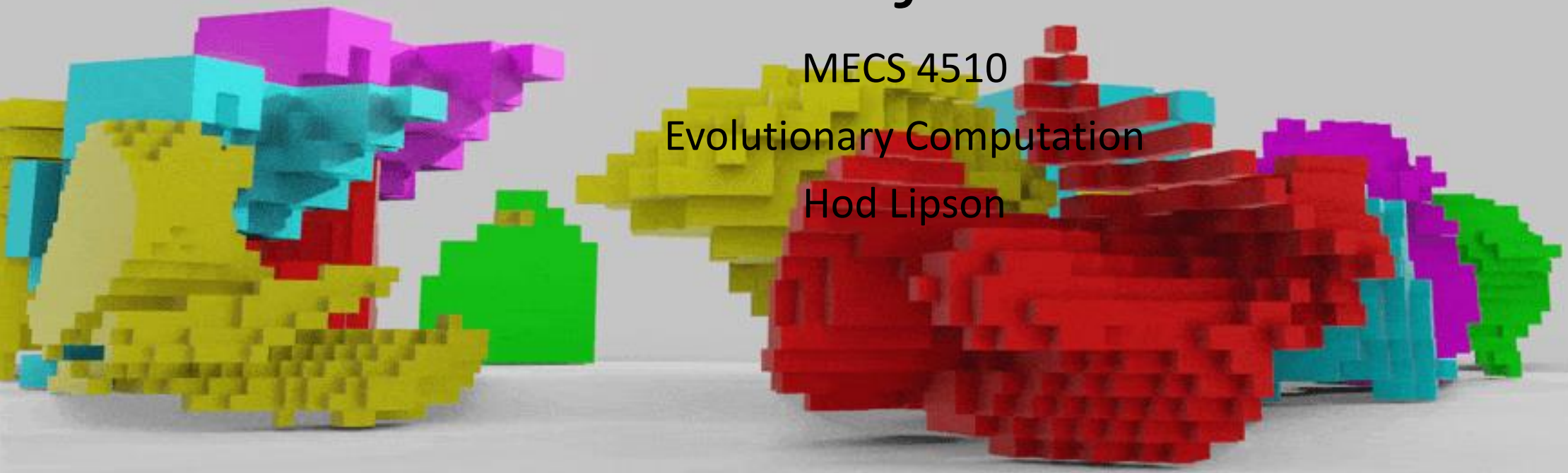
Assignment #3
Project

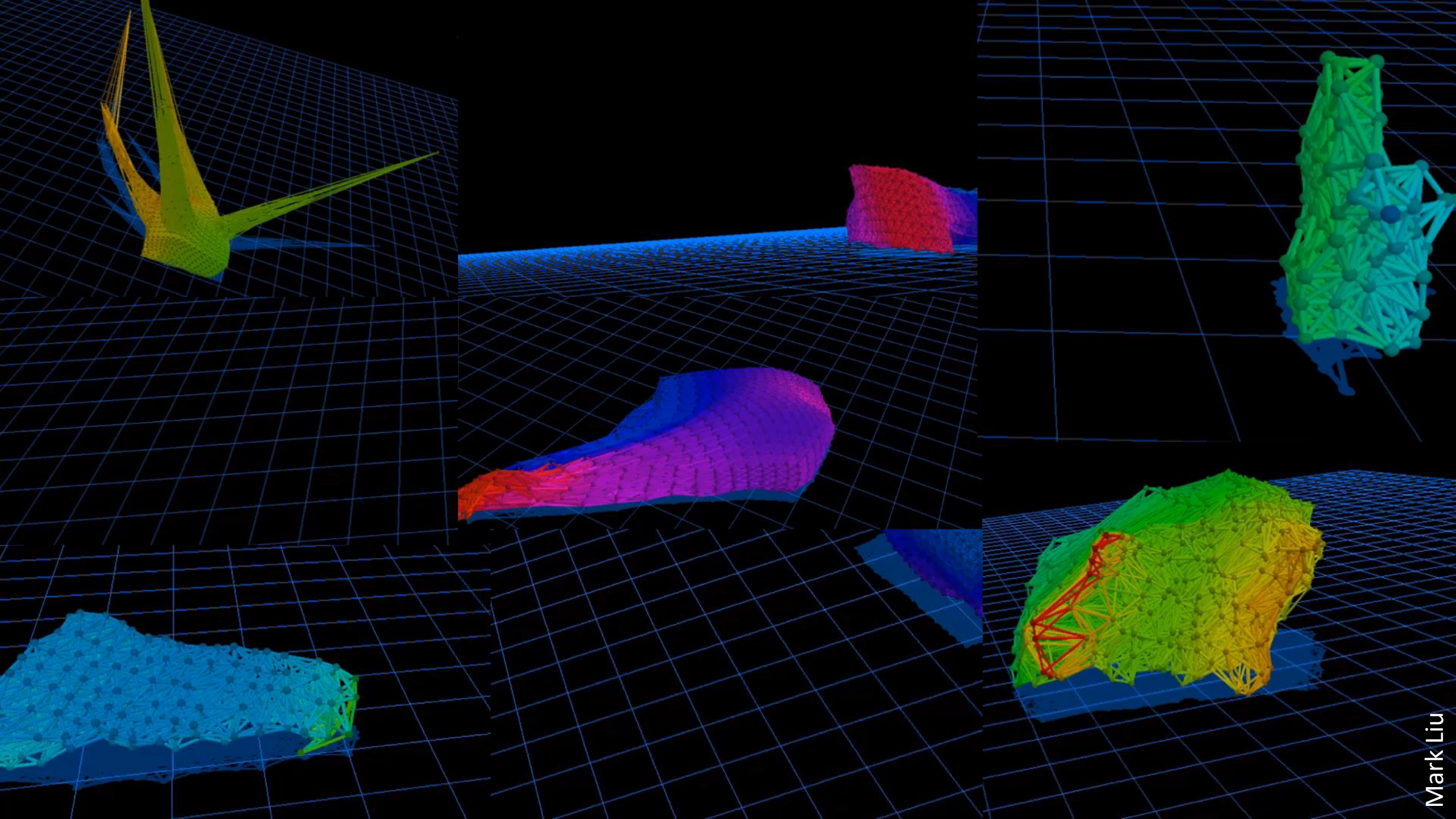
MECS 4510

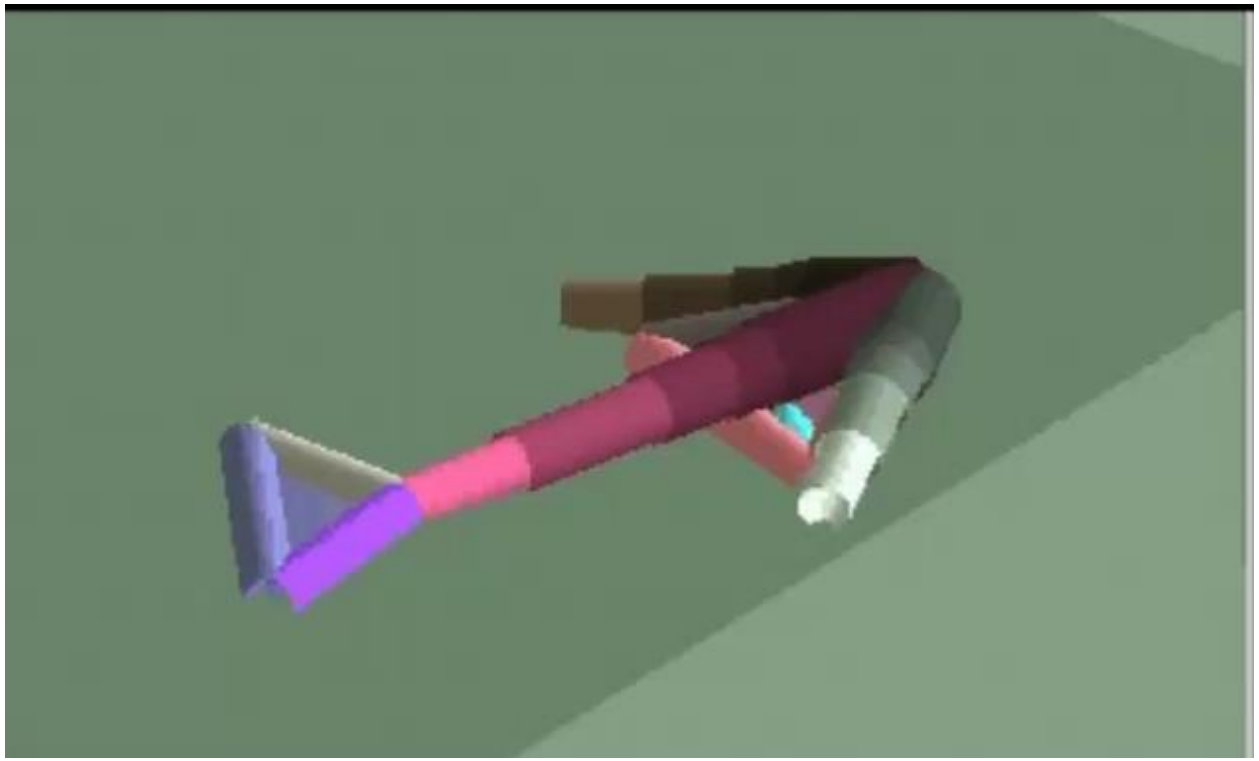
Evolutionary Computation

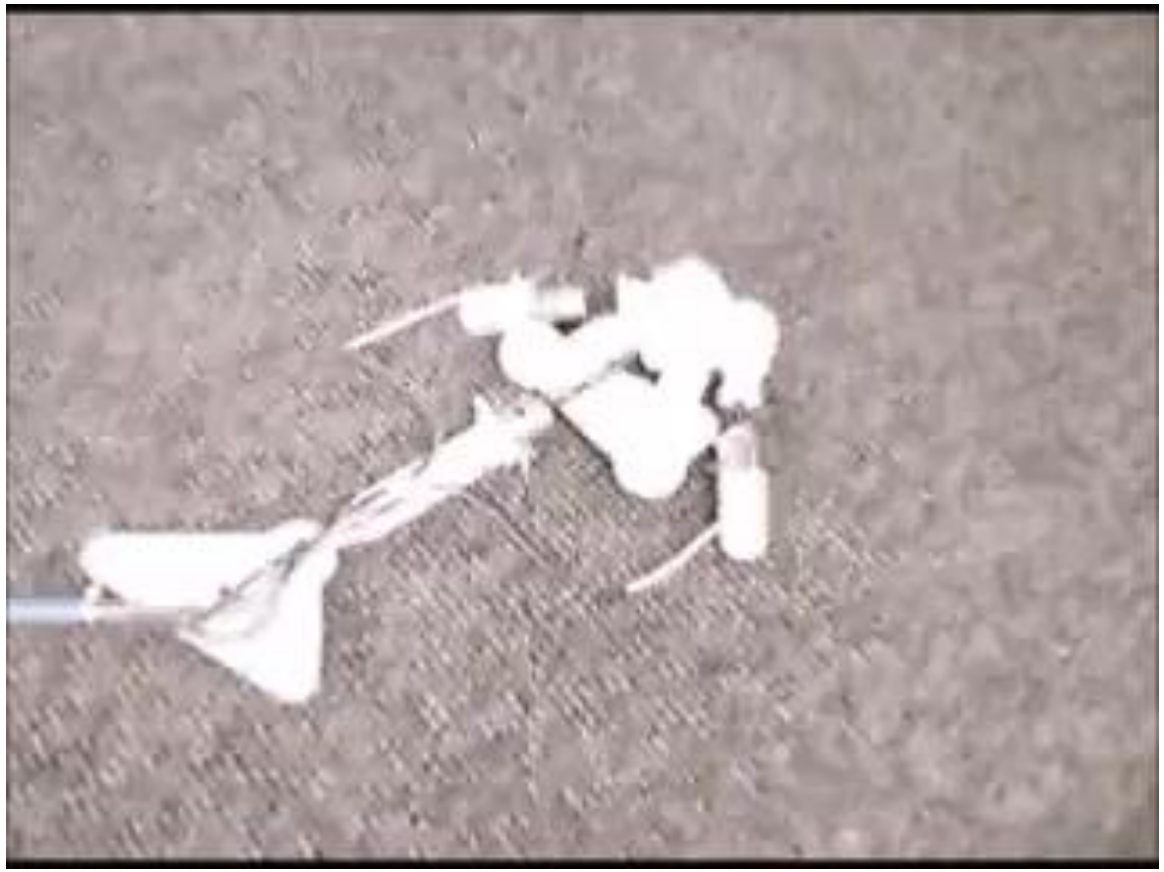
Hod Lipson

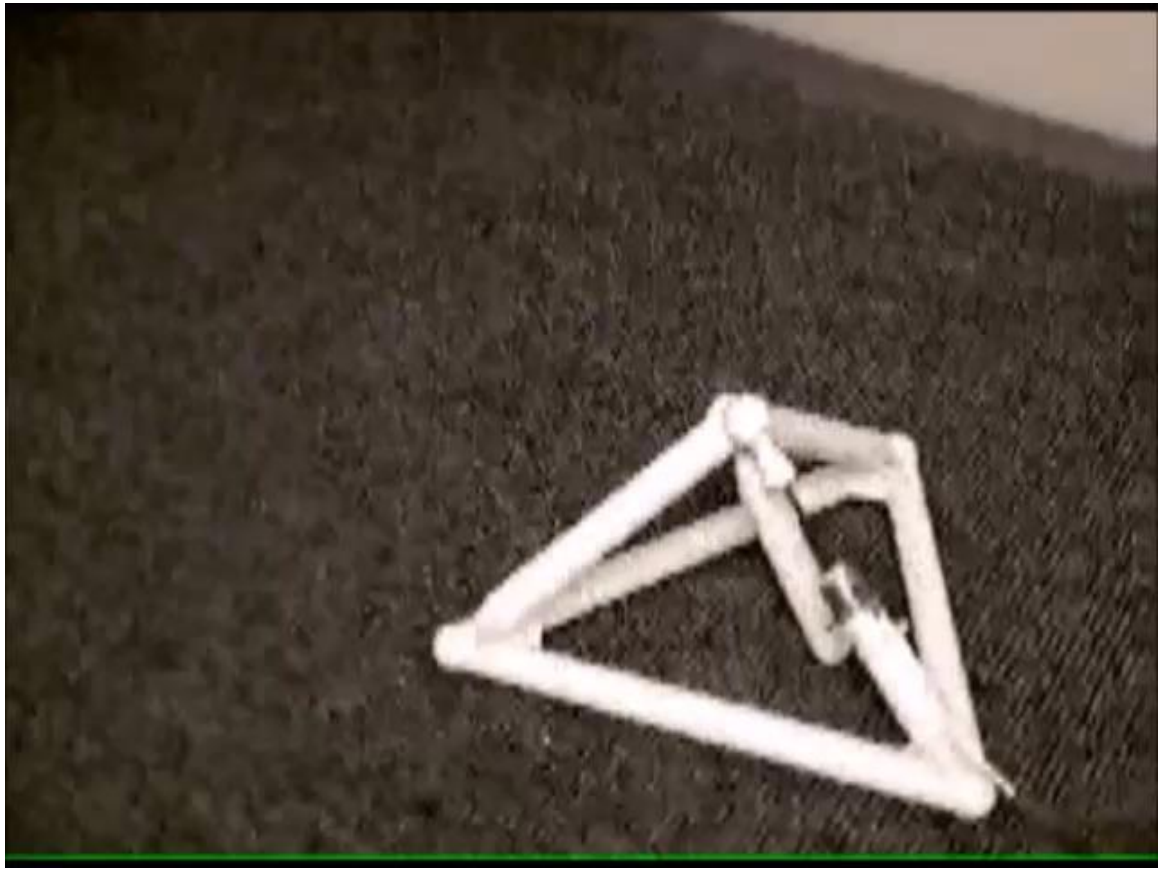


Video: Huy Ha


Mark Liu







Lipson & Pollack, Nature 406, 2000

MECS 4510
Evolutionary Computation and Design Automation
Fall 2019

Instructor: Hod Lipson
TA: Joni Mici

Assignment 3

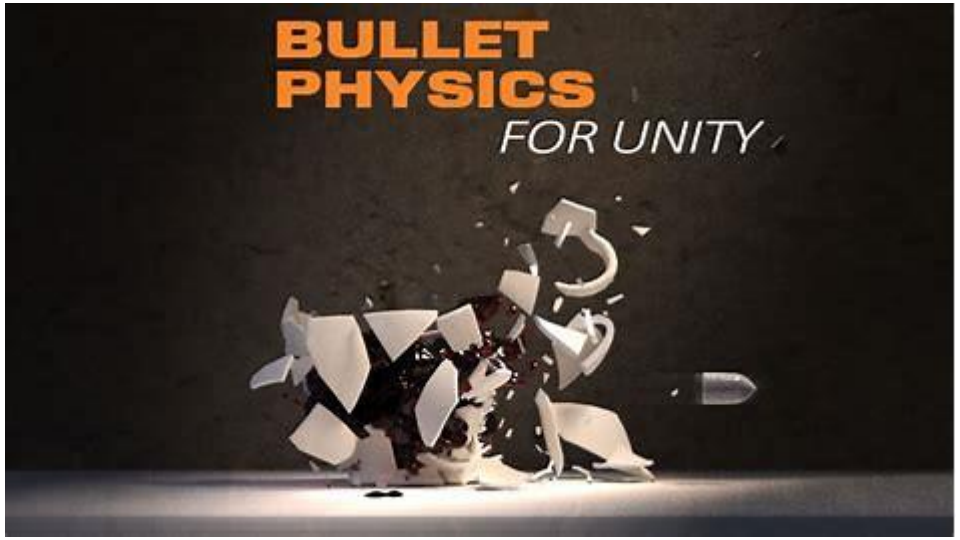
- 3a Develop a 3D physics simulator
  - Demonstrate a bouncing cube and a “breathing” cube
- 3b Evolve a fixed-shape robot
  - Manually design a robot, evolve a controller to make it move
- 3c Evolve both the shape and behavior of a robot
  - Demonstrate a moving robot of various shapes and behavoors
- Final Presentation

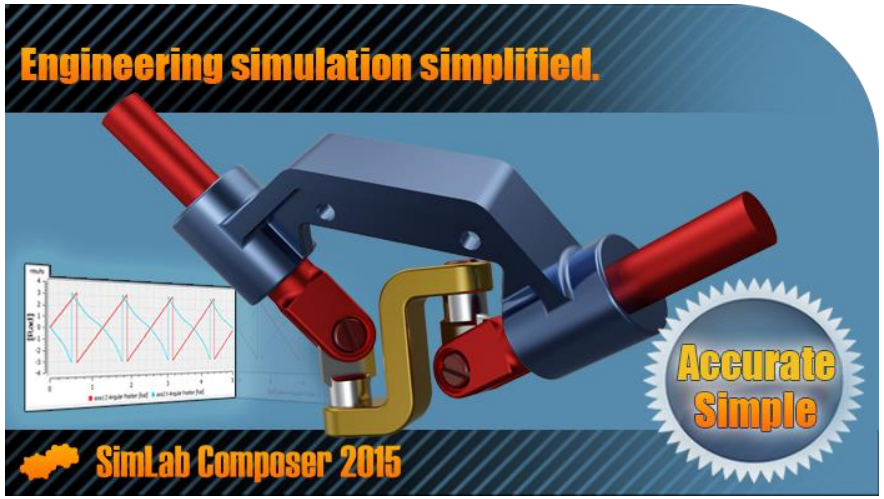
		Class	Assignment due
7	Wed, Oct 27	Robot Simulation	
8	Wed, Nov 03	Multiobjective optimization	Tue, Nov 09
9	Wed, Nov 10	Coevolutionary dynamics	
10	Wed, Nov 17	Mock exam	Tue, Nov 23
11	Wed, Nov 24	Thanksgiving Break	
12	Wed, Dec 01	Review	Tue, Dec 07
13	Wed, Dec 08	Project final presentations	
14	Wed, Dec 15	Final exam (tentative. 1-4pm)	

3a. Build a 3D simulator

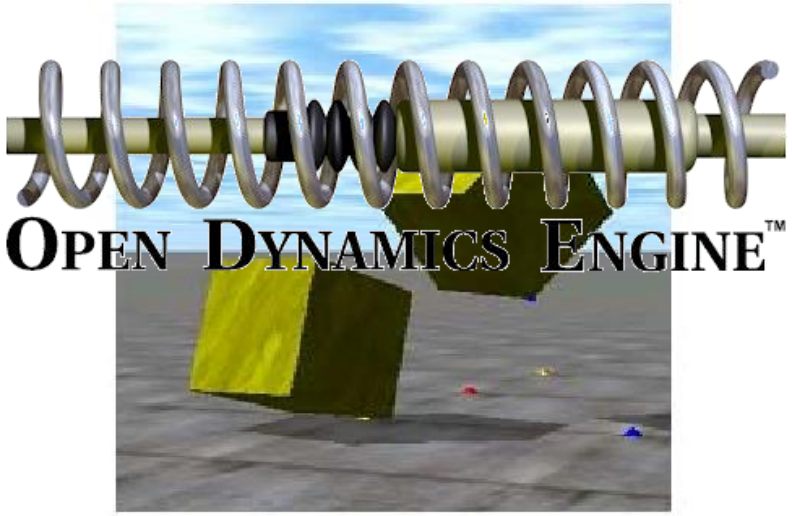
Basic steps

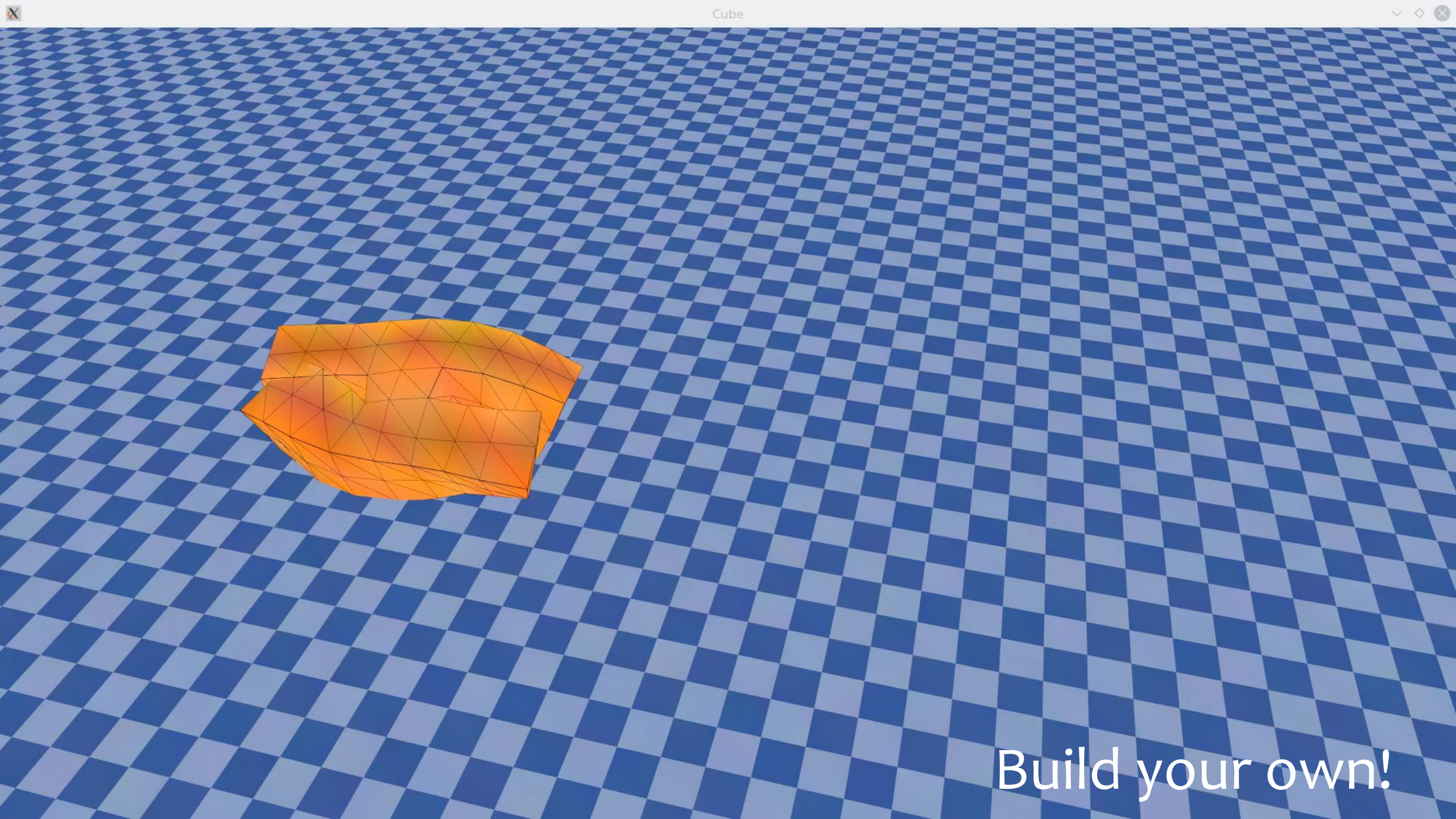
Existing Physics Simulators





GAZEBO



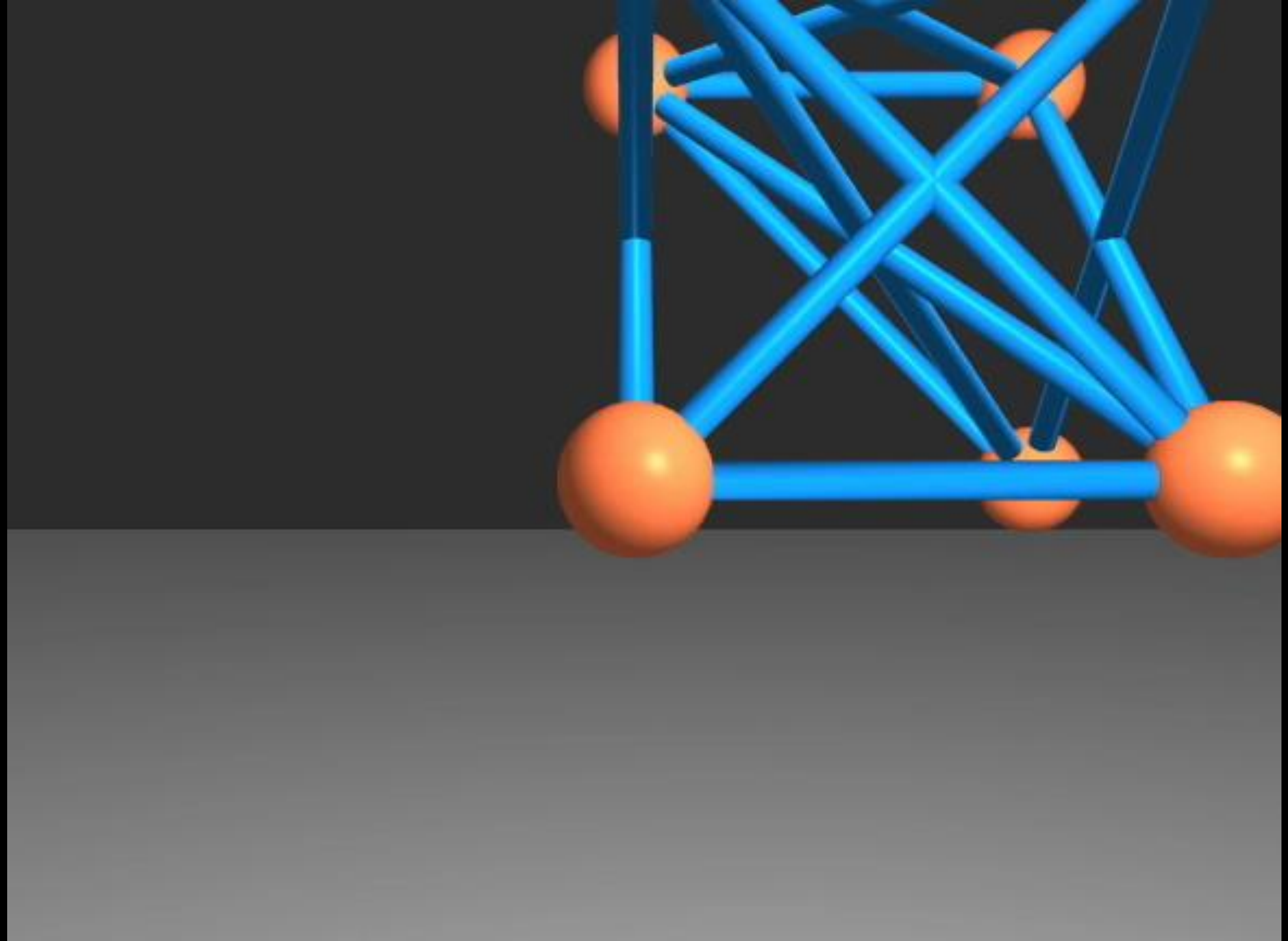

Cube
Build your own!

