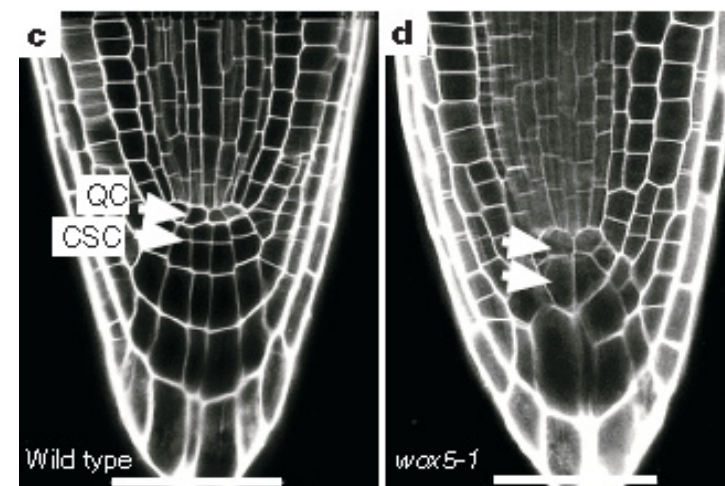


Galinha et al., *Nature* (2007)

Ding et al., *PNAS* (2010)



cellular pattern and cell identity of the stem cell niche affected



Sarkar et al., *Nature* (2007)

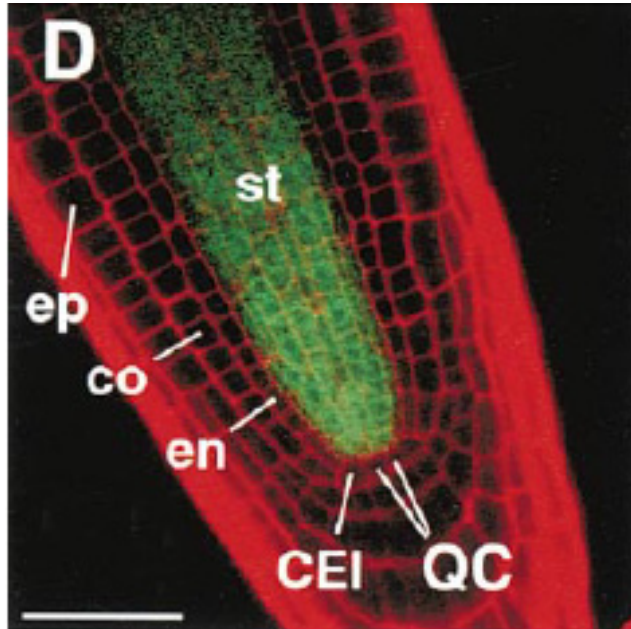


# Outline of Lesson 8

## Postembryonic Plant Development

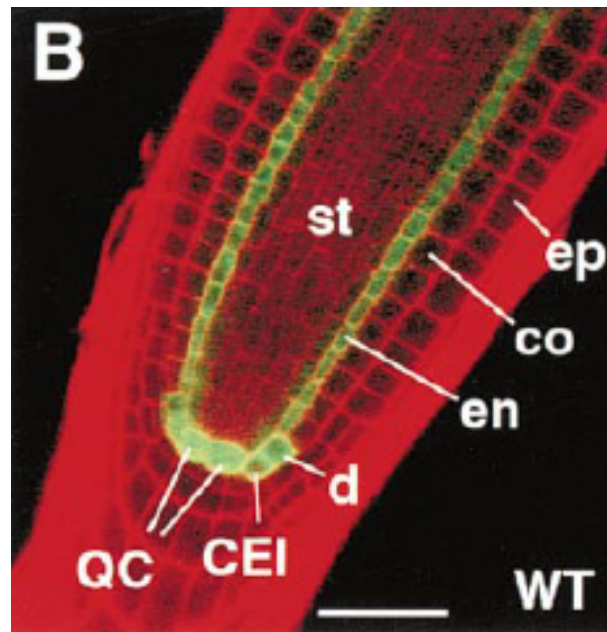
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- Root apical meristem (RAM)
  - RAM structure
  - Positioning of RAM organization centre
  - Radial root patterning

*ProSHR:GFP/WT*

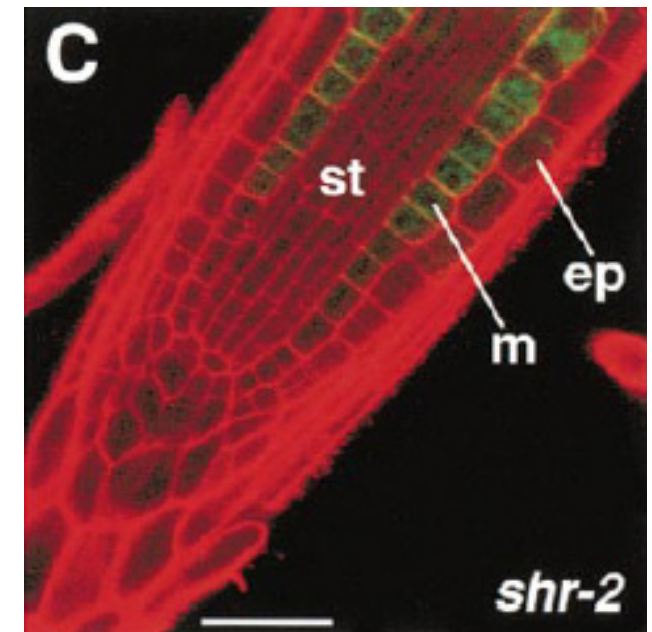


## SHR and SCR, TFs from the GRAS family

*ProSCR:GFP/WT*



*ProSCR:GFP/shr-2*

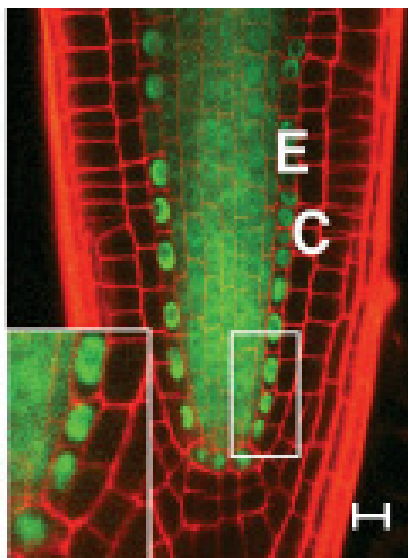


Helariutta et al., *Cell* (2000)

