Dynamic model

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Preface

This is a Quarto book.

To learn more about Quarto books visit https://quarto.org/docs/books.

1 Introduction

This is a book created from markdown and executable code.

See Knuth (1984) for additional discussion of literate programming.

2 Summary

In summary, this book has no content whatsoever.

3 Structural cereal model

```
import warnings
warnings.filterwarnings('ignore', category=DeprecationWarning)
```

```
import sys
# caution: path[0] is reserved for script path (or '' in REPL)
sys.path.insert(1, '../src')
```

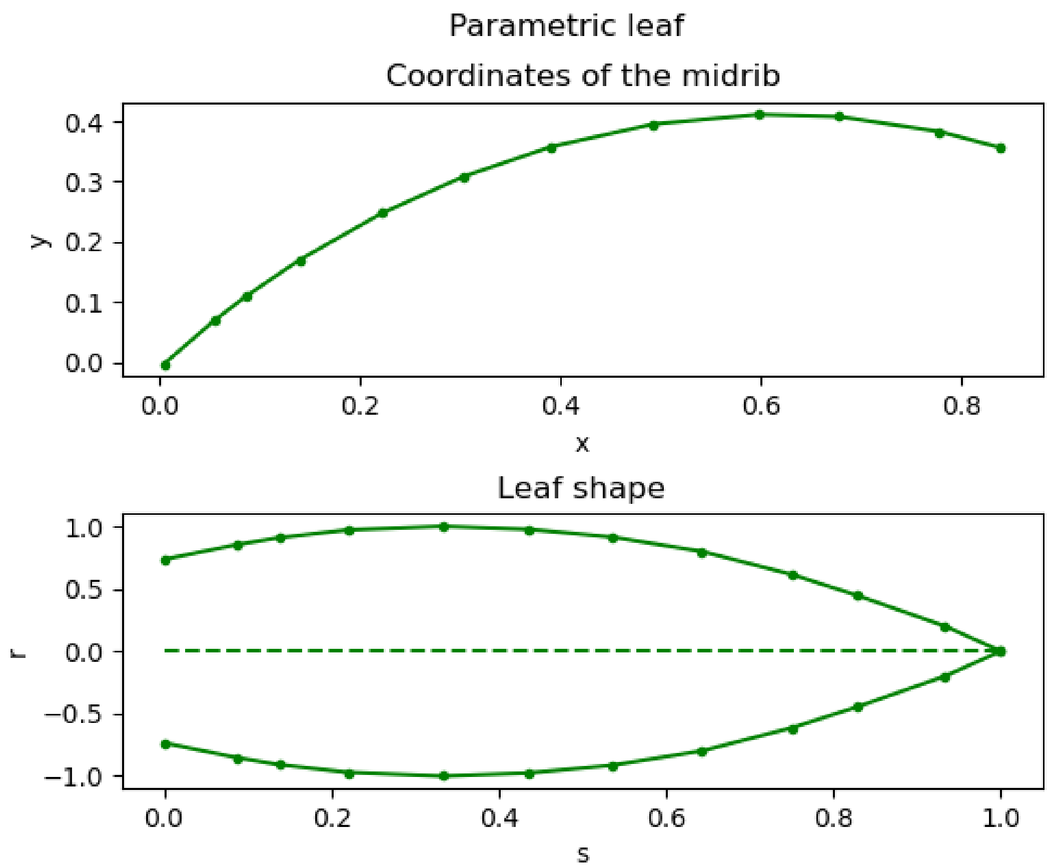
In this section, we define a static structural model for cereals.
The paragraphs are organized so that it is easy to see how the model is built and how we can play on parameters

3.1 Create a parametric leaf

A parametric leaf is here defined by two sets of coordinates:
- (x, y) coordinates for the midrib in a vertical plane (origin = leaf base) - (s, r) parallel array for curviliear abcissa / relative leaf width along leaf shape

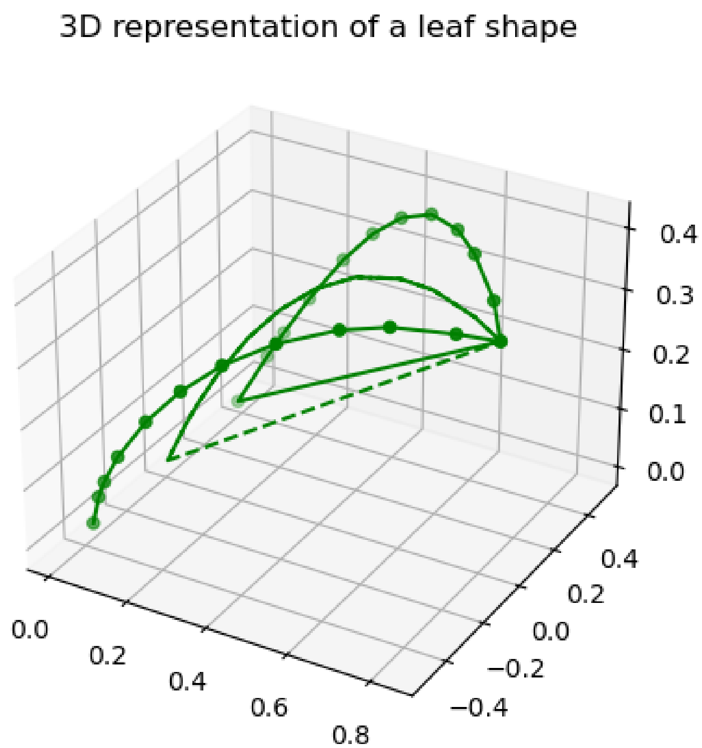
```
import numpy as np
import matplotlib.pyplot as plt

from heapq import *
from scipy.interpolate import splprep, splev
from scipy.integrate import simps, trapz
from openalea.plantgl.all import Vector3

from cereals_leaf import leaf_shape_perez, sr_prevot, parametric_leaf
# or
# from simple_maize import leaf_shape_perez, sr_prevot, parametric_leaf
# from fitting import leaf_shape_perez

from generator import curvilinear_abscisse
```

```
from fitting import fit2, fit3, simplify

from simplification import distance, cost


pl=parametric_leaf(nb_segment=10, insertion_angle=40, scurv=0.7, curvature=70, alpha=-2.3)

fig, (ax1, ax2) = plt.subplots(nrows=2)
fig.suptitle('Parametric leaf')

ax1.plot(pl[0], pl[1], '.-', c="green")
ax1.set_xlabel('x')
ax1.set_ylabel('y')
ax1.set_title("Coordinates of the midrib")

ax2.plot(pl[2], pl[3], '.-', c="green")
ax2.plot(pl[2], -pl[3], '.-', c="green")
ax2.plot(np.arange(0,1.1,0.1), np.zeros(11), c="green", ls="dashed")
ax2.set_xlabel('s')
ax2.set_ylabel('r')
ax2.set_title("Leaf shape")

plt.subplots_adjust(hspace=0.5)

plt.show()
```