Why build your own physics simulator?

- Simpler than learning to use other simulator
- Simpler to integrate with your EA
- Robust (wont crash) with garbage generated by an EA
- More versatile physics
- An extra line on your resume

Basic primitives

- Masses
  - Point masses (no volume)
  - Have mass, position, velocity and acceleration
- Springs
  - Massless
  - Connect two masses
  - Have a rest length and stiffness
  - Apply restoring forces on the masses

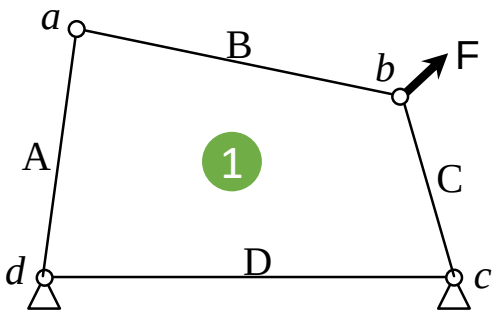


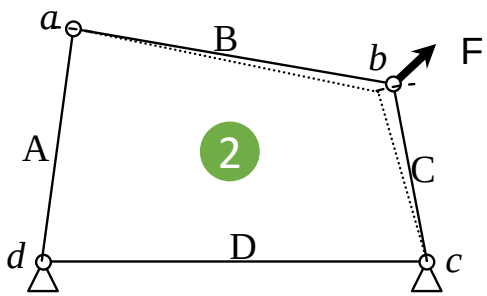
Basic simulator

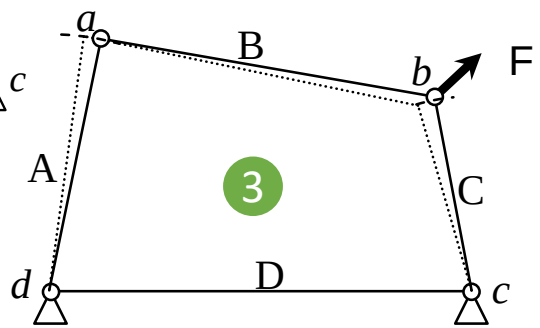
- Choose a discrete time step ***dt***
  - Not larger than a millisecond (dt=0.001).
  - Set global time variable T = 0
- At each time step:
  - T = T + dt
  - Interaction step:
    - Compute and tally all the forces acting on each mass from springs connected it
    - Add any external forces on the mass (e.g. gravity, collision, drag)
  - Integration step:
    - Update acceleration, velcoty and position each mass using Newton's laws of motion F=ma.

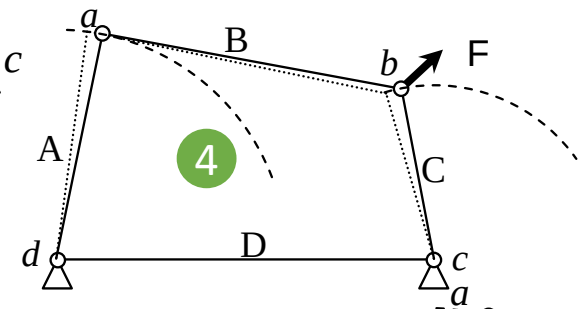
Stick to consistent unit system, e.g. MKS

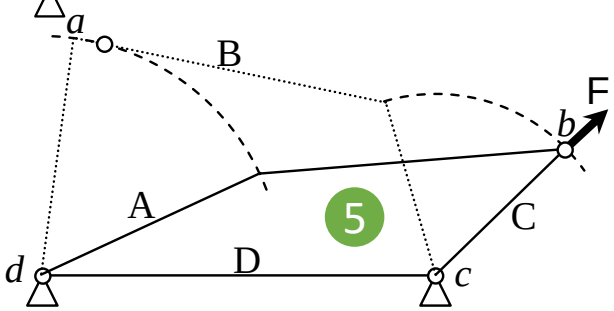
Simulation Sequence

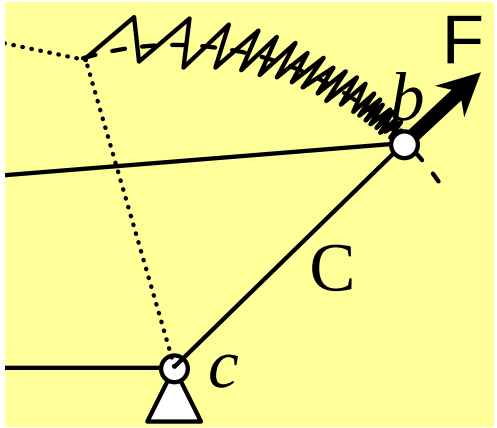


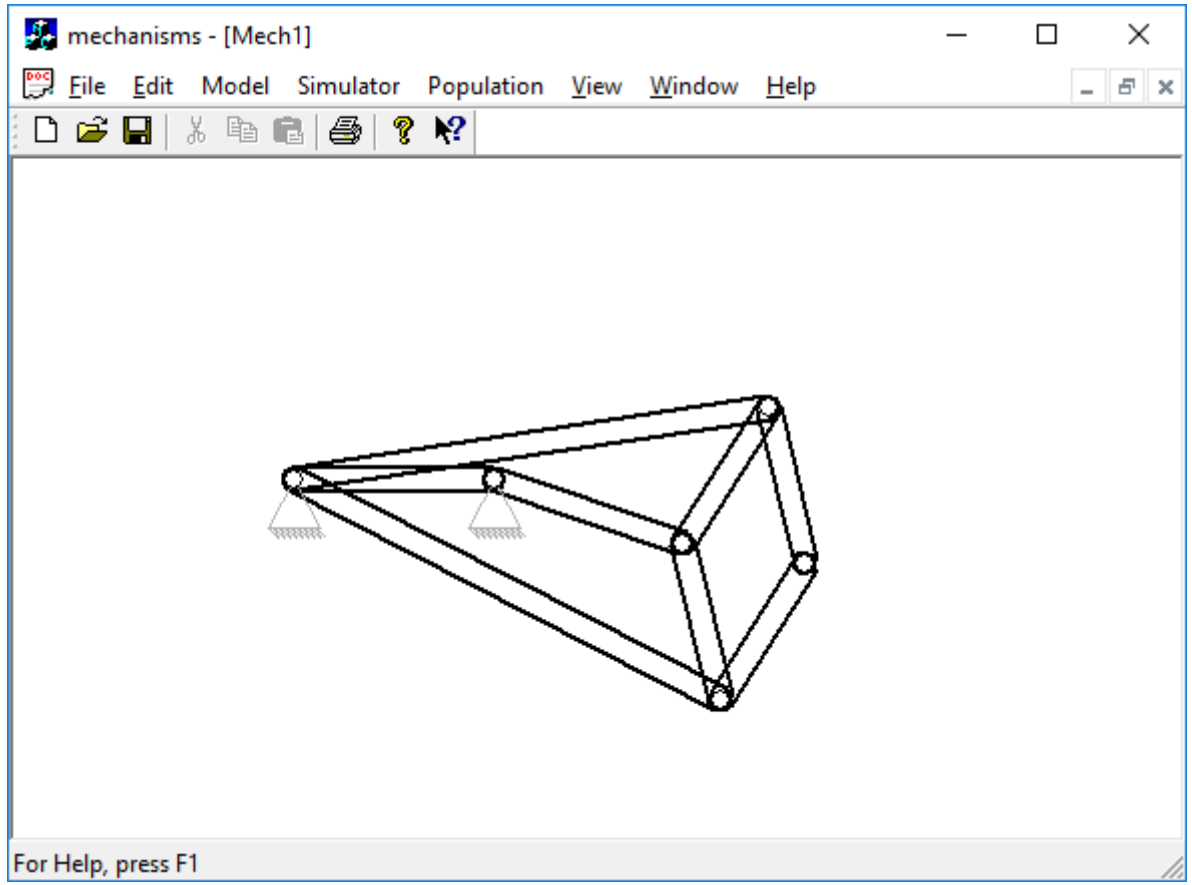


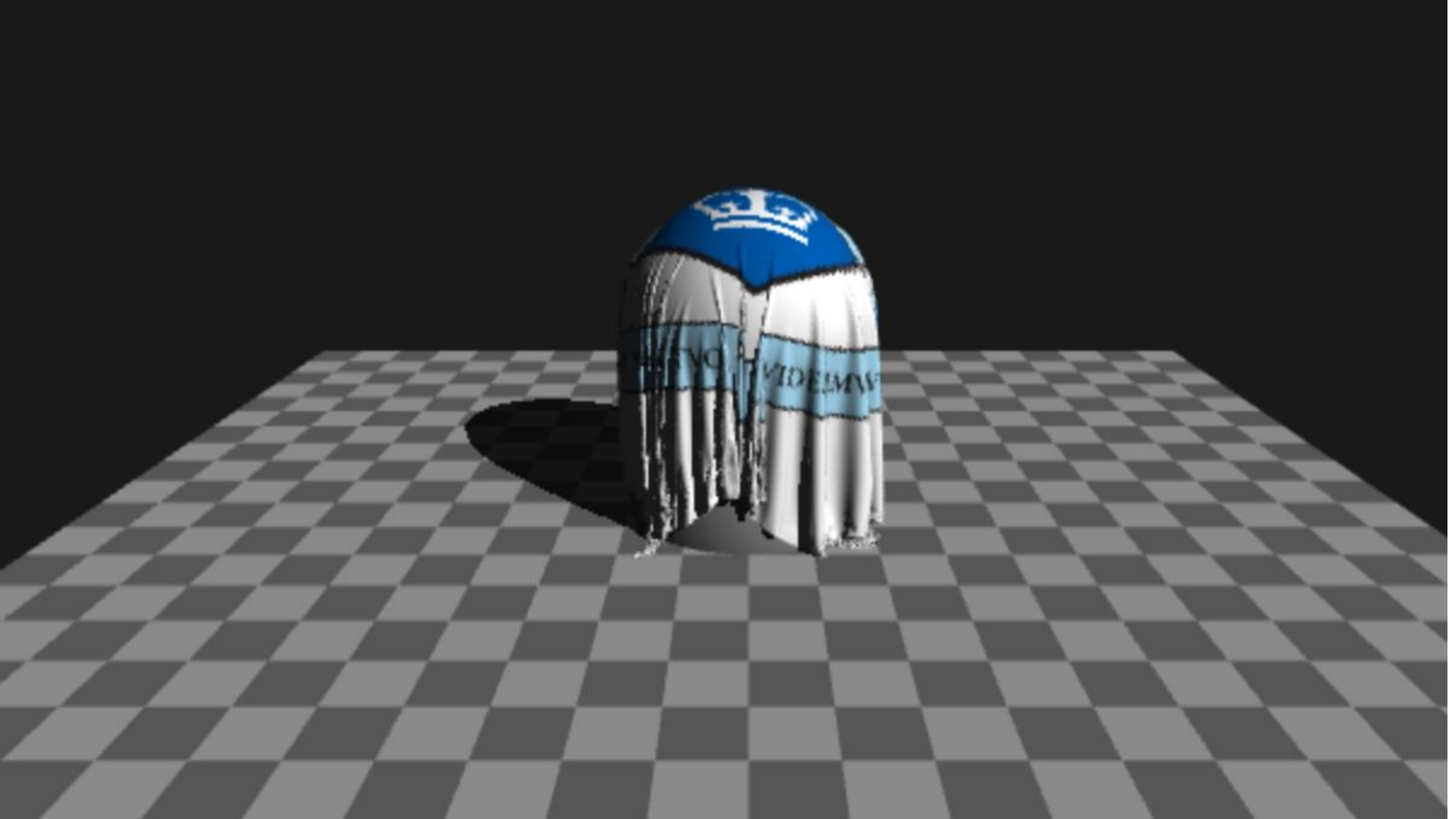









mechanisms - [Mech1]
File Edit Model Simulator Population View Window Help
For Help, press F1



First: Data structures

- Mass
  - Mass m (scalar)
  - Position $\boldsymbol{p}$ (3D Vector)
  - Velocity $\boldsymbol{v}$ (3D Vector)
  - Acceleration $\boldsymbol{a}$ (3D Vector)
  - External forces $\boldsymbol{F}$ (3D Vector)
- Spring
  - Rest length L_0 (Scalar)
  - Spring constant k (scalar) (=EA/L for bars)
  - Indices of two masses m_1, m_2

Dynamic Simulation

- Time increment
  - T = T +dt
- Interaction step
  - For all springs:
    - Calculate compression/extension using $F=k(L-L_0)$
  - For all masses:
    - Tally forces on each mass
    - Add gravity, collision, external forces (if any)
- Integration Step
  - Calculate a = F/m (from *F=ma*)
  - Update v = v + dt*a;
  - Update p = p + v*dt
- Repeat forever or until reaches equilibrium

dt = simulation timestep (0.001)

Dynamic = real time; geometry, mass, forces, velocities, accelerations

Dynamic Simulation

- Time increment
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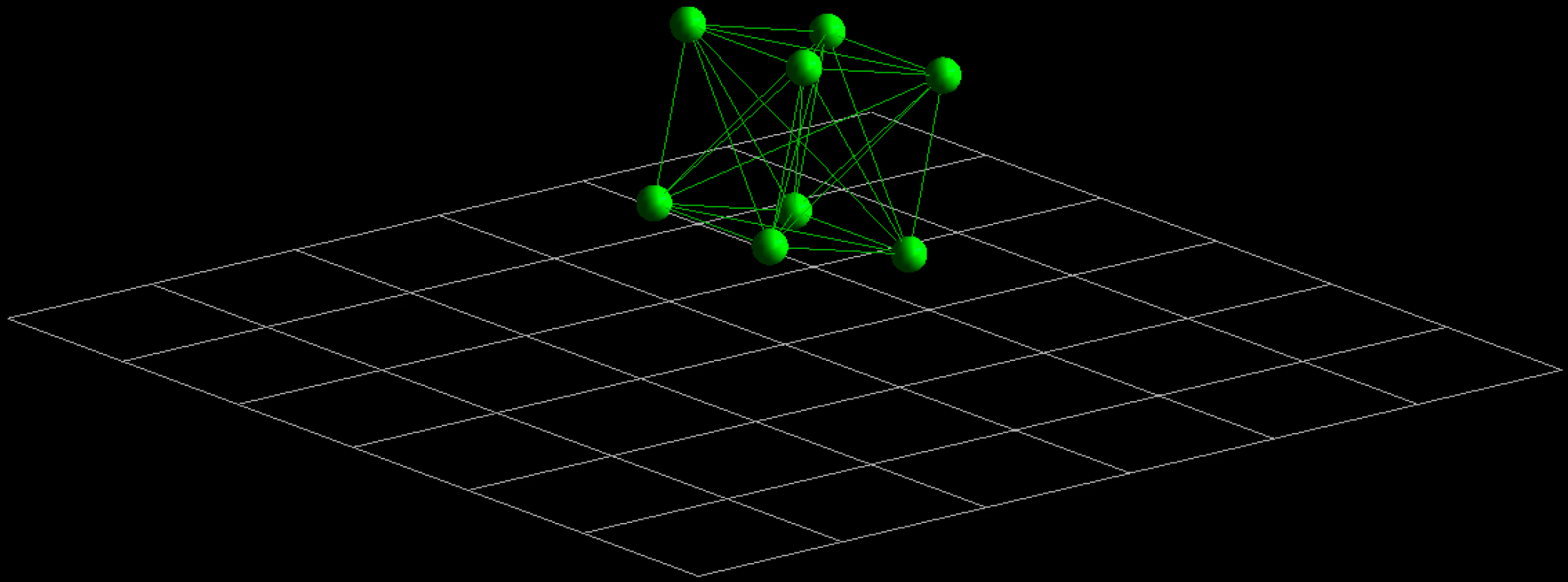
  - For all masses:
    - Tally forces on each mass
    - Add gravity, collision, external forces (if any)
- Integration Step
  - Calculate a = F/m (from *F=ma*)
  - Update v = v + dt*a;
    - If mass is fixed, set v=0
    - If dampening, reduce speed v=v*0.999
    - If colliding with ground, apply restoring force
  - Update p = p + v*dt
- Repeat forever or until reaches equilibrium

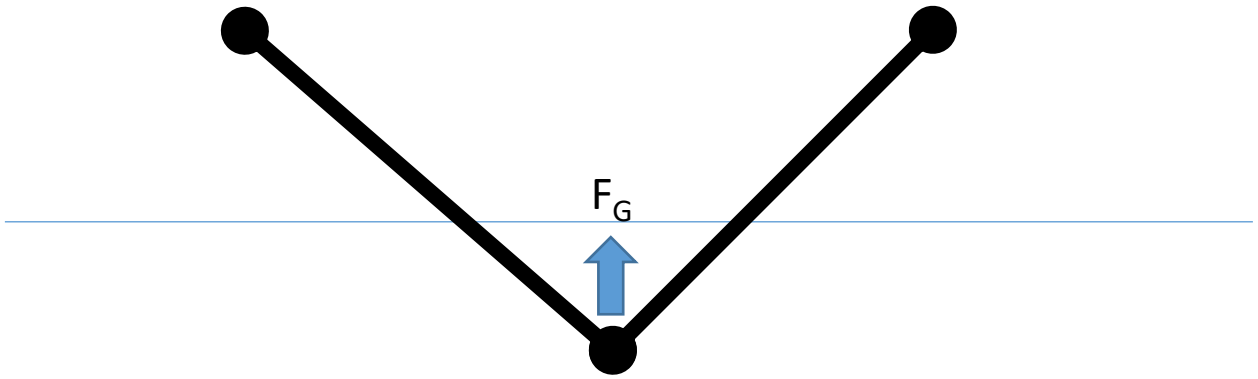
dt = simulation timestep (0.001)

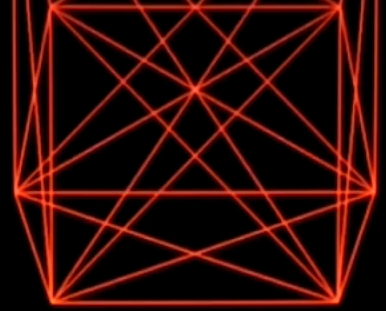
Dynamic = real time; geometry, mass, forces, velocities, accelerations



How to handle collisions with the ground?

- Apply a ground reaction force F_G once a node goes below ground ($z<0$)
  - $F_G = (0,0,-z*K_G)$
  - K_G is the spring coefficient of the ground, e.g. 100,000

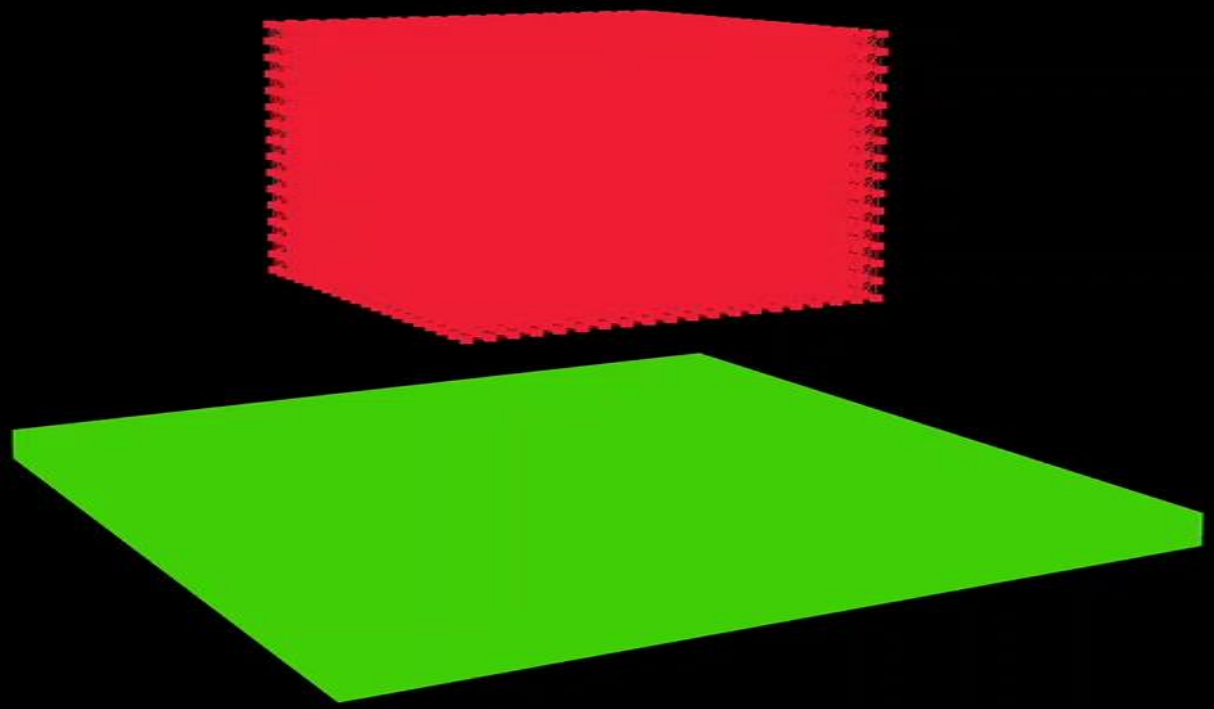


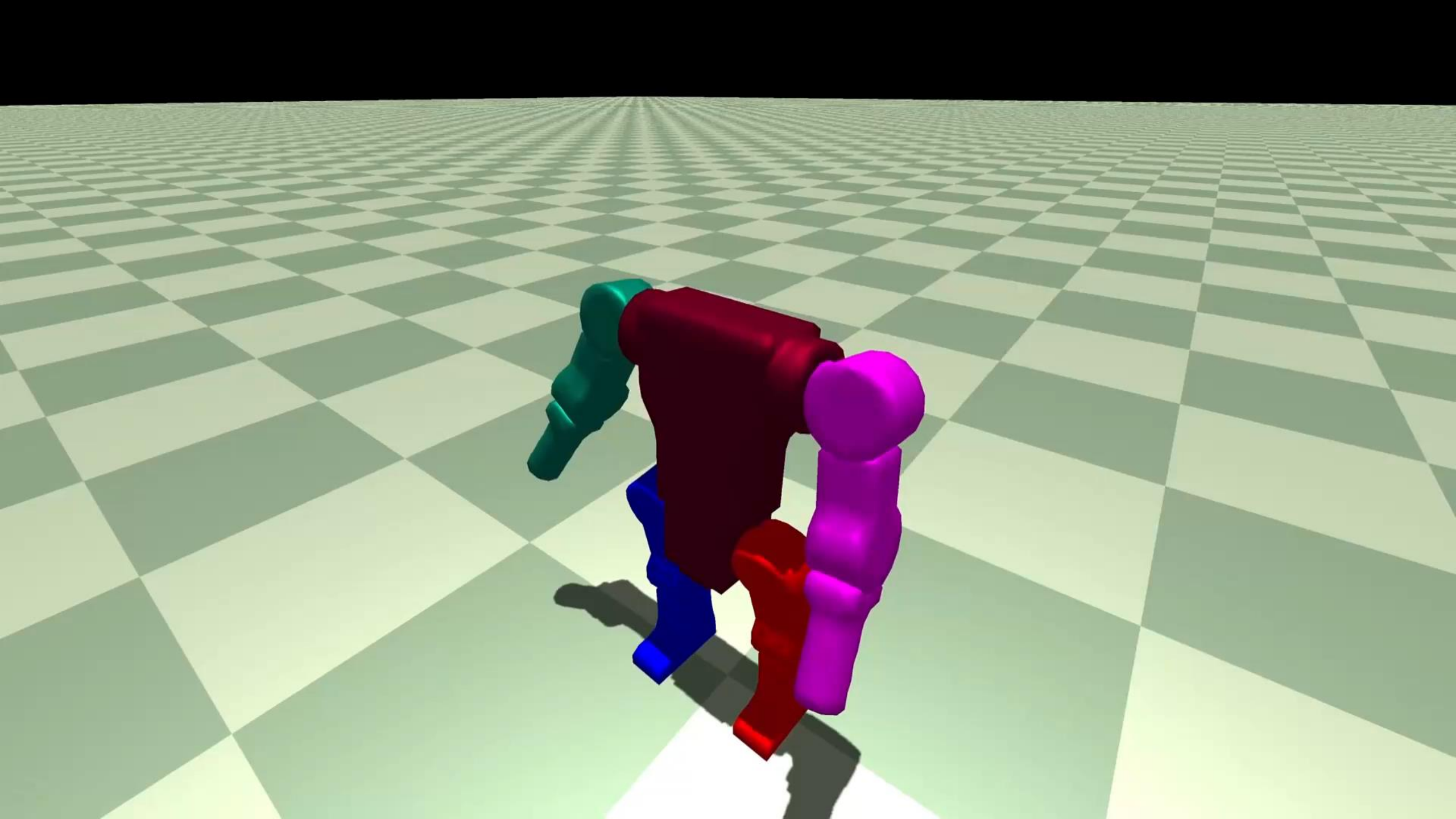


```
const double GRAVITY = -9.81;
const double damping = 0.9999;
const double DT = 0.0001; // 1E-4 simulation timestep
const double friction_mu_s = 1; // friction coefficient rubber-concrete
const double friction_mu_k = 0.8;// friction coefficient rubber-concrete
const double k_vertices_soft = 5000; // spring constant of the edges
const double k_ground = 100000;// constant of the ground reaction force
double omega = 10;// breathing oscillation frequency rad/sec
```

Create more complex structures

- Add more cubes
  - Share vertices and share springs
- Try making structures out of tetrahedra or other primitives





General tips

- Choosing *k* and *dt* is tricky. If the structure is too “wobbly”, *k* is too small. If the structure “vibrates”, *k* is too high. If the structure “explodes”, your timestep dt or k is too large. Generally, set *dt* to a small step (e.g. 1E-5) and set *k* to a low stiffness (e.g. 10,000), and increase them from there*.
- Once you get it to work, you can easily parallelize the loop in 4a and 4b to use all your CPU cores. For example, in C++ use OMP. If you are really ambitious, you can even use GPU/CUDA.
- Be sure to use double precision numbers for all your calculations.