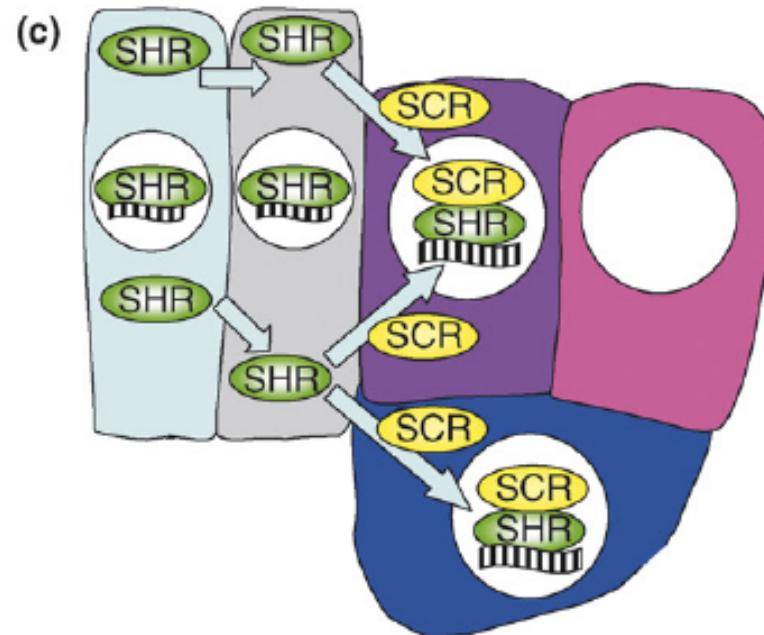
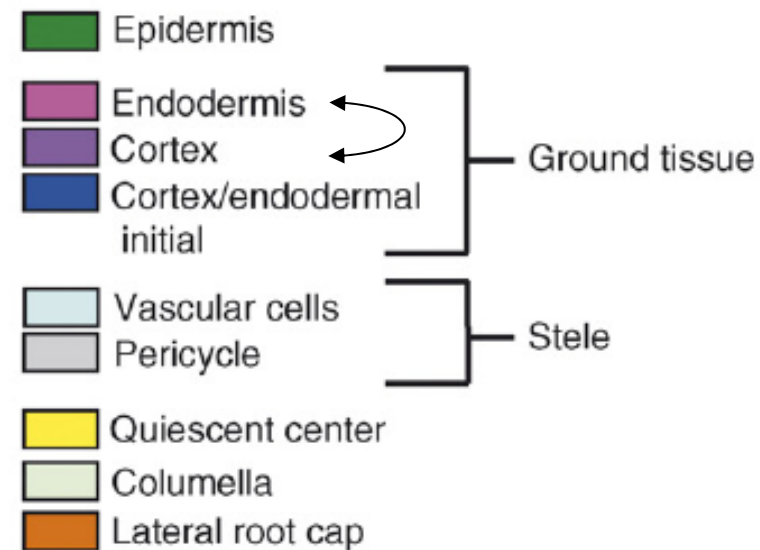
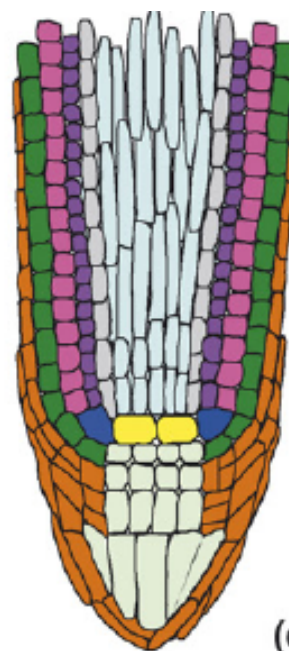
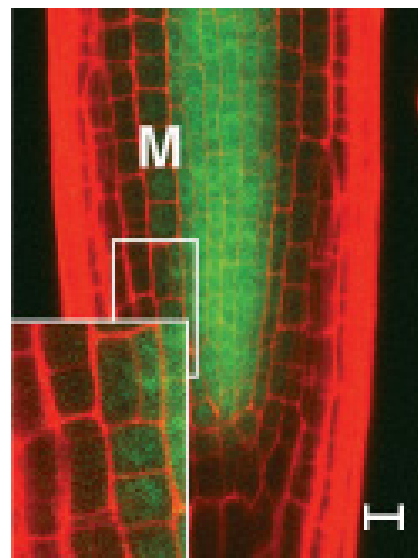


ProSHR:SHR-GFP

WT

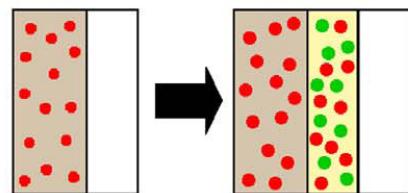


*scr*

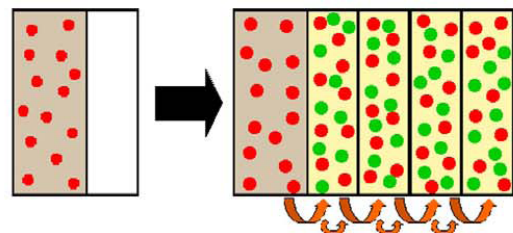


Petricka & Benfey, *Curr Opin Genet Dev* (2008)

WT



ProSCR:SHR

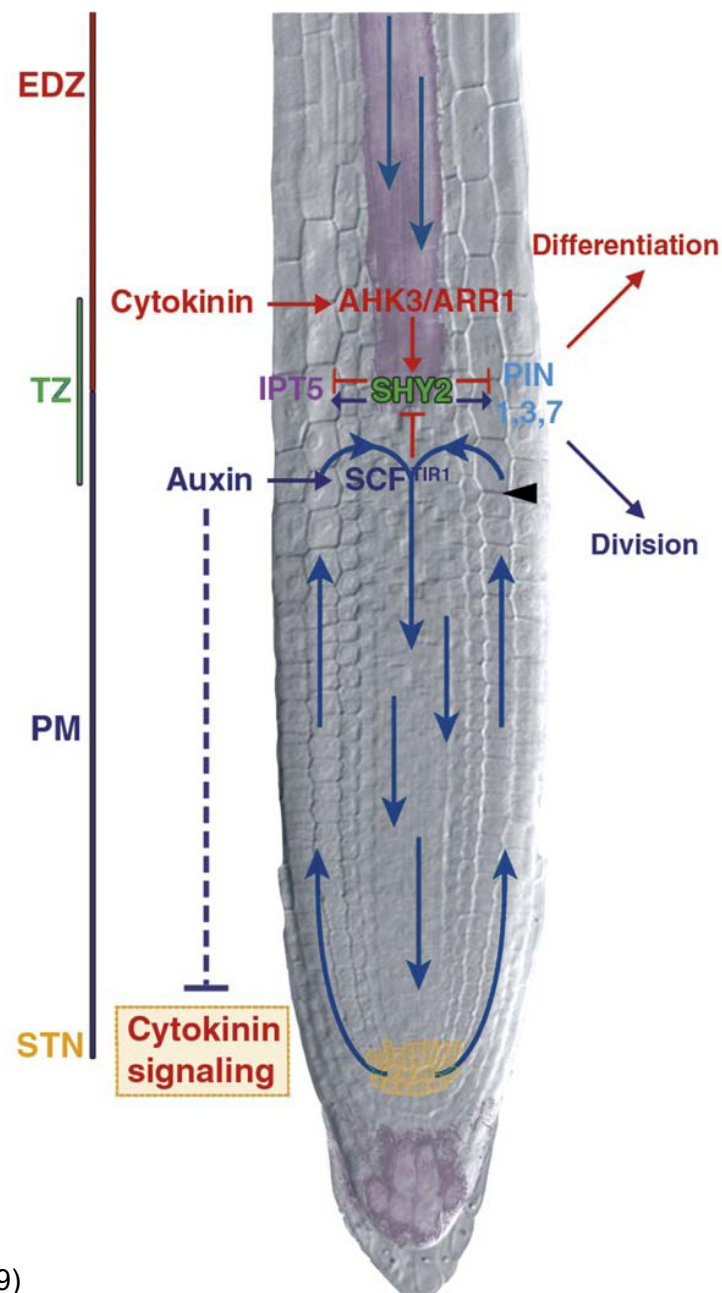




# Outline of Lesson 8

## Postembryonic Plant Development

- The role of plant meristems in the plant postembryonic development
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  - Fibonacci series and golden mean in the nature
  - Molecular determinants of phyllotaxy
- Root apical meristem (RAM)
  - RAM structure
  - Positioning of RAM organization centre
  - Radial root patterning
  - RAM size determination



Moubayidin et al., *Trends in Plant Sci* (2009)