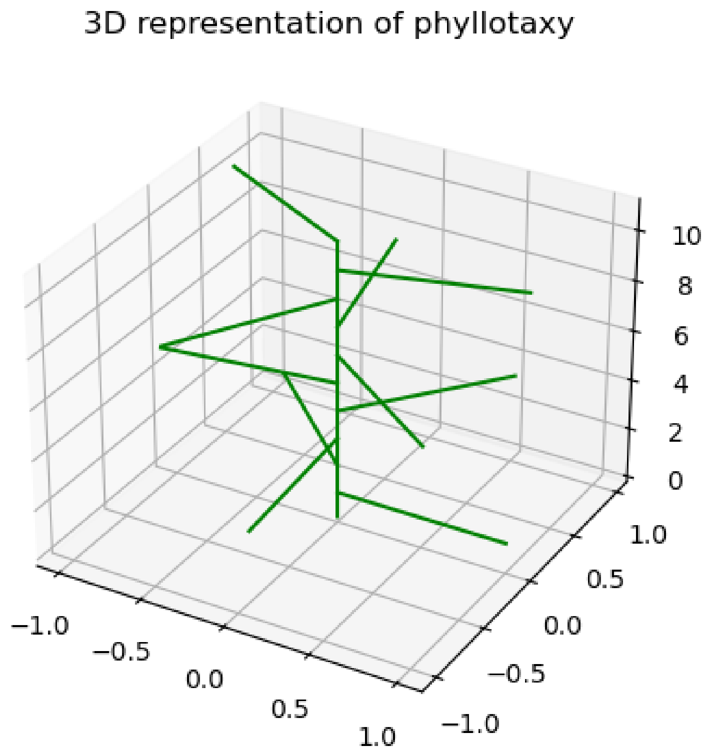

```
# Enable interactive plotting
%matplotlib ipympl

from mpl_toolkits.mplot3d import Axes3D
from scipy.interpolate import interp2d
import matplotlib.tri as mtri

from fitting import leaf_to_mesh_2d

xy=pl[0:2]
r=pl[3]

pts,ind=leaf_to_mesh_2d(xy[0], xy[1], r)

xs=[pt[0] for pt in pts]
ys=[pt[1] for pt in pts]
zs=[pt[2] for pt in pts]
```

```
X,Y=np.meshgrid(xs, ys)

tri = mtri.Triangulation(xs, ys)

fig = plt.figure()
ax = fig.add_subplot(111, projection='3d')
ax.scatter(xs,ys,zs,c="green")
ax.plot(xs,ys,zs,c="green")
ax.plot(xs,np.zeros(len(ys)),zs,c="green",ls="dashed")
ax.set_title("3D representation of a leaf shape")
plt.show()
```



3.2 Generate leaf azimuth series

```
# from itertools import cycle

from plant_design import leaf_azimuth

nb_phy=10
phyllotactic_angle=137
spiral=True
phyllotactic_deviation=0
plant_orientation=0
la=leaf_azimuth(size=nb_phy, phyllotactic_angle=phyllotactic_angle, phyllotactic_deviation=pl

x = np.cos(la*np.pi/180)
y = np.sin(la*np.pi/180)
z = np.linspace(1,len(la)+1,len(la))

fig, ax = plt.subplots(subplot_kw=dict(projection='3d'))
# ax.scatter(x, y, z, c="green")
for i,a in enumerate(la):
    ax.plot(np.linspace(0,x[i],2), np.linspace(0,y[i],2), [z[i],z[i]], c="green")
ax.plot([0,0], [0,0], [0,z[-1]], c="green")

ax.set_title("3D representation of phyllotaxy")

plt.show()
```

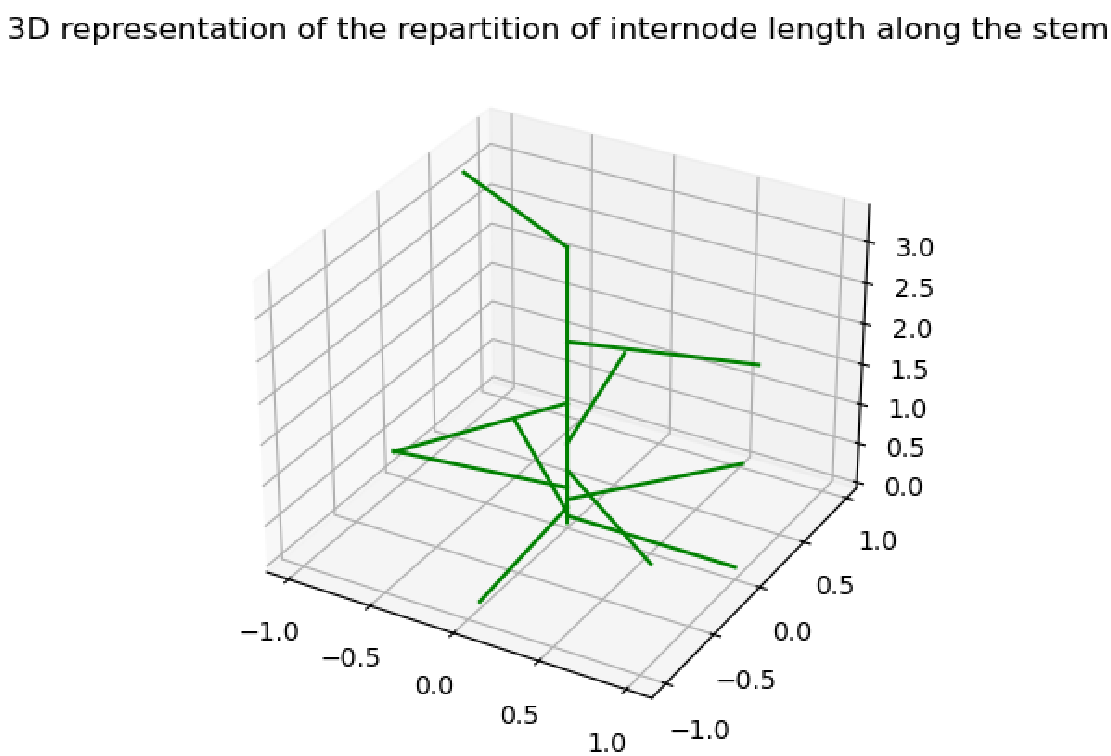


3.3 Manage internode lengths

```
def geometric_dist(height, nb_phy, q=1):
    """ returns distances between individual leaves along a geometric model """

    if q == 1:
        u0 = float(height) / nb_phy
    else:
        u0 = height * (1. - q) / (1. - q ** (nb_phy + 1))

    return [u0 * q ** i for i in range(nb_phy)]
```

```
plant_height=15
q=1.5
```