*Some students reported good results with k=100,000 and dt = 0.0008

How to easily simulate a structure made of many springs and masses

Hod Lipson

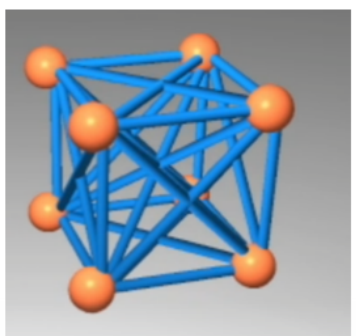
These instructions explain how to create a basic spring-mass physics simulation. You can implement this in any language. You will need to be able to plot some 3D graphics (lines and points). Assume that ***x,y*** plane is horizontal and ***z*** axis is pointing upwards.

First, let's implement a bouncing cube, like this:

https://1drv.ms/v/s!Ap6pJEdQihYkhZAzoncgCWfIjUSQRw

Implementation Steps

1. Create data structures for masses and springs
    a. Create two lists (arrays): One for springs and one for masses.
    b. Each mass needs the following attributes: ***m*** (mass, [kg]); ***p*** (3D position vector [meter]), ***v*** (3D velocity vector, meter/s), ***a*** (3D acceleration vector, meters/s^2)
    c. Each spring has the following properties: ***k*** (spring constraint, [N/m]), L_0 (original rest length, [meters]), and the indices of the two masses it connects: m_1, m_2
2. Populate data structure with an initial test structure – a 3D cube
    a. Create an initial cube sized 0.1x0,1x01m, total weight 0.8 Kg.
    b. Initialize corner masses with 0.1Kg masses at all 8 corners
    c. Create 28 springs connecting all pairs of masses: 12 edges, 12 short diagonals and 4 long diagonals. Set ***k* =10,000 (or 1000)**, for example.
    d. Set the rest length of all springs to their initial Euclidean length and the velocities and accelerations of each mass to zero
    e. Plot the cube in 3D to make sure it looks ok. (you will need some 3D graphics library that can draw lines, like OpenGL)
3. Set Global variables of the simulation:



See Courseworks Files→HW3

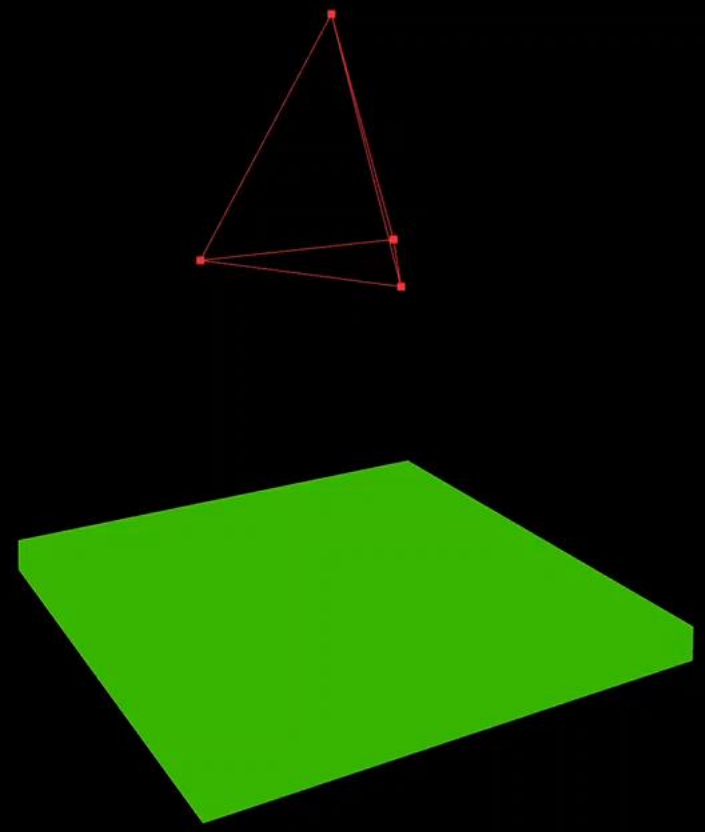
Simulation performance

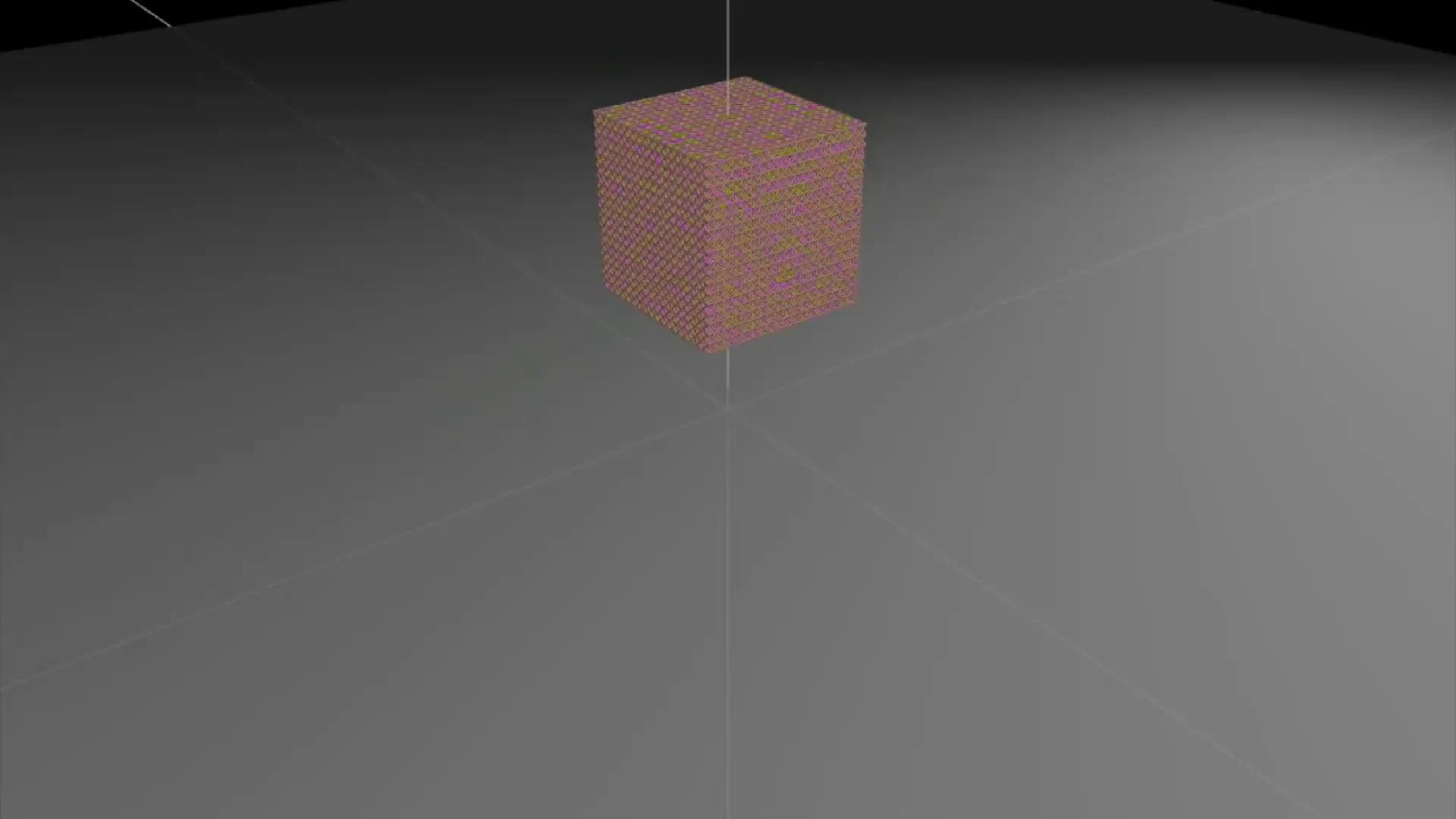
Speed and efficiency

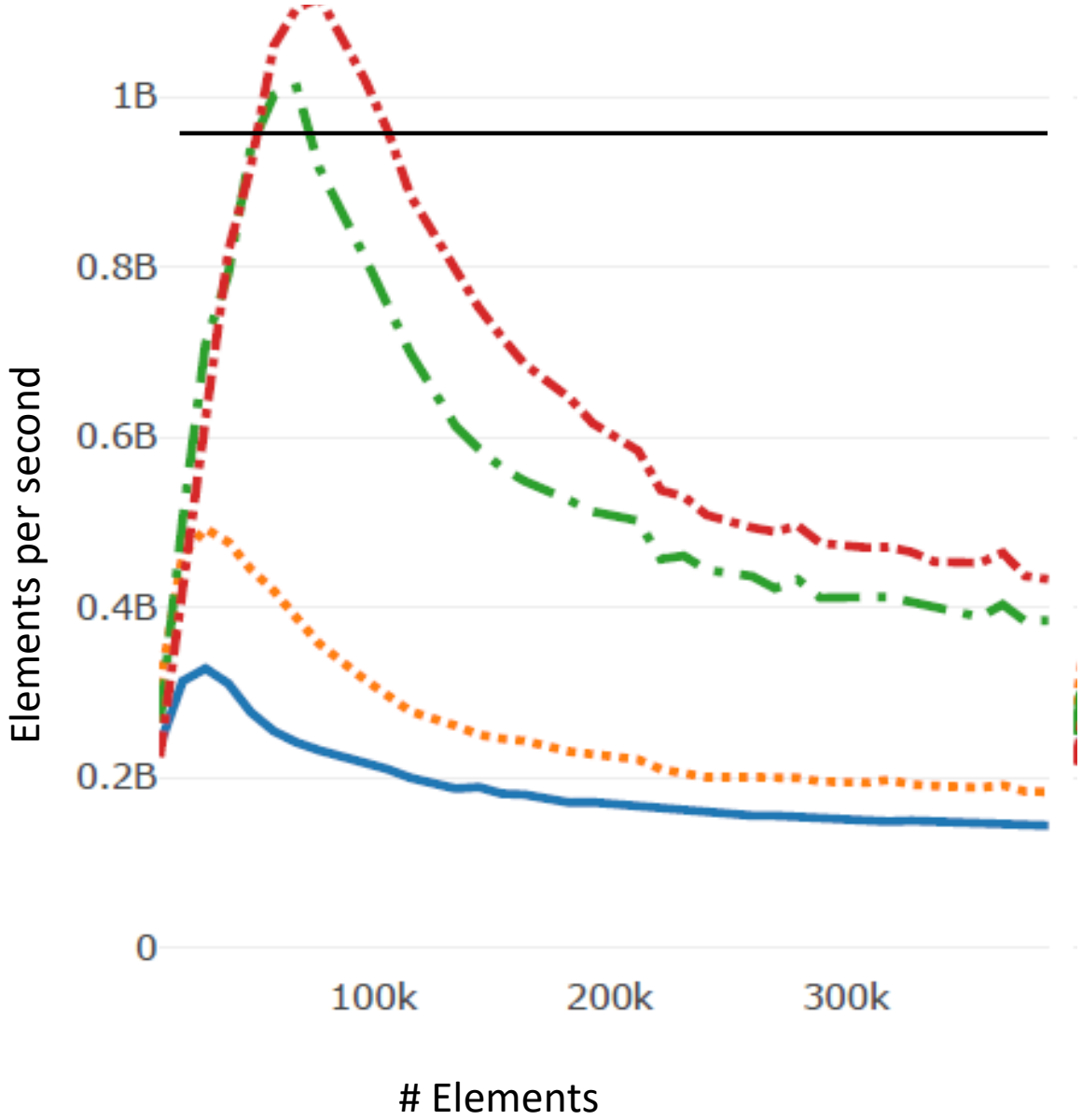
Simulation efficiency

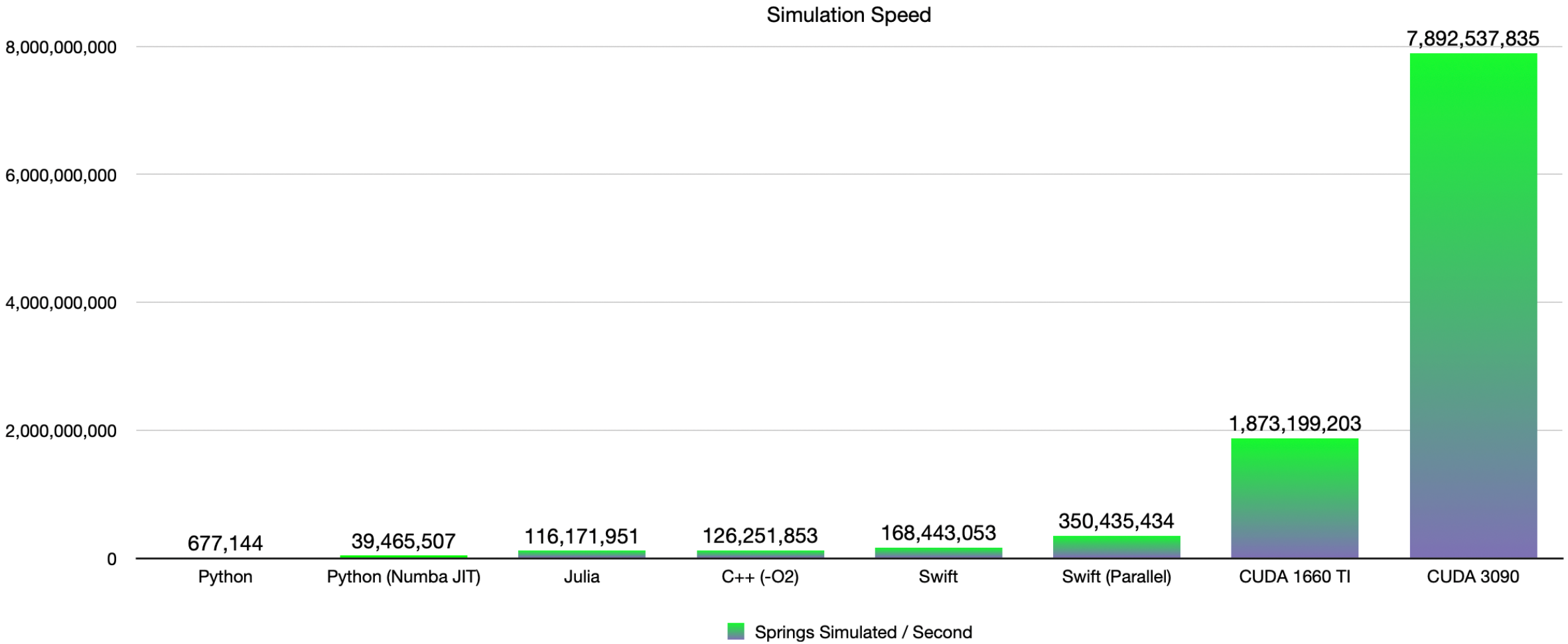
- Measured in spring evaluations per second
  - Per real second, not per simulated second
- Typical values
  - Python: 10K springs/sec
  - C++: 1 Million springs/sec per CPU core
  - CUDA/GPU: 1 Billion springs/sec per GPU (RTX3090, 4000+ cores)
- If efficiency is low, keep structures simple
  - Less than 1000 springs

The simplest possible 3D object?






1B
0.8B
0.6B
0.4B
0.2B
0
Elements per second
100k
200k
300k
Elements


Simulation Speed
8,000,000,000
6,000,000,000
4,000,000,000
2,000,000,000
0
677,144
39,465,507
116,171,951
126,251,853
168,443,053
350,435,434
1,873,199,203
7,892,537,835
Python
Python (Numba JIT)
Julia
C++ (-O2)
Swift
Swift (Parallel)
CUDA 1660 TI
CUDA 3090
Springs Simulated / Second

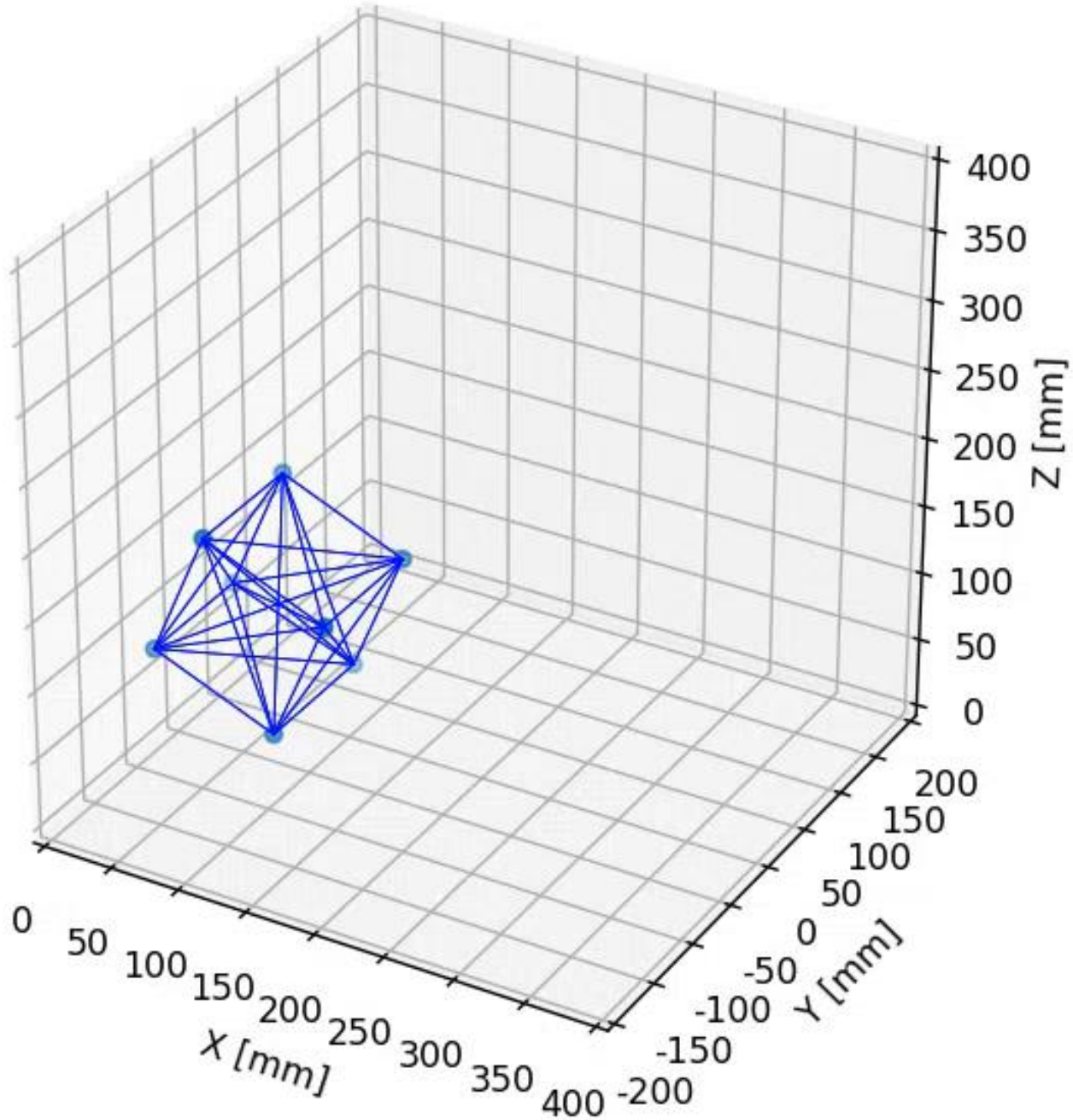
Max Segan

Visualization

For showing results and debugging

3D Graphics

- Visualization is important
  - 3D graphics available for python, MATLAB, C++
  - Draw all springs and masses
  - Draw ground plane clearly (e.g. grid in different colors)
  - Draw external forces
- Use color for visualization, e.g.
  - Change spring color with stress (e.g. red in tension, blue in compression)
  - Change spring color depending on material type, k, etc.
- You don’t need to draw the springs and masses every time step.
  - For example, you can have a time-step of *dt=0.0001 sec* but draw the cube only every 100 time-steps



Boxi Xia - MatPlotLib

vpython.org/

VPython

3D Programming for Ordinary Mortals

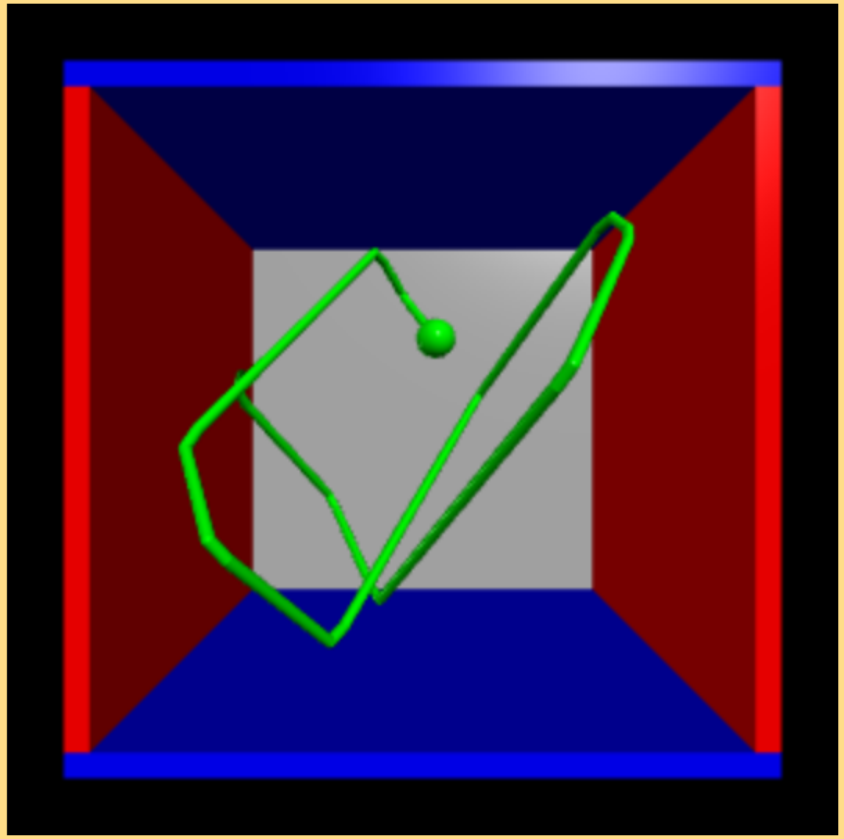
Examples

Documentation

GlowScript VPython User Forum

VPython 7 User Forum

glowscript.org



Pause

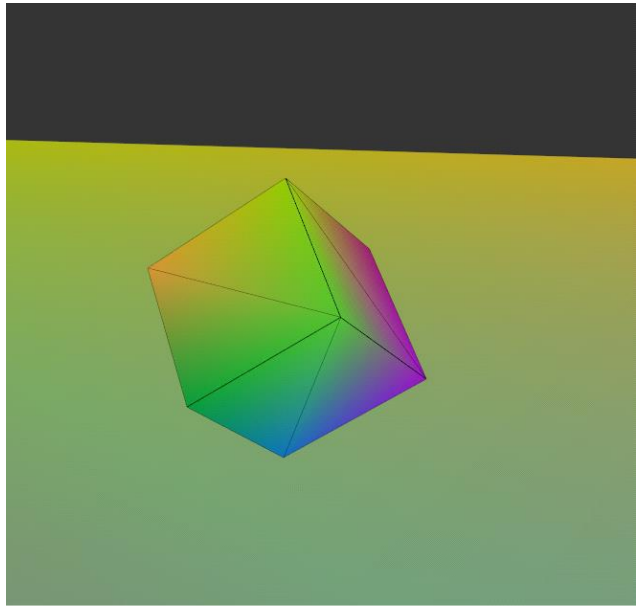
VPython makes it easy to create navigable 3D displays and animations, even for those with limited programming experience. Because it is based on Python, it also has much to offer for experienced programmers and researchers.