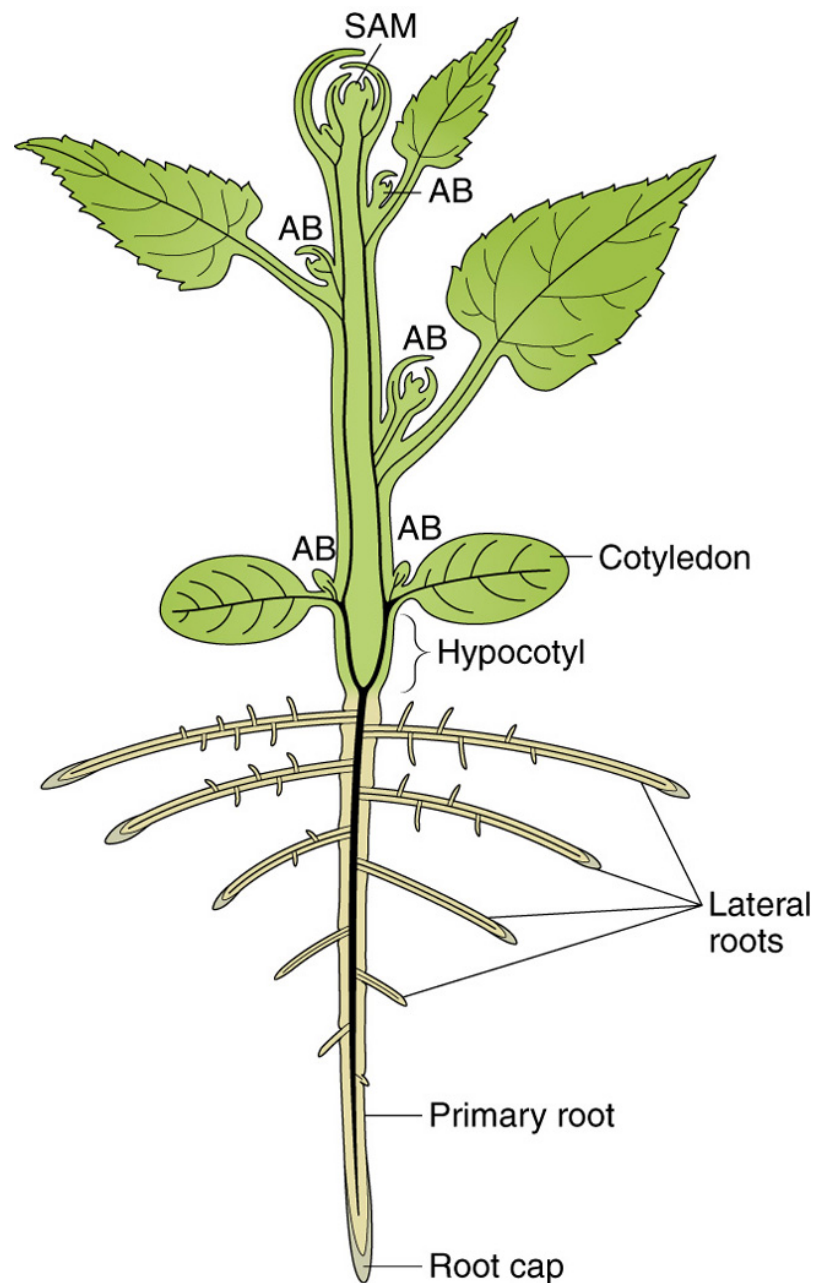


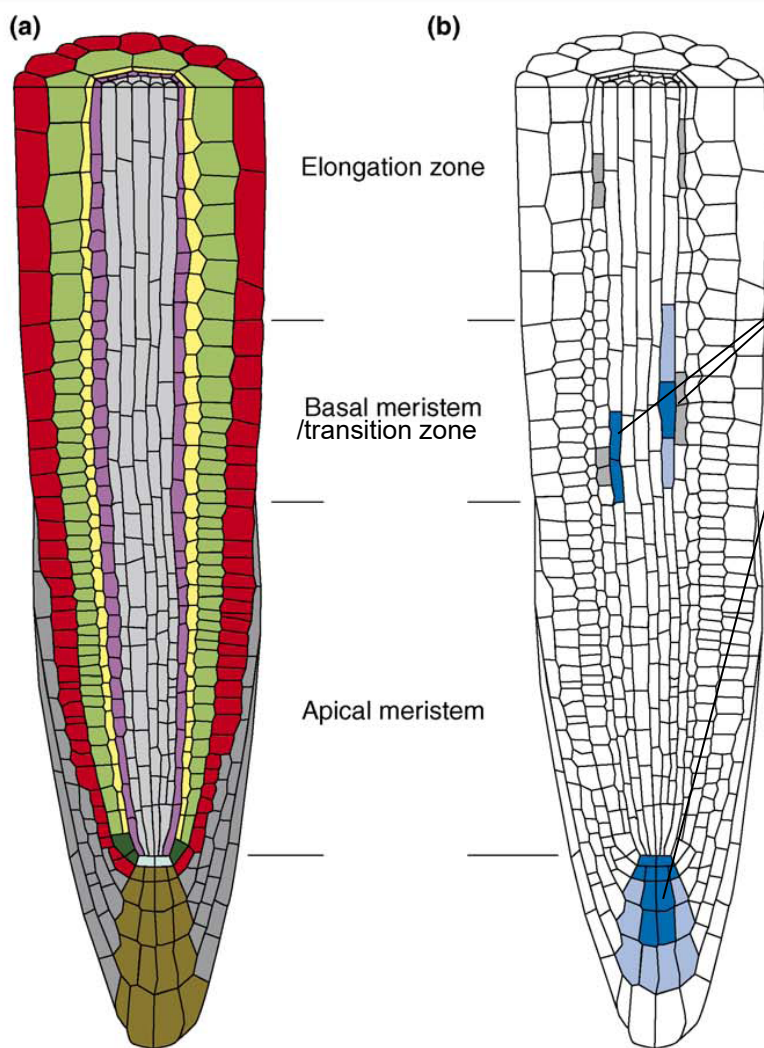
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  - Root radial patterning
  - RAM size determination
- Lateral root formation







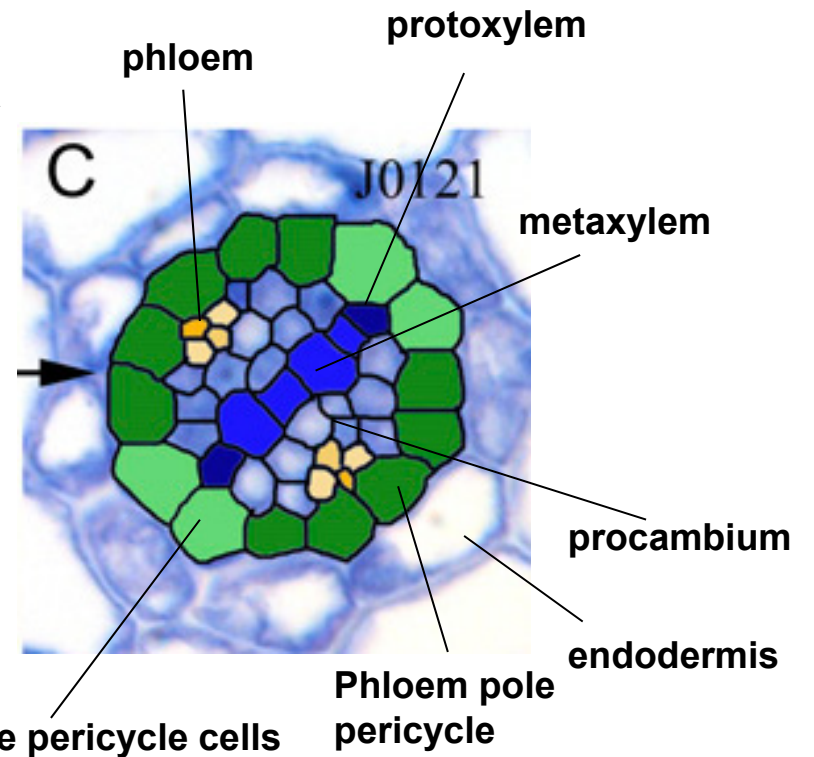
**Key:**

■ Epidermis	■ Quiescent center	■ Auxin maximum
■ Cortex	■ Cortex/endodermis initials	■ Primed pericycle cells
■ Endodermis	■ Columella root cap	
■ Pericycle	■ Lateral root cap	
■ Stele		

