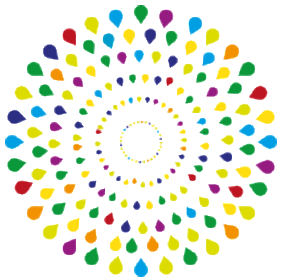


biohaviour

GEOMETRIC CHALLENGES FOR THE BLIND WATCHMAKER

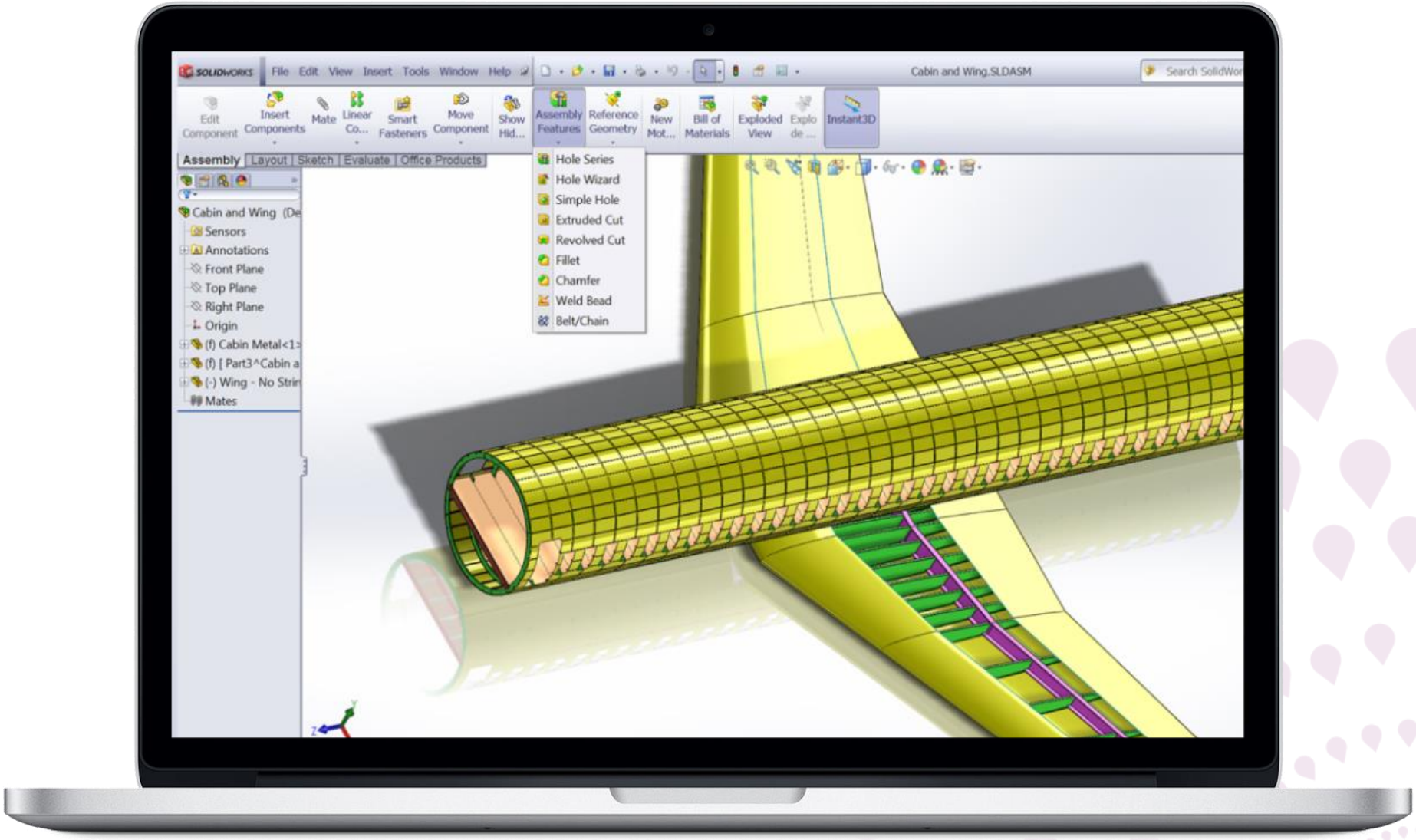
Queen's University Belfast

Mark Price
Trevor Robinson
Wei Zhang

Sanjiv Sharma
Henry Bucklow
Geoff Butlin
Alan McDonald

BIO-INSPIRED GENERATIVE DESIGN SYSTEMS

- Inspiration
- Investigations
- Implementation


SOLIDWORKS
File Edit View Insert Tools Window Help
Cabin and Wing.SLDASM
Search SolidWor
Edit Component
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Reference Geometry
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Layout
Sketch
Evaluate
Office Products
Hole Series
Hole Wizard
Simple Hole
Extruded Cut
Revolved Cut
Fillet
Chamfer
Weld Bead
Belt/Chain
Cabin and Wing (De
Sensors
Annotations
Front Plane
Top Plane
Right Plane
Origin
(f) Cabin Metal<1>
(f) [Part3^Cabin a
(-) Wing - No Strir
Mates

ORDER FROM CHAOS

Simple Rules - Extraordinary Results.
3 Rules for Flocking:

1 SEPARATION

avoid crowding neighbours (short range repulsion)

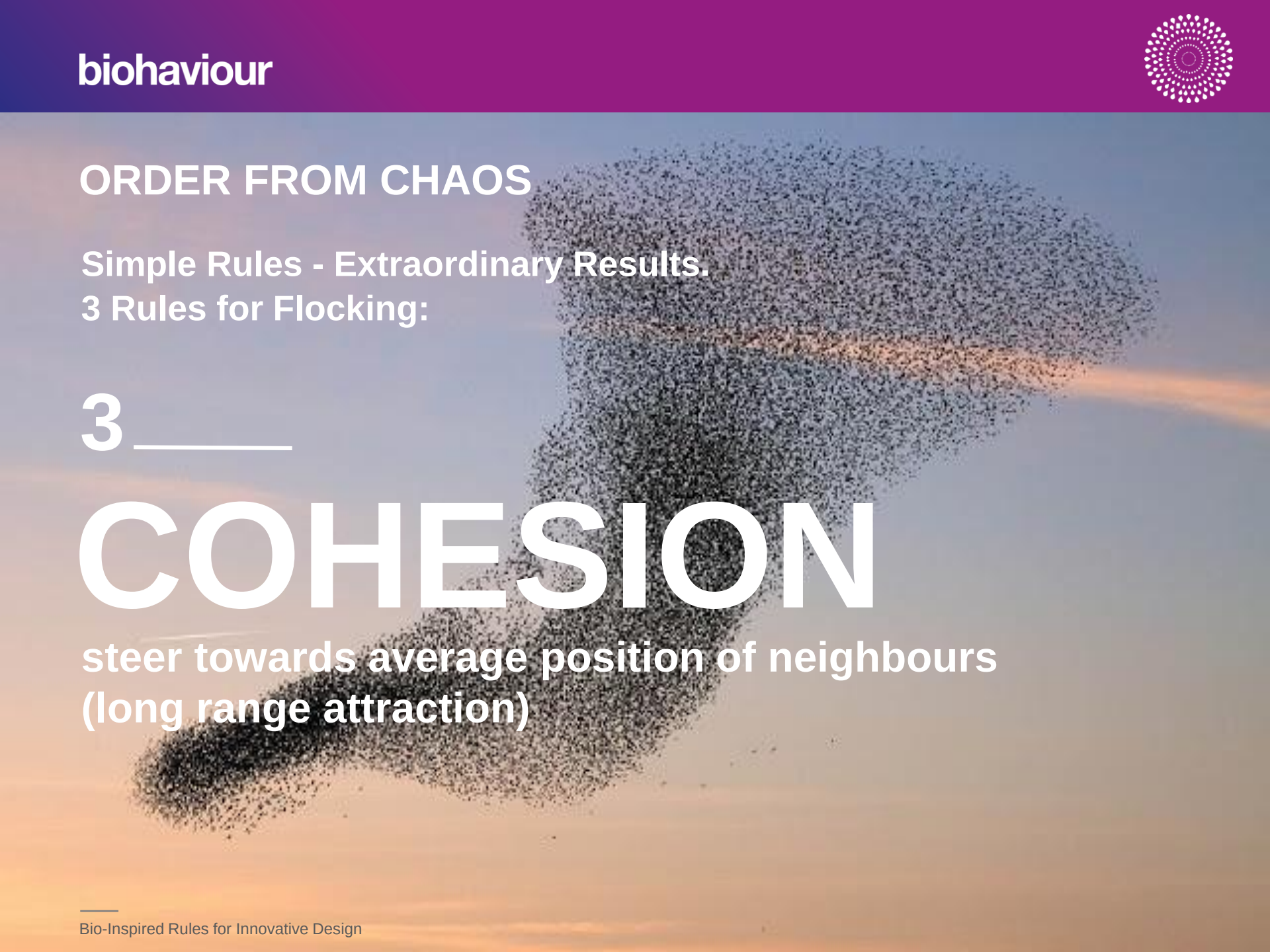
ORDER FROM CHAOS

Simple Rules - Extraordinary Results.
3 Rules for Flocking:

2

ALIGNMENT

steer towards average heading of neighbours



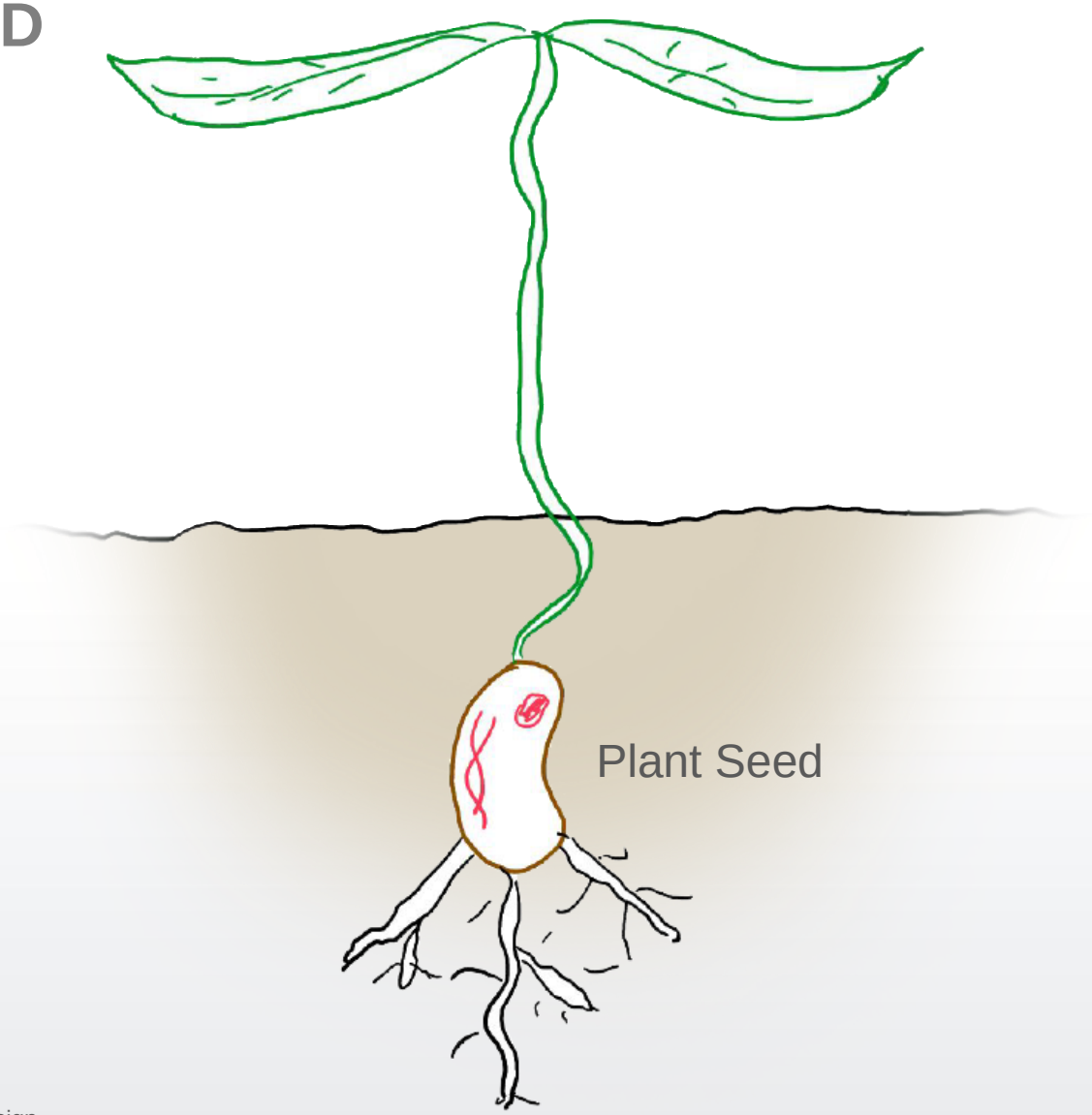
ORDER FROM CHAOS

Simple Rules - Extraordinary Results.
3 Rules for Flocking:

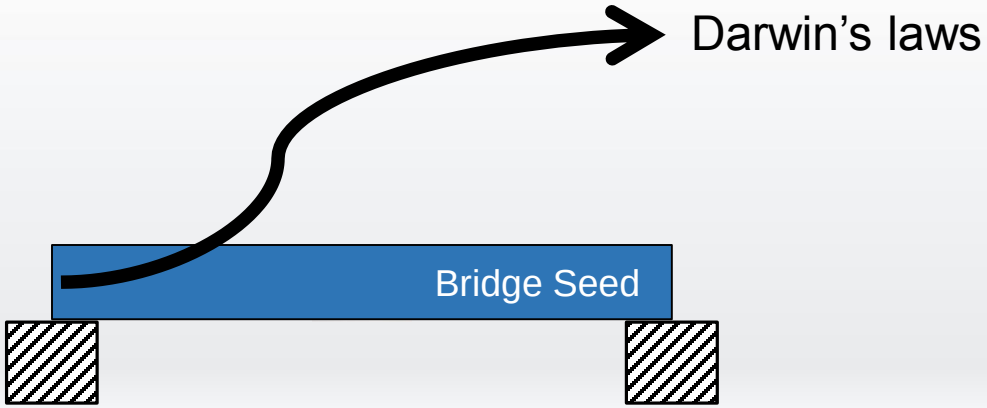
3 COHESION

steer towards average position of neighbours (long range attraction)