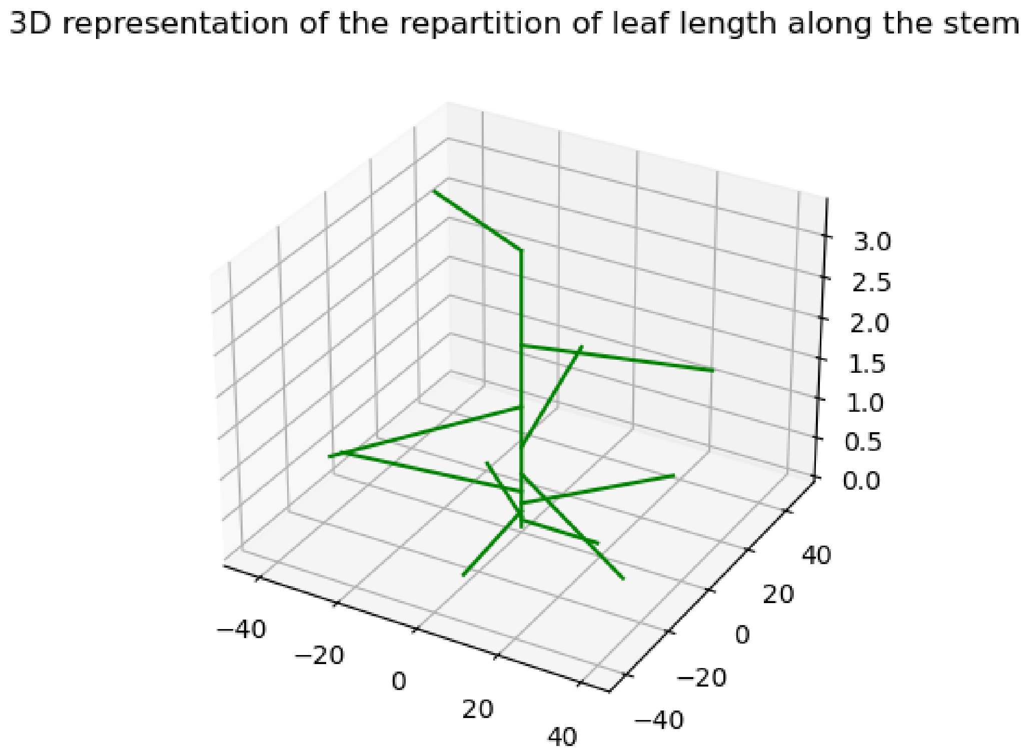
```
x = np.cos(la*np.pi/180)
y = np.sin(la*np.pi/180)
z = geometric_dist(height=plant_height, nb_phy=nb_phy, q=q)

fig, ax = plt.subplots(subplot_kw=dict(projection='3d'))
for i,a in enumerate(la):
    ax.plot(np.linspace(0,x[i],2), np.linspace(0,y[i],2), [z[i],z[i]], c="green")
ax.plot([0,0], [0,0], [0,z[-1]], c="green")

ax.set_title("3D representation of the repartition of internode length along the stem")

plt.show()
```



3.4 Manage leaf lengths as a function of height

```
def bell_shaped_dist(max_leaf_length, nb_phy, rmax=.7, skew=0.15):
    """ returns leaf area of individual leaves along bell shaped model """

    k = -np.log(skew) * rmax
    r = np.linspace(1. / nb_phy, 1, nb_phy)
    relative_length = np.exp(-k / rmax * (2 * (r - rmax) ** 2 + (r - rmax) ** 3))
    # leaf_length = relative_length / relative_length.sum() * max_leaf_length
    leaf_length = relative_length * max_leaf_length
    return leaf_length.tolist()
```

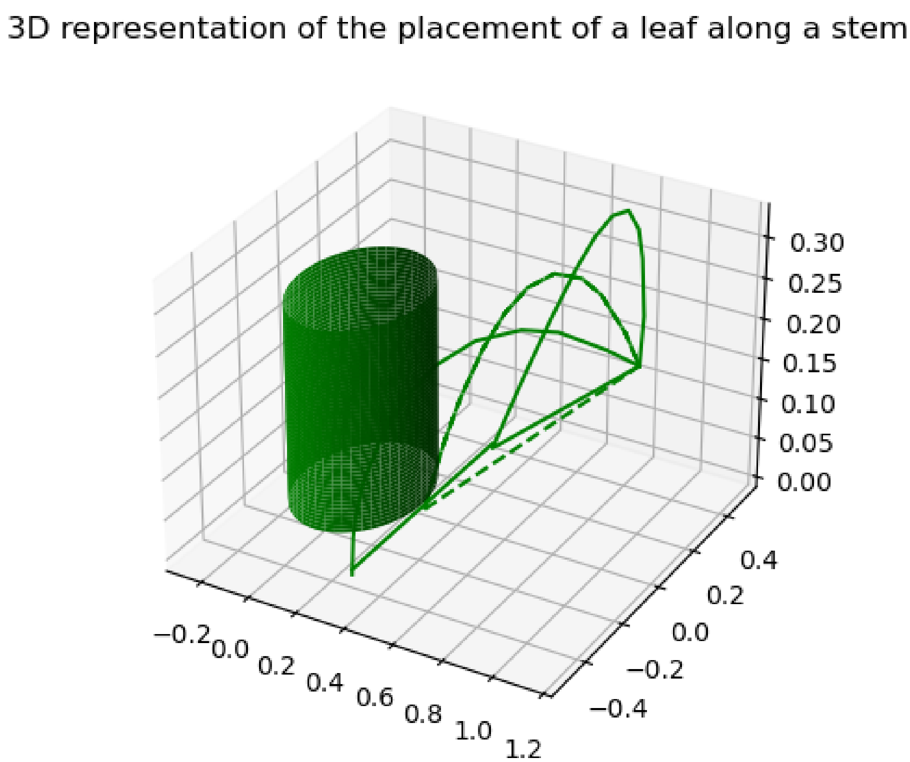
```
max_leaf_length=50

bsd=bell_shaped_dist(max_leaf_length=max_leaf_length, nb_phy=nb_phy, rmax=.7, skew=0.15)
x = np.cos(la*np.pi/180)*bsd
y = np.sin(la*np.pi/180)*bsd
z = geometric_dist(height=plant_height, nb_phy=nb_phy, q=q)

fig, ax = plt.subplots(subplot_kw=dict(projection='3d'))
for i,a in enumerate(la):
    ax.plot(np.linspace(0,x[i],2), np.linspace(0,y[i],2), [z[i],z[i]], c="green")
ax.plot([0,0], [0,0], [0,z[-1]], c="green")

ax.set_title("3D representation of the repartition of leaf length along the stem")

plt.show()
```