Peret et al., *Trends in Plant Sci* (2009)

*TRENDS in Plant Science*

**Auxin maxima**

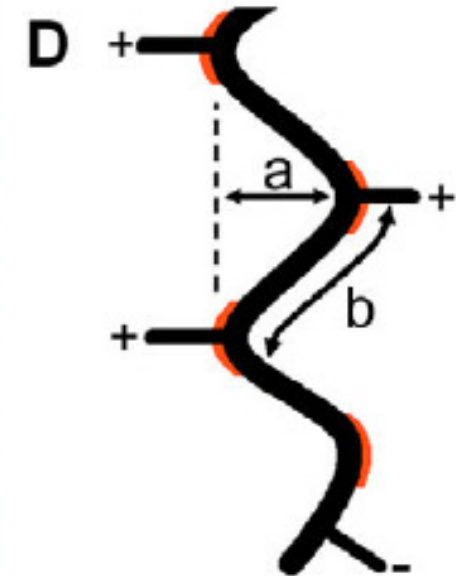
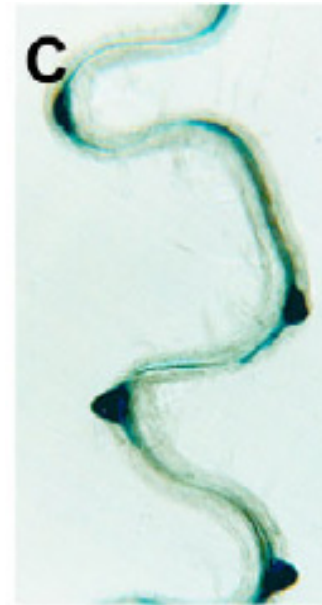
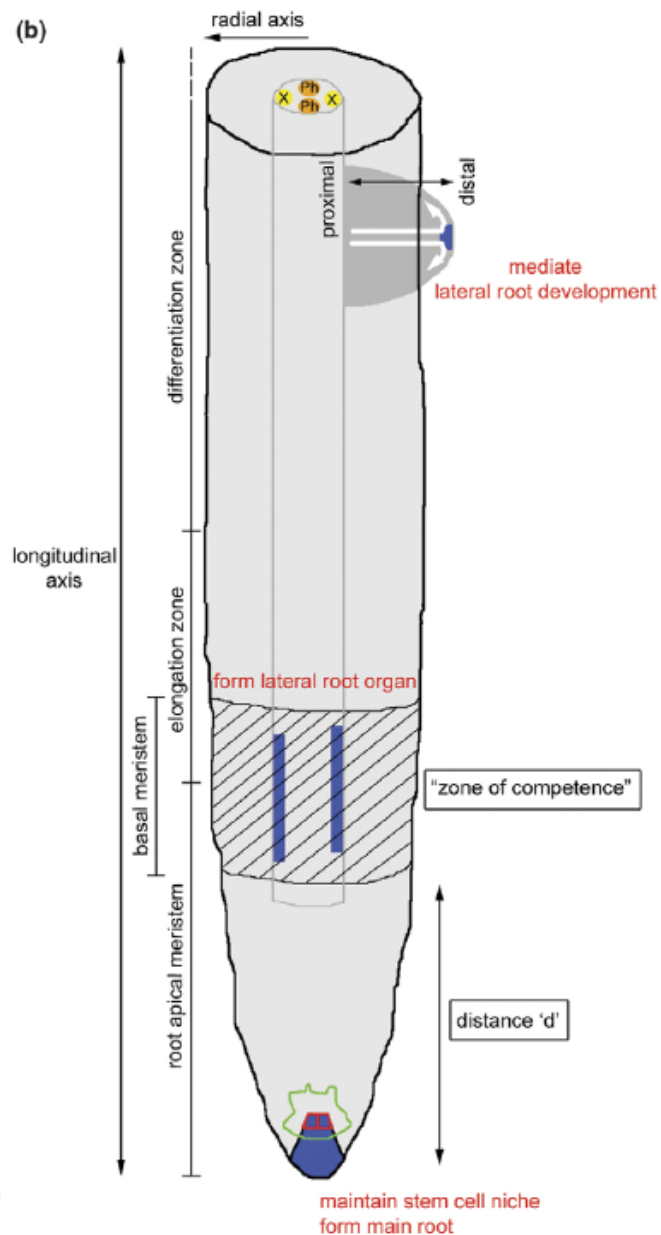


**G2 phase**

**G1 phase**

**auxin maxima → LRP formation**

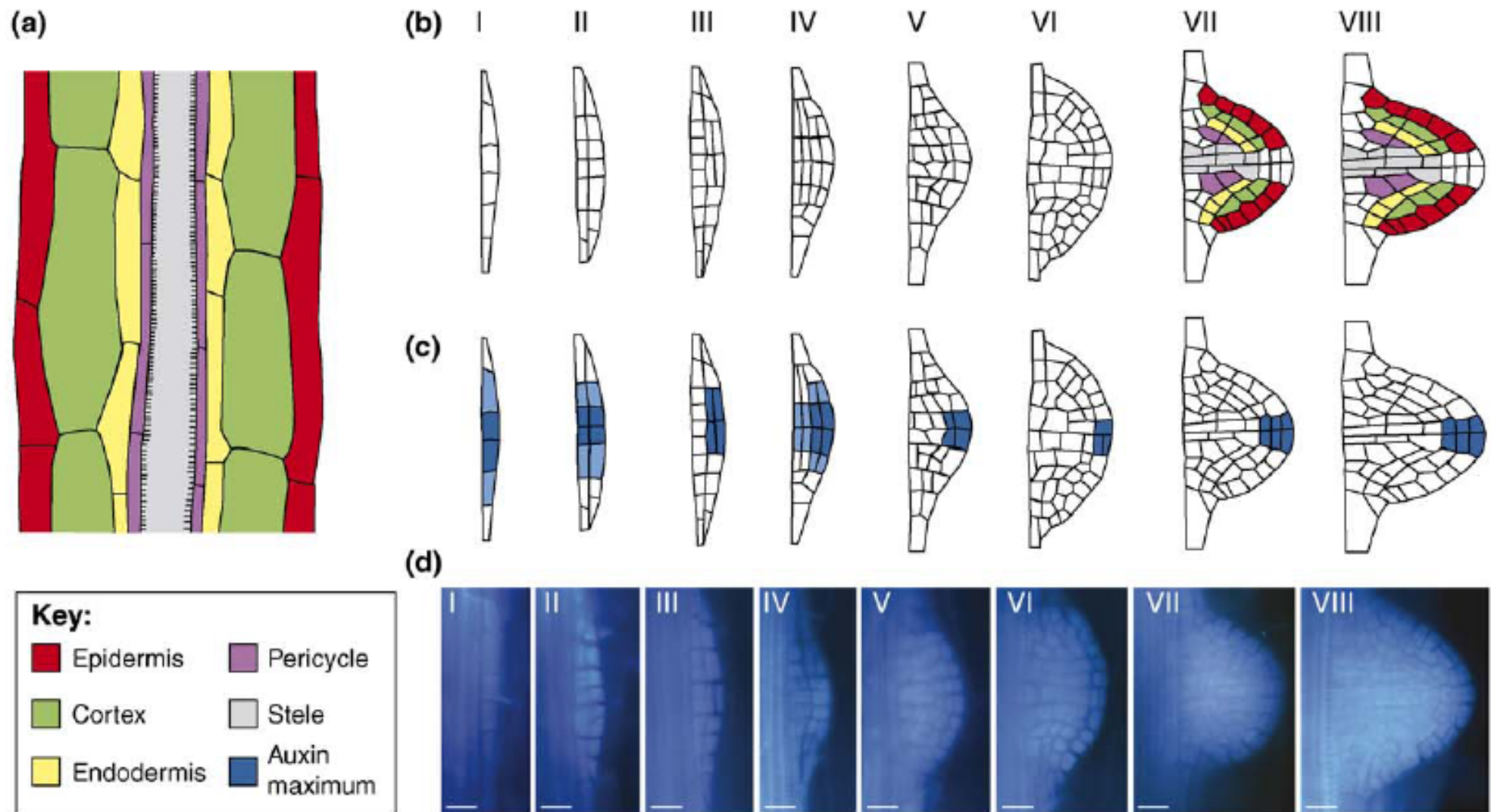
Parizot et al., *Plant Physiol* (2008)