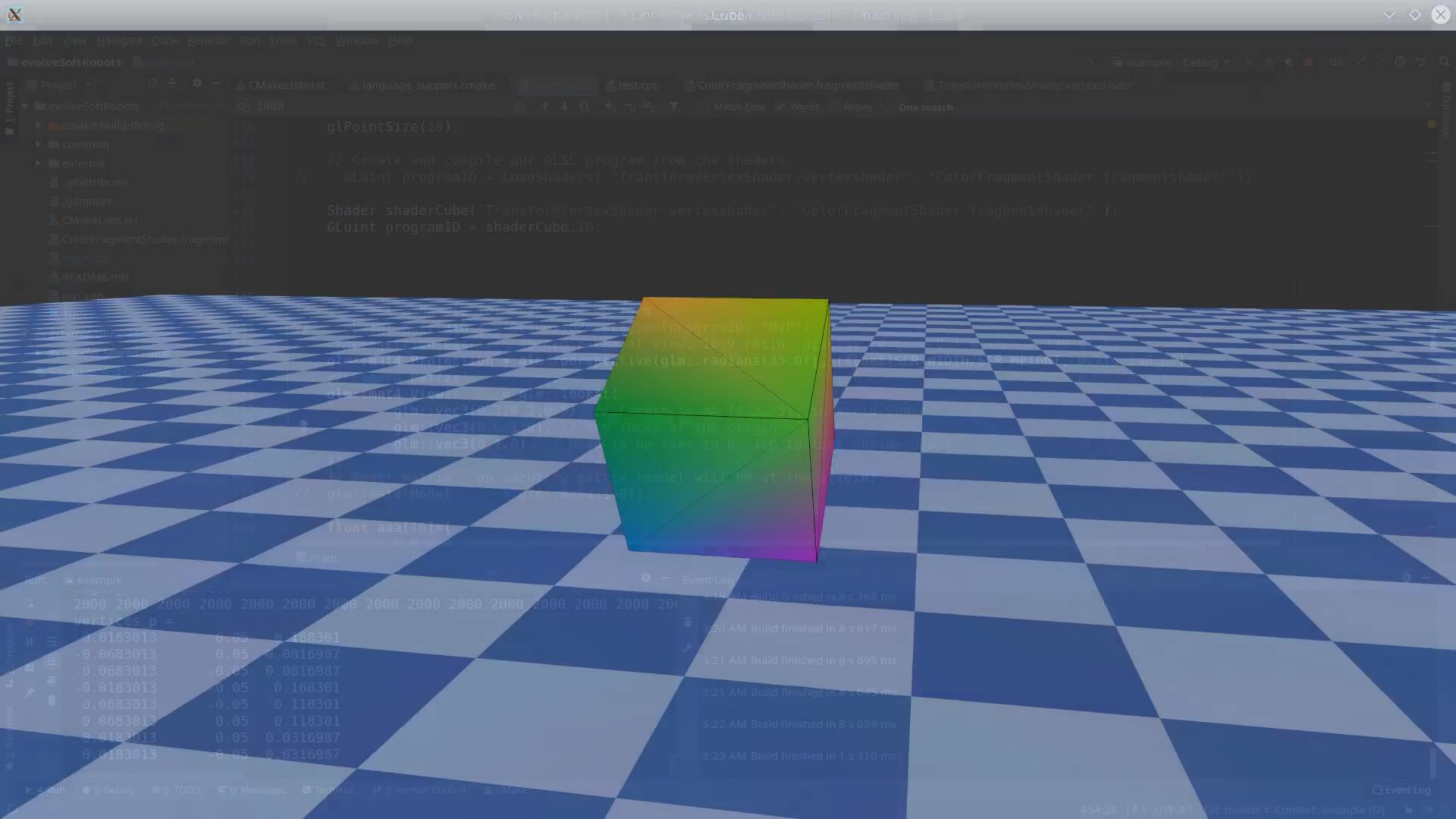
OpenGL resources

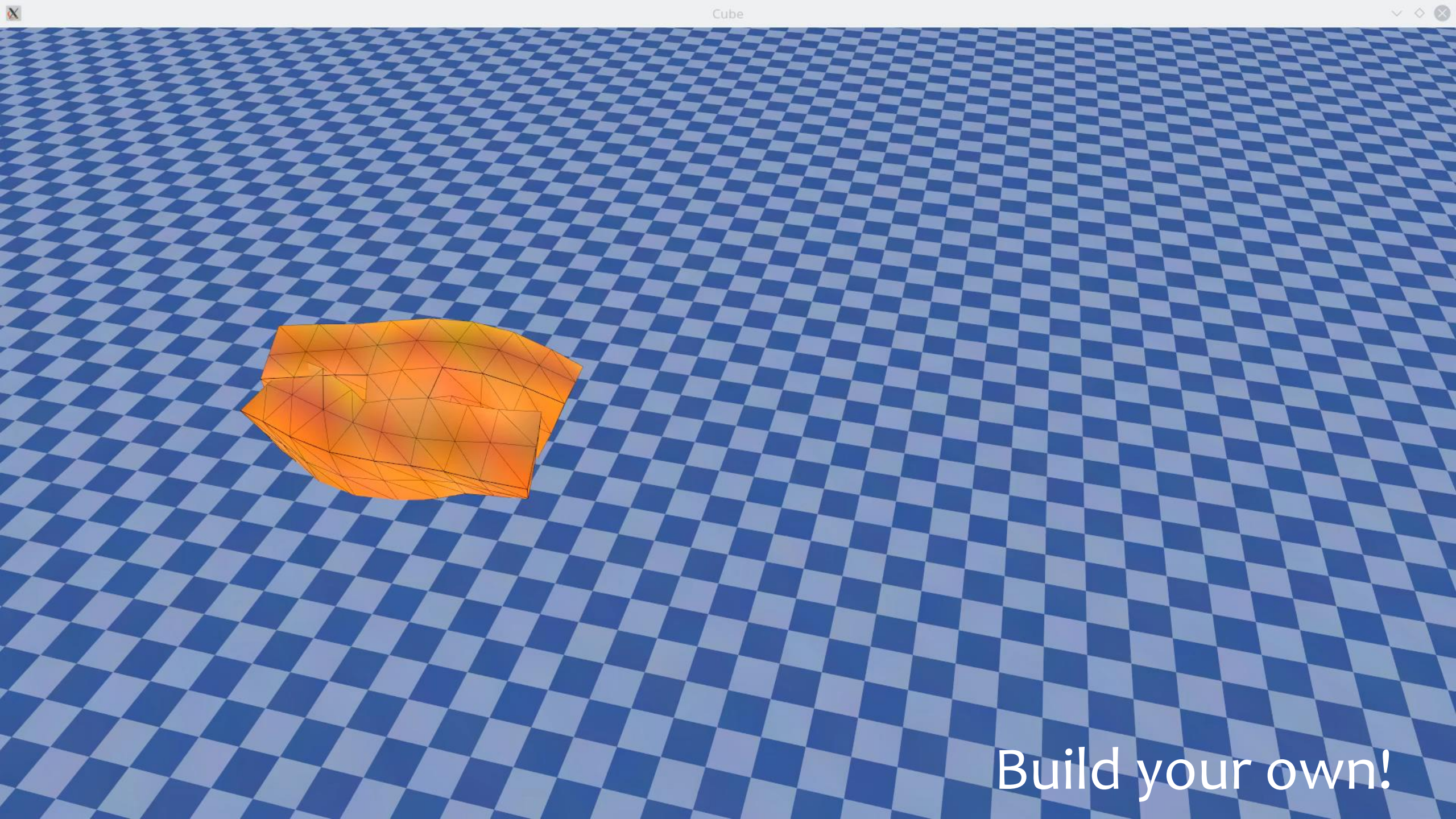
OpenGL is useful for rendering:
For c++ (this is probably the fastest):
GLFW: https://www.glfw.org/
Tutorials:
http://www.opengl-tutorial.org/
https://learnopengl.com/
For Java (slower):
LWJGL: https://www.lwjgl.org/
For python (even slower):
ModernGL: https://github.com/moderngl/moderngl

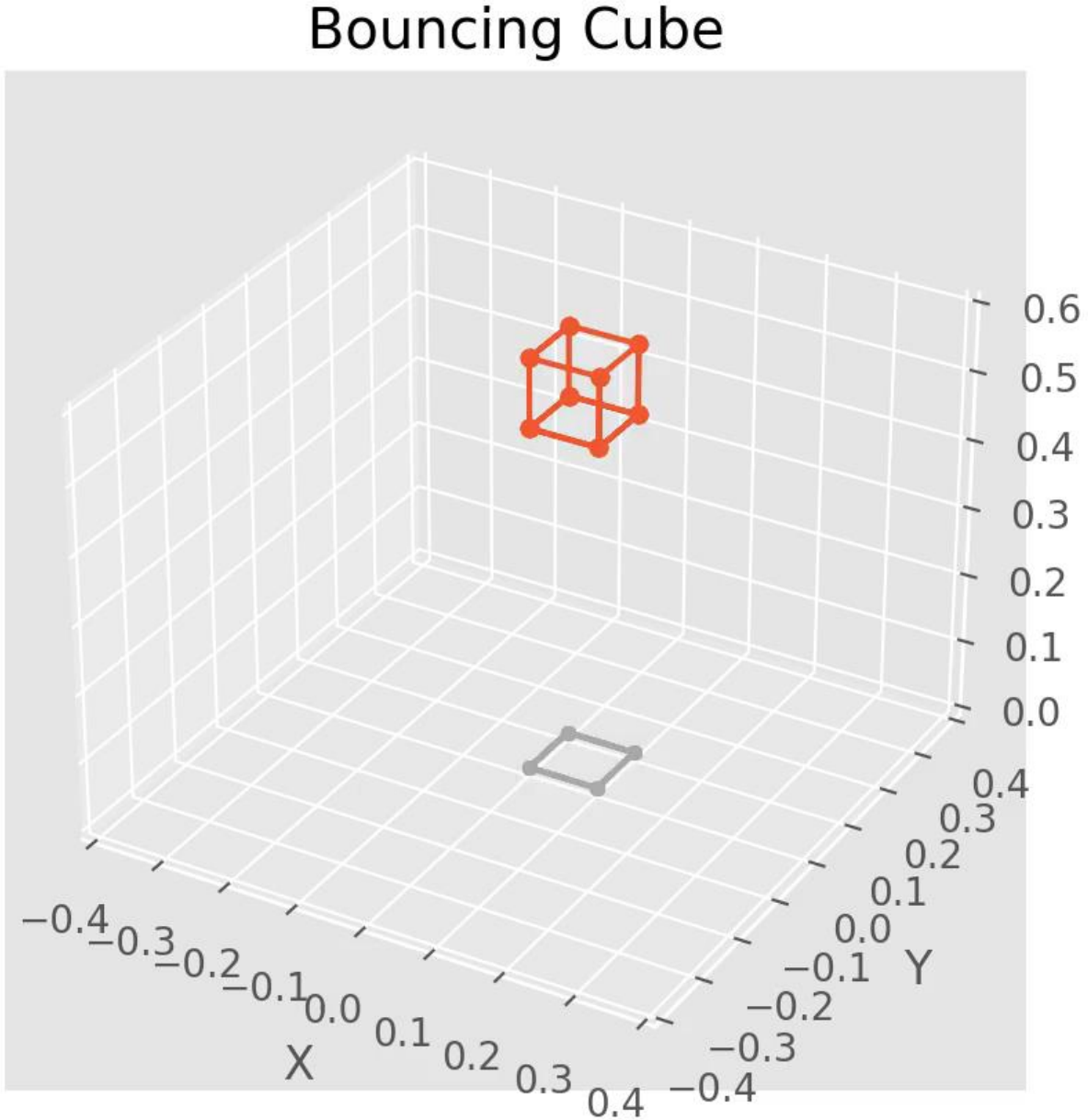
Solid appearance

- You scan make the robot look solid by shading (filling in) all the exterior triangles of the robot.




Cube
File Edit View Navigate Code Refactor Run Tools VCS Window Help
evolveSoftRobots
Project
CMakeLists.txt
language_support.cmake
test.cpp
ColorFragmentShader.fragmentshader
TransformVertexShader.vertexshader
cmake-build-debug
common
external
.gitattributes
.gitignore
CMakeLists.txt
ColorFragmentShader.fragment
main.cpp
README.md
glPointSize(10);
// Create and compile our GLSL program from the shaders
// GLuint programID = LoadShaders("TransformVertexShader.vertexshader", "ColorFragmentShader.fragmentshader");
Shader shaderCube("TransformVertexShader.vertexshader", "ColorFragmentShader.fragmentshader");
GLuint programID = shaderCube.ID;
float aaa[]={
main
example
2000 2000 2000 2000 2000 2000 2000 2000 2000 2000 2000 2000 2000 2000 2000 20
vertices_p =
0.0183013 0.05 0.168301
-0.0683013 0.05 0.0816987
-0.0683013 -0.05 0.0816987
-0.0183013 0.05 0.168301
0.0683013 -0.05 0.118301
0.0683013 0.05 0.118301
0.0183013 0.05 0.0316987
0.0183013 -0.05 0.0316987
Event Log
3:20 AM Build finished in 8 s 617 ms
3:21 AM Build finished in 8 s 695 ms
3:22 AM Build finished in 8 s 659 ms
3:23 AM Build finished in 1 s 310 ms
Run
Debug
TODO
Messages
Terminal
Version Control
CMake
Event Log


Cube
Build your own!



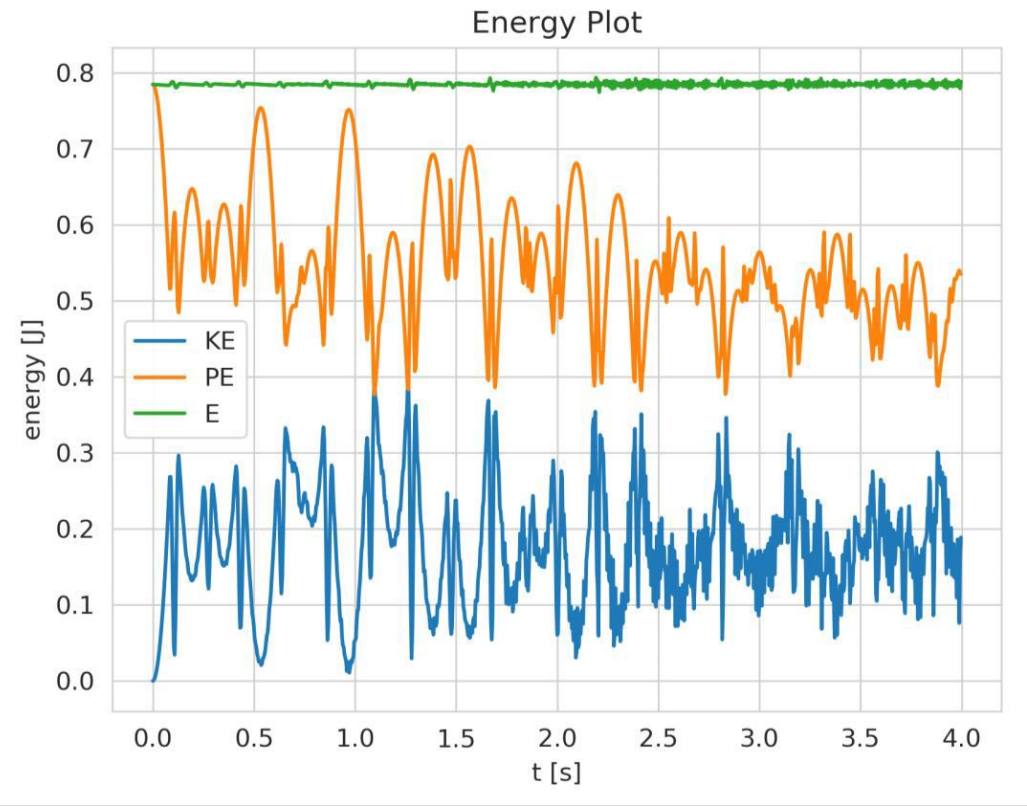
Or, draw just the outer edges (skip the diagonals)

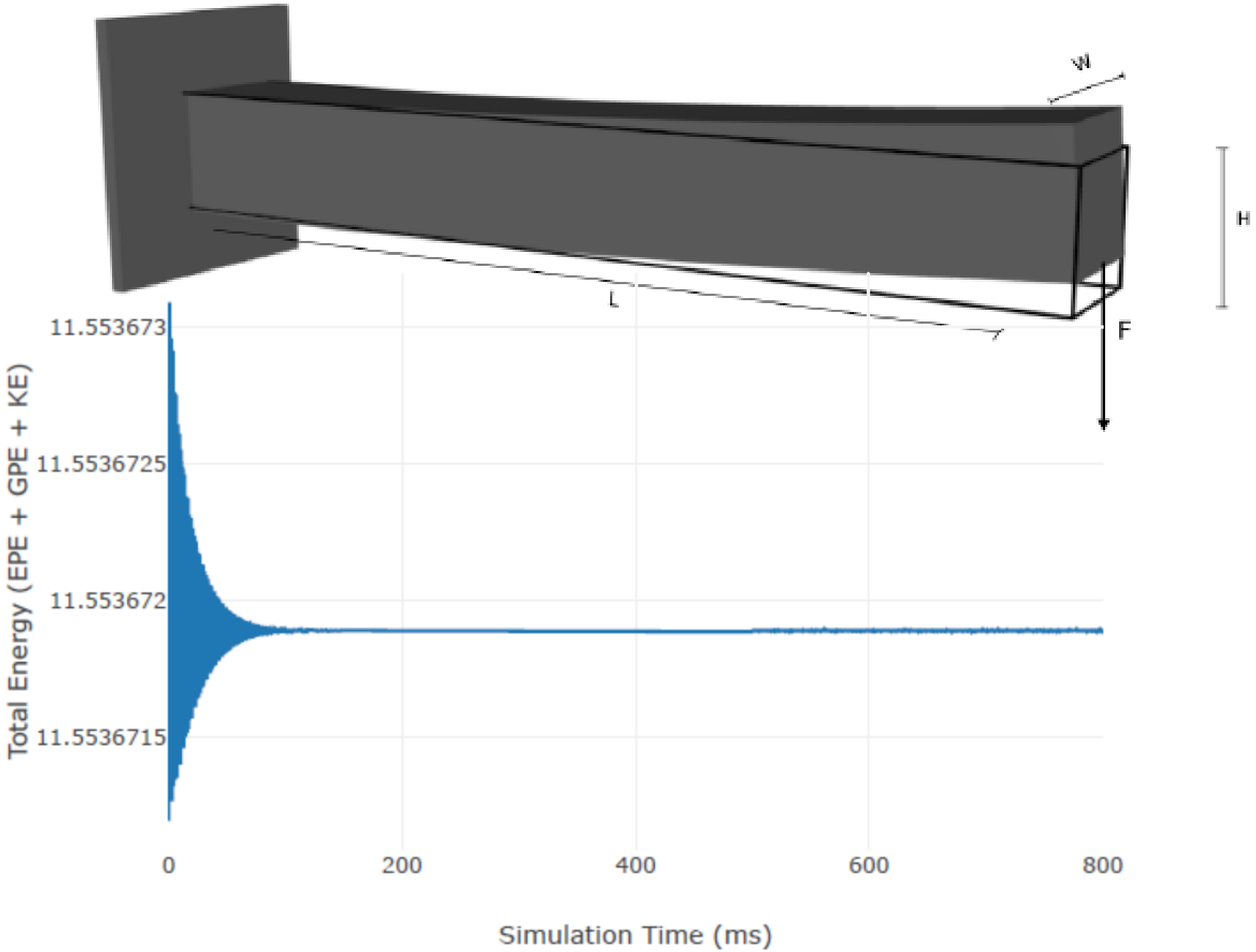
Validation

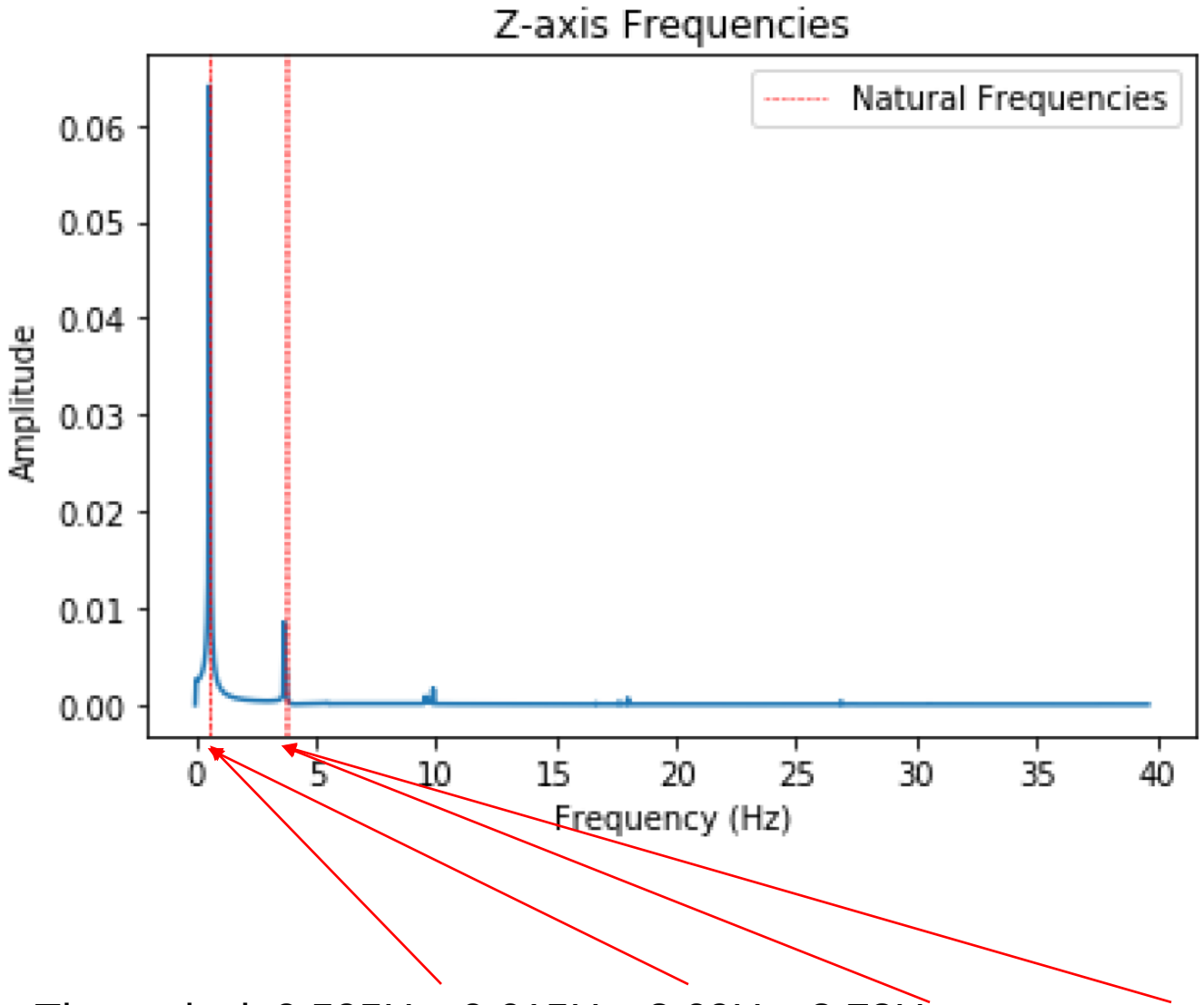
Is this a legit simulator?