3.5 Arrange a leaf to be placed along a stem with a given inclination.

```
from math import pi, cos, sin, radians
import openalea.plantgl.all as pgl

# from cereals_leaf import arrange_leaf
# or
from geometry import arrange_leaf

stem_diameter=0.5
inclination=1.2

al=arrange_leaf(leaf=pl, stem_diameter=stem_diameter, inclination=inclination, relative=True)
```

```python
x=al[0]
y=al[1]
s=al[2]
r=al[3]

pts,ind=leaf_to_mesh_2d(x, y, r)

xs=[pt[0] for pt in pts]
ys=[pt[1] for pt in pts]
zs=[pt[2] for pt in pts]

X,Y=np.meshgrid(xs, ys)

tri = mtri.Triangulation(xs, ys)

fig = plt.figure()
ax = fig.add_subplot(111, projection='3d')
# ax.scatter(xs,ys,zs,c="green")
ax.plot(xs,ys,zs,c="green")
ax.plot([xs[0],xs[0]],[ys[0],-ys[0]],[0,0],c="green")
ax.plot(xs,np.zeros(len(ys)),zs,c="green",ls="dashed")

radius=stem_diameter/2
z = np.linspace(0, zs[-1])
theta = np.linspace(0, 2*np.pi)
theta_grid, z_stem=np.meshgrid(theta, z)
x_stem = radius*np.cos(theta_grid)
y_stem = radius*np.sin(theta_grid)

ax.plot_surface(x_stem, y_stem, z_stem, color="green")

ax.set_title("3D representation of the placement of a leaf along a stem")

plt.show()
```



3.6 Build the whole plant shoot in 3D, as an MTG.

```
import openalea.plantgl.all as pgl
from openalea.mtg.turtle import TurtleFrame

from geometry import slim_cylinder, stem_mesh, _is_iterable, as_tuples, addSets, leaf_mesh, c
# from cereals_leaf import leaf_mesh
from geometry import CerealsTurtle, CerealsVisitor

from fitting import leaf_element, leaf_to_mesh_2d, leaf_to_mesh, mesh4, plantgl_shape   # lea

from openalea.mtg import MTG, fat_mtg
from scipy.interpolate import interp1d
import pandas
```

```
from plant_design import get_form_factor, blade_dimension, stem_dimension

from generator import majors_axes_regression, line_projection, as_leaf, as_plant, cereals as

from geometry import mtg_interpreter


def build_shoot(stem_radius, insertion_heights, leaf_lengths, leaf_areas, leaf_azimuths=None
    """create a shoot

    Args:
        stem_radius: (float) the stem radius
        insertion_heights: list of each leaf insertion height
        leaf_lengths: list of each leaf length (blade length)
        leaf_areas: list of each blade area
        collar_visible: list of each collar height or True if the collar is visible and False
        leaf_shapes: list of each leaf shape, if it is not known write None
        leaf_azimuths: list of each leaf azimuth, if it is not known write None

    Returns:
        shoot:

    """
    ranks = range(1, len(leaf_lengths) + 1)
    ntop = max(ranks) - np.array(ranks) + 1
    if leaf_shapes is None:
        a_leaf = parametric_leaf()
        leaf_shapes = [a_leaf for r in ranks]
    if leaf_azimuths is None:
        leaf_azimuths = leaf_azimuth(len(ranks))
    leaf_azimuths[1:] = np.diff(leaf_azimuths)
    ff = [get_form_factor(leaf) for leaf in leaf_shapes]
    blades = blade_dimension(area=leaf_areas, length=leaf_lengths, ntop=ntop)
    stem = stem_dimension(h_ins=insertion_heights, d_internode=np.array(stem_radius) * 2, nto
    df = blades.merge(stem)
    df['leaf_azimuth'] = leaf_azimuths
    df['leaf_rank'] = ranks
    df['leaf_shape'] = [leaf_shapes[n - 1] for n in df.leaf_rank]
    return df, cereals_generator(plant=df)
```

```
def build_shoot_w_pseudo(nb_phy, plant_height, insertion_heights, leaf_lengths, leaf_areas,
                pseudostem_dist=1.4, stem_dist=1.2,
                diam_base=2.5, diam_top=1, pseudostem_height=20,
                leaf_azimuths=None, leaf_shapes=None, wl=0.1):
    """create a shoot, with pseudostems and stems

    Args:
        stem_radius: (float) the stem radius
        insertion_heights: list of each leaf insertion height
        leaf_lengths: list of each leaf length (blade length)
        leaf_areas: list of each blade area
        collar_visible: list of each collar height or True if the collar is visible and False
        leaf_shapes: list of each leaf shape, if it is not known write None
        leaf_azimuths: list of each leaf azimuth, if it is not known write None

    Returns:
        shoot:

    """
    ranks = range(1, len(leaf_lengths) + 1)
    ntop = max(ranks) - np.array(ranks) + 1

    nb_phy = int(nb_phy)

    # Lejeune an Bernier formula + col =
    nb_young_phy = int(round((nb_phy - 1.95) / 1.84 / 1.3))

    # distances between leaves
    pseudostem = geometric_dist(pseudostem_height, nb_young_phy,
                               pseudostem_dist)
    stem = geometric_dist(plant_height - pseudostem_height,
                         nb_phy - nb_young_phy, stem_dist)
    internode = pseudostem + stem
    # stem diameters
    diameter = ([diam_base] * nb_young_phy +
                np.linspace(diam_base, diam_top,
                            nb_phy - nb_young_phy).tolist())

    if leaf_shapes is None:
        a_leaf = parametric_leaf()
        leaf_shapes = [a_leaf for r in ranks]
    if leaf_azimuths is None:
```

```
        leaf_azimuths = leaf_azimuth(len(ranks))
    leaf_azimuths[1:] = np.diff(leaf_azimuths)
    ff = [get_form_factor(leaf) for leaf in leaf_shapes]
    # blades = blade_dimension(area=leaf_areas, length=leaf_lengths, ntop=ntop)
    blades = blade_dimension(length=leaf_lengths, form_factor=ff, ntop=ntop, wl=wl)
    # stem = stem_dimension(h_ins=insertion_heights, d_internode=diameter, ntop=ntop)
    stem = stem_dimension(internode=internode, d_internode=diameter, ntop=ntop)

    df = blades.merge(stem)
    df['leaf_azimuth'] = leaf_azimuths
    df['leaf_rank'] = ranks
    df['leaf_shape'] = [leaf_shapes[n - 1] for n in df.leaf_rank]
    return df, cereals_generator(plant=df)

# shoot, g = build_shoot(3.0, [2,4,6,8], [2,4,6,8], [2,4,6,8])
# scene, nump = build_scene(g)
# display_scene(scene)
```