De Smet and Jurgens., Current Opinion in Genetics & Development (2007)

De Smet et al., PNAS (2007)

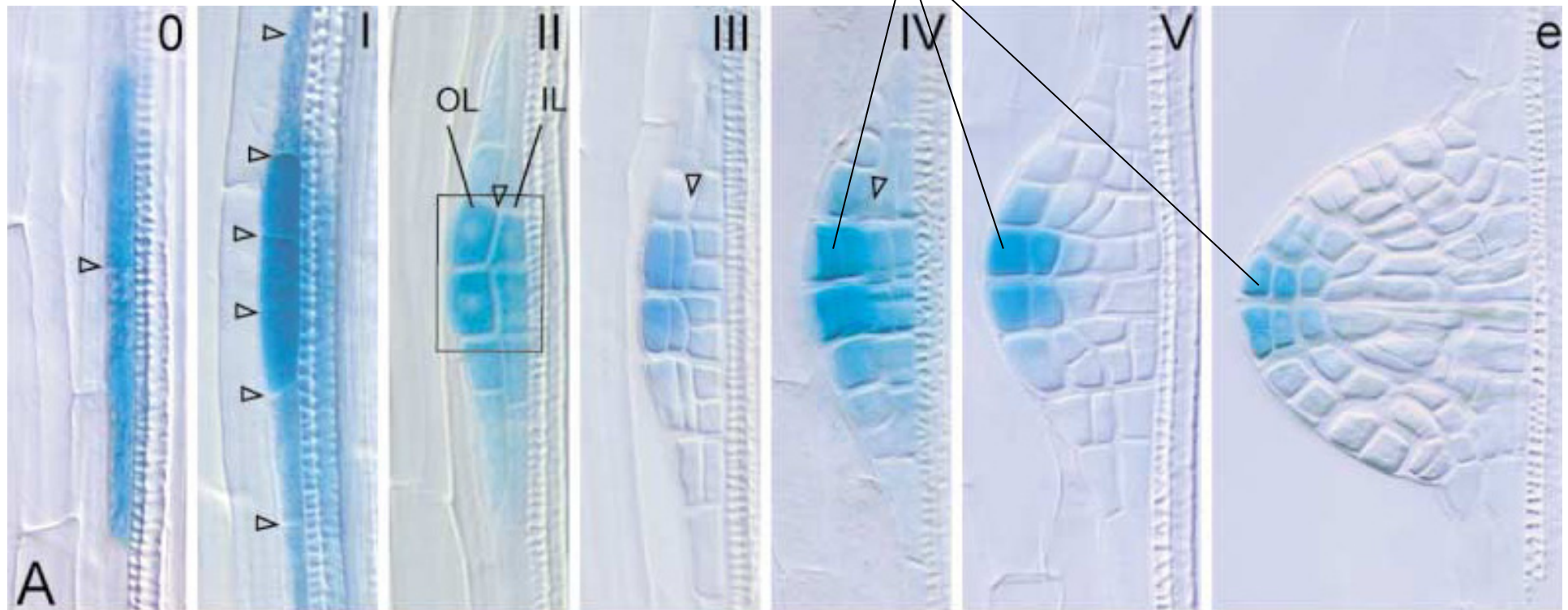




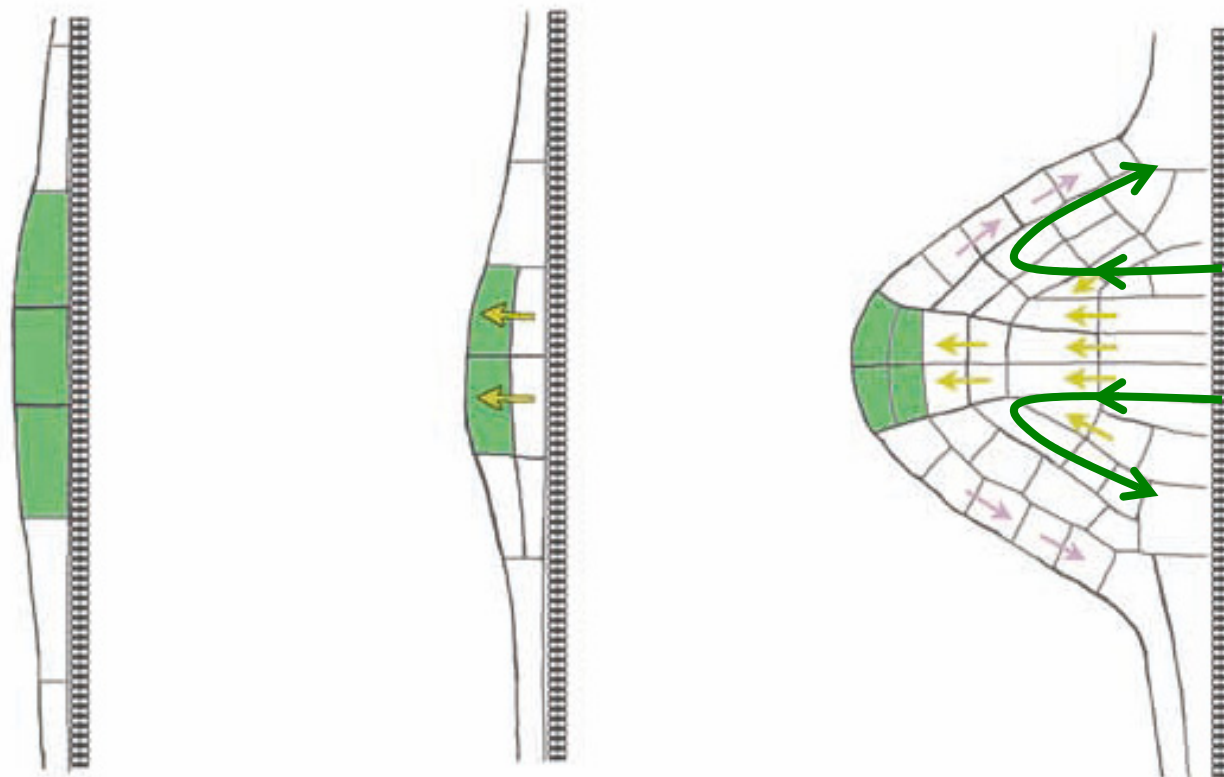
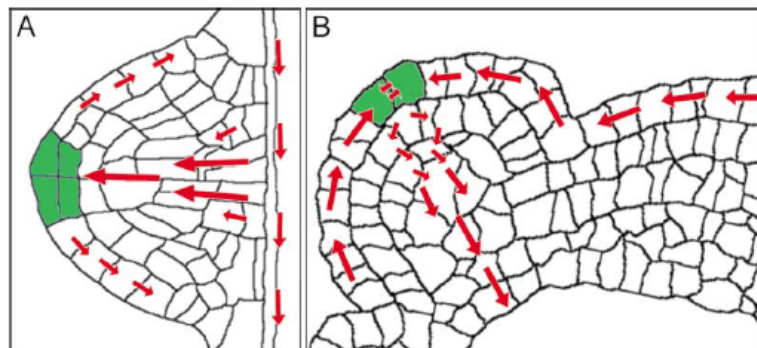
Peret et al., *Trends in Plant Sci* (2009)