BIO-INSPIRED



BIO-INSPIRED



F=ma [F] = [K][d]

$$\sum_{i=1}^{n}\sum_{k=1}^{m} f_{i,j} = 0$$

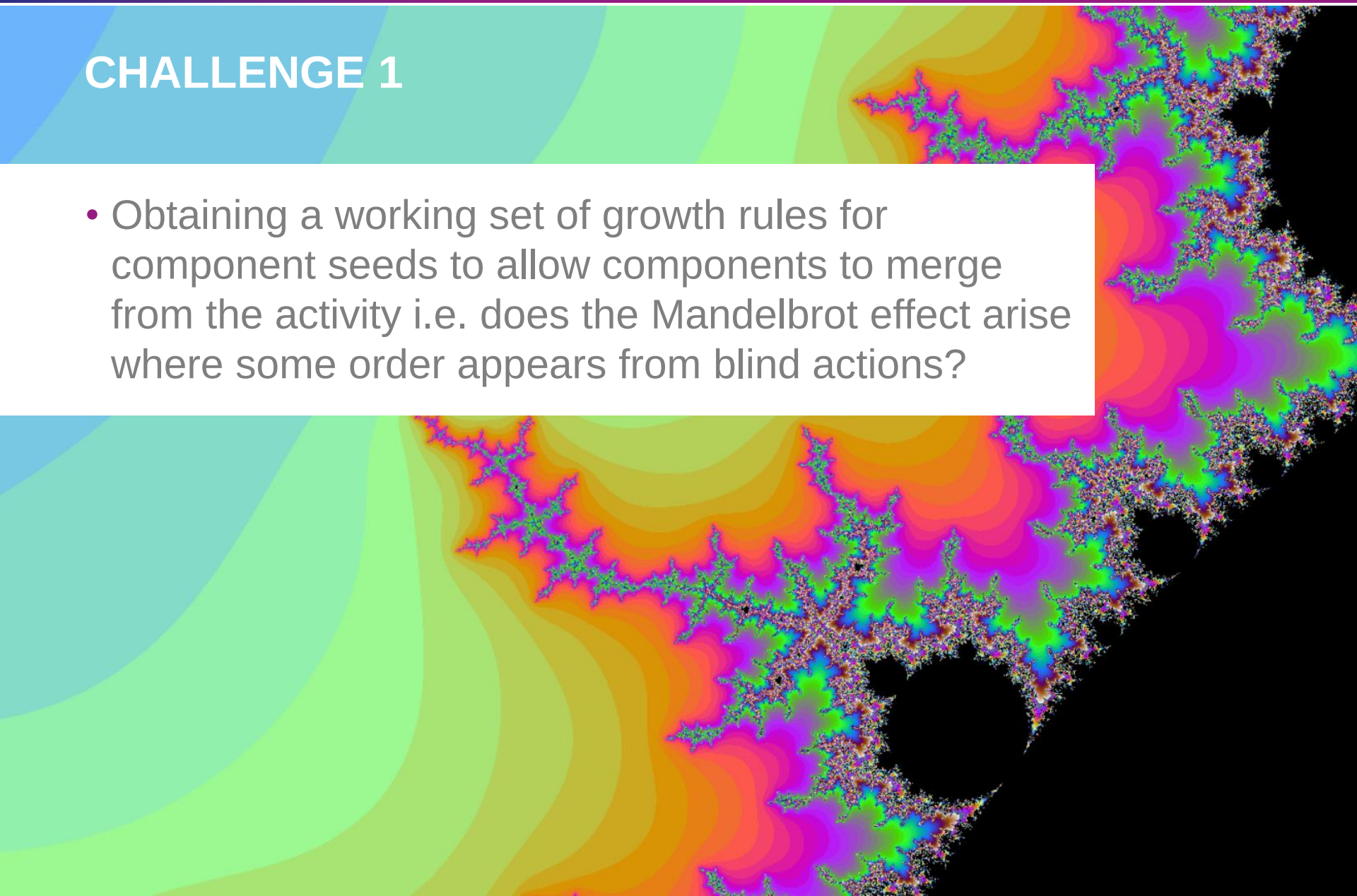
Newton's 3 laws

ETHOS

- Rethink design rules and processes
- Create a new autonomous design process
- Radically change roles and activities in the manufacturing organisation
- Embrace emergent behaviour for design innovation

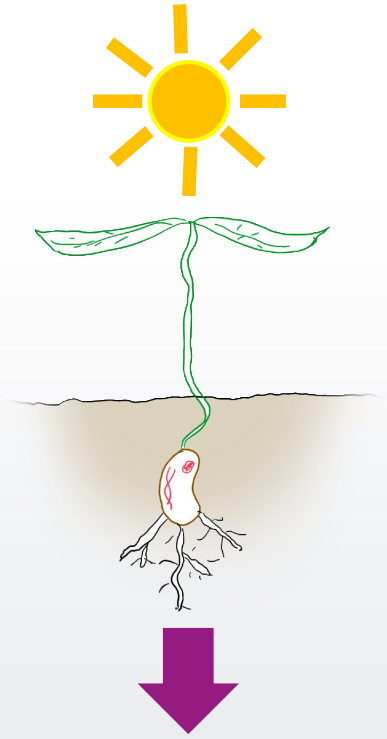
CHALLENGE 1

- Obtaining a working set of growth rules for component seeds to allow components to merge from the activity i.e. does the Mandelbrot effect arise where some order appears from blind actions?



CHALLENGE 2

- **Defining stimuli** that will make the component seeds grow and establishing if that growth can be controlled via the stimuli.



GRAVITY?

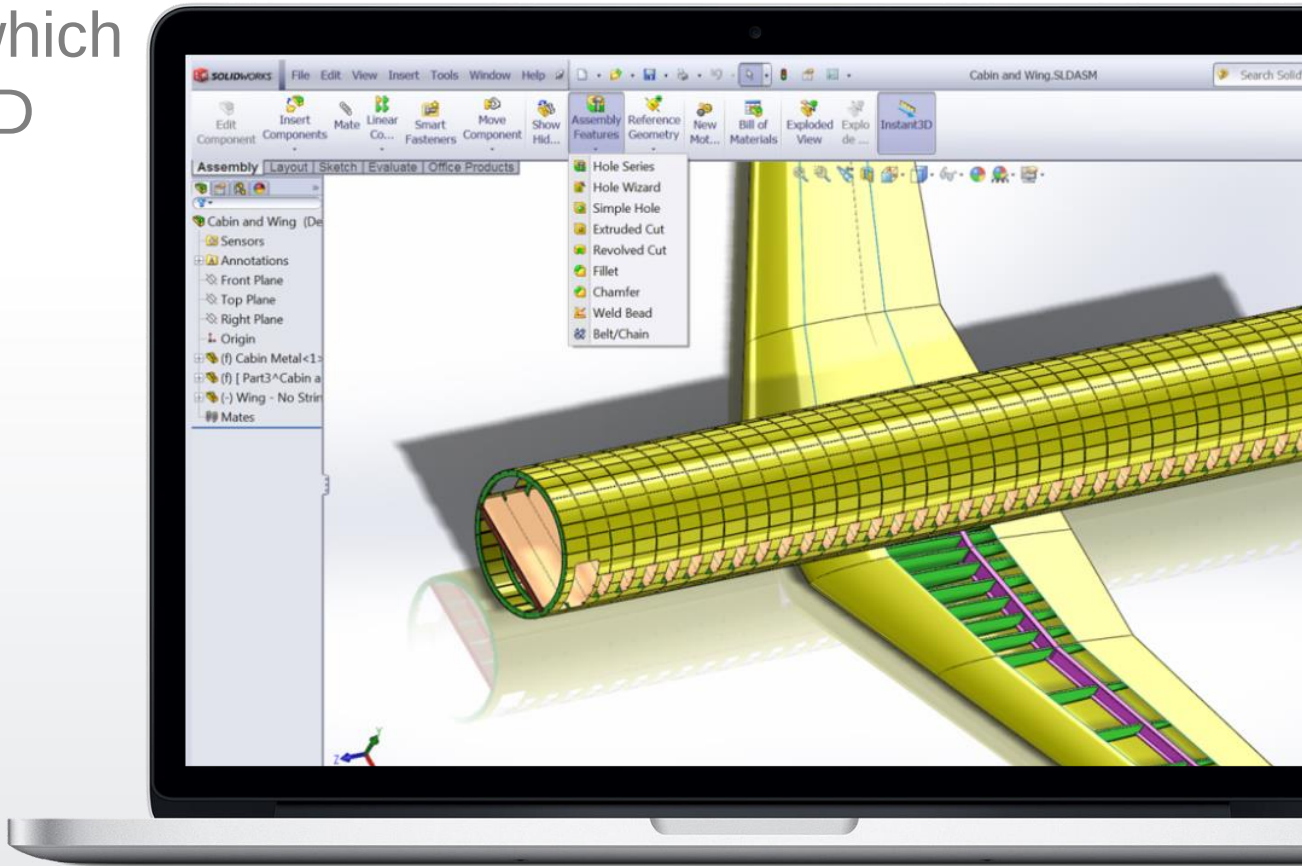
STRESS?

COST?

ENERGY?

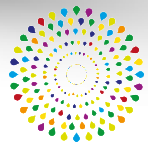
CHALLENGE 3

- Capturing emergent behaviour into a working set of parameters that can interact with existing design & manufacturing systems - i.e. is there a set of parameters which will define a CAD model?



PROGRESS SUMMARY

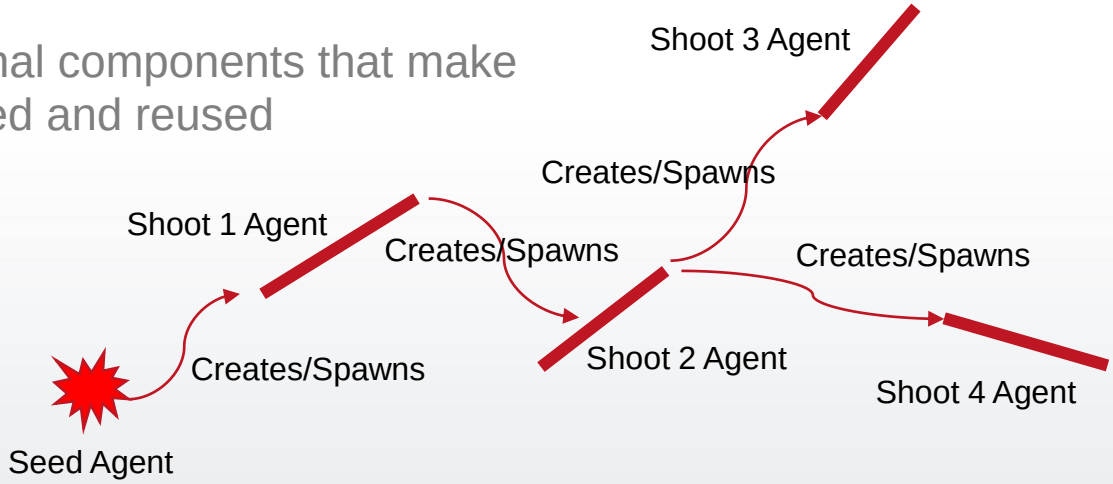
- AGENTS
- INTEGRATED SYSTEMS
- INVESTIGATIONS



AGENTS

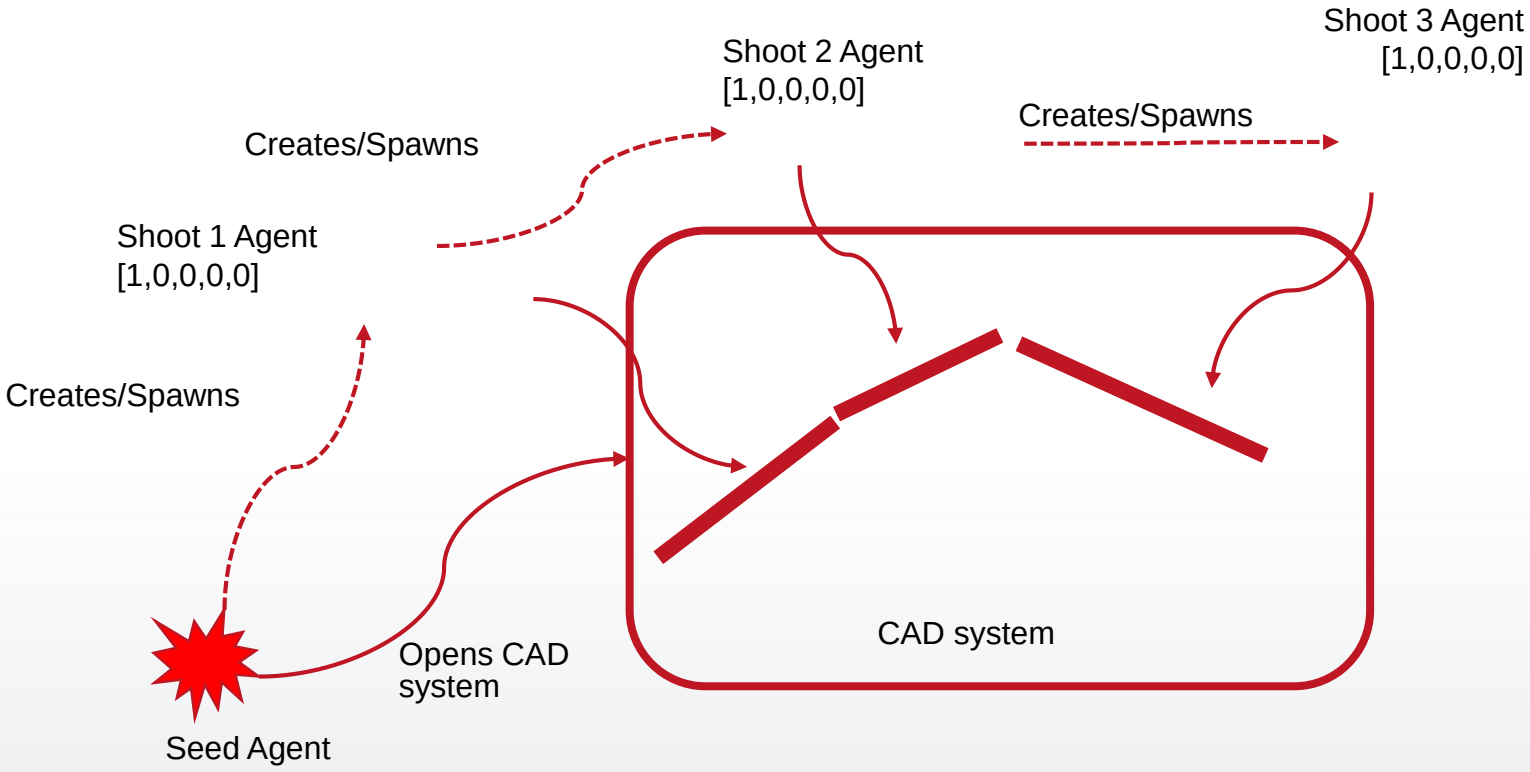
AGENTS

- Agent has:
  - (i) A Belief set: what the agent believes to be true
  - (ii) An Event: describes an occurrence in response to which the agent must take action
  - (iii) A Plan: the instructions the agent follows to try to achieve its goals and handle its designated events, and
  - (iv) A Capability: the functional components that make up an agent to be aggregated and reused



AGENTS

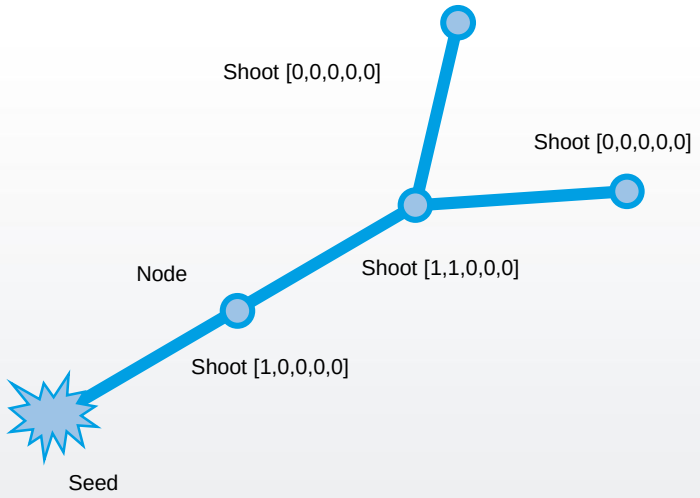
- Agents linked to CAD entities
  - Each agent represents a CAD entity line

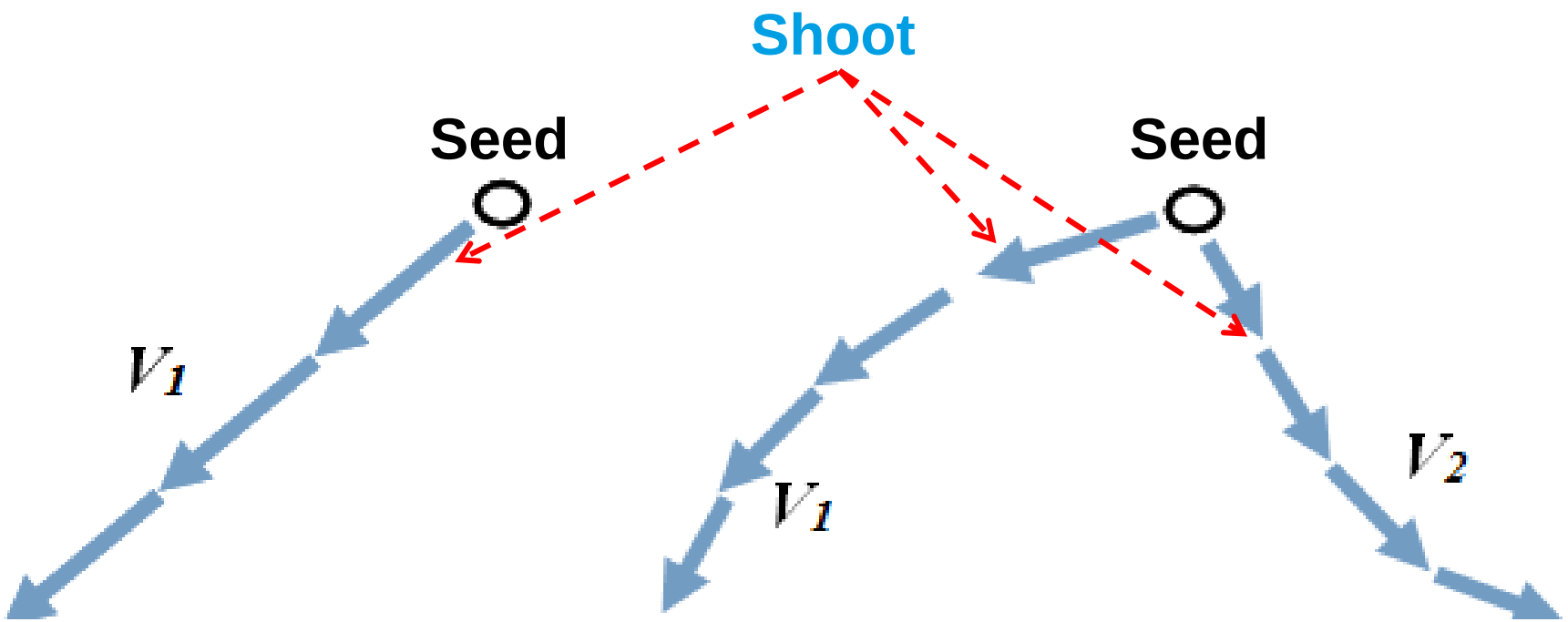


WHAT IS A GENE?