Validation

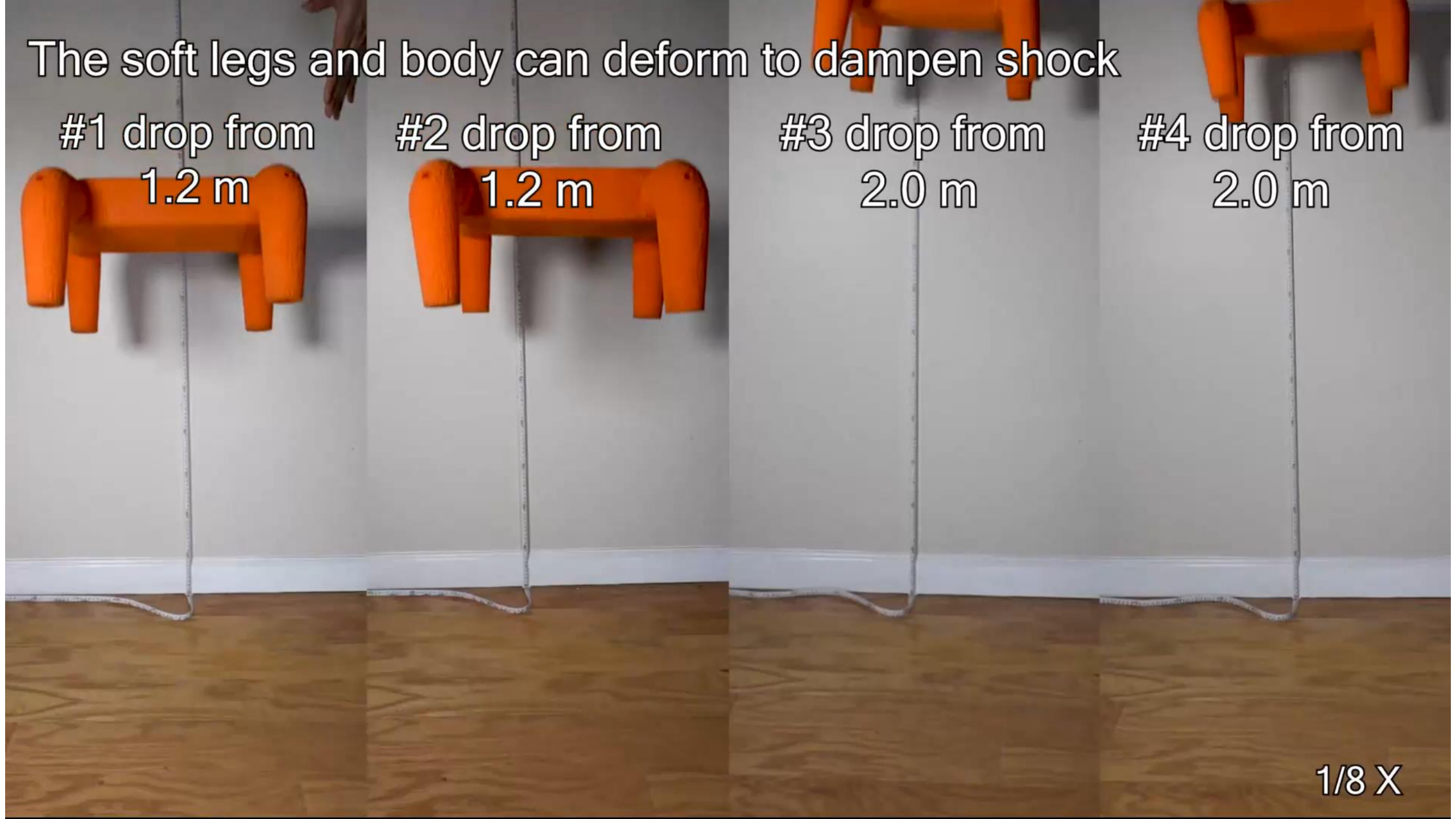
- If there is no damping or friction, energy should remain constant
  - Plot the total energy of the cube as function of time (kinetic energy, potential energy due to gravity, potential energy in the springs, as well as the energy related to the ground reaction force). The sum should be nearly constant. If it is not constant, you have some bug

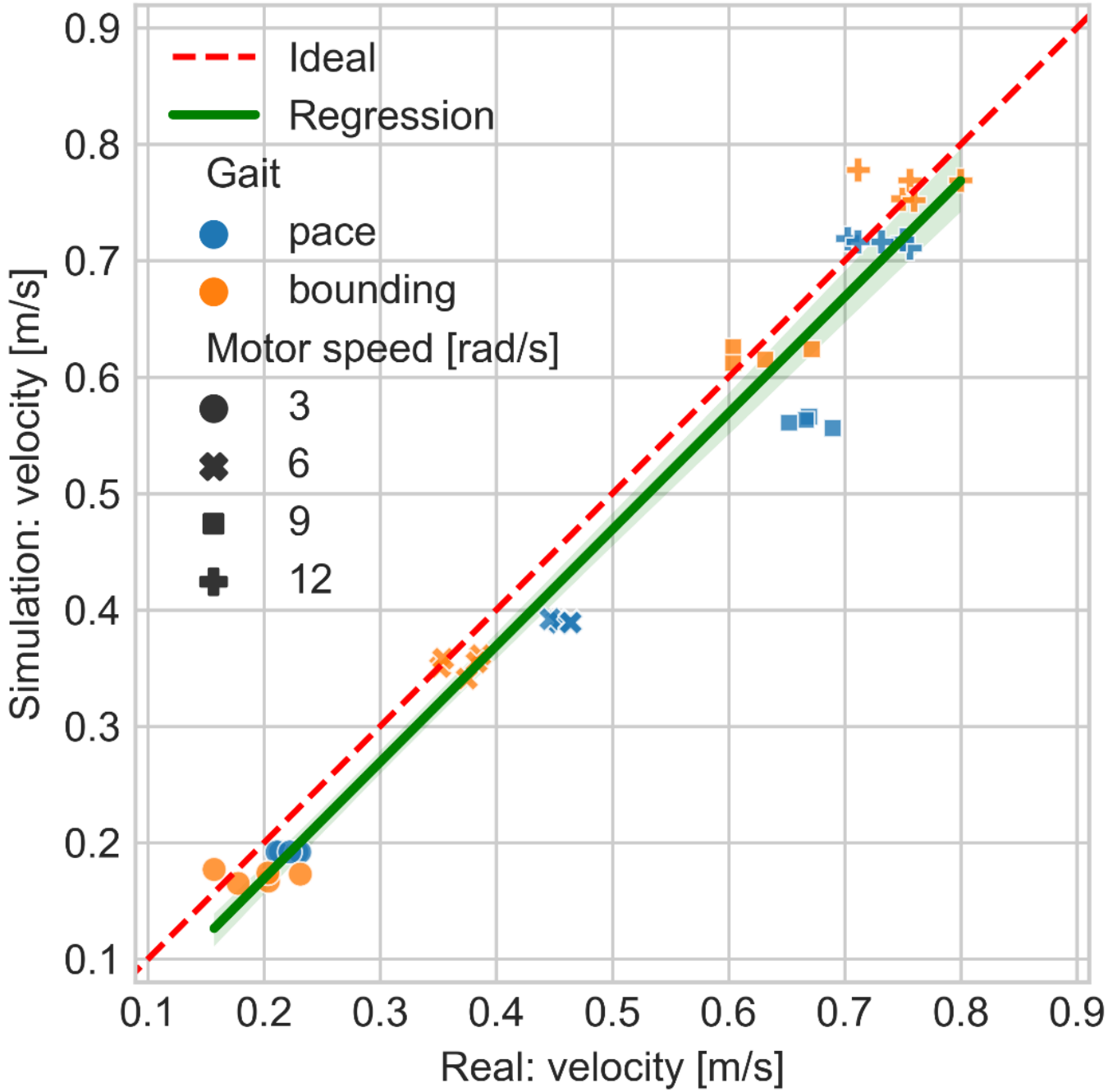



W
H
L
F
11.553673
11.5536725
11.553672
11.5536715
Total Energy (EPE + GPE + KE)
0
200
400
600
800
Simulation Time (ms)



Theoretical: 0.595Hz, 0.615Hz, 3.69Hz, 3.78Hz

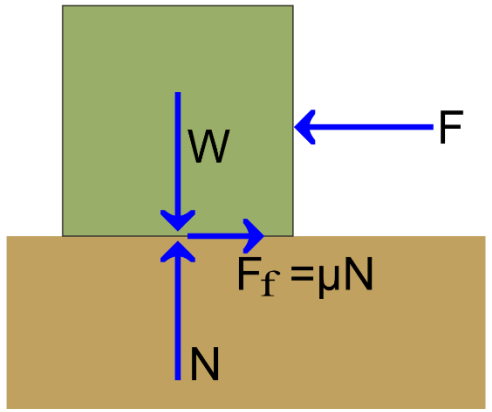

The soft legs and body can deform to dampen shock
#1 drop from 1.2 m
#2 drop from 1.2 m
#3 drop from 2.0 m
#4 drop from 2.0 m
1/8 X


Ideal
Regression
Gait
pace
bounding
Motor speed [rad/s]
3
6
9
12
Simulation: velocity [m/s]
Real: velocity [m/s]
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9

Boxi Xia

Add friction

- When a mass is at or below the ground, you can simulate friction and sliding. Assume μ_s is a coefficient of friction and μ_k is the kinetic coefficient
- Calculate the horizontal force $F_H=\text{sqrt}(F_x^2+F_y^2)$ and the normal force F_n
- If $F_n<0$ (i.e. force pointing downward) then:
  - If $F_H< -F_n*\mu_s$ then zero the horizontal forces of the mass
  - If $F_H\geq -F_n*\mu_s$ then reduce the horizontal force of the mass by μ_k*F_n
- Update the mass velocity based on the total forces, including both friction and ground reaction forces

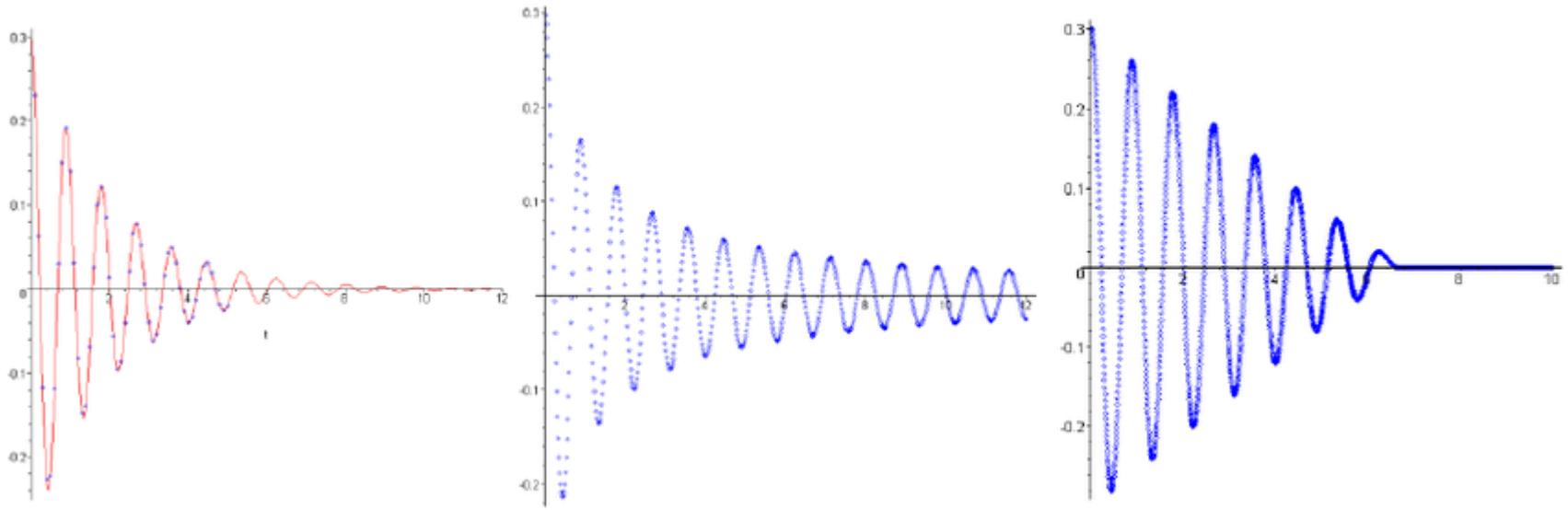


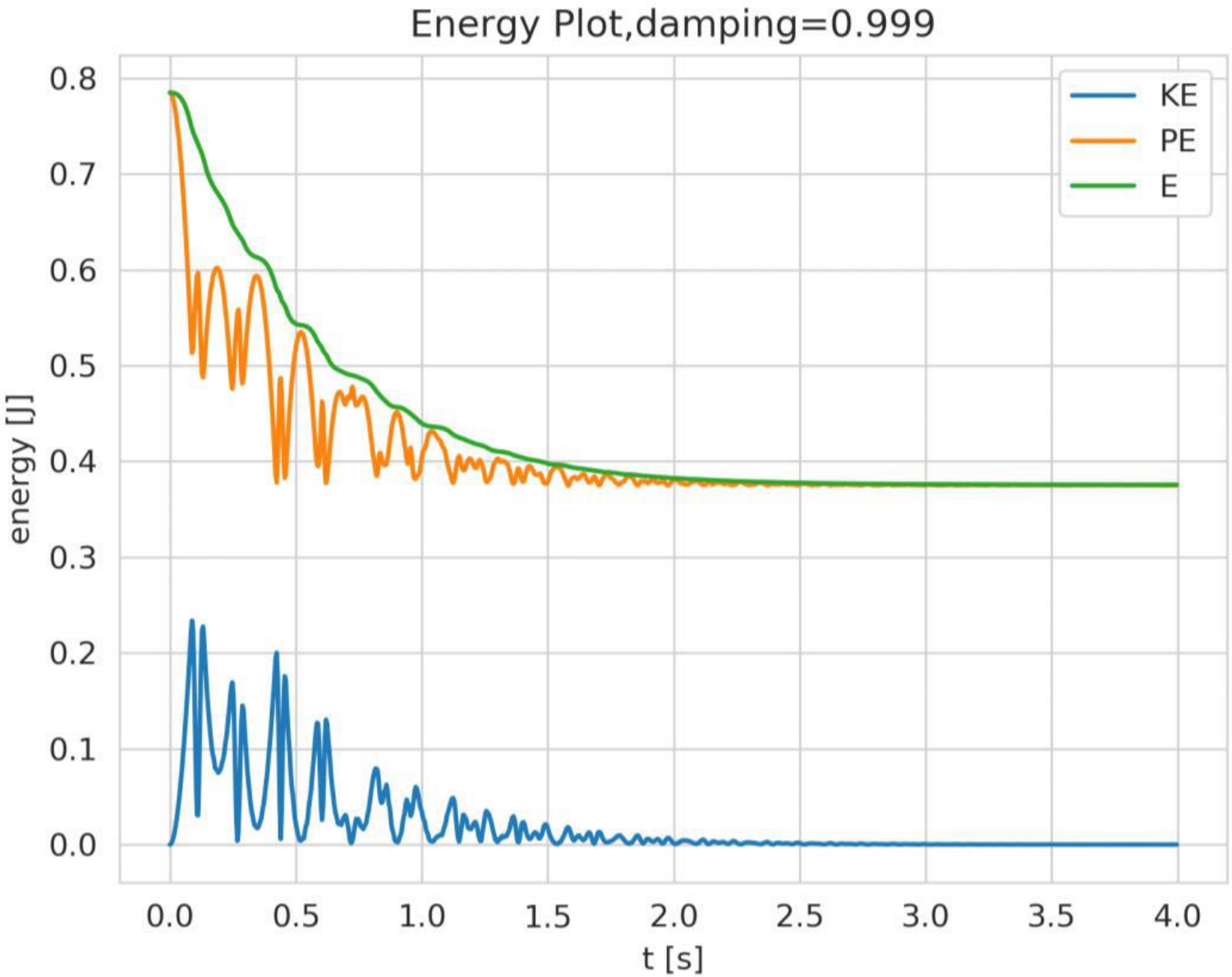
Coefficients of Friction for Common Surfaces

Materials	μ_s value	μ_k value
Steel on Steel	0.74	0.57
Aluminum on Steel	0.61	0.47
Copper on Steel	0.53	0.36
Rubber on Concrete	~1.0	0.8
Wood on Wood	0.25 – 0.50	0.2
Glass on Glass	0.94	0.4
Waxed wood on wet snow	0.14	0.10
Waxed wood on dry snow	0.01	0.04
Metal on Metal (lubricated)	0.15	0.06
Ice on Ice	0.10	0.03
Teflon on Teflon	0.04	0.04
Synovial joints in Humans	0.01	0.003

Add dampening

- Velocity dampening
  - Multiply the velocity **V** by 0.999 (or similar) each time step
  - Helps reduce vibration, wobbling, and snapping

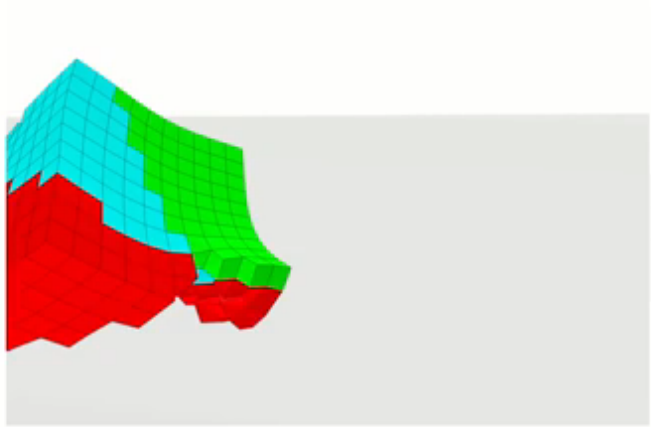



Energy Plot,damping=0.999
KE
PE
E
energy [J]
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
t [s]

Add dampening

- Velocity dampening
  - Multiply the velocity V by 0.999 (or similar) each time step
  - Helps reduce vibration and wobbling
- **Add water/viscous dampening**
  - **Apply drag force $F_D=cv^2$ in the opposite direction of *v* (*c* is drag coef).**

Recently soft robots have been evolved to run, and to grow like plants



Cheney et al., 2013

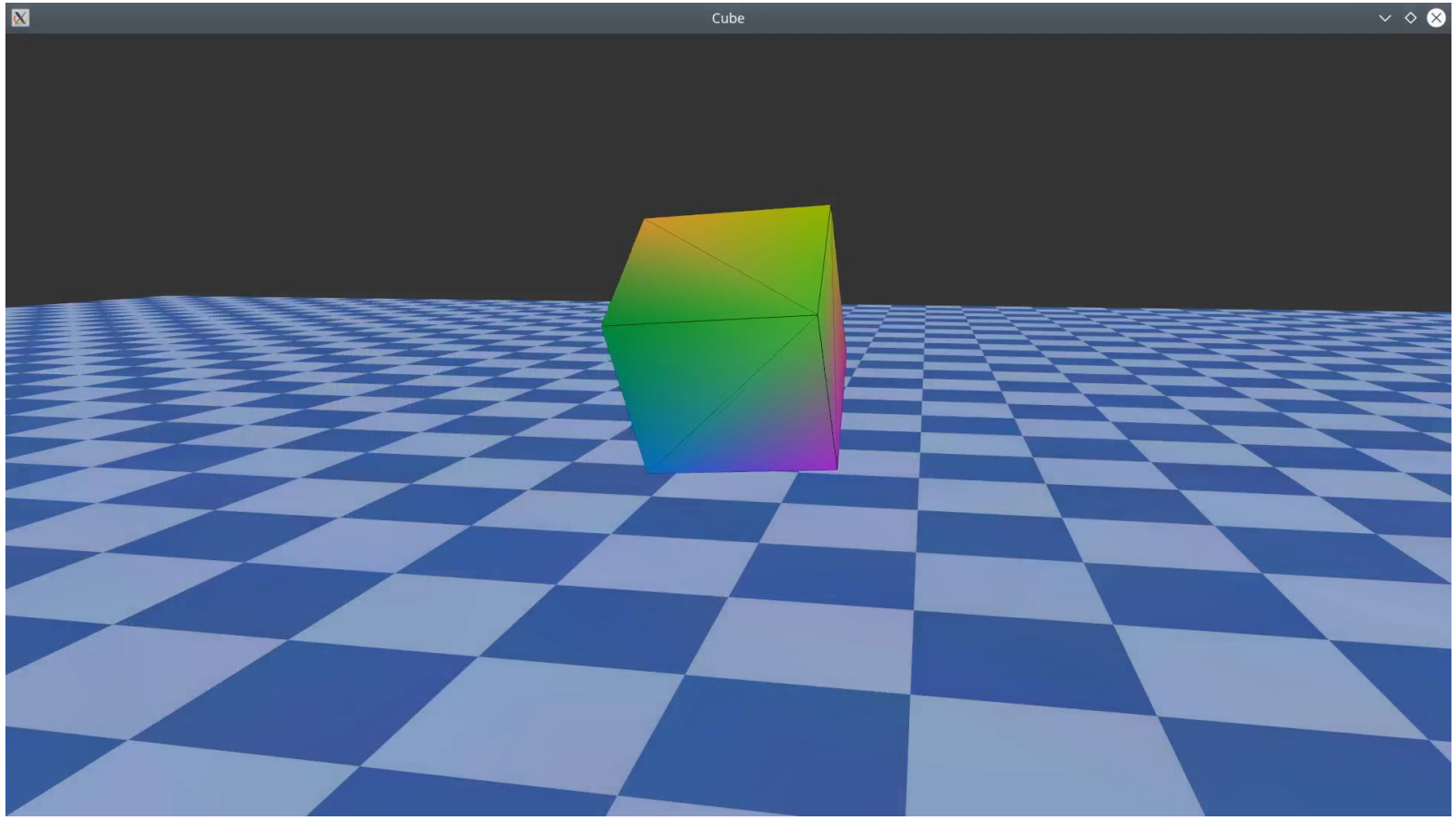
Corucci et al., 2016

Constraints

- Hard constraints
  - Fixing mass at some x,y,z position
- Soft constraints
  - Attaching a temporary spring between mass and desired position

Anchors

- Anchor points by setting v=0
- Constrain points to a curve or surface, e.g. set v_x=0

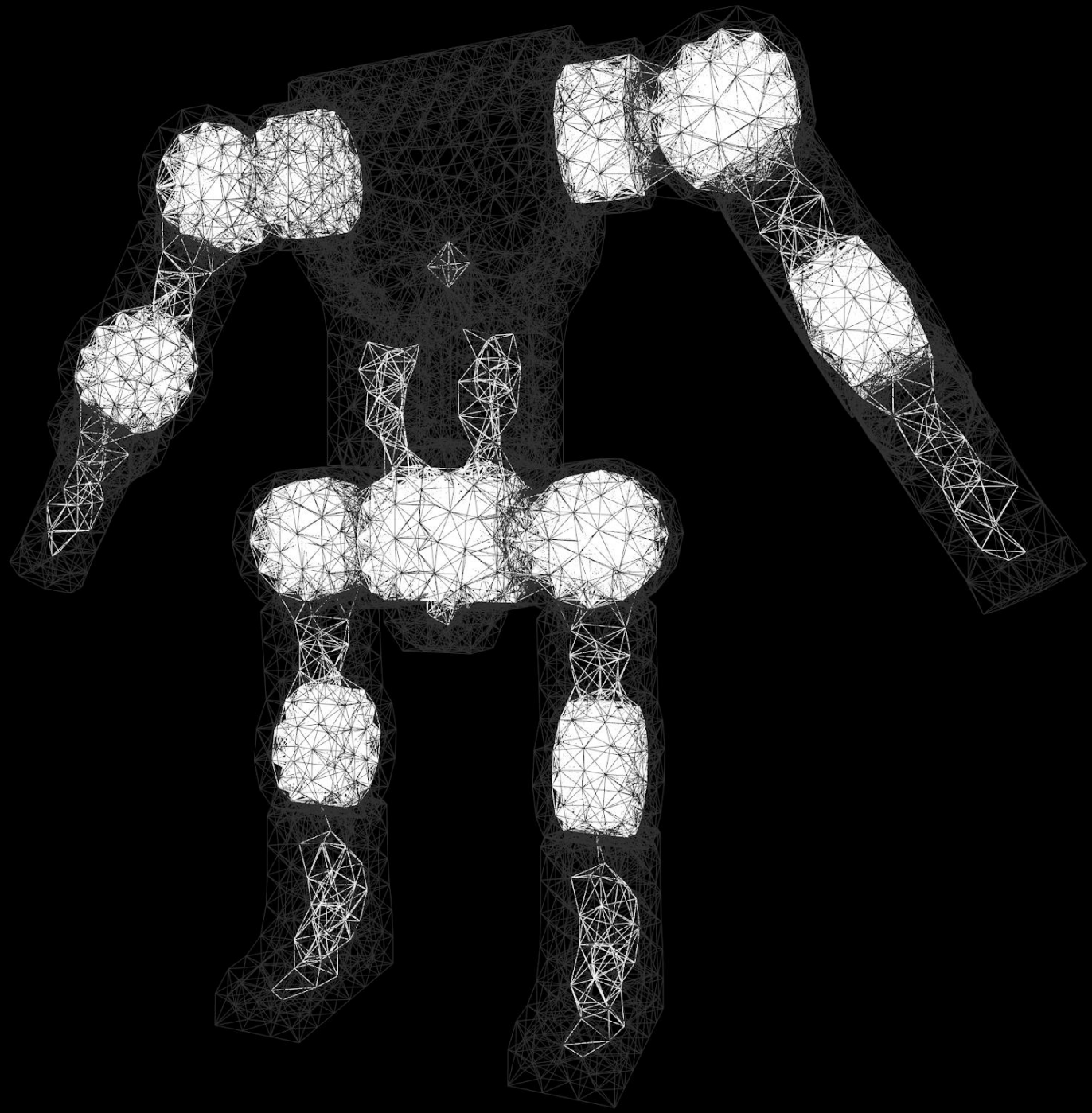


Constrain mass to a plane

- How can we constrain a mass to a plane?
  - Plane equation $ax+by+cz=d$
  - Answer: 
- How can we constrain a mass to a sphere?