Auxin maxima



Benkova et al., *Cell* (2003)

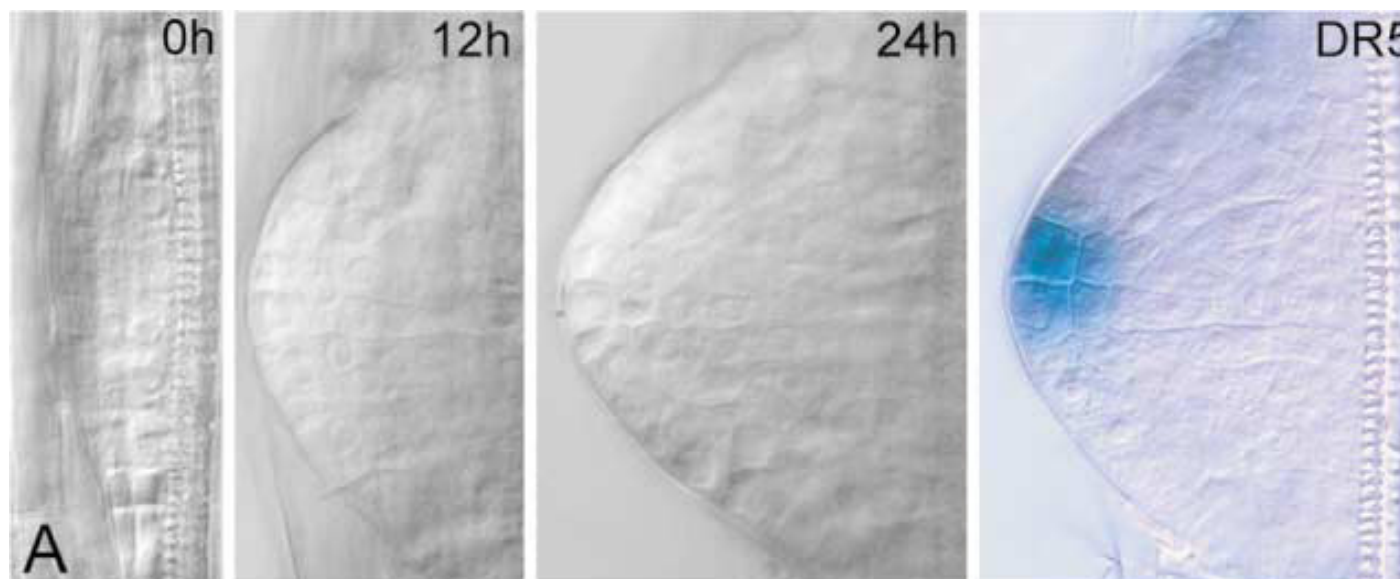


fountain-like  
auxin flow

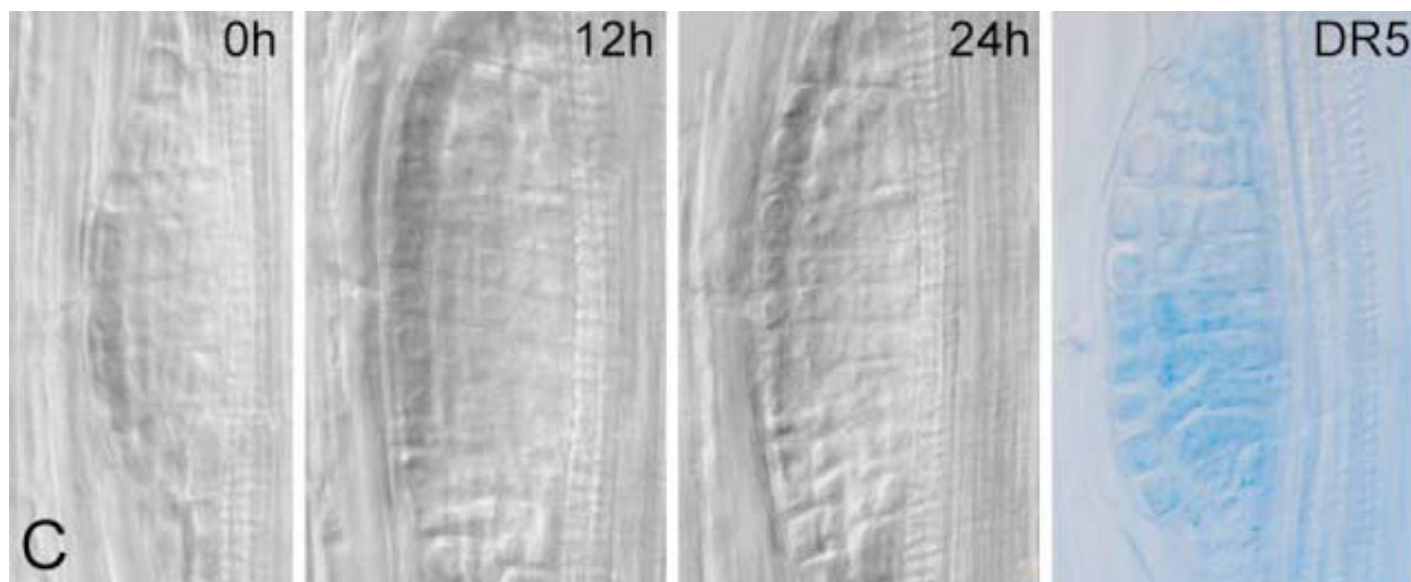
PIN1  
PIN2  
Auxin

Tanaka et al., *Cell Mol Life Sci* (2003)

*WT*



*pin1*



Benkova et al., *Cell* (2003)