3.7 Display scenes according to different scenarii

3.7.1 A single cereal

```
from display import display_mtg, build_scene, display_scene
from oawidgets.plantgl import *
# from oawidgets.mtg import *

%gui qt

# generation of a 3D plant from descritive parameters
stem_radius=1 # realistic, number or growing with phytomer age ?
height=1500 # from crop model
nb_phy=15 # from 0 to fixed max nb of phytomers
max_leaf_length=70
insertion_angle=40
scurv=0.7
curvature=80
phyllotactic_angle=120
spiral=True
```

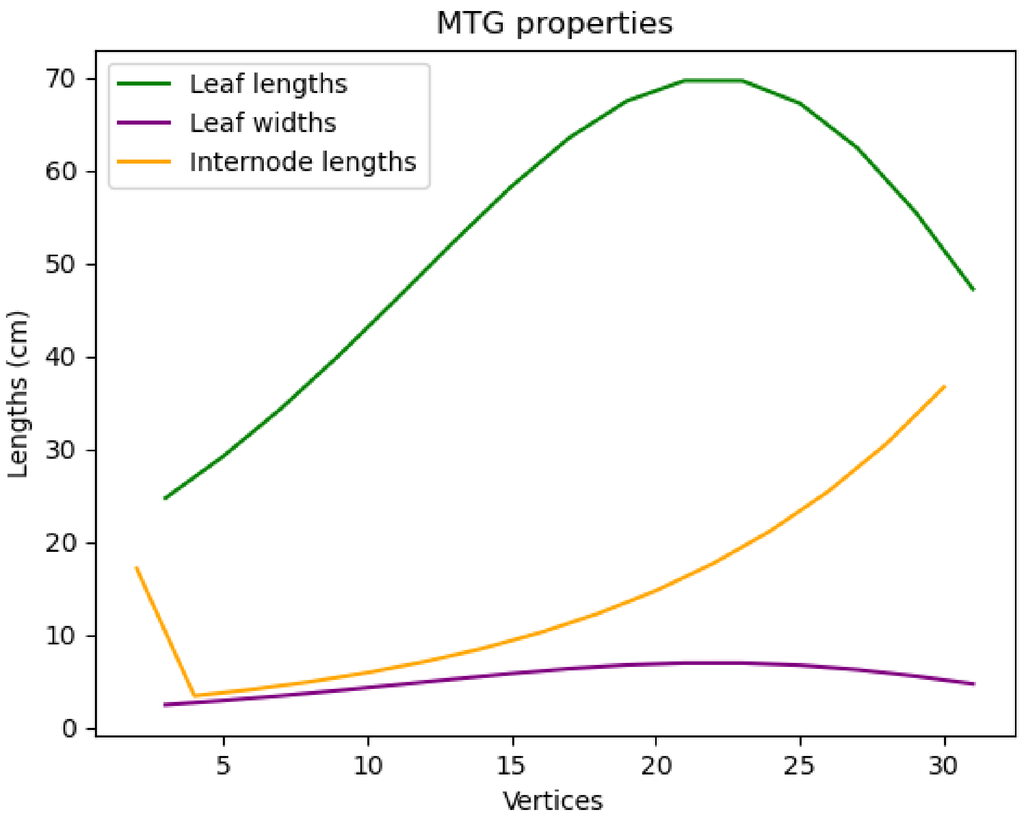
```
insertion_heights=np.array(geometric_dist(height, nb_phy, q=1.2)) # further separate stem and

leaf_lengths=np.array(bell_shaped_dist(max_leaf_length=max_leaf_length, nb_phy=nb_phy, rmax=0
# leaf_areas=bell_shaped_dist(plant_area=1, nb_phy=15, rmax=0.7, skew=0.15) # cf blade_dimens

a_leaf = parametric_leaf(nb_segment=10, insertion_angle=insertion_angle, scurv=scurv, curvatu
leaf_shapes = [a_leaf for l in leaf_lengths] # replace leaf_length by nb_phy or...

leaf_azimuths = leaf_azimuth(size=len(leaf_lengths), phyllotactic_angle=phyllotactic_angle, p

# shoot, g = build_shoot_w_pseudo(nb_phy=nb_phy, plant_height=height, insertion_heights=inser
#                  pseudostem_dist=1.4, stem_dist=1.,
#                  diam_base=2.5, diam_top=1, pseudostem_height=20,
#                  leaf_azimuths=None, leaf_shapes=None)

shoot, g_single = build_shoot(stem_radius=stem_radius, insertion_heights=insertion_heights, l
                leaf_shapes=leaf_shapes, leaf_azimuths=leaf_azimuths)


# g_single.display()

scene_single, nump = build_scene(g_single, leaf_material=Material(Color3((50,100,0))), stem_m
# display_scene(scene_single)
PlantGL(scene_single)
```

```
Plot(antialias=3, axes=['x', 'y', 'z'], axes_helper=1.0, axes_helper_colors=[16711680, 65280
```

```
from oawidgets.mtg import *

# Properties on the MTG: this exclude all the topological properties
print(g_single.property_names())

# Retrieve one property for the MTG (dict)

labels = g_single.property('label')
# print(labels)

length = g_single.property('length')
# print(length)

leaf_lengths=[]
```

```
leaf_ind=[]
internode_lengths=[]
internode_ind=[]
for k,v in length.items():
    if k%2==0: # could have done it using labels
        internode_ind.append(k)
        internode_lengths.append(v)
    else:
        leaf_ind.append(k)
        leaf_lengths.append(v)

width = g_single.property('shape_max_width')
# print(width)

leaf_widths=[]
for k,v in width.items():
    leaf_widths.append(v)


plt.figure()
plt.plot(leaf_ind, leaf_lengths, c="green", label="Leaf lengths") # == 'shape_mature_length'
plt.plot(leaf_ind, leaf_widths, c="purple", label="Leaf widths")
plt.plot(internode_ind, internode_lengths, c="orange", label="Internode lengths")
plt.xlabel("Vertices")
plt.ylabel("Lengths (cm)")
plt.title("MTG properties")
plt.legend()
plt.show()
```

```
['edge_type', 'label', 'length', 'is_green', 'diameter_base', 'diameter_top', 'azimuth', 'sha
```



The leaf lengths and widths follow the bell shaped curve described before.
The first internode in the MTG actually corresponds to the pseudostem, i.e. the about 4 to 8 short first internodes that rapidly lose their leaves. The lengths following internodes follow the geometric model described before.

```
# classes = list(set(g.class_name(vid) for vid in g.vertices() if g.class_name(vid)))
# print(classes)

# def vertices(g, class_name='P'):
#     return [vid for vid in g.vertices() if g.class_name(vid)==class_name]

# vids_U = vertices(g, 'U')

# plot(g_single, selection=vids_U)

# plot(g_single, selection=[vid for vid in g_single.vertices() if g_single.class_name(vid)==
```