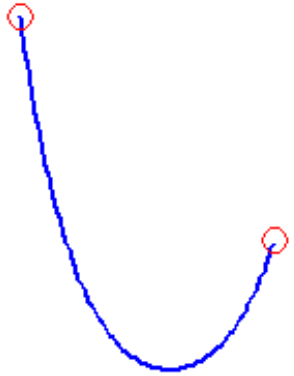
Change material property

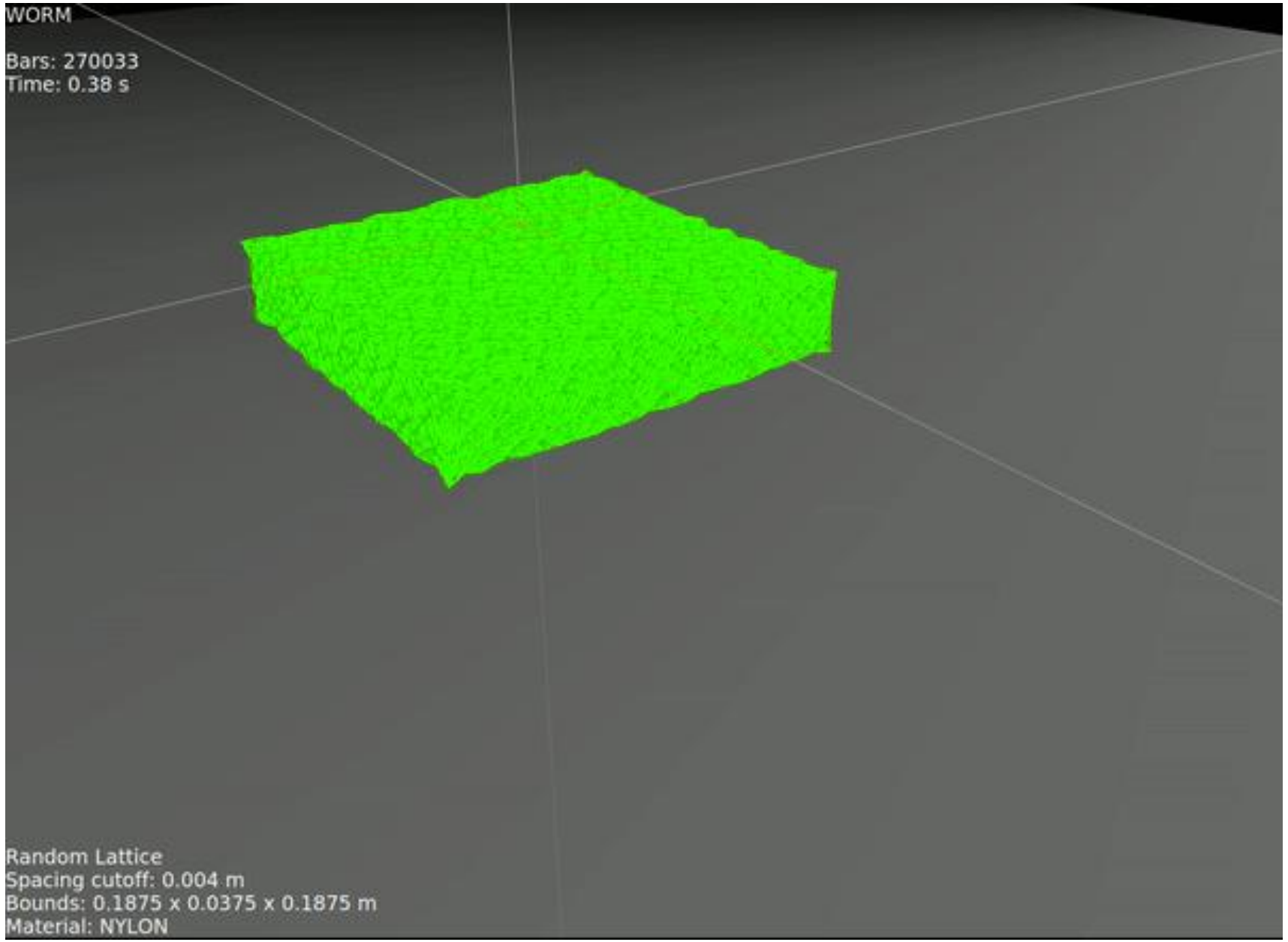
- Set spring constant to represent hard and soft materials
  - k = 10000 Hard material
  - k = 1000 soft material
  - Change k as a function of spring length (nonlinear material)
  - Change k with time?
- Note: Higher k needs smaller simulation dt



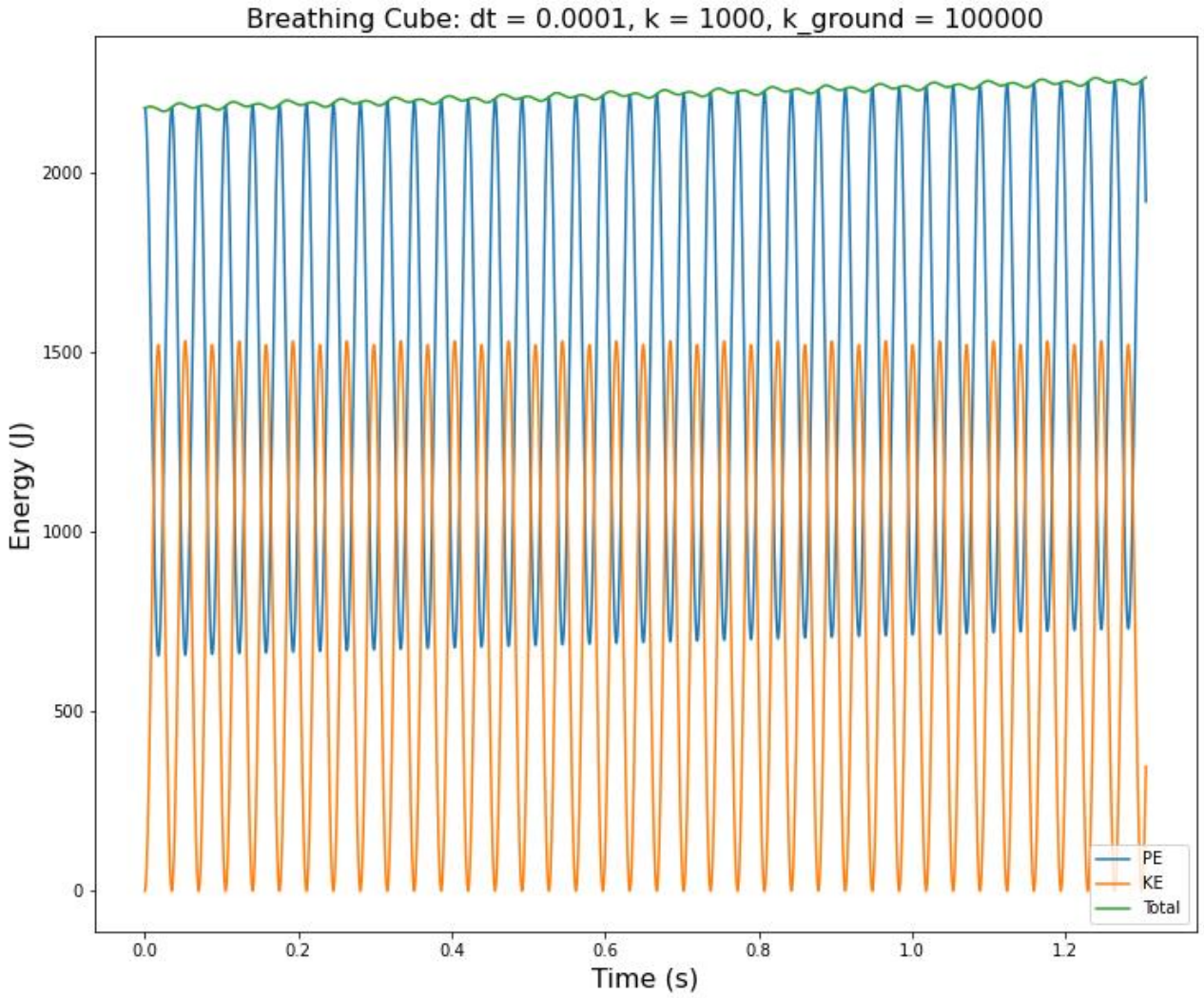
Nonlinear behavior

- When K and L_0 are not constant, but are a function of something we get interesting “nonlinear” behavior
  - E.g. Cables, actuators
- A cable with rest length L_0
  - $K = k_0$ if $L > L_0$
  - $K = 0$ if $L <= L_0$
- An actuator with a rest length L_0 that changes with time
  - $L_0 = a+b*\sin(\omega t+c)$




WORM
Bars: 270033
Time: 0.38 s
Random Lattice
Spacing cutoff: 0.004 m
Bounds: 0.1875 x 0.0375 x 0.1875 m
Material: NYLON

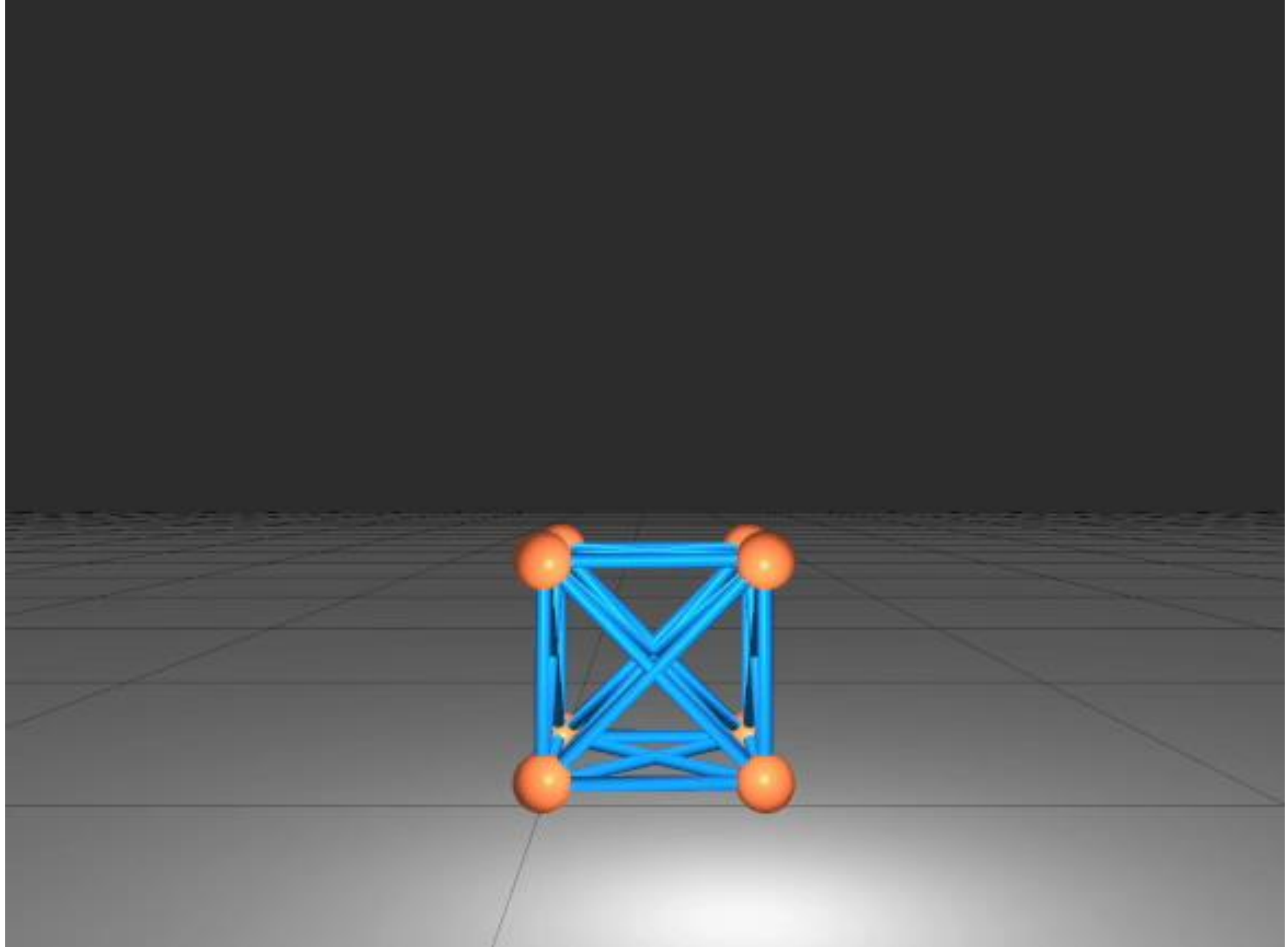
Energy plot with actuator



Daniel Pak

Final submission for 3a: Breathing cube

- For each spring set k and $L_0 = a+b*\sin(\omega t+c)$
  - ω is global frequency. *a,b,c,k* are spring parameters (*k* is spring coef)
  - Cycle period is $2\pi/\omega$



Summary:

3a: Create and demonstrate a physics simulator

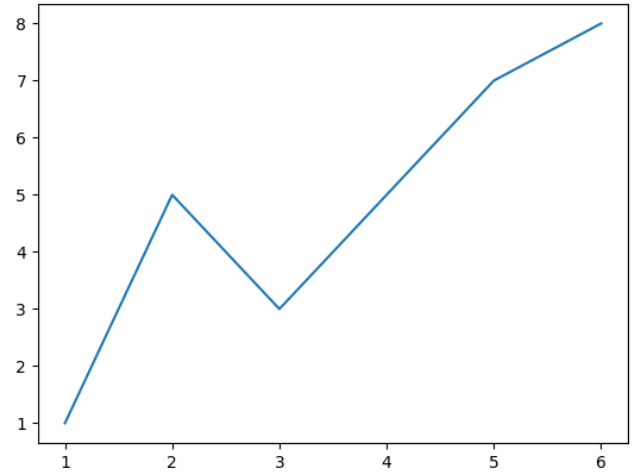
1. Cover page includes all information
2. General quality of the report (grammar, layout)
3. Video of bouncing cube with at least three bounces
4. Video of breathing cube with at least three breathing cycles provided
5. Cube bounces correctly
6. Cube launched with a slight spin (creating complex bounce sequence)
7. Multiple cubes dropped simultaneously (up to 10) in random orientations
8. Description of all simulation parameters provided
9. Description of all breathing parameters provided
10. All Energy curves provided
11. Energy plot for bouncing cube is constant
12. Simpler/different problem(s) tested for debugging, e.g. tetrahedron.
13. Cube faces and floor tiles are shaded to have solid appearance
14. Post video of cube on ed (provide screenshot and link)at least 24h before deadline

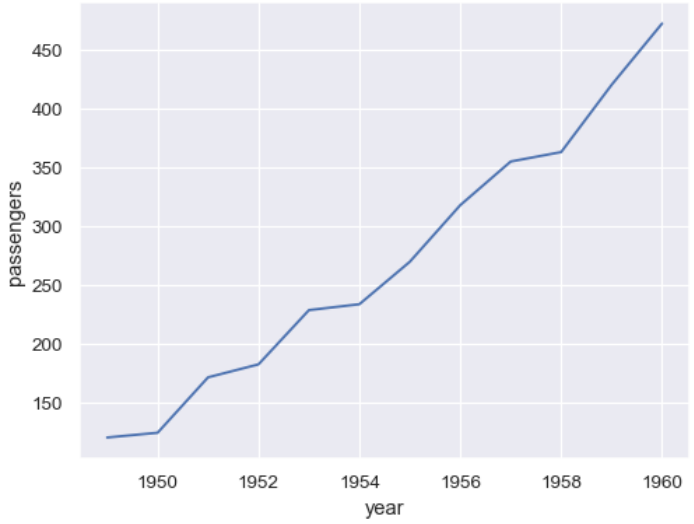
Tips

- Draw springs, masses and floor grid first – useful for debugging
- Give the cube a slight spin by applying a brief force to one of the masses – creates mor inserting dynamics
- Give every spring a different phase offset so that the cube breathes in an interesting way
- Post short video on Ed and include which language and graphics library you used, what k and dt you chose, and how many springs per second your software is evaluating

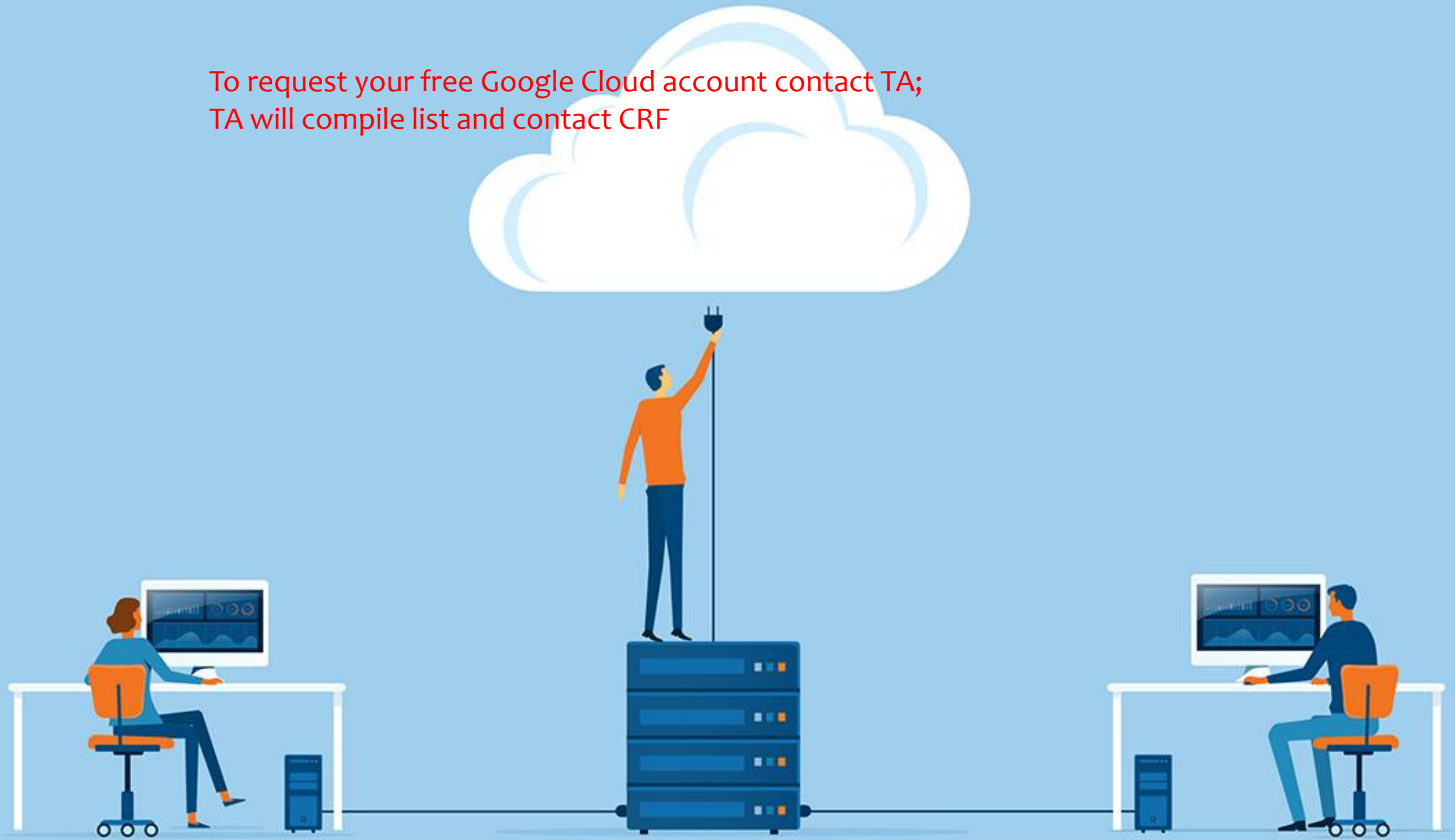
Charting in Python

- Matplotlib (https://matplotlib.org/)
  - Example: https://stackabuse.com/matplotlib-line-plot-tutorial-and-examples/
- Seaborn (https://seaborn.pydata.org/)
  - Example: https://seaborn.pydata.org/generated/seaborn.lineplot.html





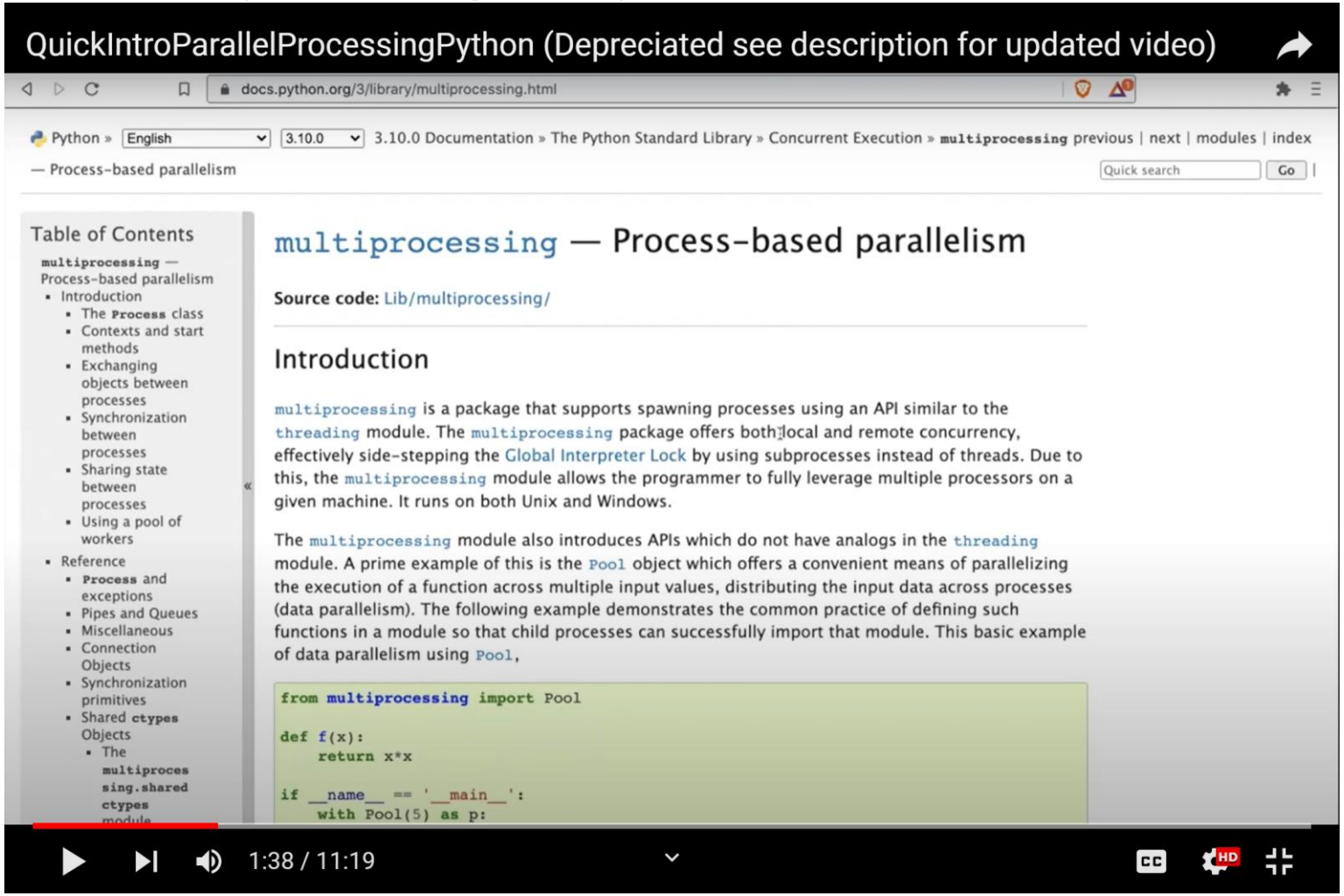
To request your free Google Cloud account contact TA;
TA will compile list and contact CRF



https://youtu.be/cmLfMVorjgI

Philippe Wyder

Parallel Computing (Python/MATLAB)



[PythonParallelComputingIntroduction - YouTube]