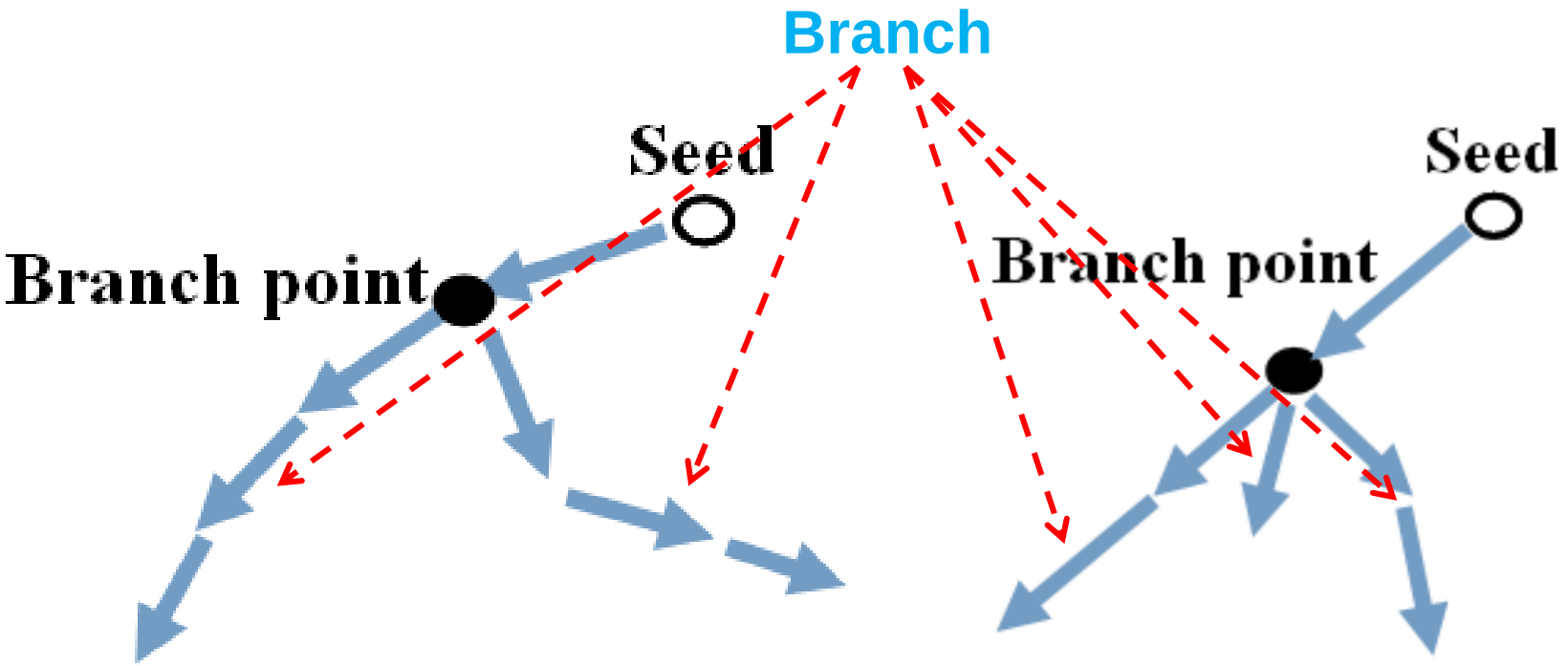
- **Design Gene:** is a vector, string or sequence, of binary values which represents the total behaviour of the design.
- **Design Seed:** is a collection of design genes which characterise a complete product.
- **Tree-like gene** = [1, 1, 1, 0, 1]

Gene Function	Value	Action
Grow	1	Grow in a direction
Branch	1	Split / fork
Stem	1	Grow vertically only
Leaf	0	Form a surface
Thicken	1	Allowed to get thicker





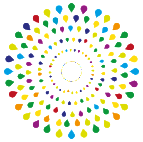
Non-split; grow along any directions
until a growth criterion is satisfied



Split; grow along any directions until a split condition met, then the shoots split, each with its own new direction and magnitude set.

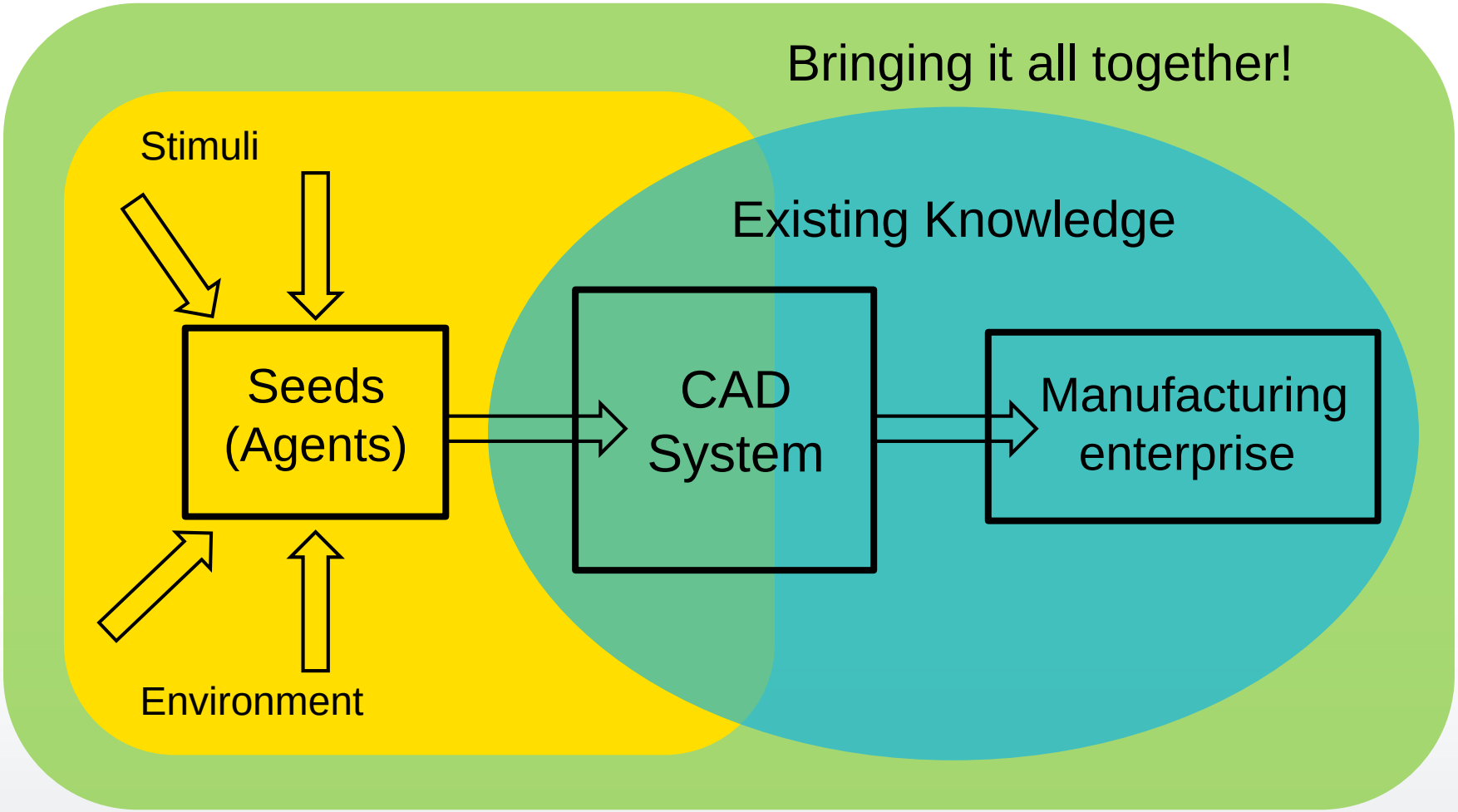
Blind actions……

- Unknown growth occurs in response to stimuli
- Every element persists for the life of the design
- Every element makes its own blind actions, unaware of the overall design



INTEGRATED SYSTEM

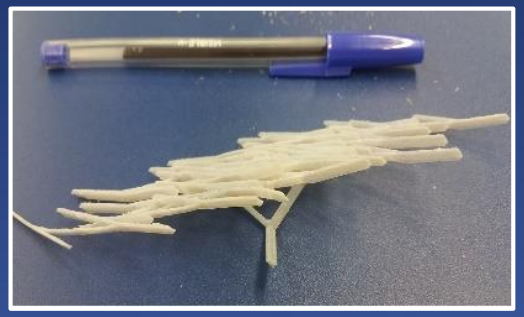
PROPOSED SYSTEM SCHEMATIC

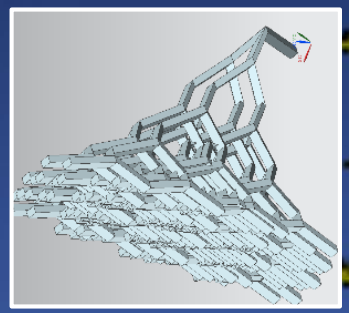


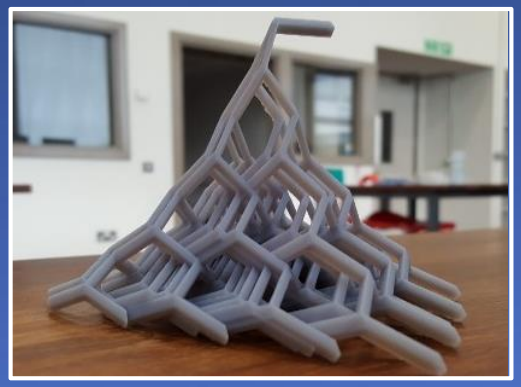
ADVANCED MANUFACTURING

CAD models can be 3D printed

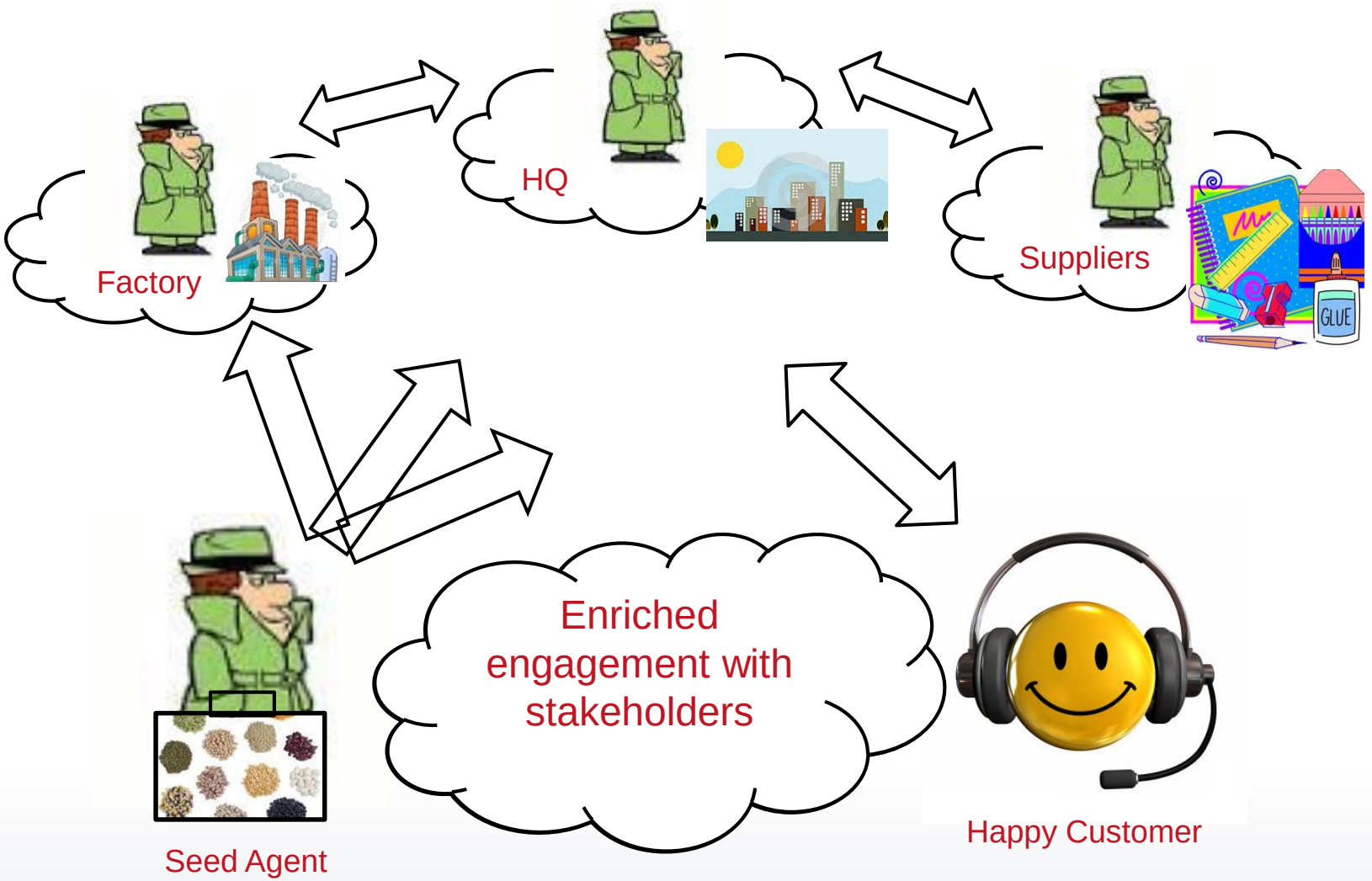
Design process to exploit the abilities of novel manufacturing