3.7.2 A cereal crop with variability

```
from stand import agronomic_plot
from display import display_mtg, build_scene, display_scene
from random import *
from oawidgets.plantgl import *
# from oawidgets.mtg import *

%gui qt

seed(1)

# generation of a crop of 3D plants from descritive parameters with variability
plants_in_crop=[]
length_plot=5
width_plot=5
sowing_density=10
plant_density=10
inter_row=0.5
nplants, positions, domain, domain_area, unit = agronomic_plot(length_plot, width_plot, sowin

for n in range(nplants):
    stem_radius=1 # realistic, number or growing with phytomer age ?
    height=1000*(1+random()-0.5) # from crop model
    nb_phy=15 # from 0 to fixed max nb of phytomers
    max_leaf_length=50*(1+random()-0.5)
    insertion_angle=40*(1+random()-0.5)
    scurv=0.7*(1+random()-0.5)
    curvature=70*(1+random()-0.5)
    phyllotactic_angle=137*(1+random()-0.5)
    spiral=True

    insertion_heights=np.array(geometric_dist(height, nb_phy, q=1.2)) # further separate ster

    leaf_lengths=np.array(bell_shaped_dist(max_leaf_length=max_leaf_length, nb_phy=nb_phy, rm
    # leaf_areas=bell_shaped_dist(plant_area=1, nb_phy=15, rmax=0.7, skew=0.15) # cf blade_di

    a_leaf = parametric_leaf(nb_segment=10, insertion_angle=insertion_angle, scurv=scurv, cur
    leaf_shapes = [a_leaf for l in leaf_lengths] # replace leaf_length by nb_phy or...

    leaf_azimuths = leaf_azimuth(size=len(leaf_lengths), phyllotactic_angle=phyllotactic_angl
```

```
    # shoot, g = build_shoot_w_pseudo(nb_phy=nb_phy, plant_height=height, insertion_heights=i
    #                  pseudostem_dist=1.4, stem_dist=1.,
    #                  diam_base=2.5, diam_top=1, pseudostem_height=20,
    #                  leaf_azimuths=None, leaf_shapes=None)
    shoot, g_var = build_shoot(stem_radius=stem_radius, insertion_heights=insertion_heights,
                    leaf_shapes=leaf_shapes, leaf_azimuths=leaf_azimuths)

    plants_in_crop.append(g_var)


scene_var, nump = build_scene(plants_in_crop, positions, leaf_material=Material(Color3((50,10
# display_scene(scene_var)
PlantGL(scene_var)
```

```
Plot(antialias=3, axes=['x', 'y', 'z'], axes_helper=1.0, axes_helper_colors=[16711680, 65280
```

3.7.3 A seemingly growing plant

```
from stand import agronomic_plot
from display import display_mtg, build_scene, display_scene
from random import *
from openalea.plantgl.all import *
from oawidgets.plantgl import *
# from oawidgets.mtg import *

%gui qt

seed(1)

# generation of ""growing"" 3D plants from descritive parameters
growing_plants=[]
length_plot=1
width_plot=1
sowing_density=10
plant_density=10
inter_row=0.75
# nplants, positions, domain, domain_area, unit = agronomic_plot(length_plot, width_plot, sow
nplants=10
positions=[(x,0,0) for x in range(-500, 500, 100)]
final_height=1000
```

```
final_nb_phy=2*nplants
heights=geometric_dist(final_height, final_nb_phy, 1.2)
# insertion_heights=np.array(geometric_dist(height, nb_phy, q=1.2))

for n in range(1,nplants+1):
    stem_radius=2 # realistic, number or growing with phytomer age ?
    height=10*heights[2*n-1] # from crop model
    nb_phy=2*n # from 0 to fixed max nb of phytomers
    max_leaf_length=5*2*n
    insertion_angle=30
    scurv=0.7
    curvature=100
    phyllotactic_angle=137
    spiral=True

    insertion_heights=np.array(geometric_dist(height, nb_phy, q=1.2)) # further separate ster

    leaf_lengths=np.array(bell_shaped_dist(max_leaf_length=max_leaf_length, nb_phy=nb_phy, rm
    # leaf_areas=bell_shaped_dist(plant_area=1, nb_phy=15, rmax=0.7, skew=0.15) # cf blade_di
    # print(leaf_lengths)
    a_leaf = parametric_leaf(nb_segment=10, insertion_angle=insertion_angle, scurv=scurv, cu
    leaf_shapes = [a_leaf for l in leaf_lengths] # replace leaf_length by nb_phy or...

    leaf_azimuths = leaf_azimuth(size=len(leaf_lengths), phyllotactic_angle=phyllotactic_angl

    # shoot, g = build_shoot_w_pseudo(nb_phy=nb_phy, plant_height=height, insertion_heights=
    #                  pseudostem_dist=1.4, stem_dist=1.,
    #                  diam_base=2.5, diam_top=1, pseudostem_height=20,
    #                  leaf_azimuths=None, leaf_shapes=None)
    shoot, g_grow = build_shoot(stem_radius=stem_radius, insertion_heights=insertion_heights
                    leaf_shapes=leaf_shapes, leaf_azimuths=leaf_azimuths)

    # print(g_grow)

    growing_plants.append(g_grow)


scene_grow, nump = build_scene(growing_plants[2:], positions[2:], leaf_material=Material(Colo
# display_scene(scene_grow)
PlantGL(scene_grow)
```

```
Plot(antialias=3, axes=['x', 'y', 'z'], axes_helper=1.0, axes_helper_colors=[16711680, 65280
```