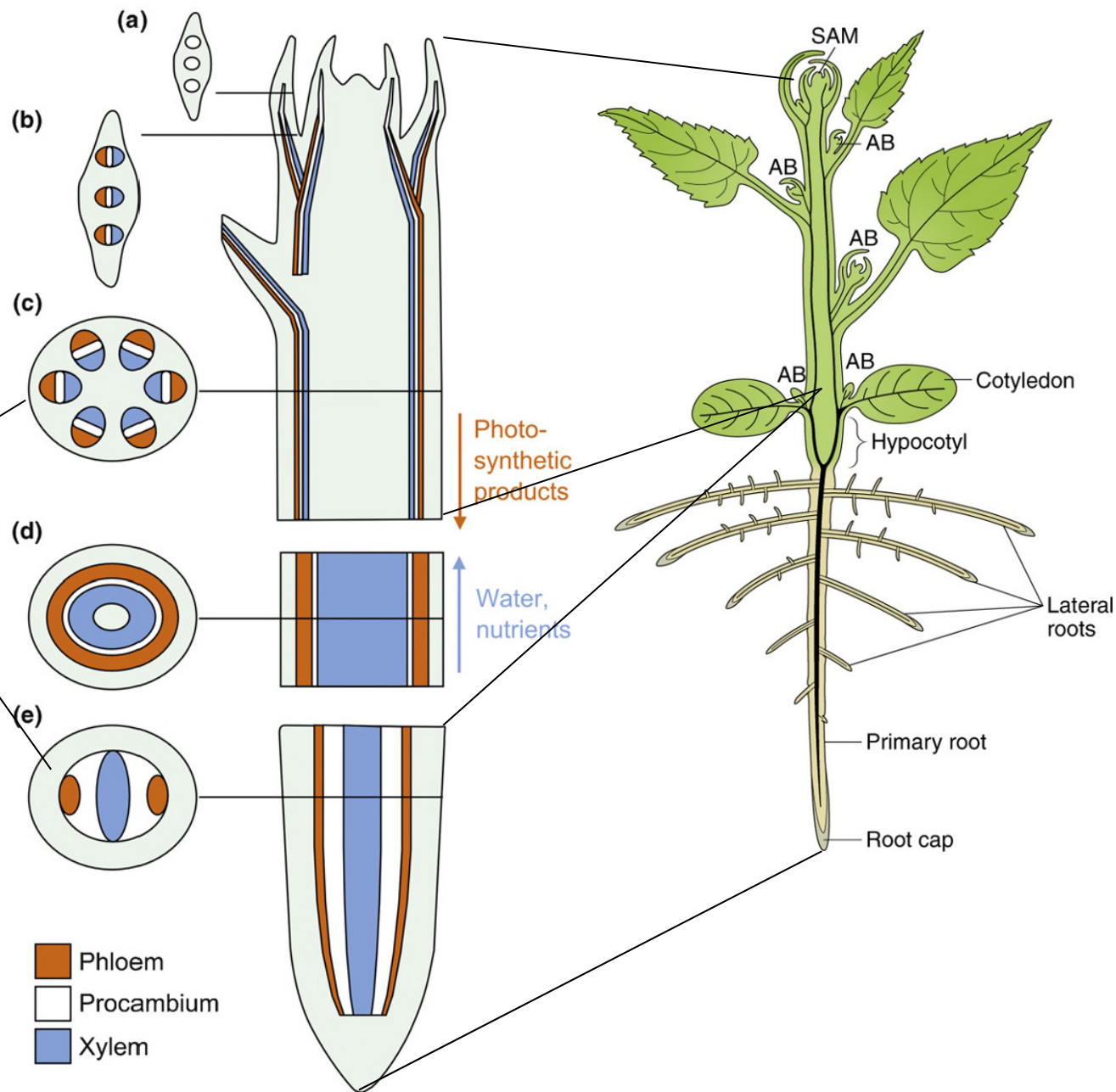
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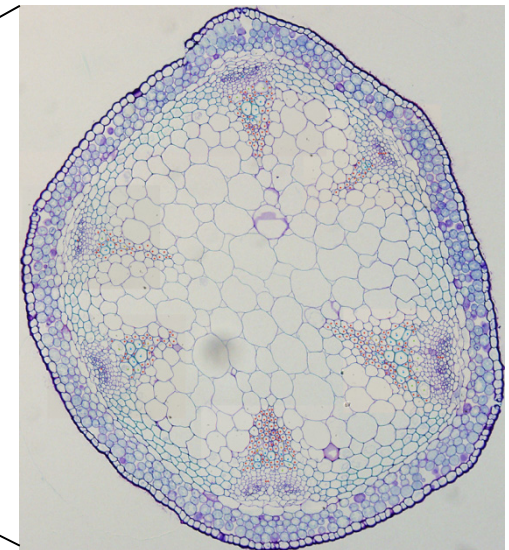
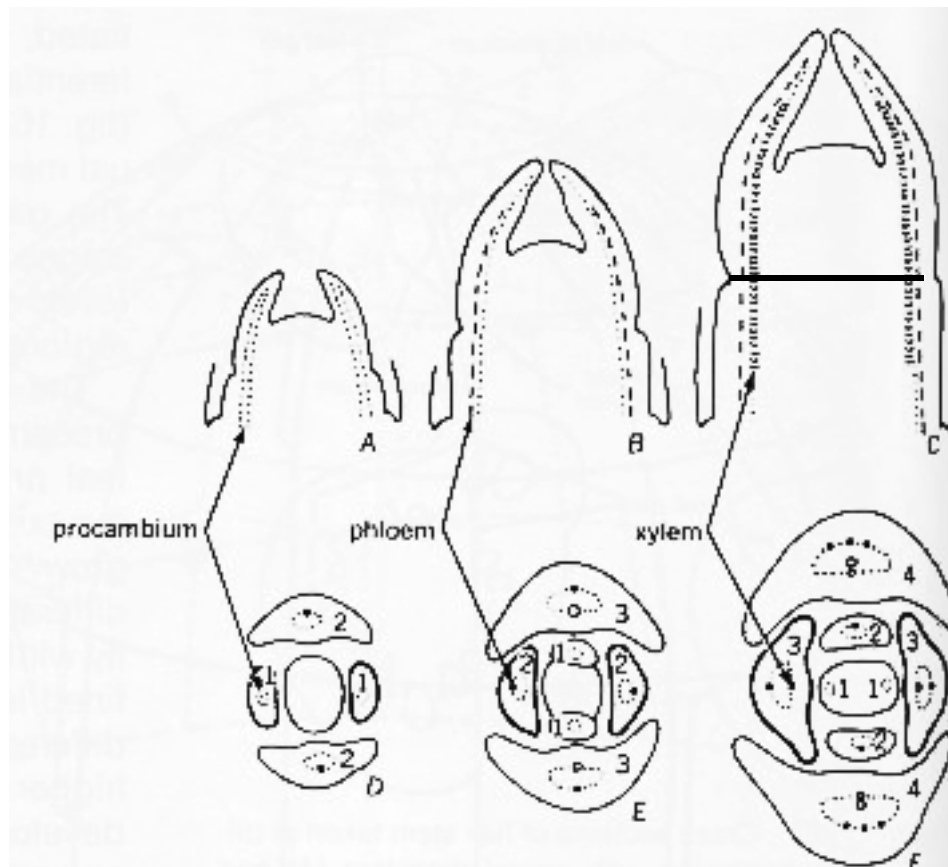
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  - Radial root patterning
  - RAM size determination
- Lateral root formation
- Vascular tissue formation in shoot and root



**Radial expansion  
of both shoot and  
root thanks to  
(pro)cambium**



Lehesranta et al., *Trends in Plant Sci* (2010)