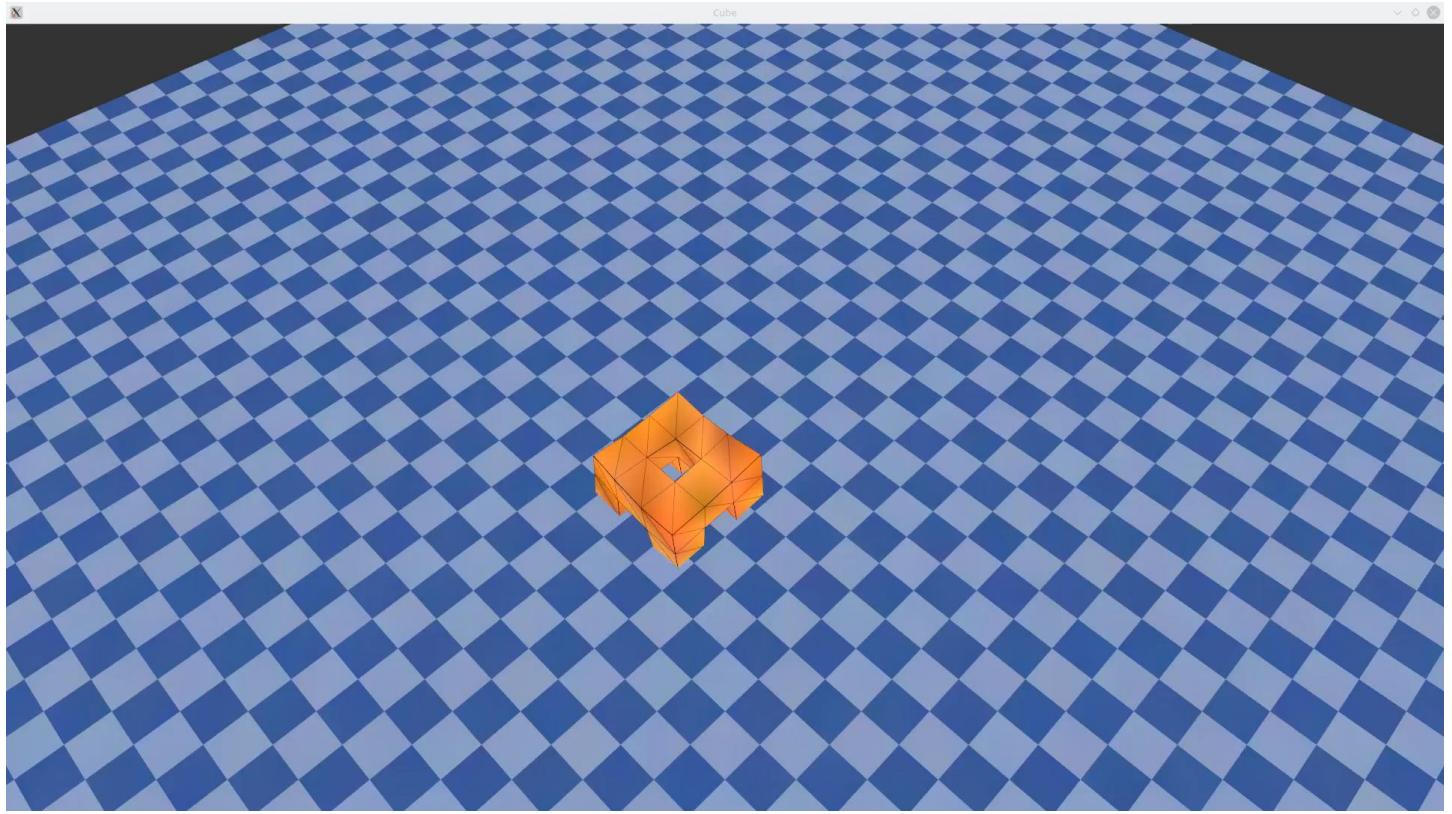
Philippe Wyder

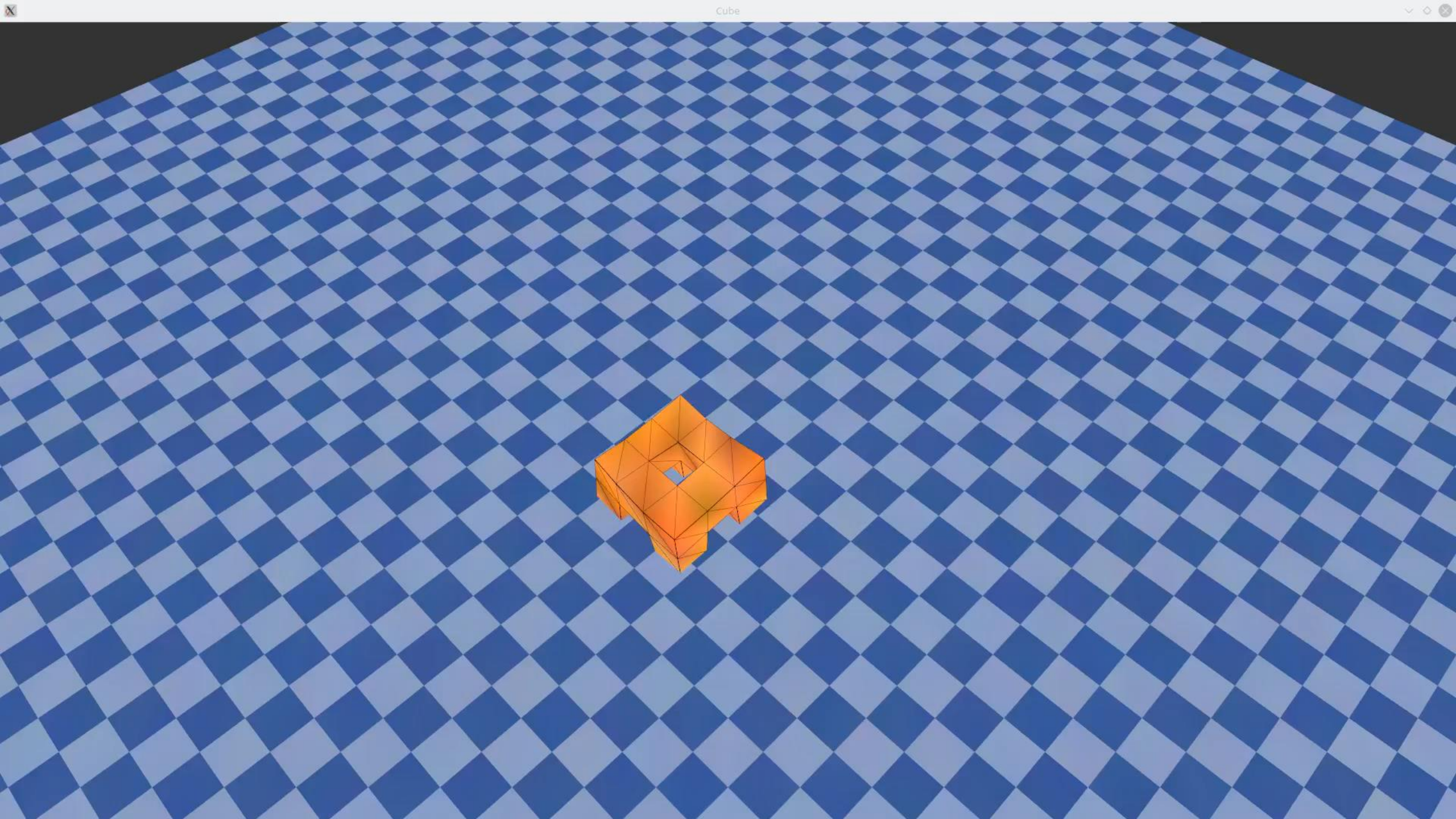
Assignment 3b

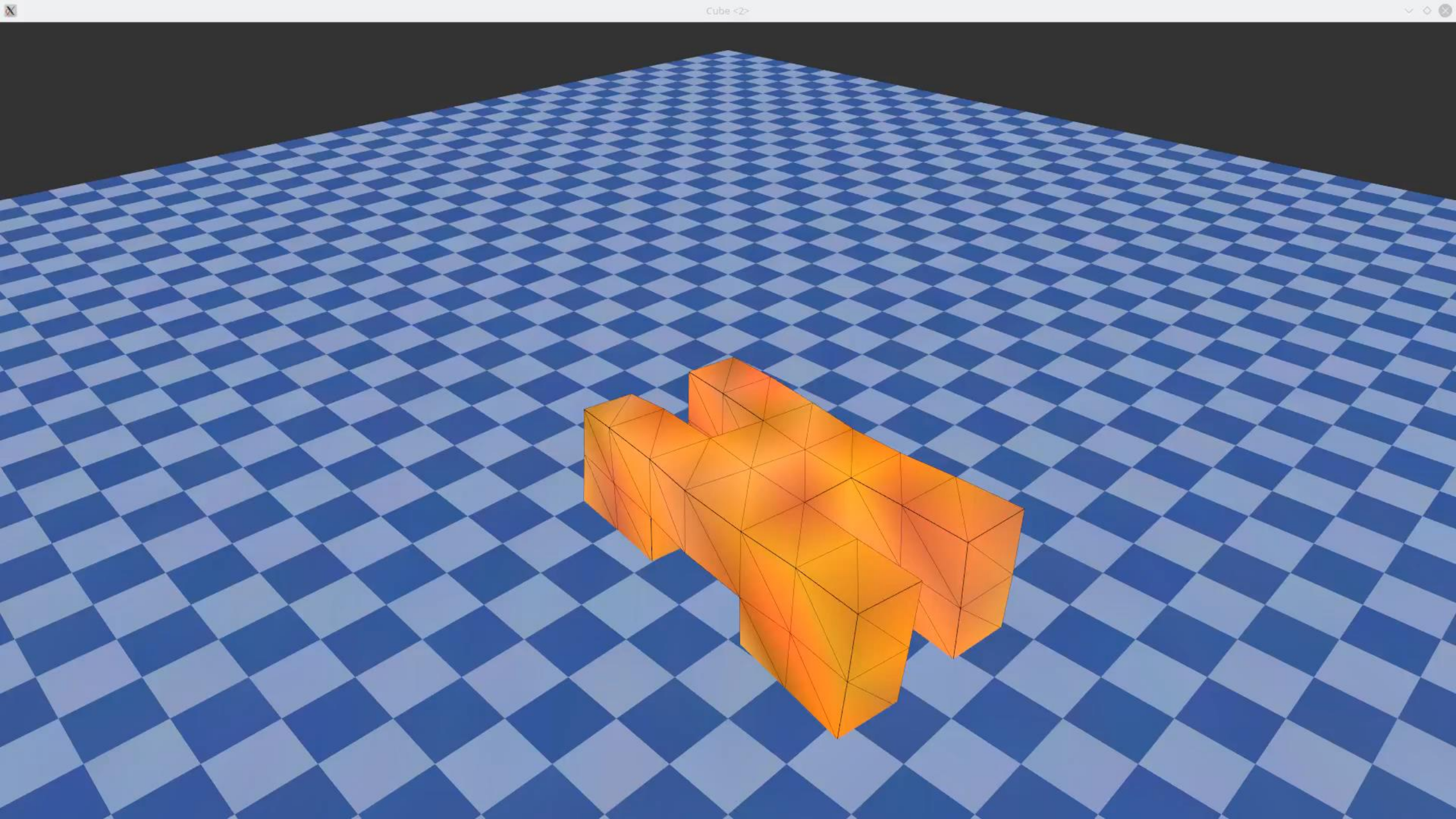
Evolve a robot with a fixed morphology

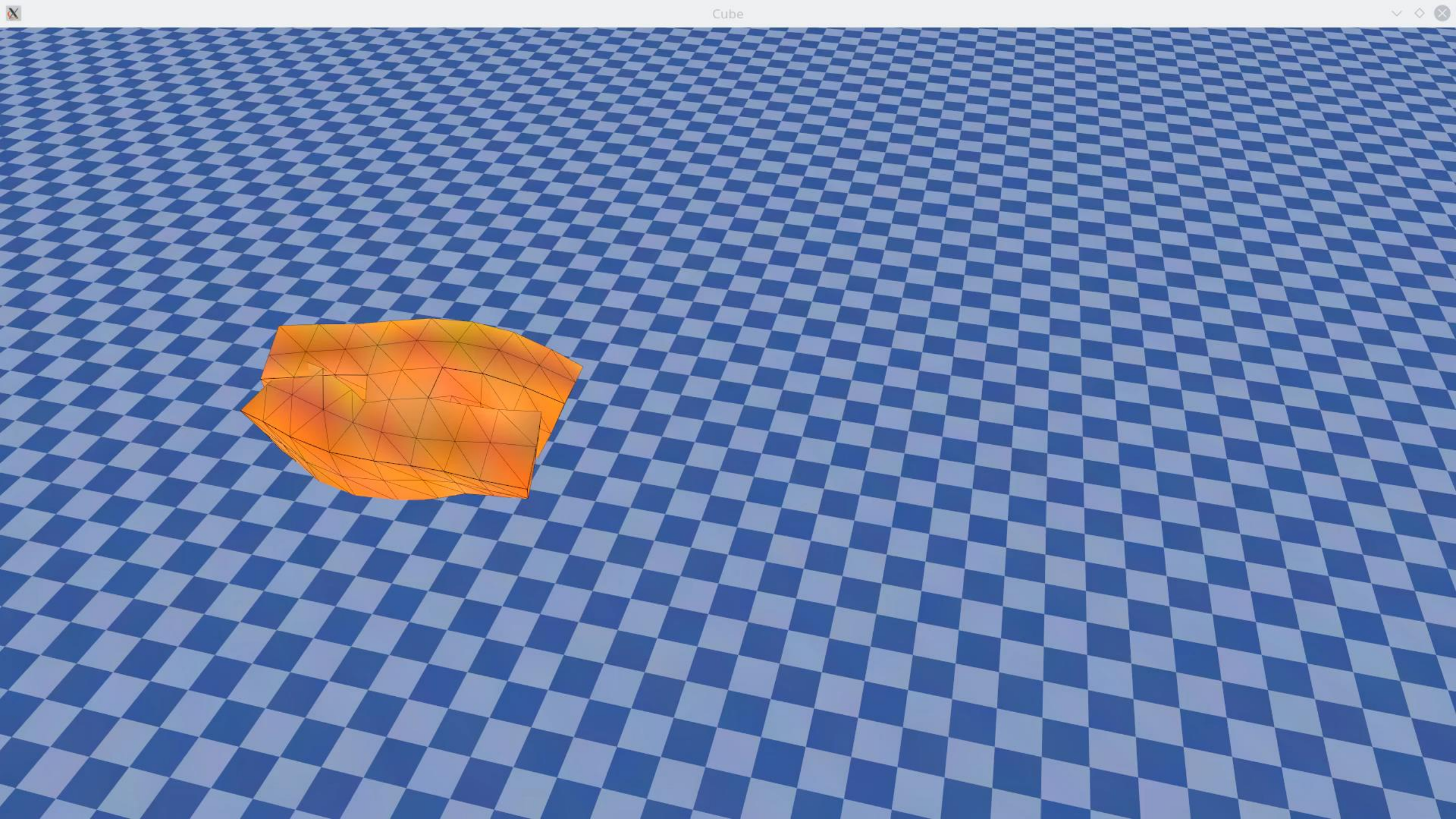
Assignment 3b

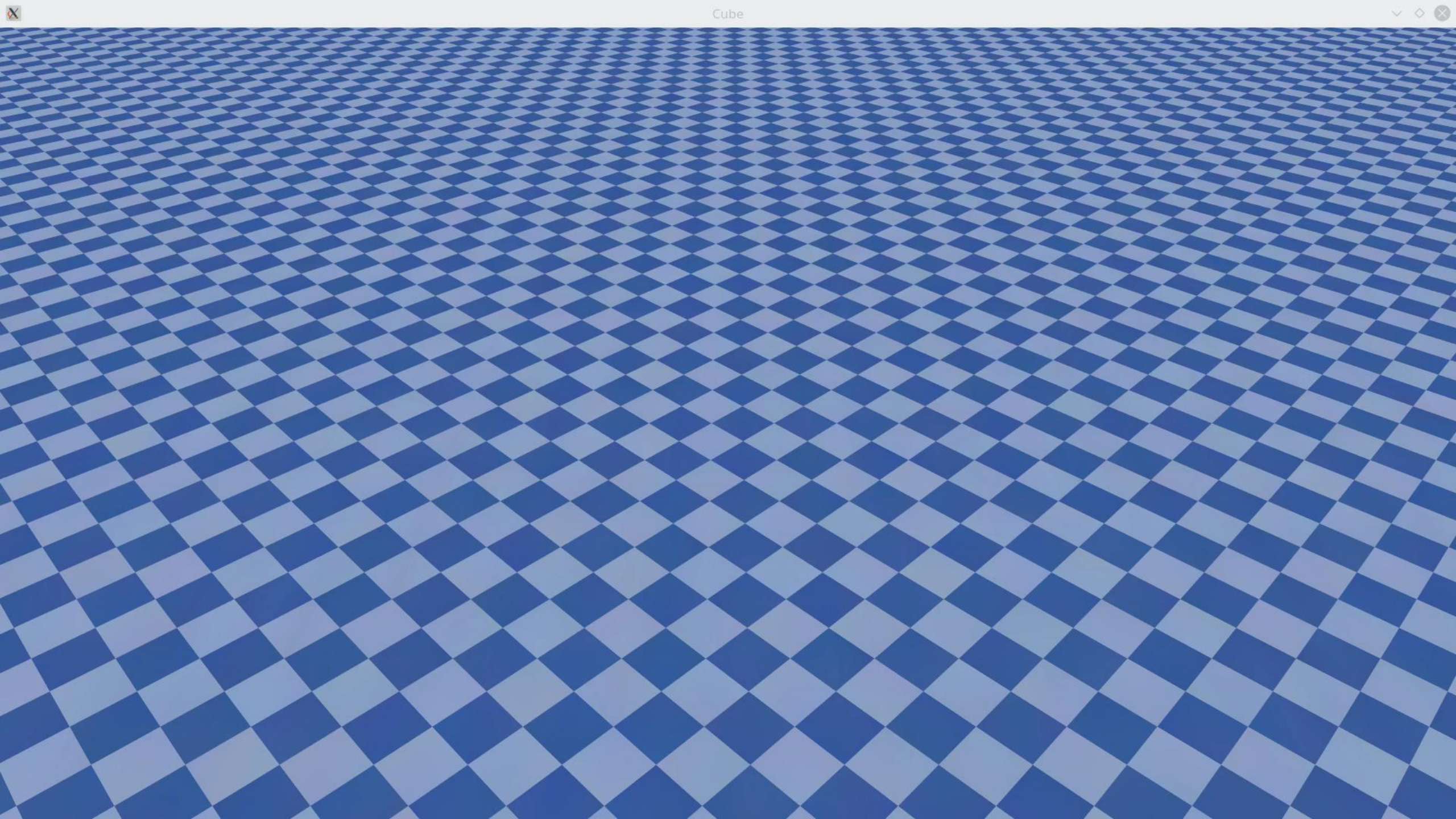
- Parametrically evolve spring rest lengths coefficients to make a manually designed robot move




Cube

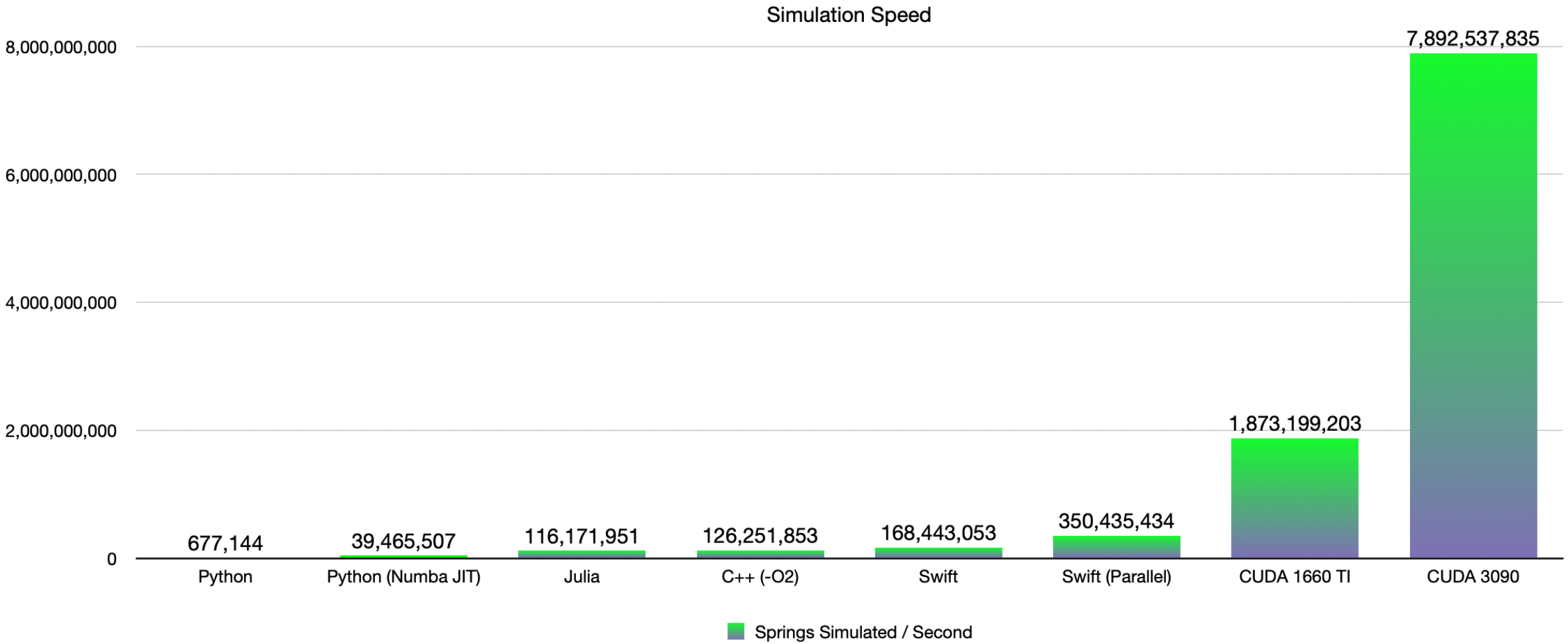

Cube <2>


Cube

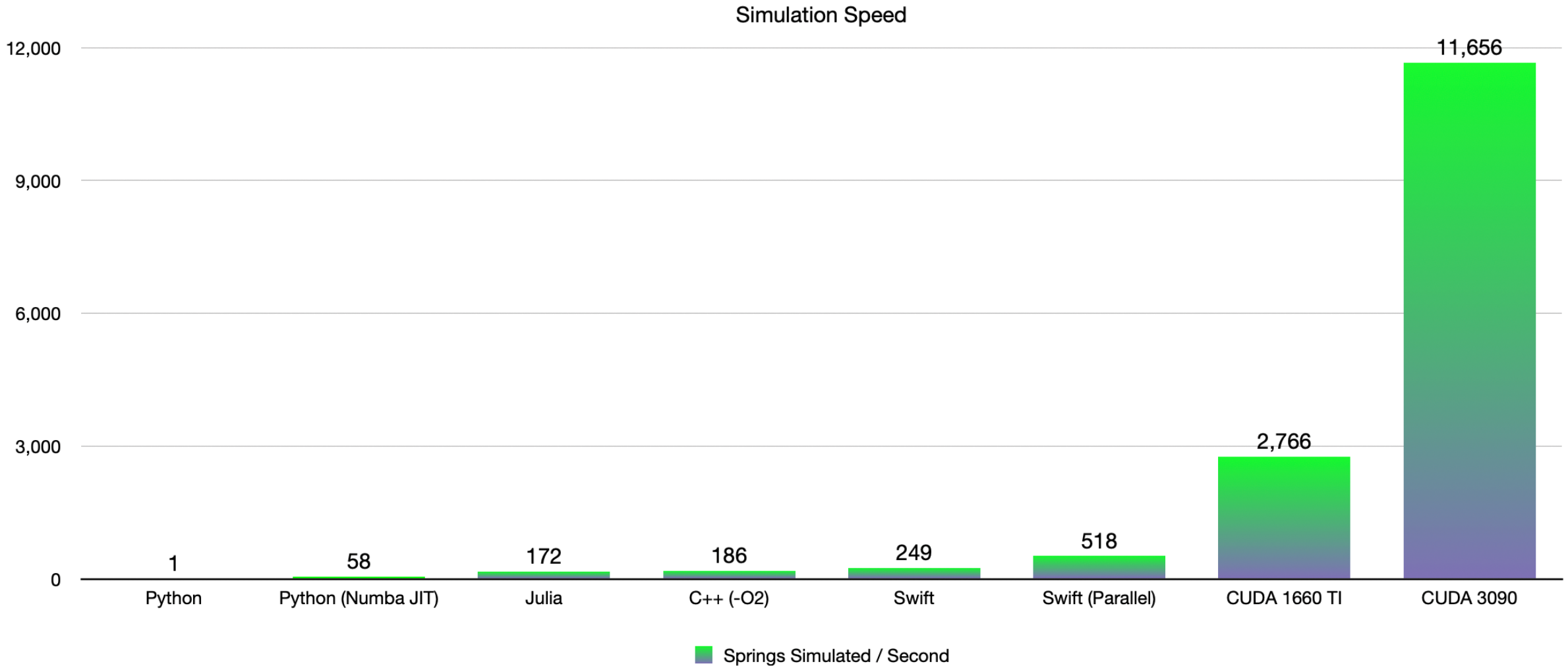

Cube

Evolve a robot with a fixed morphology

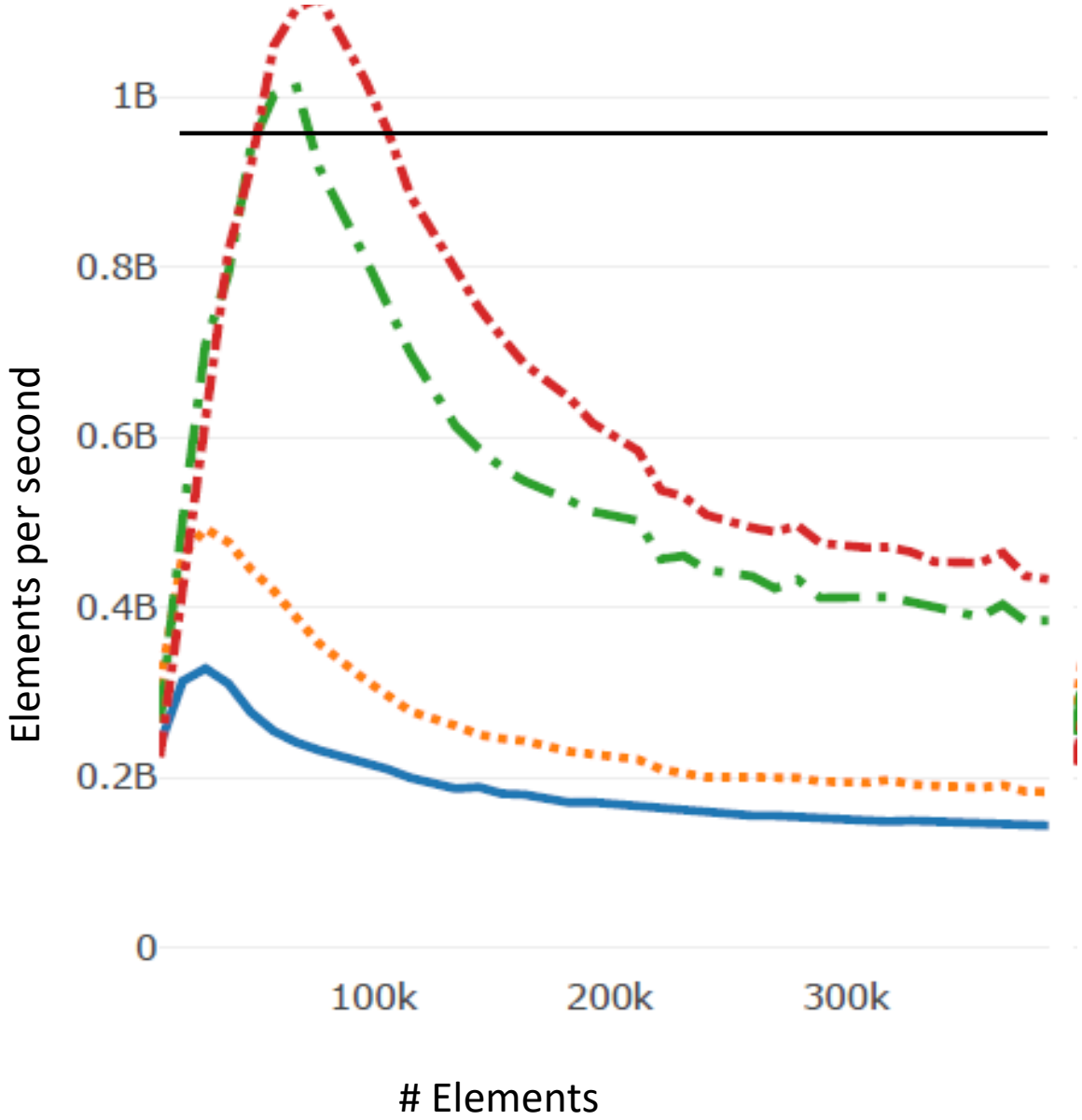
1. Cover page includes all information
2. General quality of the report (grammar, layout)
3. Video of fastest robot with at least three cycles shown
4. Video of fastest robot bouncing on the ground
5. Nice rendering of the robot (bars, spheres, ground plane, shaded faces)
6. Multiple robots showed in a single video
7. Description of all simulation parameters
8. Description of all robot parameters
9. Description of all evolutionary parameters
10. Learning curve
11. Dot chart
12. Diversity chart
13. Discussion of what works and did not work
14. Performance (speed of robot) in robot maximum diameter per cycle.
15. Innovative robot shown
16. Alternative representations tried
17. Post video of robot on piazza (provide screenshot and link)