3.7.4 An intercrop organized in rows

```
from stand import agronomic_plot
from display import display_mtg, build_scene, display_scene
from random import *
from oawidgets.plantgl import *
# from oawidgets.mtg import *
from openalea.plantgl.all import Material, Color3, Shape, Scene, Viewer, Translated, AxisRota

%gui qt

seed(1)

# generation of 3D intercropped plants from descritive parameters
# plants_in_crop=[]
# length_plot=1
# width_plot=1
# sowing_density=10
# plant_density=10
# inter_row=0.75
# nplants, positions, domain, domain_area, unit = agronomic_plot(length_plot, width_plot, sow
# nplants=10

# final_height=2000
# final_nb_phy=2*nplants
# heights=geometric_dist(final_height, final_nb_phy, 1.2)
# insertion_heights=np.array(geometric_dist(height, nb_phy, q=1.2))
def plant(height, nb_phy, max_leaf_length, phyllotactic_angle, spiral):
    stem_radius=1 # realistic, number or growing with phytomer age ?
    insertion_angle=30
    scurv=0.7
    curvature=100

    insertion_heights=np.array(geometric_dist(height, nb_phy, q=1.2)) # further separate ster

    leaf_lengths=np.array(bell_shaped_dist(max_leaf_length=max_leaf_length, nb_phy=nb_phy, rm
    # leaf_areas=bell_shaped_dist(plant_area=1, nb_phy=15, rmax=0.7, skew=0.15) # cf blade_di

    a_leaf = parametric_leaf(nb_segment=10, insertion_angle=insertion_angle, scurv=scurv, cur
    leaf_shapes = [a_leaf for l in leaf_lengths] # replace leaf_length by nb_phy or...

    leaf_azimuths = leaf_azimuth(size=len(leaf_lengths), phyllotactic_angle=phyllotactic_angl
```

```
    # shoot, g = build_shoot_w_pseudo(nb_phy=nb_phy, plant_height=height, insertion_heights=i
    #                  pseudostem_dist=1.4, stem_dist=1.,
    #                  diam_base=2.5, diam_top=1, pseudostem_height=20,
    #                  leaf_azimuths=None, leaf_shapes=None)
    shoot, g = build_shoot(stem_radius=stem_radius, insertion_heights=insertion_heights, leaf
                      leaf_shapes=leaf_shapes, leaf_azimuths=leaf_azimuths)

    return g


### Mixture organized in alternate rows

n_rows = 10
len_rows = 10

d_inter = 70
d_intra = 50

def plant_in_row(i):
     if i%(4*d_inter)==0 or i%(4*d_inter)==d_inter: return plant(height=1700, nb_phy=15, max_
     else: return plant(height=900, nb_phy=20, max_leaf_length=40, phyllotactic_angle=60, spi

# ms=[]

# for x in range(0, n_rows*d_inter, d_inter):
#     for y in range(0, len_rows*d_intra, d_intra):
#         g, col=plant_in_row(x)
#         ts=Translated((x,y,0), g)
#         sh=Shape(ts, col)

#         ms.append(sh)

# scene=Scene(ms)

# Viewer.display(scene)

plants_in_intercrop = [plant_in_row(x) for x in range(0, n_rows*d_inter, d_inter) for y in ra

positions=[(x,y,0) for x in range(0, n_rows*d_inter, d_inter) for y in range(0, len_rows*d_in

scene_ic, nump = build_scene(plants_in_intercrop, positions, leaf_material=Material(Color3((5
# display_scene(scene_ic)
```

```
PlantGL(scene_ic)
```

```
Plot(antialias=3, axes=['x', 'y', 'z'], axes_helper=1.0, axes_helper_colors=[16711680, 65280
```

3.8 Tillering / Branching

```
# Copy MTG single plant
g_branch = g_single.sub_mtg(g_single.root)

# g_branch.display()

# REARRANGE MTG WITH SCALES: PLANT, AXE, METAMER (with internode and leaf), ELEMENTS (StemEle
```

```
# Add branch

from openalea.mtg import MTG

g = MTG()

plant_id = g.add_component(g.root, label='P1')

# scale 1
v1 = g.add_child(plant_id, label='A1')
v2 = g.add_child(plant_id, label='A2')
v3 = g.add_child(plant_id, label='A3')
v4 = g.add_child(v1, label='I1')
v5 = g.add_child(v1, label='I2')

g.display()

from oawidgets.mtg import *
# plot(g)
```

```
MTG : nb_vertices=7, nb_scales=2
/P1         (id=1)
    /A1         (id=2)
        /I1         (id=5)
        /I2         (id=6)
    /A2         (id=3)
    /A3         (id=4)
```

3.9 Light interception with Caribu

```
from alinea.caribu.CaribuScene import CaribuScene
from alinea.caribu.data_samples import data_path

sky = str(data_path('Turtle16soc.light'))
# opts = map(str, [data_path('par.opt'), data_path('nir.opt')])

# complete set of files
cs = CaribuScene(scene=scene_var, light=sky) # opt=opts, ) #pattern=pattern)
raw,agg=cs.run(simplify=True)

# print(raw.keys())

scene,values = cs.plot(raw['Ei'],display=False)

v99 = np.percentile(values, 99)
nvalues=np.array(values)
nvalues[nvalues>v99]=v99
values = nvalues.tolist()

PlantGL(scene, group_by_color=False, property=values)
```

```
Plot(antialias=3, axes=['x', 'y', 'z'], axes_helper=1.0, axes_helper_colors=[16711680, 65280
```

```
from alinea.caribu.CaribuScene import CaribuScene
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sky = str(data_path('Turtle16soc.light'))
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cs = CaribuScene(scene=scene_ic, light=sky) # opt=opts, ) #pattern=pattern)
raw,agg=cs.run(simplify=True)

scene,values = cs.plot(raw['Ei'],display=False)

v99 = np.percentile(values, 99)
nvalues=np.array(values)
nvalues[nvalues>v99]=v99
values = nvalues.tolist()
```

```python
PlantGL(scene, group_by_color=False, property=values)
```

```
Plot(antialias=3, axes=['x', 'y', 'z'], axes_helper=1.0, axes_helper_colors=[16711680, 65280
```

3.10 Next steps:

- Configure Caribu to simulate the same light as in STICS
- Adapt for different species (parameters for cereals, some functions for legumes)

4 Dynamic model

```
import sys
# caution: path[0] is reserved for script path (or '' in REPL)
sys.path.insert(1, '../src')
```

We have an MTG which represents the potential plant with a fixed final number of phytomers and branches. At each thermal time step, the turtle visits each element and adds a value to a time series for each (almost) properties of the MTG.

OR

At each thermal time step, the MTG is replicated and the growing elements ar modified, and new elements are added if needed.

Parametrized area of a leaf :

$$\mathcal{S}_normalized = 2|\int_0^1 \mathcal{C}(s(t))ds(t)|$$

$$\mathcal{S}_total = 2 * w * |\int_0^L \mathcal{C}(\frac{s(t)}{L})d\frac{s(t)}{L}|$$

$$\frac{d\mathcal{S}_total}{dt} = 2 * w * |\int_{ds(t)/L} \mathcal{C}(\frac{s(t)}{L})d\frac{s(t)}{L}|$$