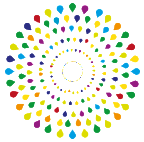






POTENTIAL IMPACT



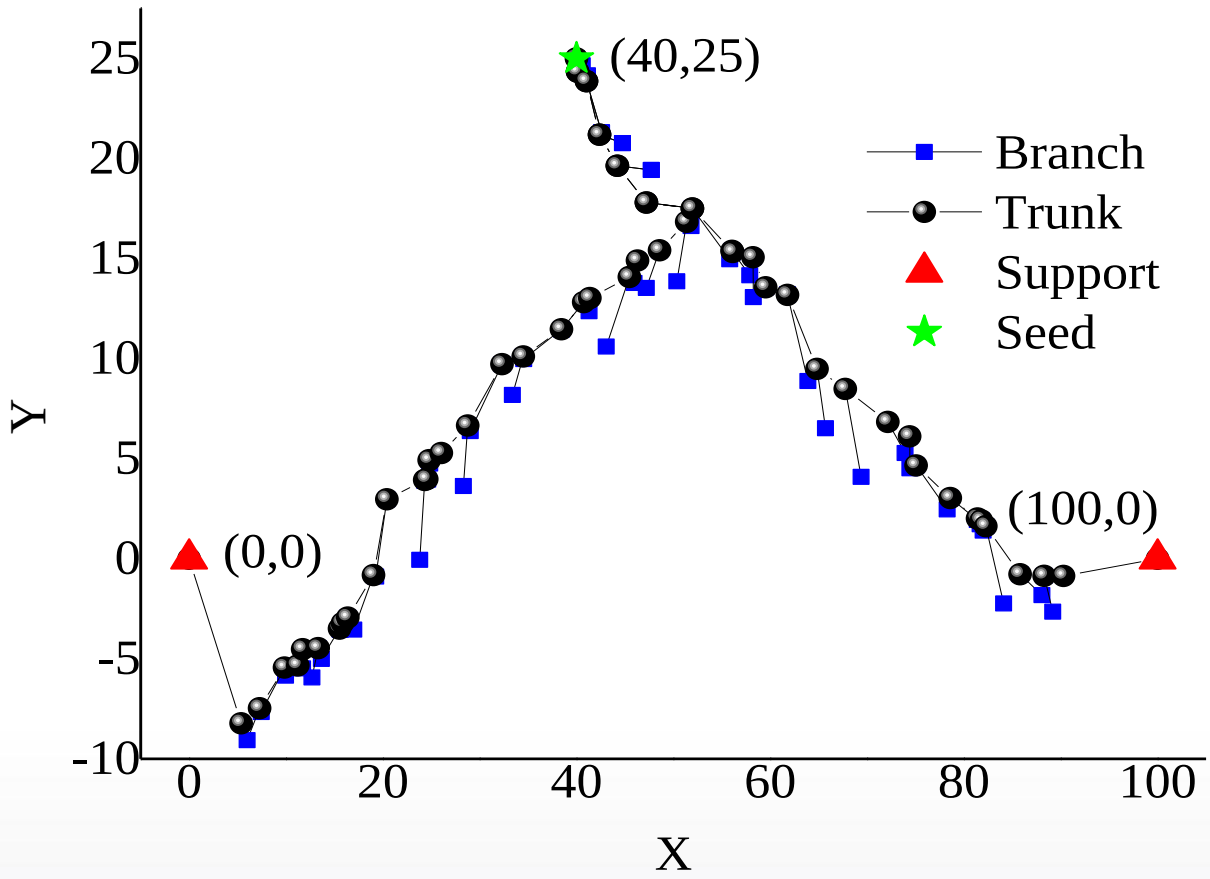


INVESTIGATIONS

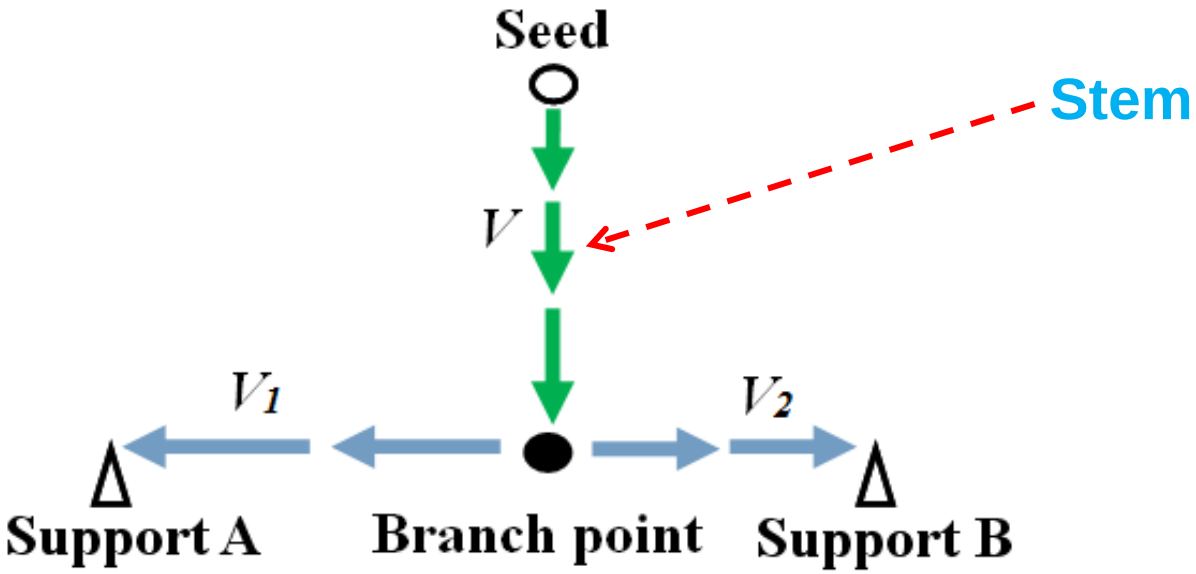
$$\min_{S_{seed}(S_x,S_y)\in\vec{\mathbf{V}}\in\Omega} T(G_s, G_g)$$

- **Core algorithm**
  - Given growth functions for **length** and **angle**

```
While growth step Gs < Gg
    If condition 1 is satisfied
        Set design gene type 1 on
            Update length and angle using growth function 1
    Else
        Set design gene type 2 on
            Update length and angle using growth function 2
    End
End
```

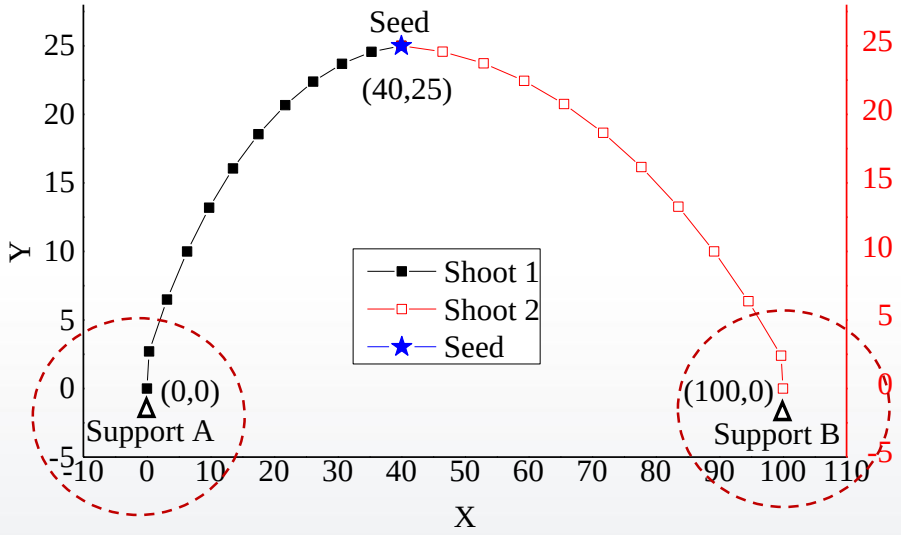


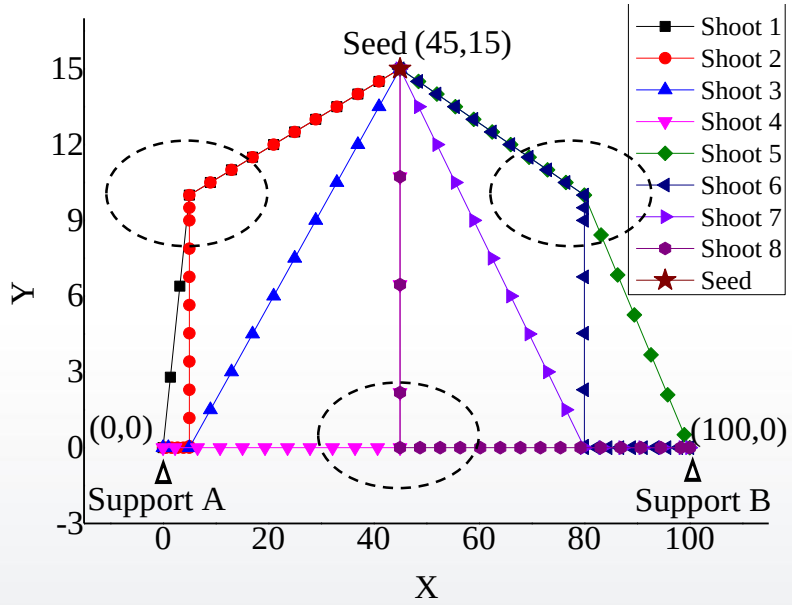
Grow along a random direction and/or length



Grow up or down only

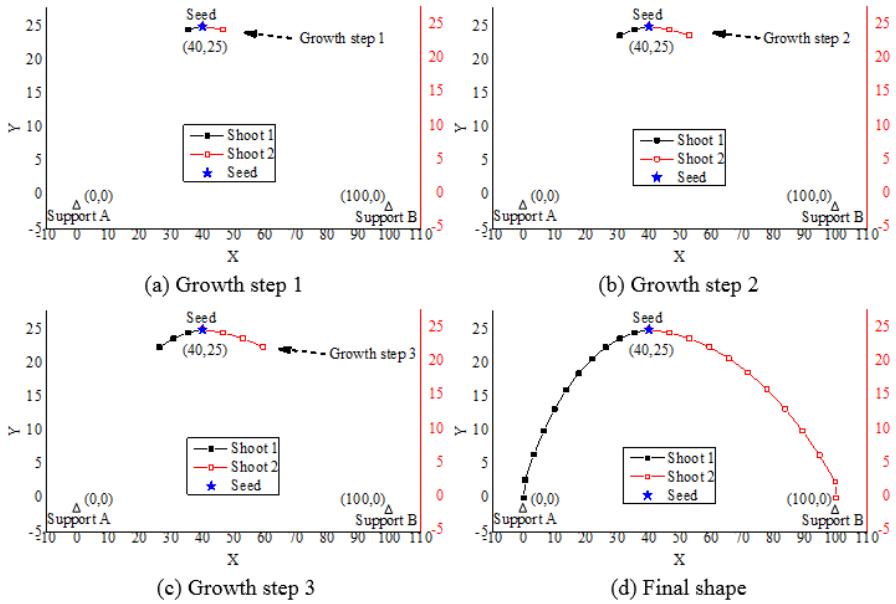
- With simple control rules, it is easy to create familiar structures, like frameworks.



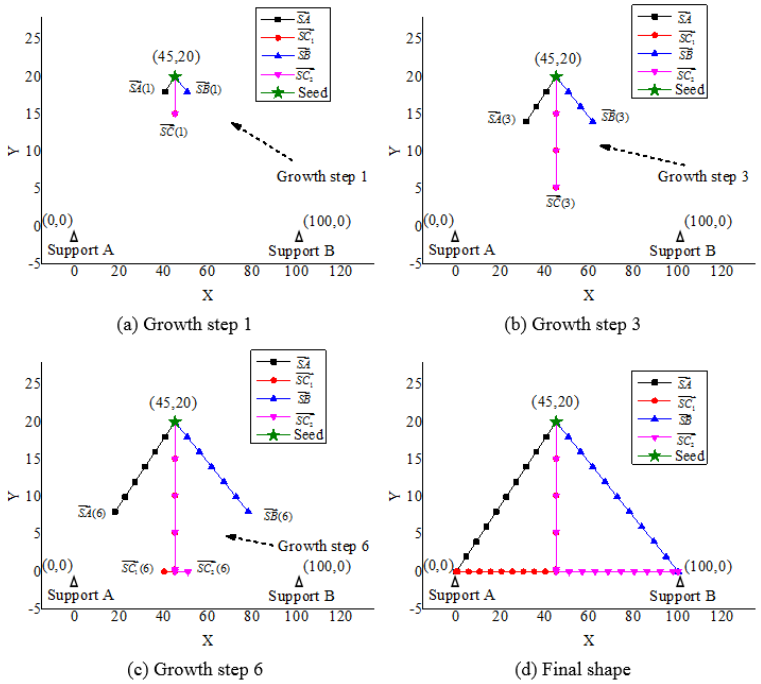


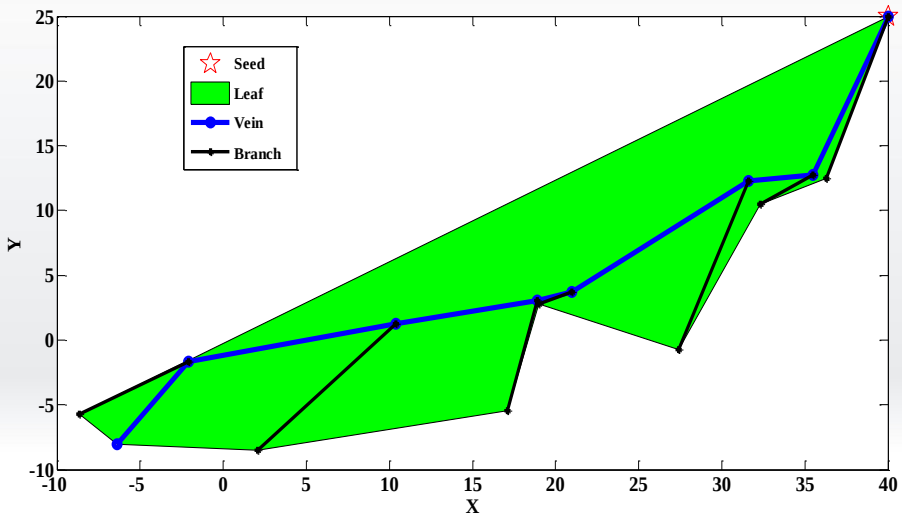
GENES FOR GROWTH

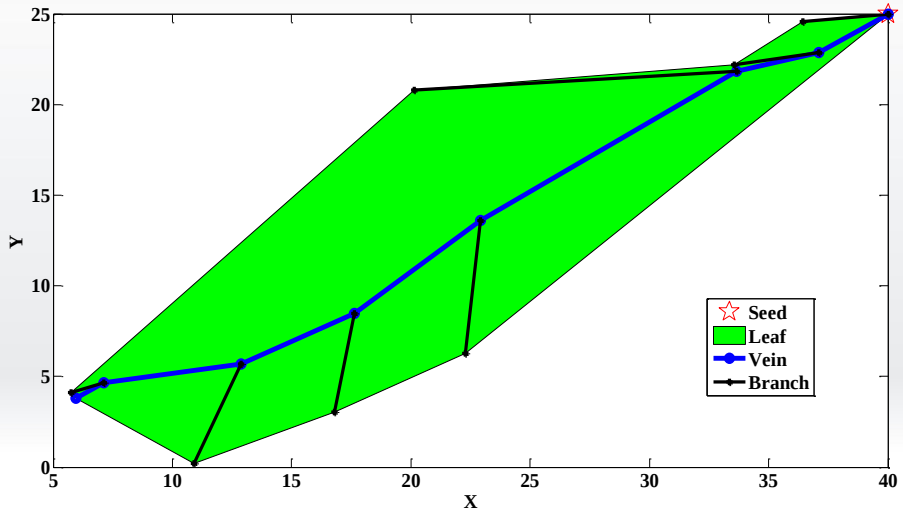
- Branch at the beginning and then grows towards supports