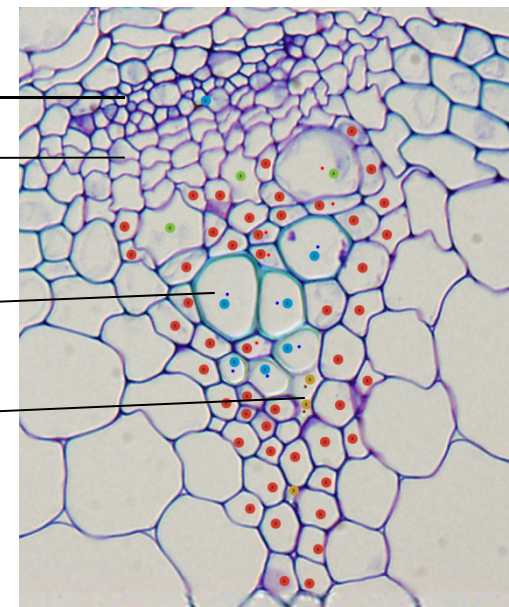


Phloem

Procambium

Metaxylem

Protoxylem

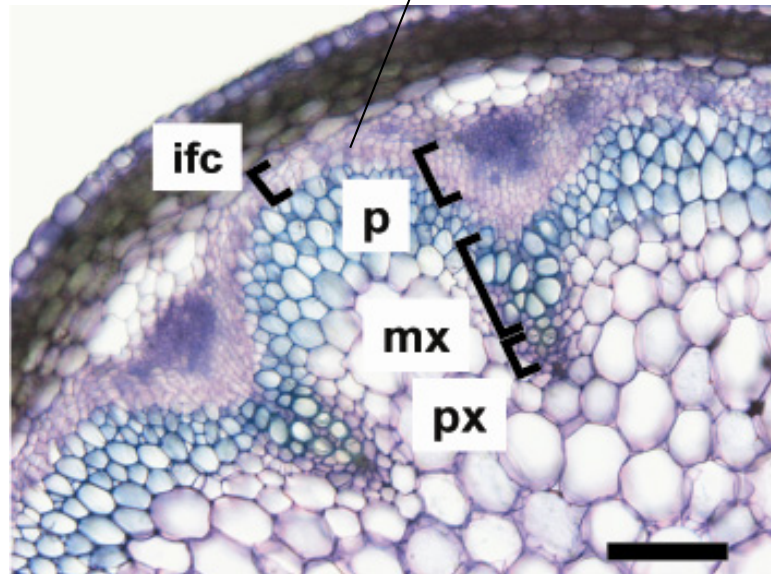


Esau, 1977

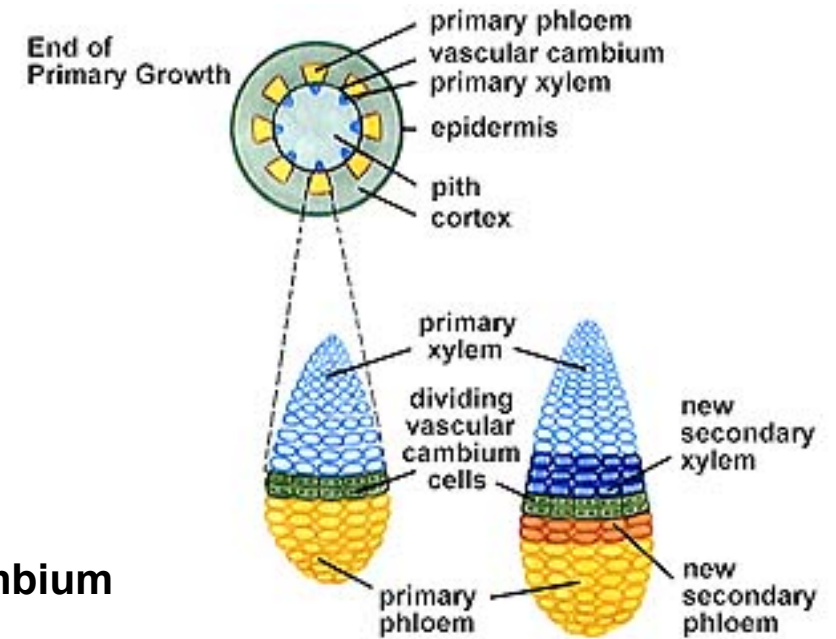
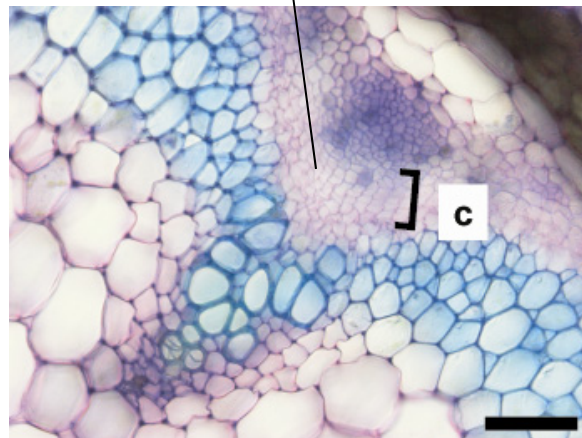
Hejatkó et al., *Plant Cell* (2009)



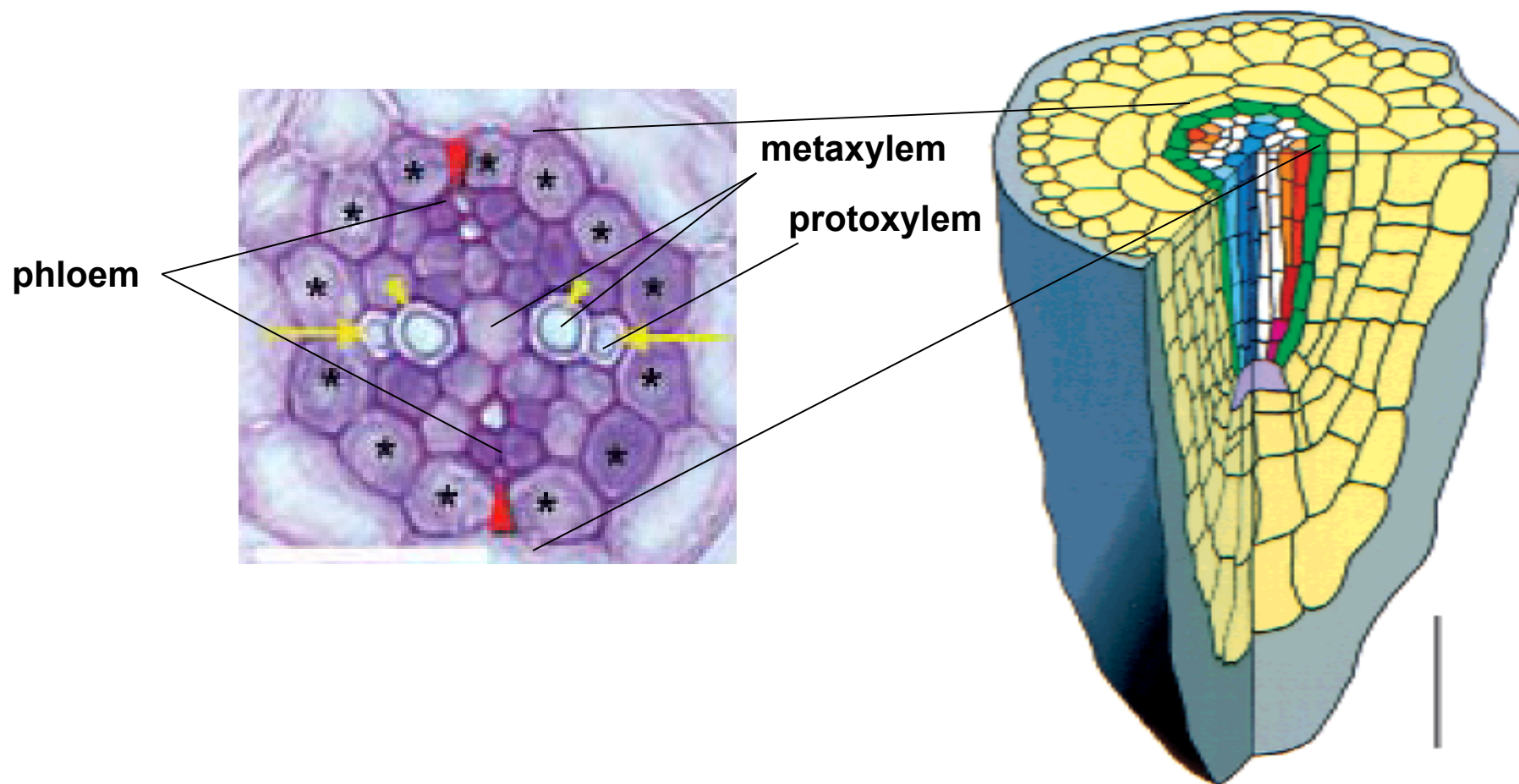
## Interfascicular cambium



## Vascular cambium



Hejatko et al., *Plant Cell* (2009)







# Key Concepts

## Postembryonic Plant Development

- Plants, in contrast to animals, form most of their tissues and organs during **postembryonic development** via **postembryonic *de novo* organogenesis**.
- Both shoot and root growth occurs via **directed cell proliferation** and **differentiation** in plant **meristems**.
- **Organizing centres** are formed in both shoot and root apical meristems.
- **Auxin gradients** determine **novel organ initiation** and **spacing** in the shoot apical meristem.
- **Auxin-driven morphogen gradient** acts in the **specification of the stem cell niche** and **cell differentiation** in the root.
- **Auxin maxima** specify positions of novel organ formation e.g. **lateral root primordia**.
- **(Pro)cambium** contains **stem cell pool** and allows **vascular tissue formation** and **radial growth** of plants.