- $\mathcal{S}$: leaf area/surface, in cm^2
- $s(t)$: curvilinear abscissa of the midrib, as a function of time, such that:

$$\frac{ds(t)}{dt} = \sqrt{(dx)^2 + (dy)^2}$$

- w : final width of the leaf, in cm
- L : final length of the leaf, in cm
- t : time, in $^oC.day^{-1}$
- $\frac{d\mathcal{S}}{dt}$: gain in surface for a given leaf for a given time step

```
def mtg_turtle_time(g, symbols, time, update_visitor=None ):
    ''' Compute the geometry on each node of the MTG using Turtle geometry.

    Update_visitor is a function called on each node in a pre order (parent before children)
    This function allow to update the parameters and state variables of the vertices.

    :Example:

        >>> def grow(node, time):

    '''

    g.properties()['geometry'] = {}
    g.properties()['_plant_translation'] = {}

    max_scale = g.max_scale()

    def compute_element(n, symbols, time):
        leaf = symbols.get('LeafElement')
        stem = symbols.get('StemElement')

        leaf_rank = int(n.complex().index())
        optical_species = int(n.po)

        metamer = n.complex()

        # Length computation
        if update_visitor:
            length = n.length
            final_length = metamer.final_length
        else:
            final_length = n.final_length
            try :
                length = final_length * (time - metamer.start_tt) / (metamer.end_tt - metame
            except:
                length = n.length

        if update_visitor and  n.label.startswith('L'):
            if metamer.final_length is None:
                metamer.final_length = n.final_length
                metamer.length = n.length
            length = metamer.length
```

```
            prev_length = metamer.final_length * (n.start_tt - metamer.start_tt) / (metamer.e
            s_base = (metamer.length - prev_length - n.length) / metamer.length
        else:
            s_base = n.srb
        s_top = n.srt
        seed = n.LcIndex
        #leaf inclination

        if update_visitor and  n.label.startswith('L'):
            linc = metamer.insertion_angle
        else:
            linc = n.Linc

        element = {}
        if n.label.startswith('L'):
            radius_max = n.Lw
            element = leaf(optical_species,
                        final_length,
                        length,
                        radius_max,
                        s_base,
                        s_top,
                        leaf_rank, seed, linc)
        else:
            diameter_base = n.parent().diam if (n.parent() and n.parent().diam > 0.) else n.d
            diameter_top = n.diam
            element = stem( optical_species, length, diameter_base, diameter_top)

        can_label =  element.get('label')
        if can_label:
            can_label.elt_id = leaf_rank
            plant_node = n.complex_at_scale(scale=1)
            can_label.plant_id = plant_node.index()

        geom = element.get('geometry')

        return geom, can_label

    def adel_visitor(g, v, turtle, time):
        # 1. retriev the node

        n = g.node(v)
```

```
    # Update visitor to compute or modified the node parameters
    if update_visitor is not None:
        update_visitor(n, time)

        if 'Leaf' in n.label:
            metamer = n.complex()
            if (n.start_tt <= time < n.end_tt) or ((time >= metamer.end_tt) and n.edge_ty
                angle = float(metamer.Laz) if metamer.Laz else 0.
                turtle.rollL(angle)
    else:
        if 'Leaf' in n.label:
            if n.edge_type()=='+':
                angle = float(n.Laz) if n.Laz else 0.
                turtle.rollL(angle)
        else:
            angle = float(n.Laz) if n.Laz else 0.
            turtle.rollL(angle)

    if g.edge_type(v) == '+':
        angle = n.Ginc or n.Einc
        angle = float(angle) if angle is not None else 0.
        #angle = n.inclination
        #angle = float(angle) if angle is not None else 0.
        turtle.up(angle)

    # 2. Compute the geometric symbol
    mesh, can_label = compute_element(n, symbols, time)
    if mesh:
        n.geometry = transform(turtle, mesh)
        n.can_label = can_label

    # 3. Update the turtle
    turtle.setId(v)

    m = n.complex()
    if update_visitor:
        length = n.length
    else:
        try:
            length = n.length * (time - m.start_tt) / (m.end_tt - m.start_tt) if time < m
        except:
            length = n.length
```

```
    if ('Leaf' not in n.label) and (length > 0.):
        turtle.F(length)
    # Get the azimuth angle


def traverse_with_turtle_time(g, vid, time, visitor=adel_visitor):
    turtle = PglTurtle()
    def push_turtle(v):
        n = g.node(v)
        #if 'Leaf' in n.label:
            #    return False
        try:
            start_tt = n.complex().start_tt
            if start_tt > time:
                return False
        except:
            pass
        if g.edge_type(v) == '+':
            turtle.push()
        return True

    def pop_turtle(v):
        n = g.node(v)
        try:
            start_tt = n.complex().start_tt
            if start_tt > time:
                return False
        except:
            pass
        if g.edge_type(v) == '+':
            turtle.pop()

    if g.node(vid).complex().start_tt <= time:
        visitor(g,vid,turtle,time)
        #turtle.push()
    plant_id = g.complex_at_scale(vid, scale=1)
    for v in pre_order2_with_filter(g, vid, None, push_turtle, pop_turtle):
        if v == vid: continue
        # Done for the leaves
        if g.node(v).complex().start_tt > time:
            print('Do not consider ', v, time)
            continue
```

```
            visitor(g,v,turtle,time)

        scene = turtle.getScene()
        return g

    for plant_id in g.component_roots_at_scale_iter(g.root, scale=max_scale):
        g = traverse_with_turtle_time(g, plant_id, time)
    return g
```

```
def thermal_time(g, phyllochron=110., leaf_duration=1.6, stem_duration=1.6, leaf_falling_rate
    """
    Add dynamic properties on the mtg to simulate developpement
    leaf_duration is the phyllochronic time for a leaf to develop from tip appearance to col
    stem_duration is the phyllochronic time for a stem to develop
    falling_rate (degrees / phyllochron) is the rate at which leaves fall after colar appear
    """

    plants = g.vertices(scale=1)
    metamer_scale = g.max_scale()-1

    for plant in plants:
        tt = 0
        v = next(g.component_roots_at_scale_iter(plant, scale=metamer_scale))
        for metamer in pre_order2(g, v):
            end_leaf = tt + phyllochron*leaf_duration
            nm = g.node(metamer)
            nm.start_tt = tt
            nm.end_tt = end_leaf
            nm.frate = leaf_falling_rate / phyllochron
            sectors = [node for node in nm.components() if 'Leaf' in node.label]
            stems = [node for node in nm.components() if 'Stem' in node.label]

            nb_stems = len(stems)
            stem_tt = end_leaf
            dtt = phyllochron*stem_duration / nb_stems
            for stem in stems:
                stem.start_tt = stem_tt
                stem.end_tt = stem_tt+dtt
                stem_tt += dtt

            nb_sectors = max(1,len(sectors))
            sector_tt = end_leaf
```

```
        dtt = phyllochron*leaf_duration/nb_sectors
        for sector in sectors:
            sector.start_tt = sector_tt - dtt
            sector.end_tt = sector_tt
            sector_tt -= dtt

        tt += phyllochron

    return g
```

4.1 Next steps

- appearance and elongation of phytomers (internodes and leaves)
- Constrains from crop model

References

Knuth, Donald E. 1984. "Literate Programming." *Comput. J.* 27 (2): 97–111. https://doi.org/10.1093/comjnl/27.2.97.