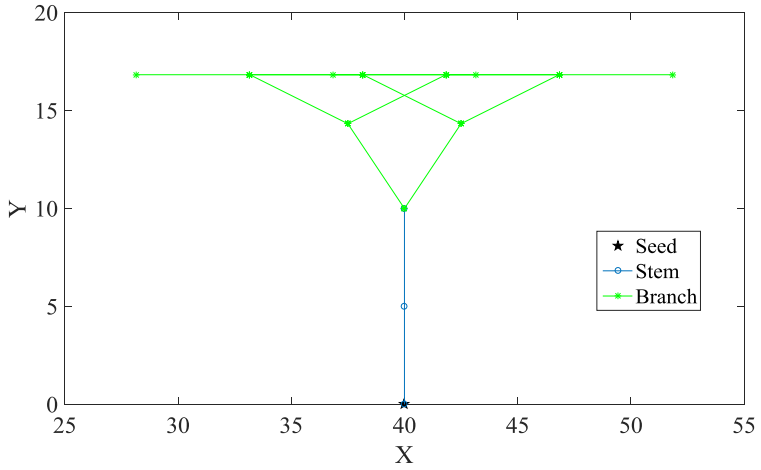
- Branch at the beginning,
  - 1 shoot with stem gene active
  - Stem branches and grows towards support



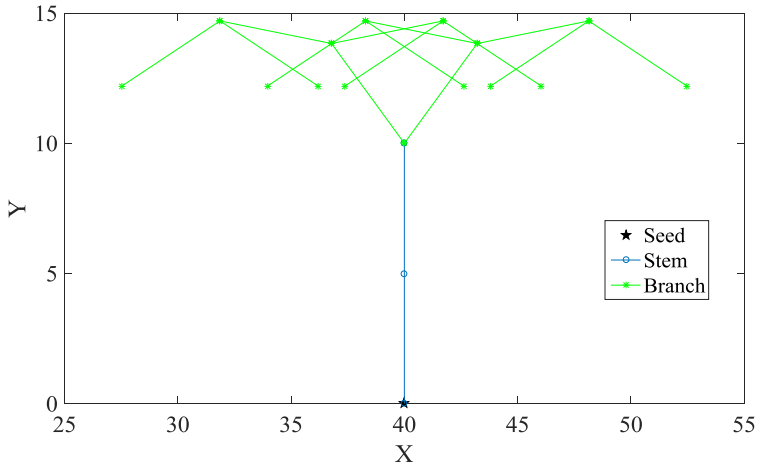




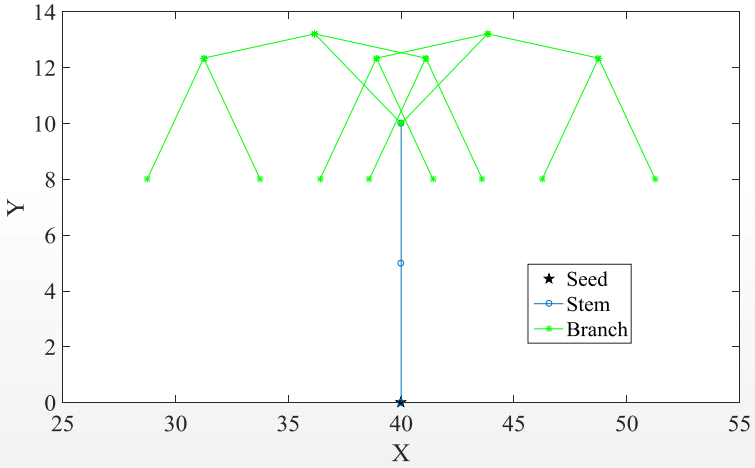
Split; grow along any directions; a surface is formed using all end points of each branch and seed



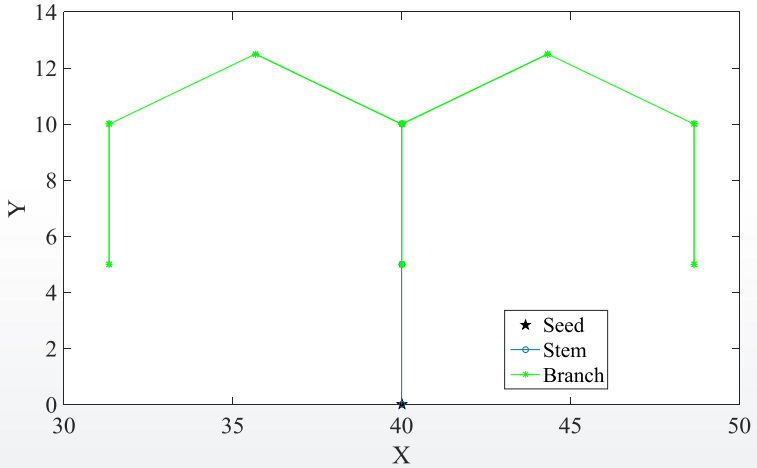
$angle_{(0)} = 60^{\circ}$



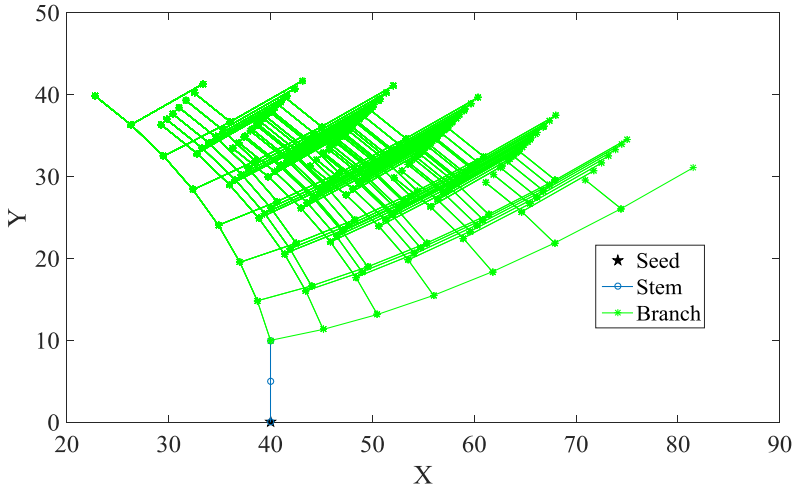
$angle_{(0)} = 50^{\circ}$



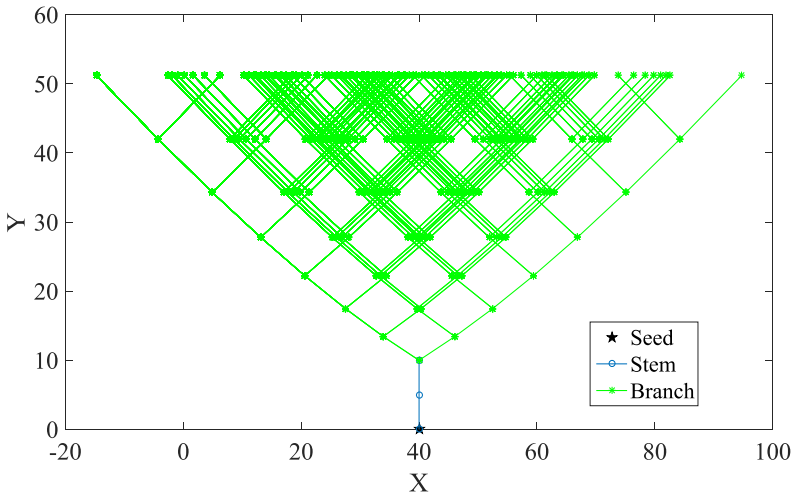
$angle_{(0)} = 40^{\circ}$



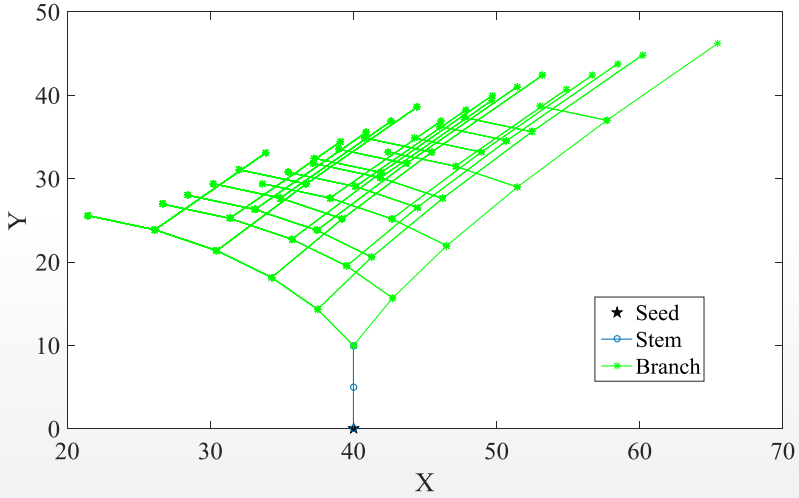
$angle_{(0)} = 30^{\circ}$



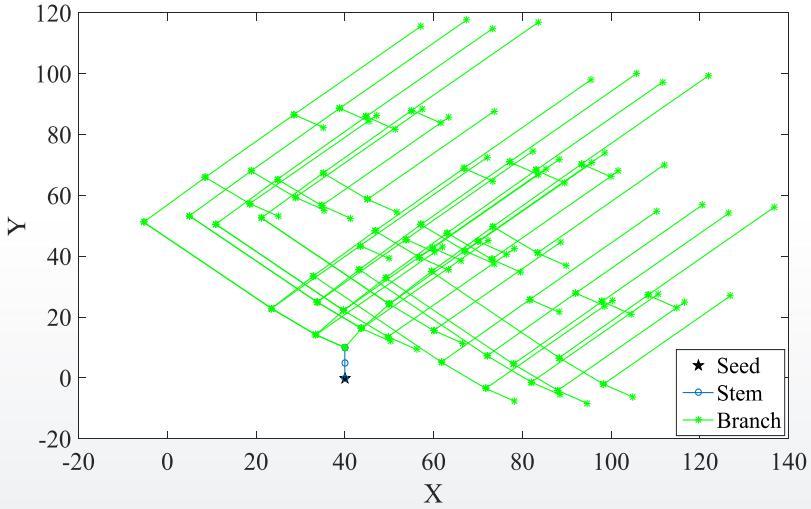
Left: circle; right: hyperbola A



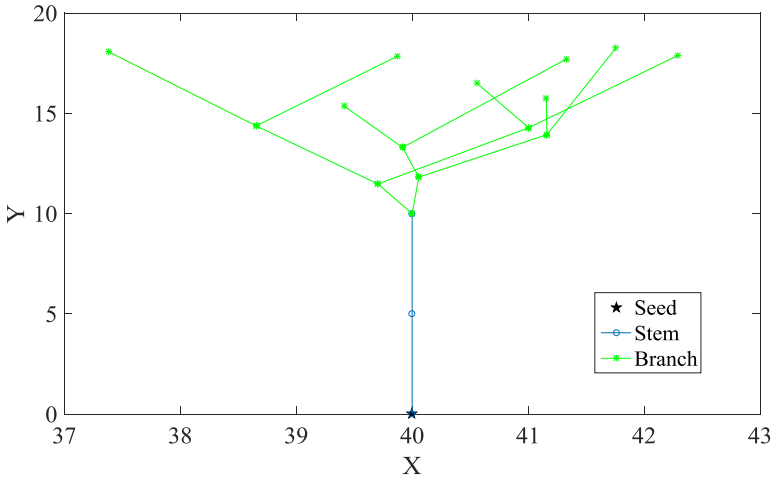
Left and right: hyperbola A



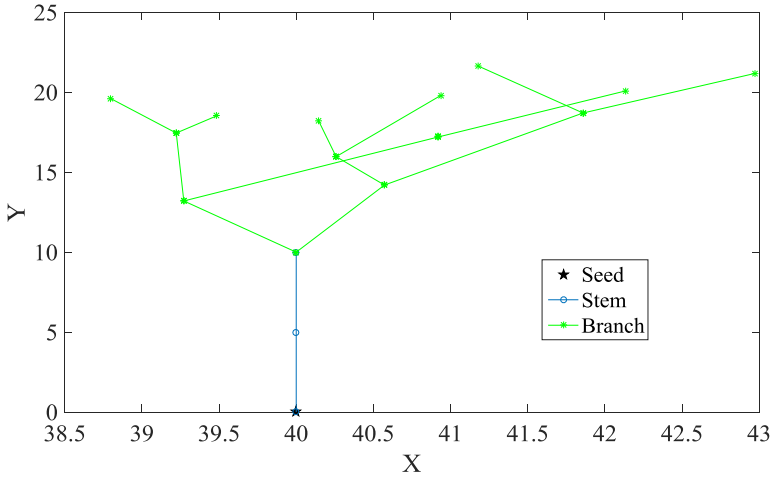
Left: circle; right: hyperbola B



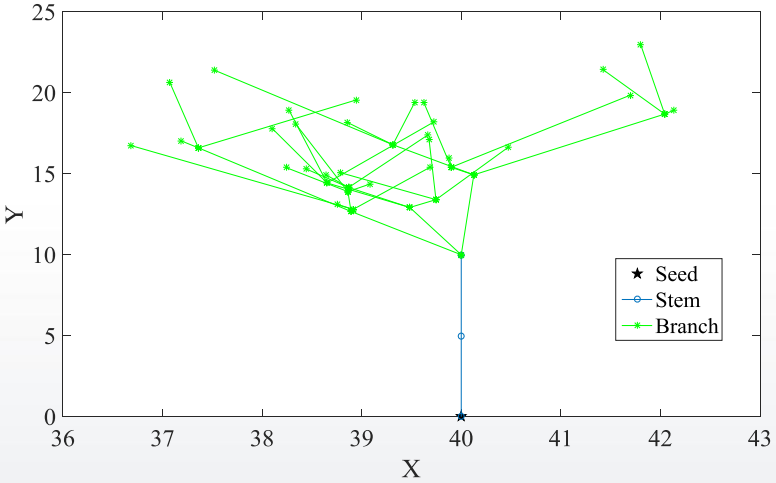
Left: hyperbola A; right: hyperbola B



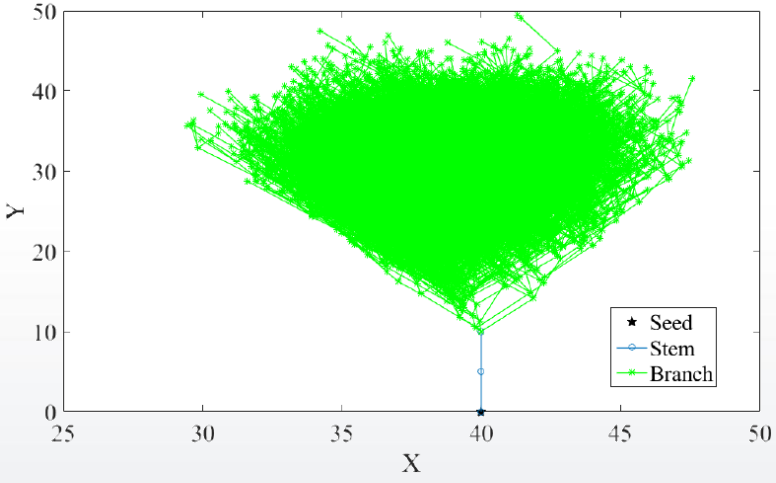
Split step 3, number of branch 2



Split step 3, number of branch 2

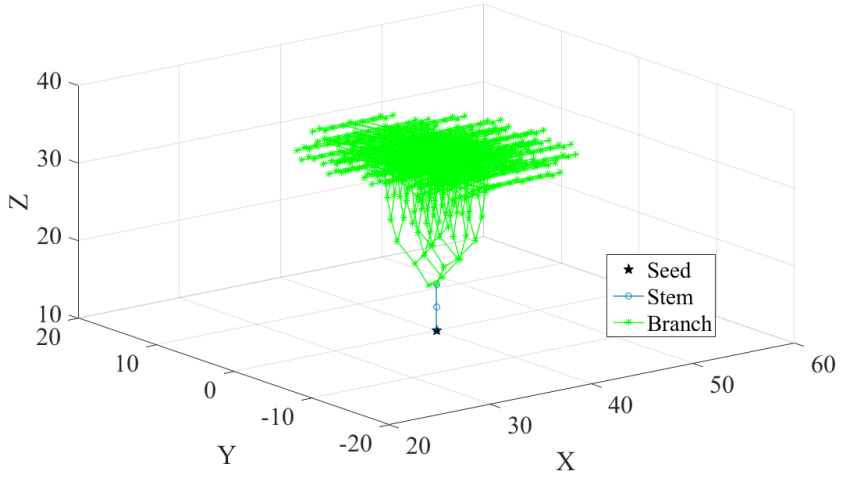


Split step 3, number of branch 3

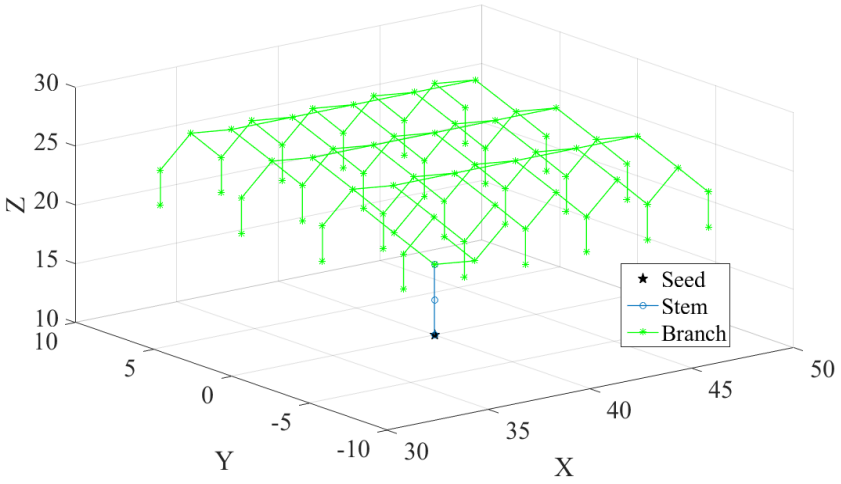


Split step 9, number of branch 3

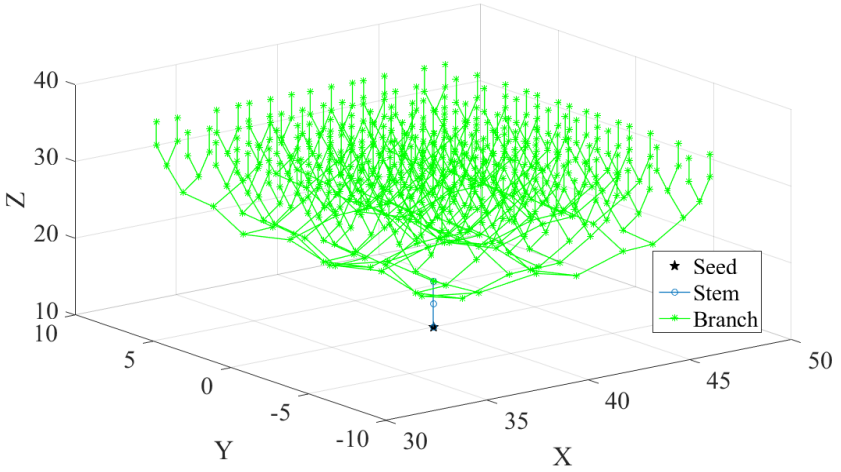
biohaviour



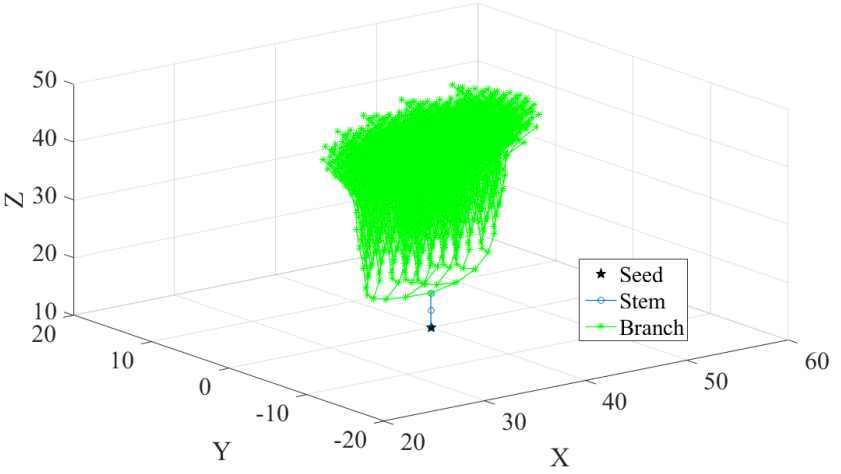
α = 40°, β=20°, L=3, split step 9



α = 90°, β=30°, L=3, split step 9

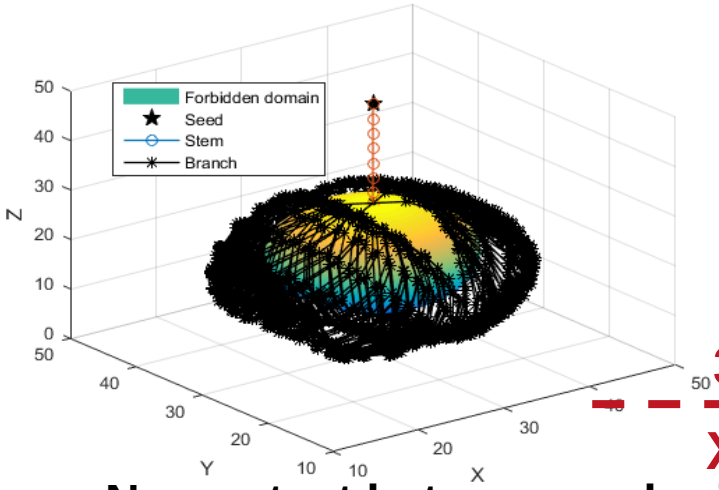


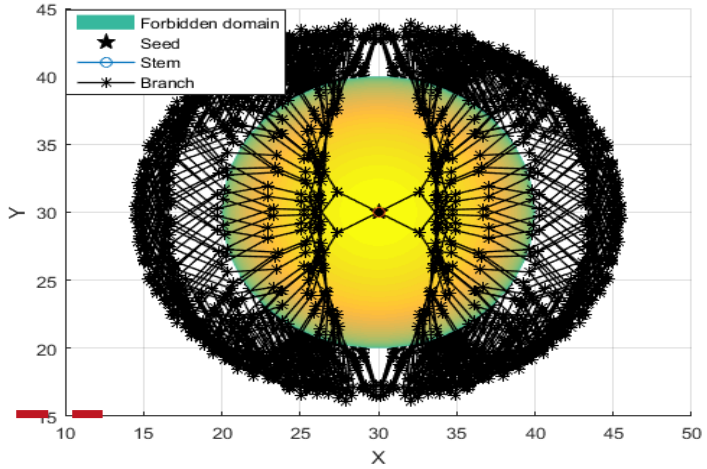
α = 90°, β=10°, L=3, split step 9



α = 10°, β=10°, L=3, split step 15

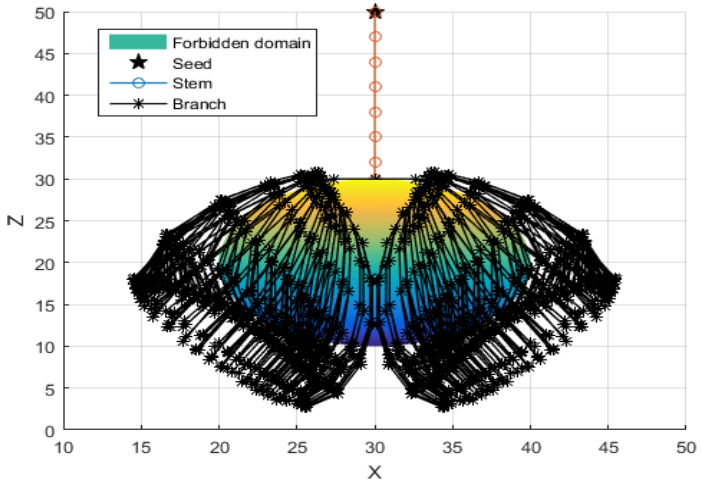
3D CASE: alpha = 15° bate = 30°, split step = 9

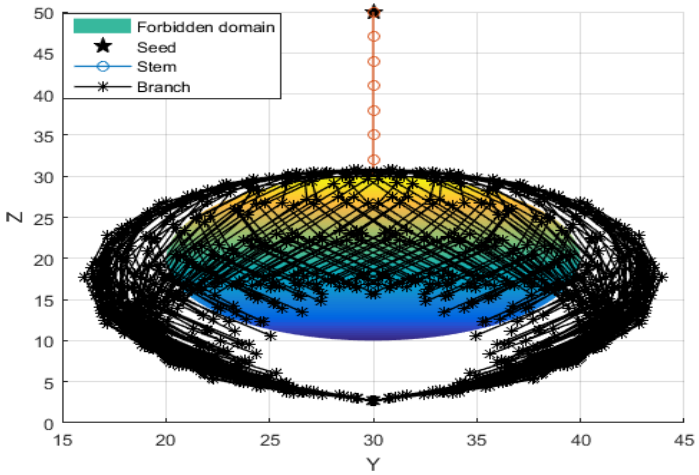




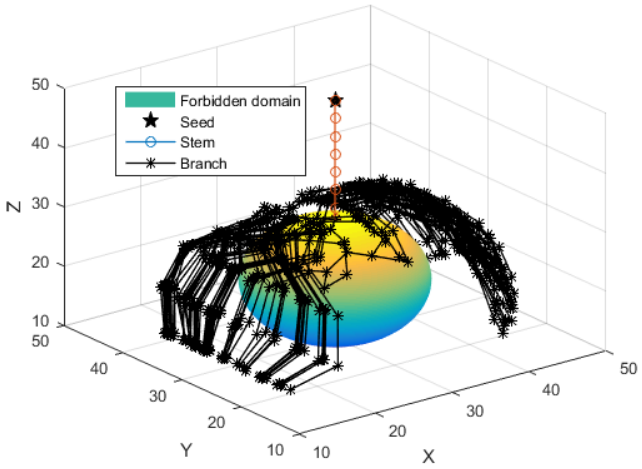
3D X-Y X-Z Y-Z

No contact between endpoints and the surface of a forbidden domain except the initial touched point

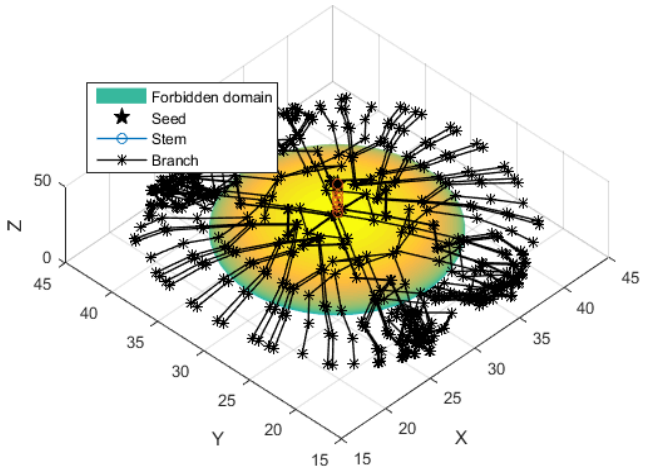




PARAMETER STUDY: angle and split step



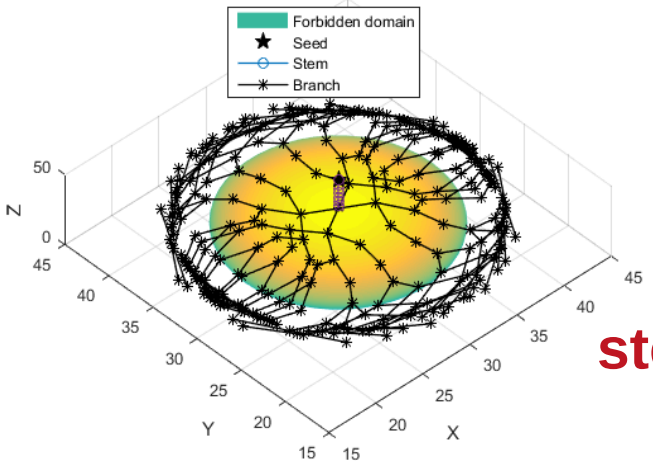
alpha = 45˚, beta = 45˚, split step = 11z



alpha = 10°, beta = 120°, split step = 9

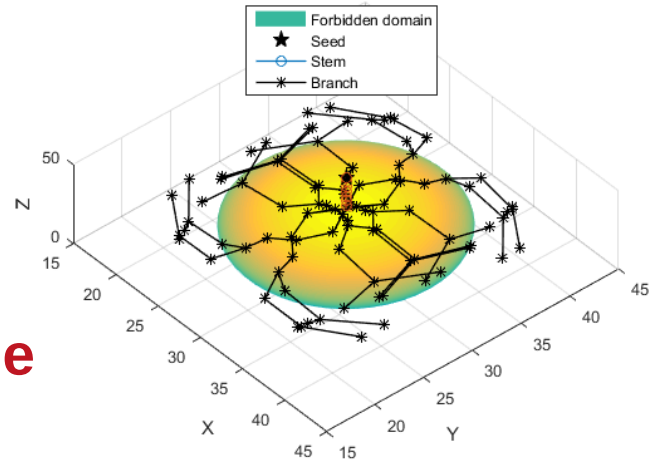
Case 1 | Case 2

Case 3 | Case 4



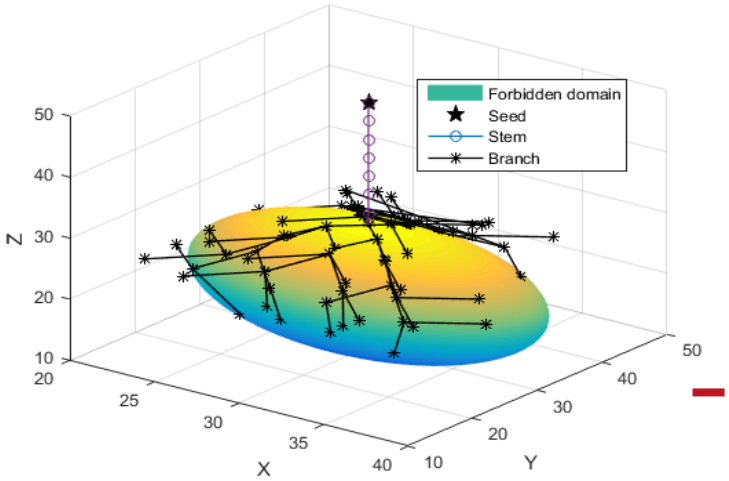
alpha = 30°, beta = 30°, split step = 6

Angle and split step can regulate the growth of design



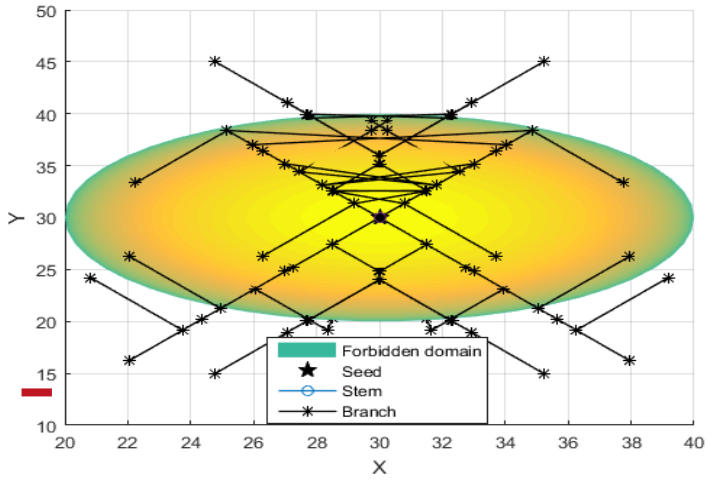
alpha = 30°, beta = 60°, split step = 6

3D CASE: alpha = 25° beta = 60°, split step = 7

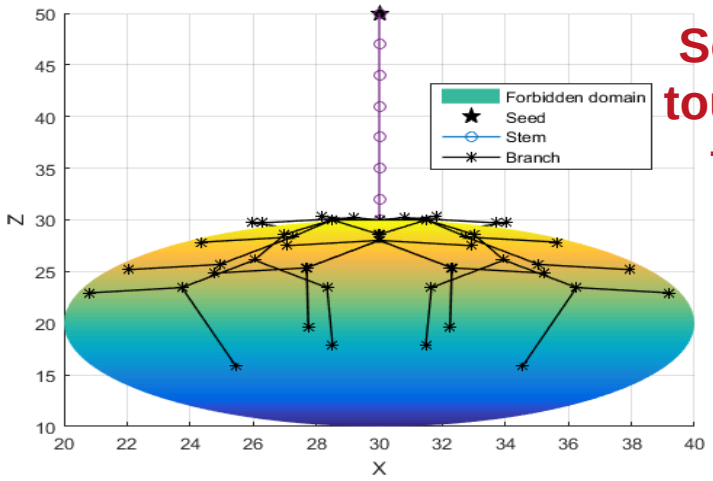


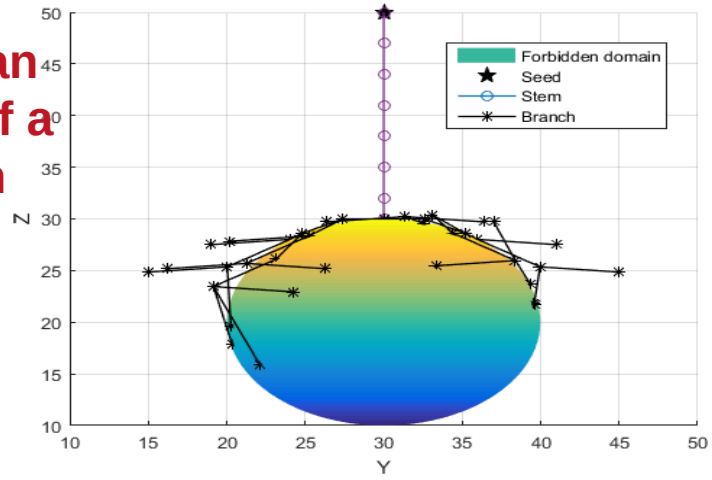
3D | X-Y

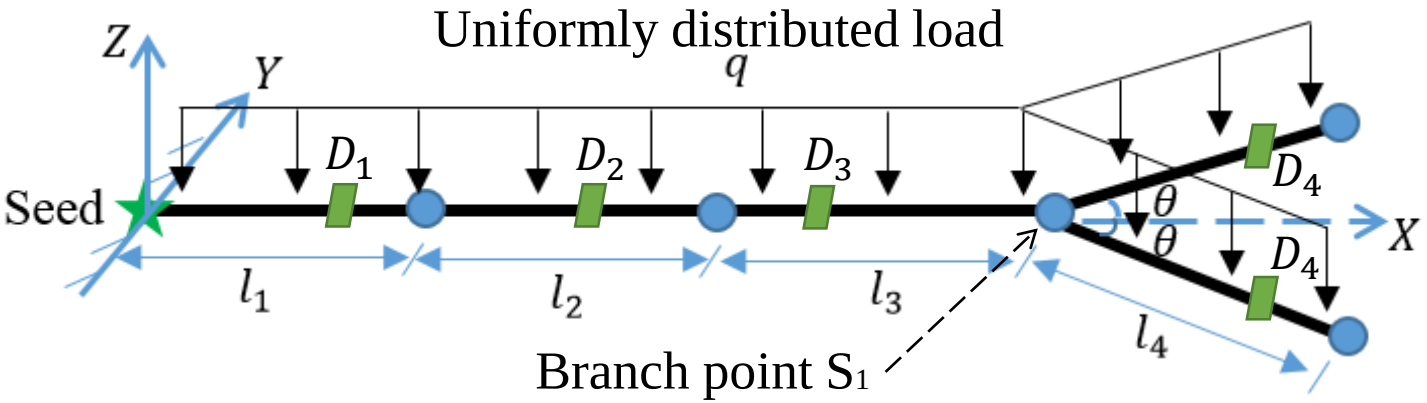
X-Z | Y-Z



Some endpoints can touch the surface of a forbidden domain







- **Outer loop: update total energy using strain energy**

$$U_{\mathrm{T}(i)} = U_{\mathrm{T}(i-1)} - U_{\mathrm{strain}(i)} = U_{\mathrm{T}(i-1)} - \int_0^L \frac{M(x)^2}{2EI}\,dx > 0$$

- **Inner loop: update maximum stresses of each section**

$$\sigma_{\mathrm{ma\,x(i,j)}} = \frac{M_{\mathrm{ma\,x(i,j)}}}{I_{i,j}} y = (q l_{i,j}^2/2)/(\pi D_{i,j}^3/\,32) \;>\; \sigma_{allow}$$

Update length and diameter

$$l_{i,j} = \sqrt{\frac{\left(\pi \sigma_{allow} D_{i,j-1}\right)^3}{16q}} - l_{i,j-1}$$

$$l_{i,j} = l_{i,j} \cdot f_l \quad if\ j = 1$$

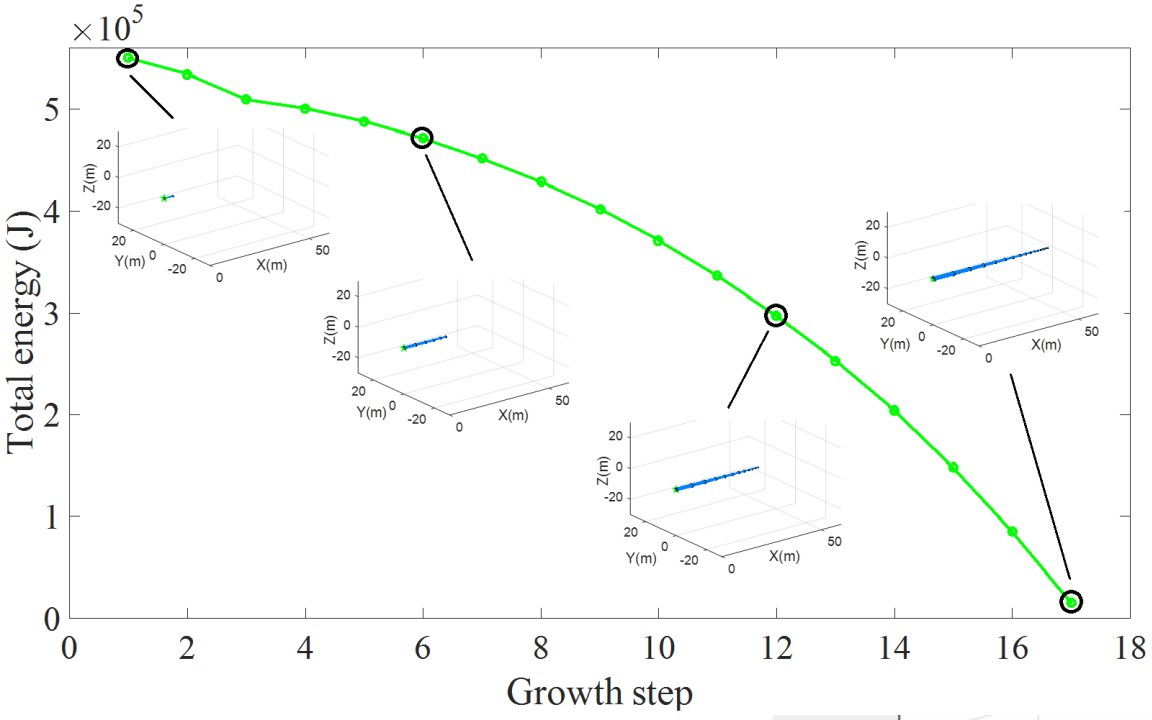
Growth factor

$$D_{i,j} = \sqrt[3]{\frac{16q\,l_{i,j}{}^2}{\pi \sigma_{allow}}}$$

i: growth step; ***j***: index of emerged beams

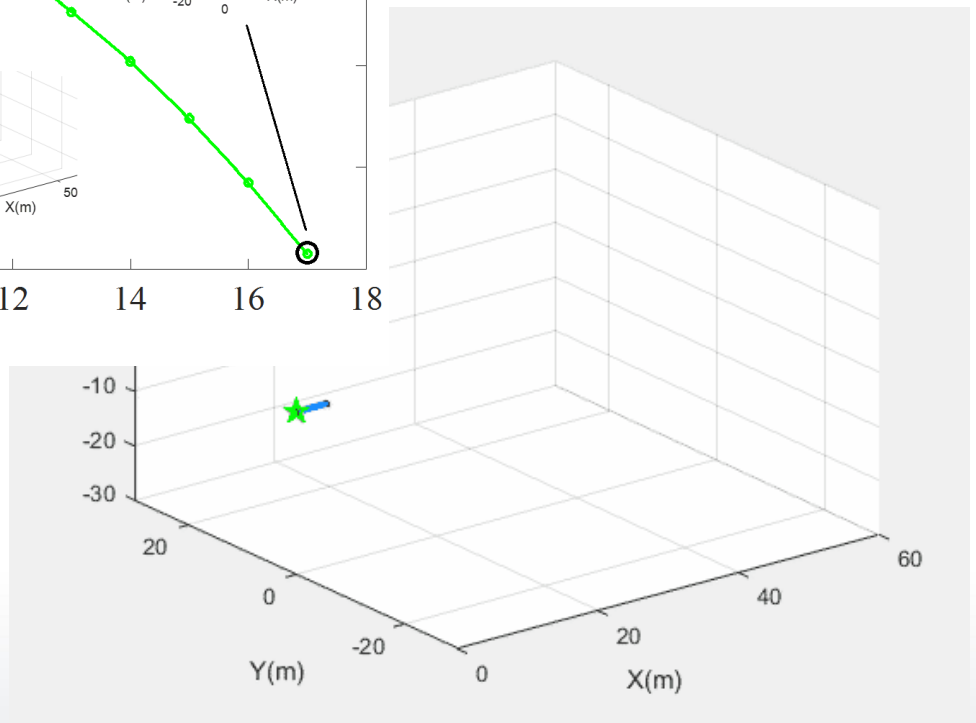
$$D_{i,j} = D_{i,j} \cdot f_D$$

Energy history of the growth process



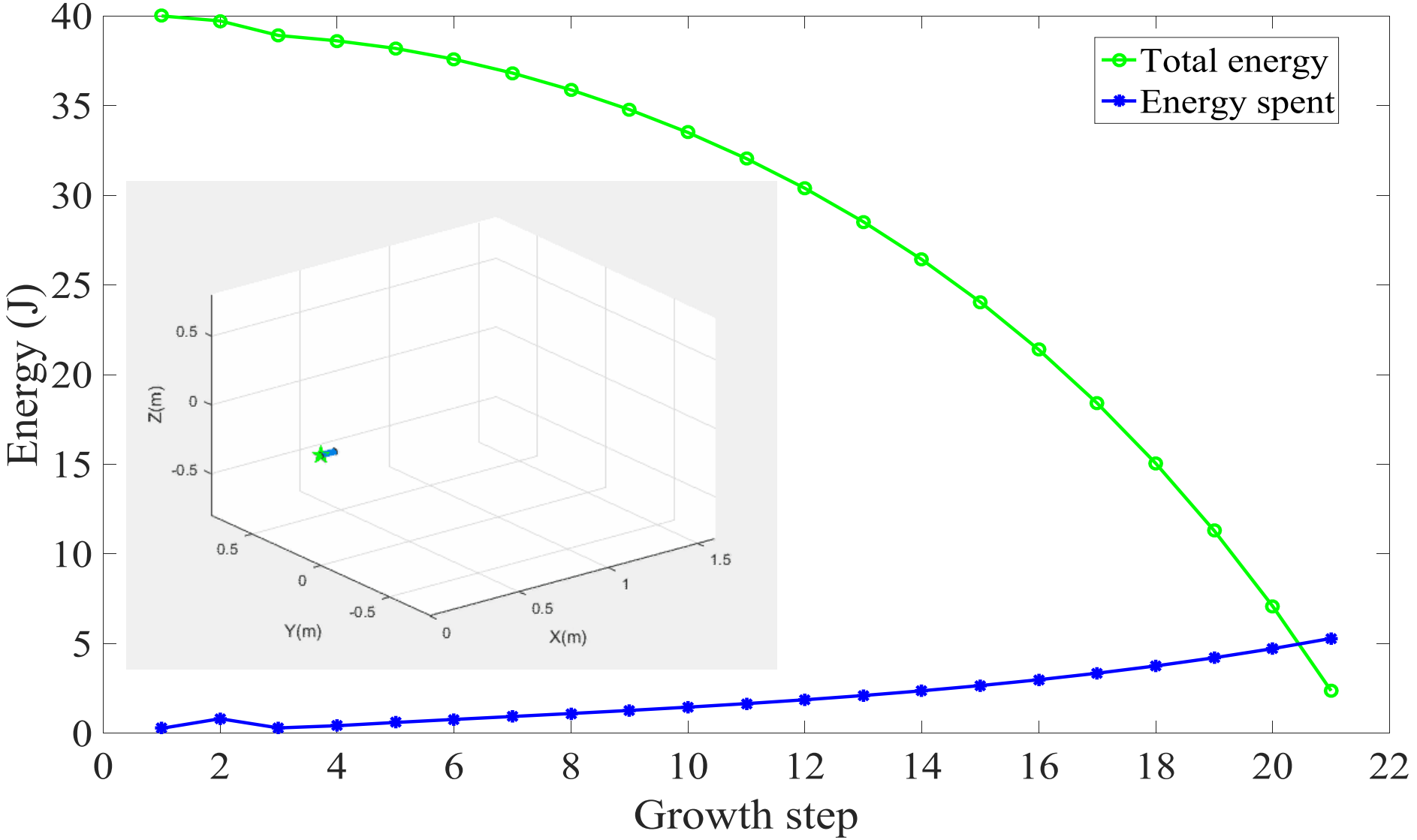
▲ **The growth stops when the total energy consumed nearly to 0**

▼ **Animation of the growth process**



Growth with random branches

Environment: Uniformly distributed load $q=3\times 10^5$N/m



Growth with complementary energy

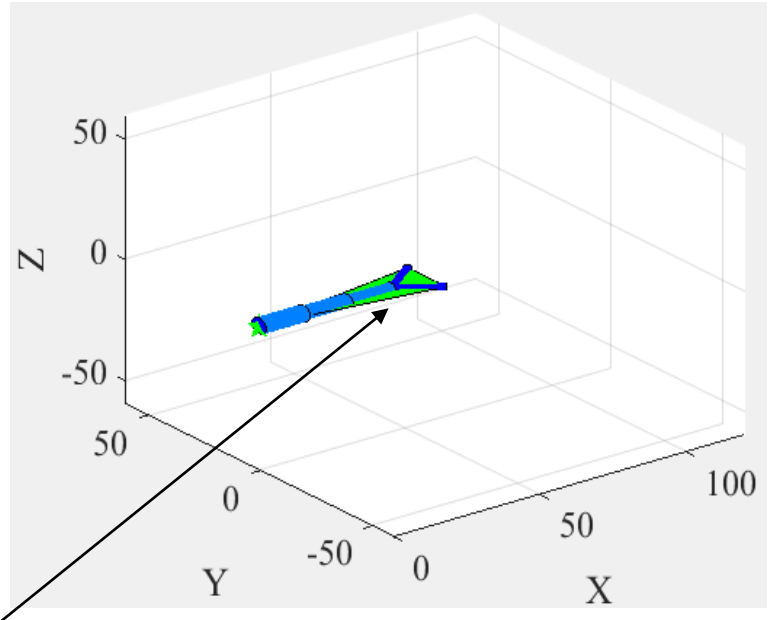
□ Basic idea

- **Calculate complementary energy using leaf area and a coefficient:**

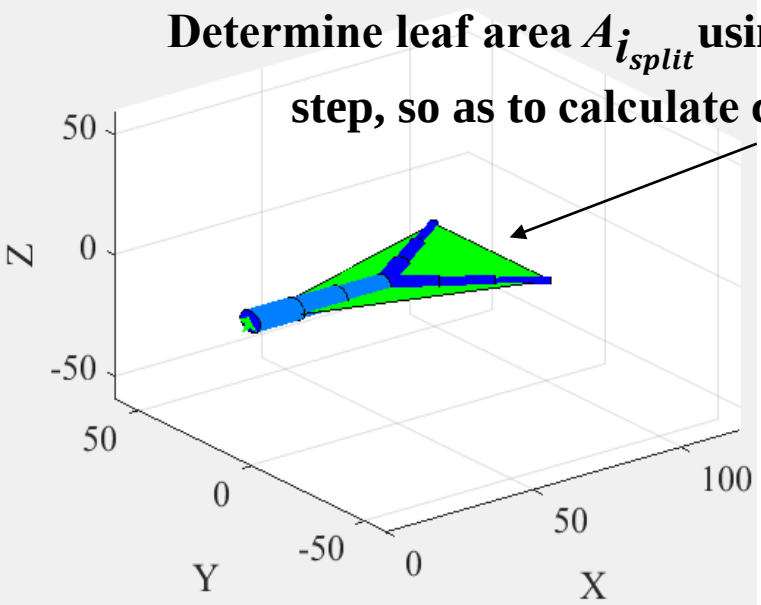
$$U_{c(i)} = f_c \cdot A_{i_{split}}$$

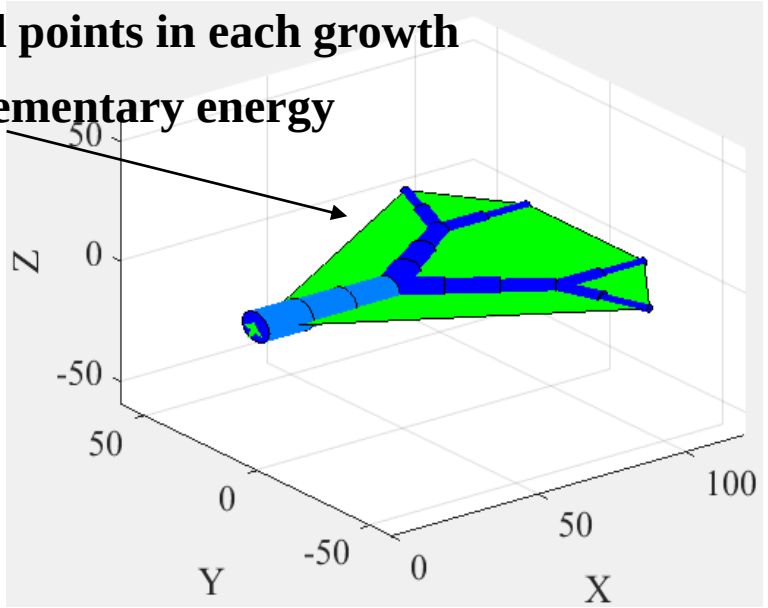
- **Update total energy using strain energy and complementary energy :**

$$U_{T(i)} = U_{T(i-1)} - U_{\text{strain}(i)} + U_{c(i)}$$



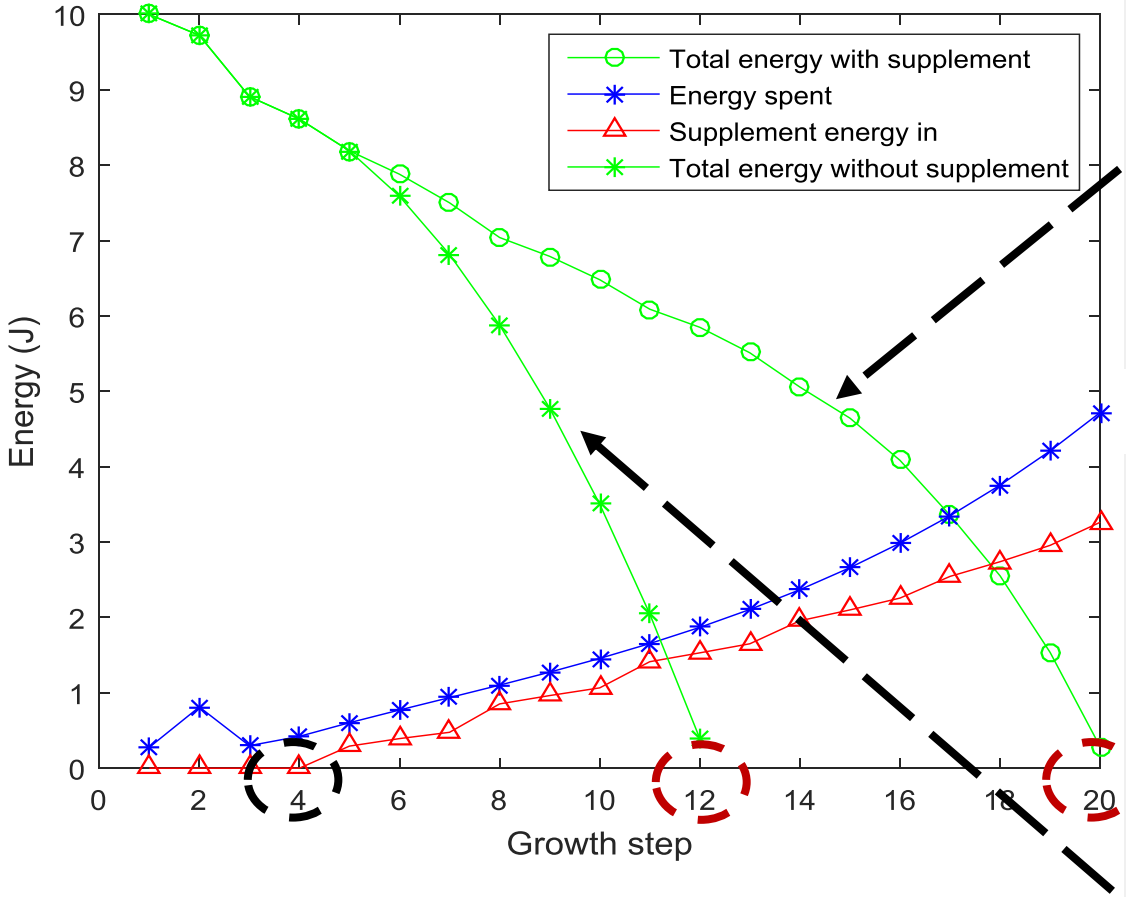
Determine leaf area $A_{i_{split}}$ using end points in each growth step, so as to calculate complementary energy

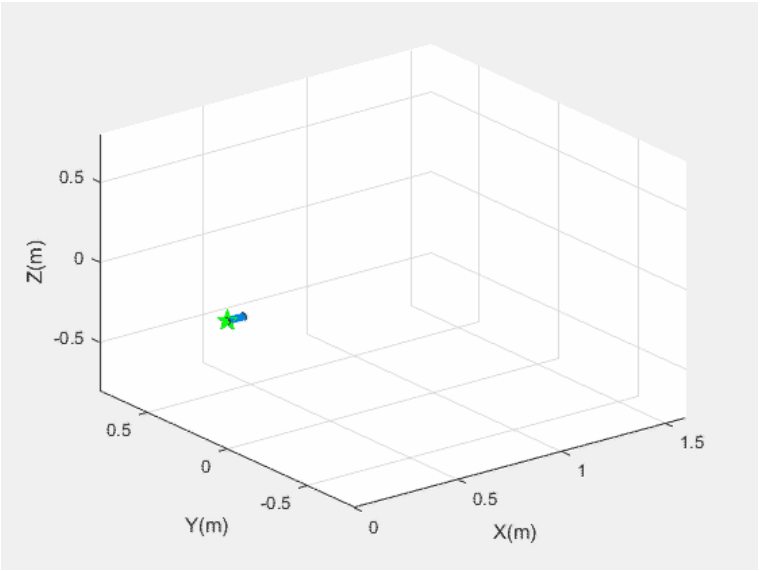


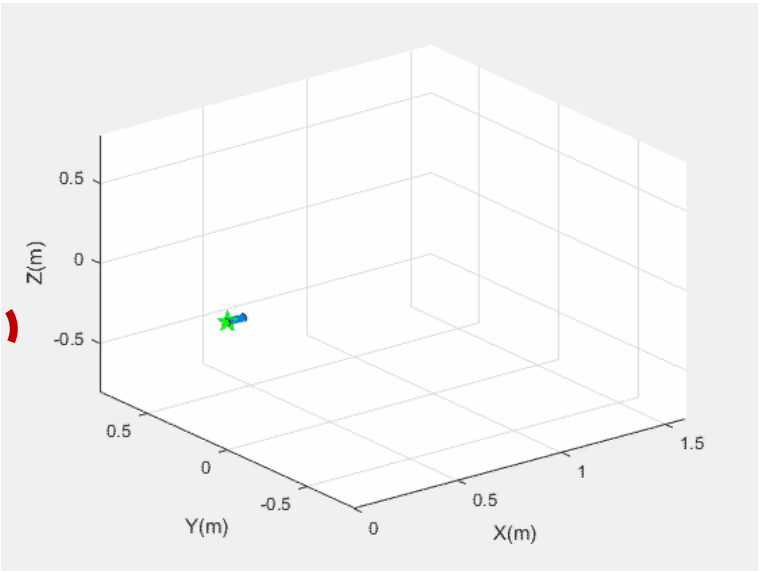


Comparison of growth with and without supplement energy

More growth steps can be guaranteed by supplement energy, so that complex structures should be formed.

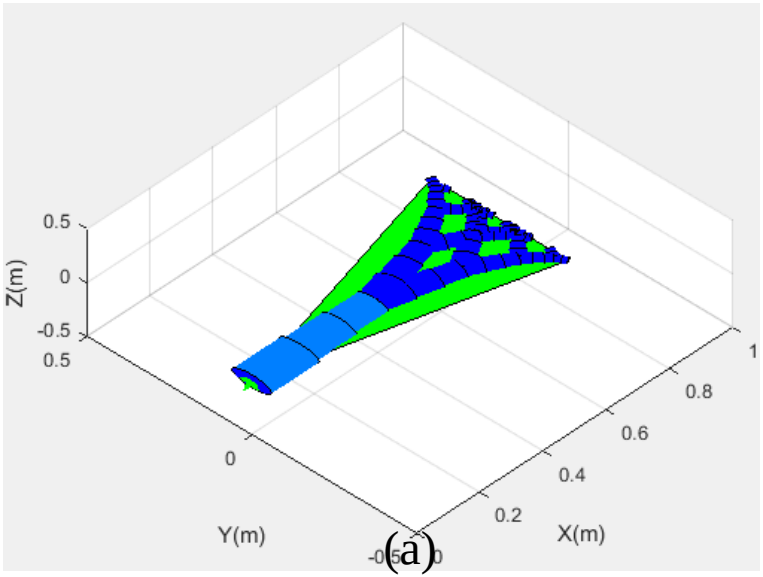




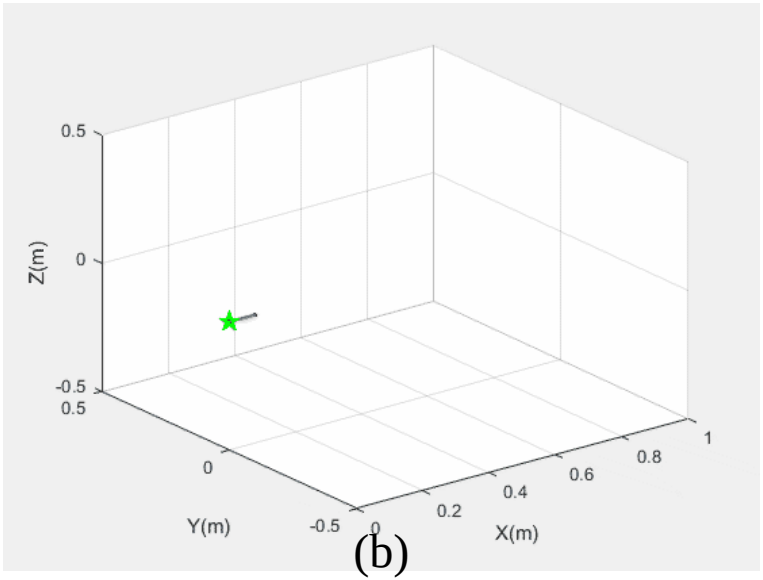


Supplement energy added by leaf surface using $U_{c(i)} = f_c \cdot A_{i_{split}}$.

Growth with branches and complementary energy

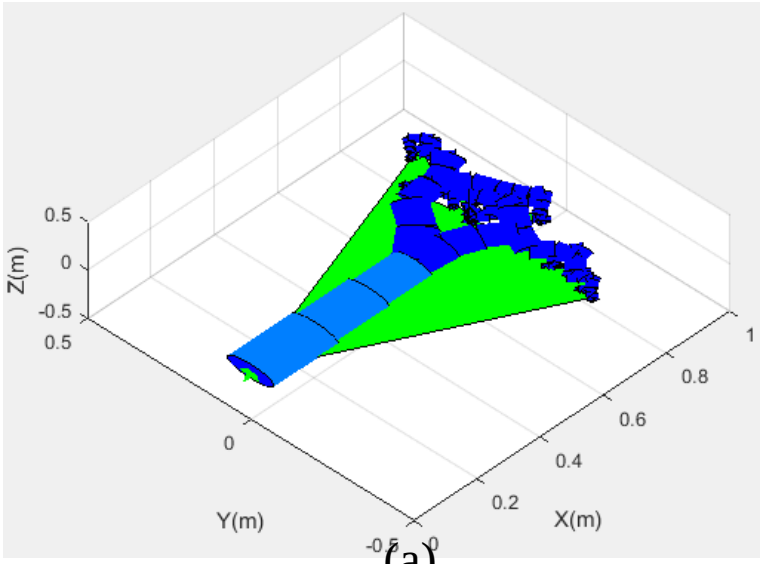


(a)

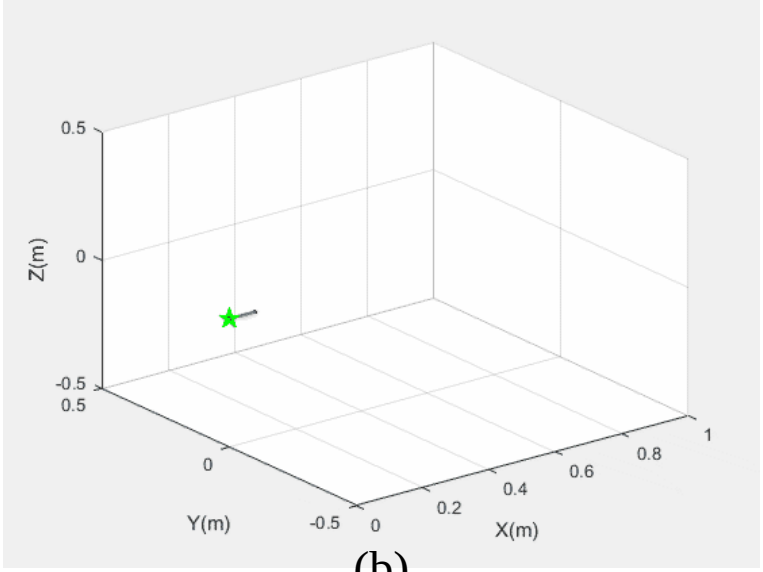


(b)

▲ initial θ_0= **15°**, determinate branches, (a):final shape; (b) animation



(a)



(b)

▲ initial θ_0= **60°**, random branches, (a):final shape; (b) animation

GEOMETRY CHALLENGES

- How can a useful parameterization be extracted?
- Dealing with multi-disciplinary mixed dimensional simulations?
- System architecture always changing – requires dynamic CAD representations?
- System elements always changing – requirement for persistence.
- Search space increases exponentially – scalable solutions?

biohaviour

THANK YOU!

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