Simulation Speed
8,000,000,000
6,000,000,000
4,000,000,000
2,000,000,000
0
677,144
39,465,507
116,171,951
126,251,853
168,443,053
350,435,434
1,873,199,203
7,892,537,835
Python
Python (Numba JIT)
Julia
C++ (-O2)
Swift
Swift (Parallel)
CUDA 1660 TI
CUDA 3090
Springs Simulated / Second

Max Segan


Simulation Speed
12,000
9,000
6,000
3,000
0
1
58
172
186
249
518
2,766
11,656
Python
Python (Numba JIT)
Julia
C++ (-O2)
Swift
Swift (Parallel)
CUDA 1660 TI
CUDA 3090
Springs Simulated / Second

Max


1B
0.8B
0.6B
0.4B
0.2B
0
Elements per second
100k
200k
300k
Elements

GPU- Accelerated Physics Simulations with CUDA

- GPU (CUDA) accelerated physics simulation sandbox capable of running complex spring/mass simulations in a fraction of the time of traditional CPU-based software while the CPU continues to perform optimizations.
- Capable of simulating 100,000 springs at about 4000 frames per second, or about 400,000,000 spring updates per second

```
int main()  {

    Mass * m1 = sim.createMass(Vec(1, 0, 0)); // create two masses at positions (1, 0, 0), (-1, 0, 0)
    Mass * m2 = sim.createMass(Vec(-1, 0, 0));
    Spring * s1 = sim.createSpring(m1, m2); // connect them with springs

    Cube * c1 = sim.createCube(Vec(0, 0, 3), 1); // create fully-connected cube with side length 1 and center (0, 0, 3)

    Plane * p = sim.createPlane(Vec(0, 0, 1), 0); // constraint plane z = 0 (constrains object above xy plane)


    sim.setTimeStep(0.0001) // increment simulation in 0.0001 second intervals
    sim.setBreakpoint(5.0); // ends simulation at 5 seconds
    sim.run( ); // run simulation

    // perform other optimizations on the CPU while the simulation continues to run, like topology optimization, robotics, etc.


    return 0;
}
```

Titan

Interested in CUDA library? https://www.creativemachineslab.com/titan-library.html

Contact Sofia Wyetzner sofiaw@stanford.edu or Boxi Xia bx2150@columbia.edu

Evolving Motion

- For each spring set k and L_0 = a+b*sin(ωt+c)
  - ω is global frequency. *a,b,c,k* are spring parameters (*k* is spring coef)
  - Cycle period is $2\pi/\omega$
- Evolve locomotion
  - Fitness: net distance travelled by center of mass
- Representation
  - Direct encoding: Chromosome with *a,b,c,k* for each spring
  - Indirect encoding: Chromosome specifies how a,b,c,k are determined

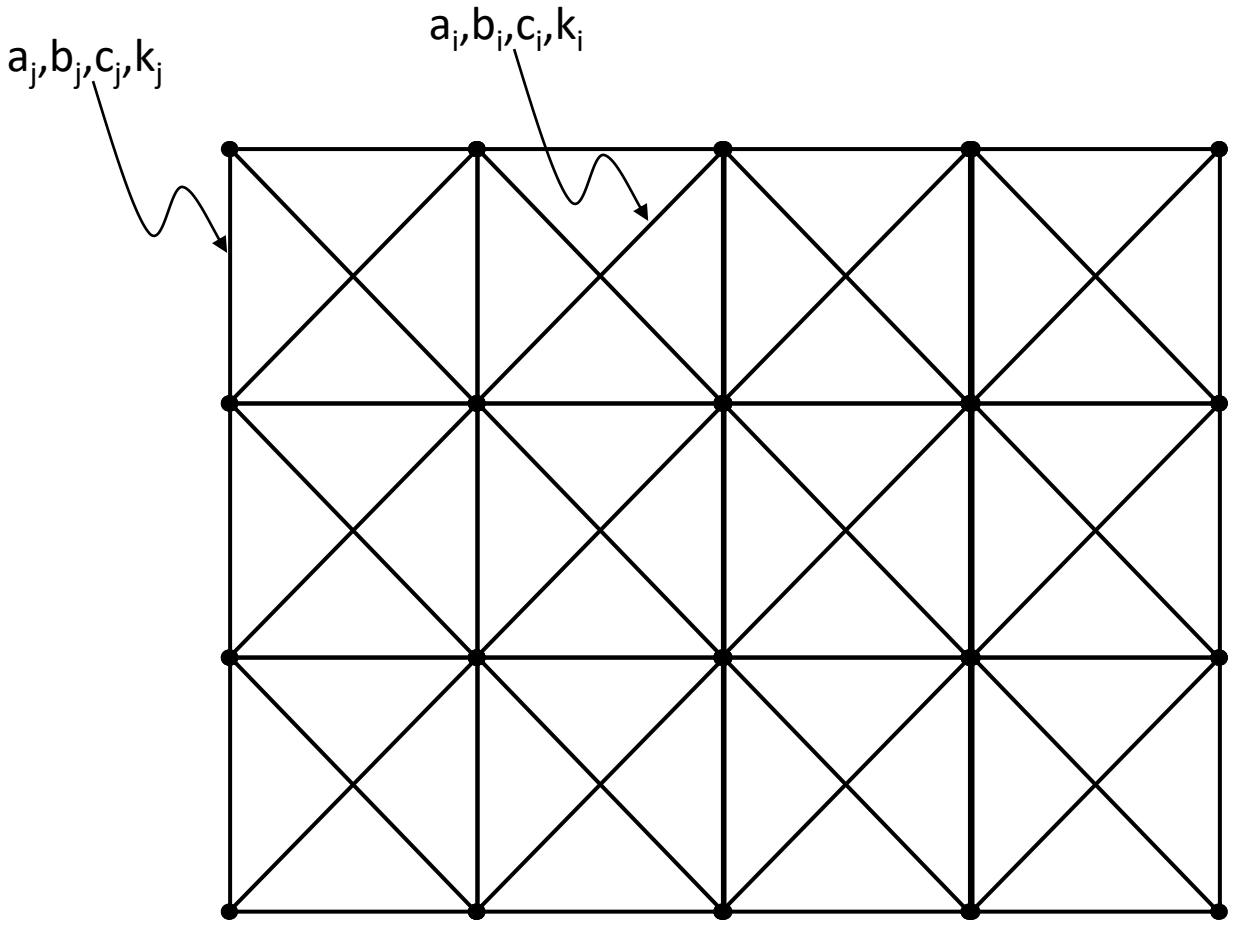
Direct encoding

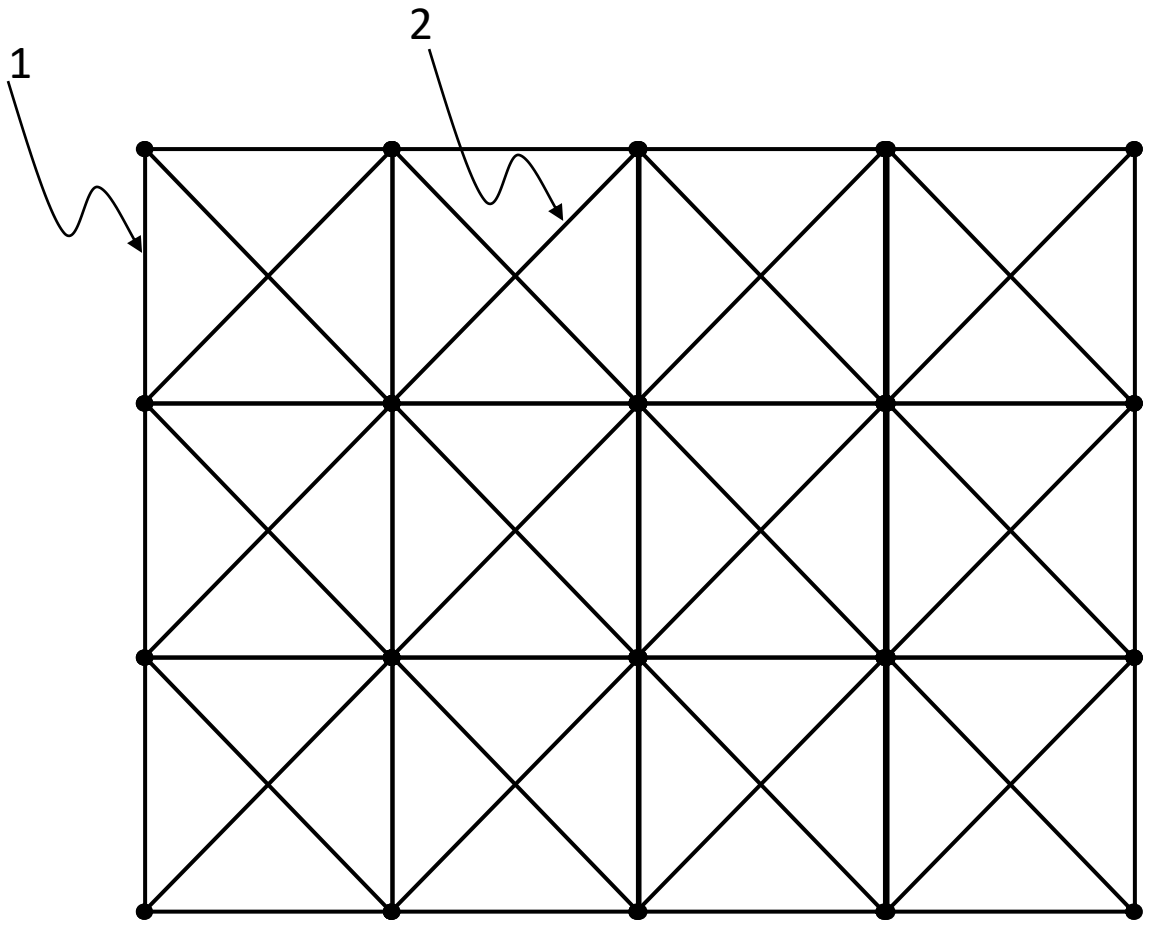
a_1, b_1, c_1, k_1
a_2, b_2, c_2, k_2
…
a_n, b_n, c_n, k_n

n = number of springs

Fitness? Mutation? Crossover?

$L_0 = a+b*\sin(\omega t+c)$

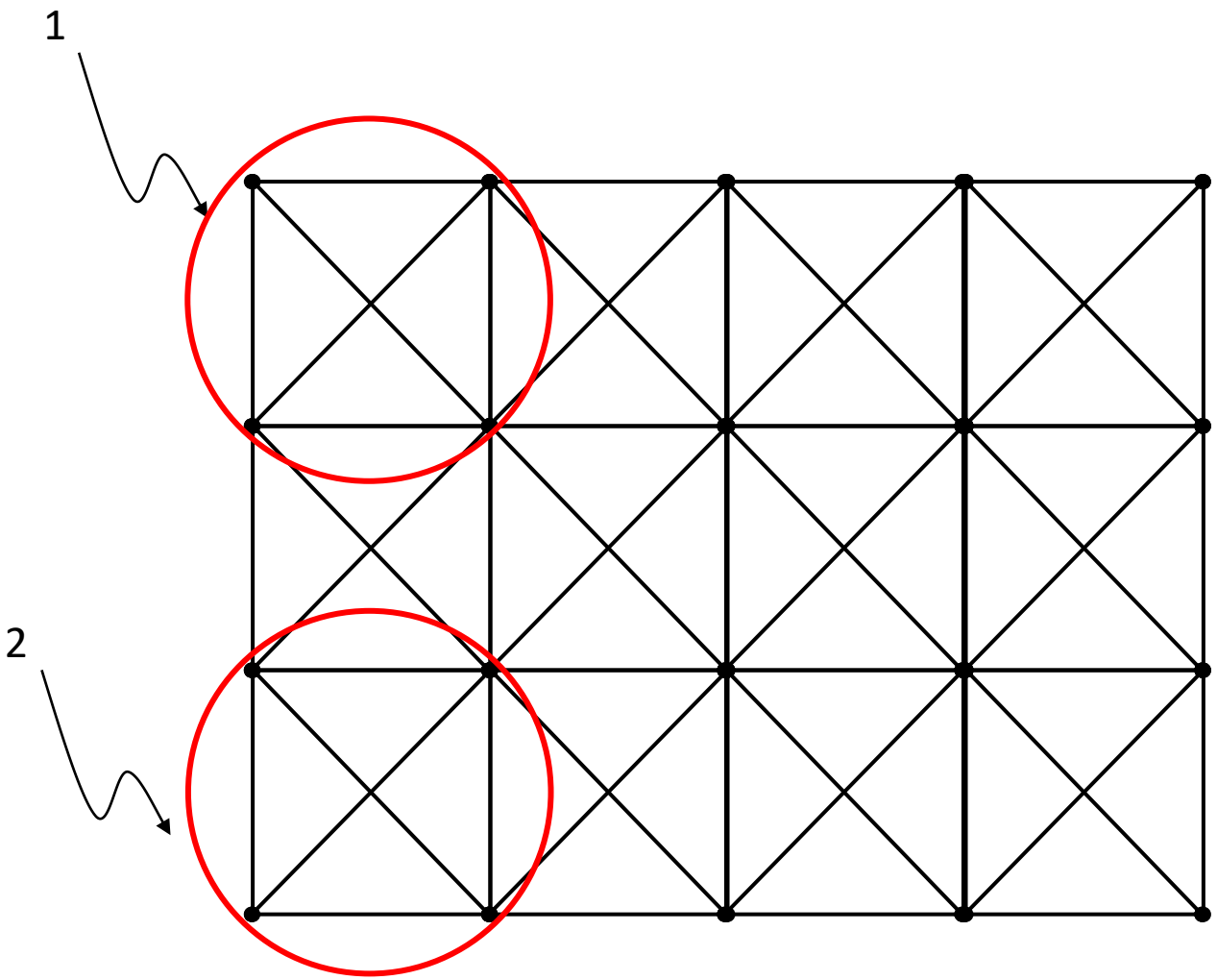




$L_0 = a+b*\sin(\omega t+c)$

1. k=1000 b=c=0
2. K=20,000 b=c=0
3. K=5000 b=0.25 c=0
4. K=5000 b=0.25 c=π

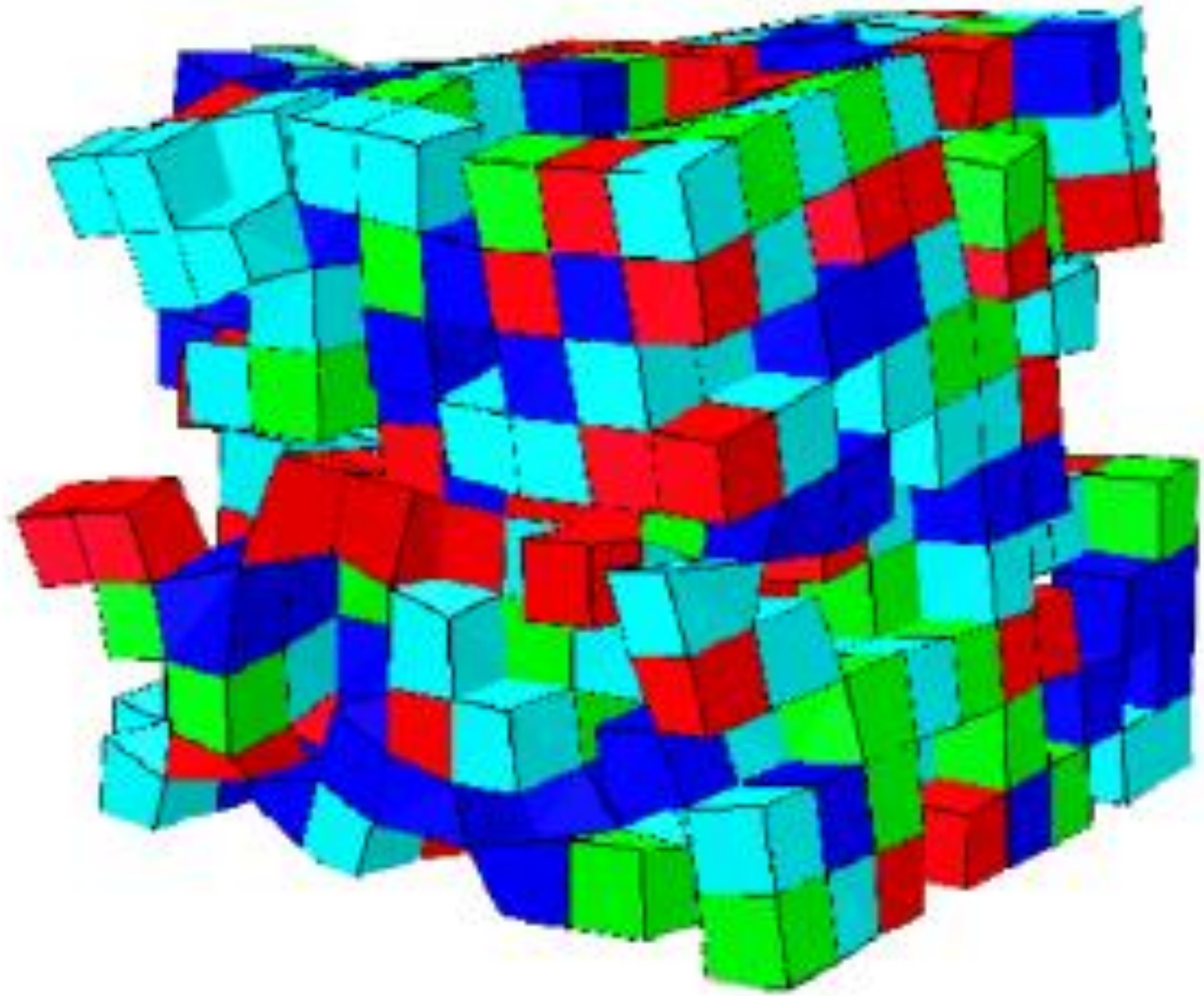
Cycle period: $T=2\pi/\omega$



$L_0 = L_{0\_int}*[1+b*\sin(wt+c)]$

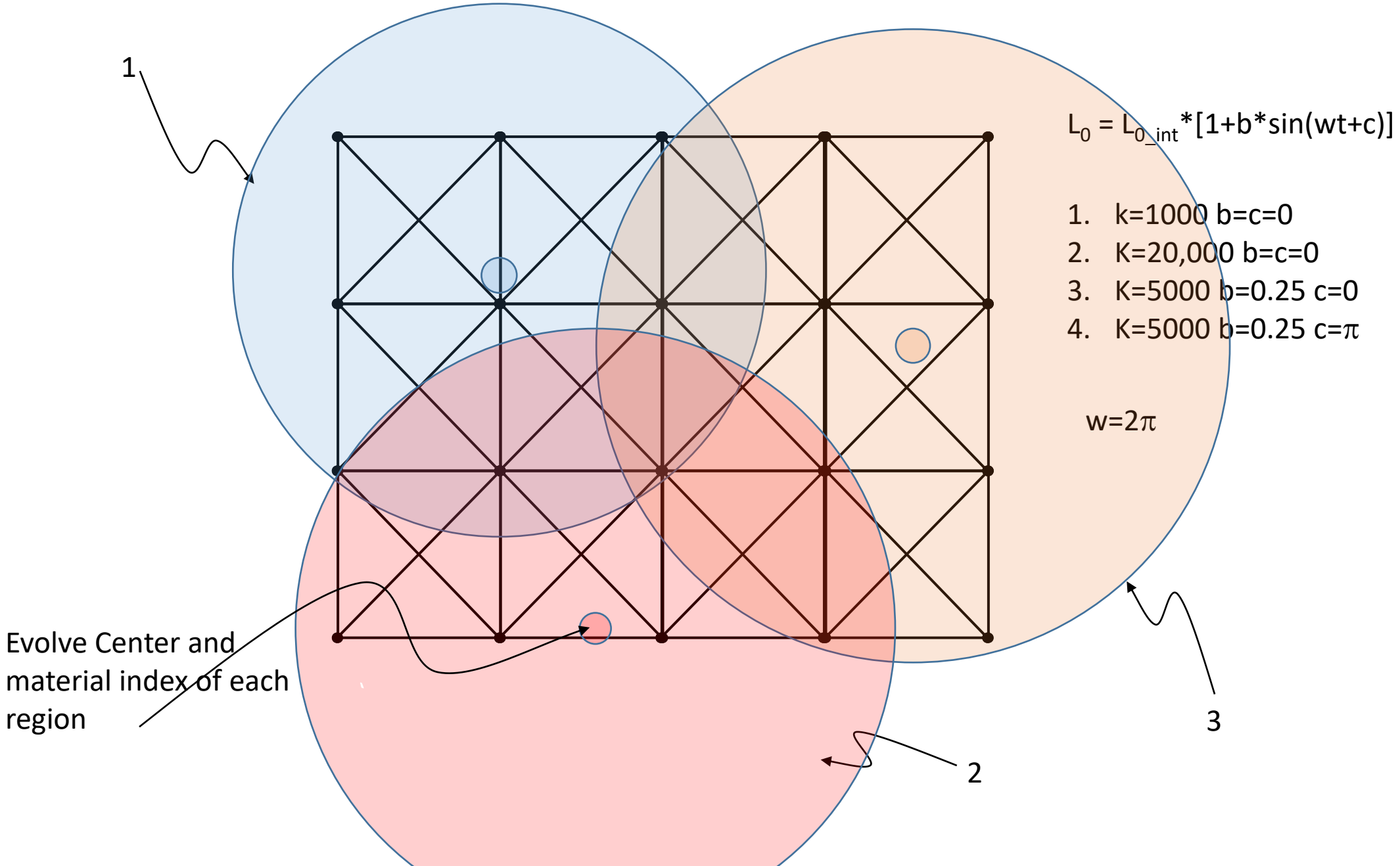
1. k=1000 b=c=0
2. K=20,000 b=c=0
3. K=5000 b=0.25 c=0
4. K=5000 b=0.25 c=π

w=2π

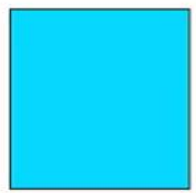


Breakout

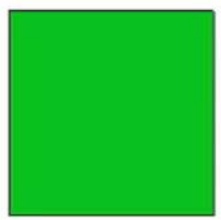
- Suggest a representation that would indirectly encode spring parameters for a large robot


1
$L_0 = L_{0\_int}*[1+b*\sin(wt+c)]$
1. k=1000 b=c=0
2. K=20,000 b=c=0
3. K=5000 b=0.25 c=0
4. K=5000 b=0.25 c=π
w=2π
Evolve Center and material index of each region
2
3

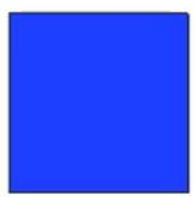
Muscle: contract then expand



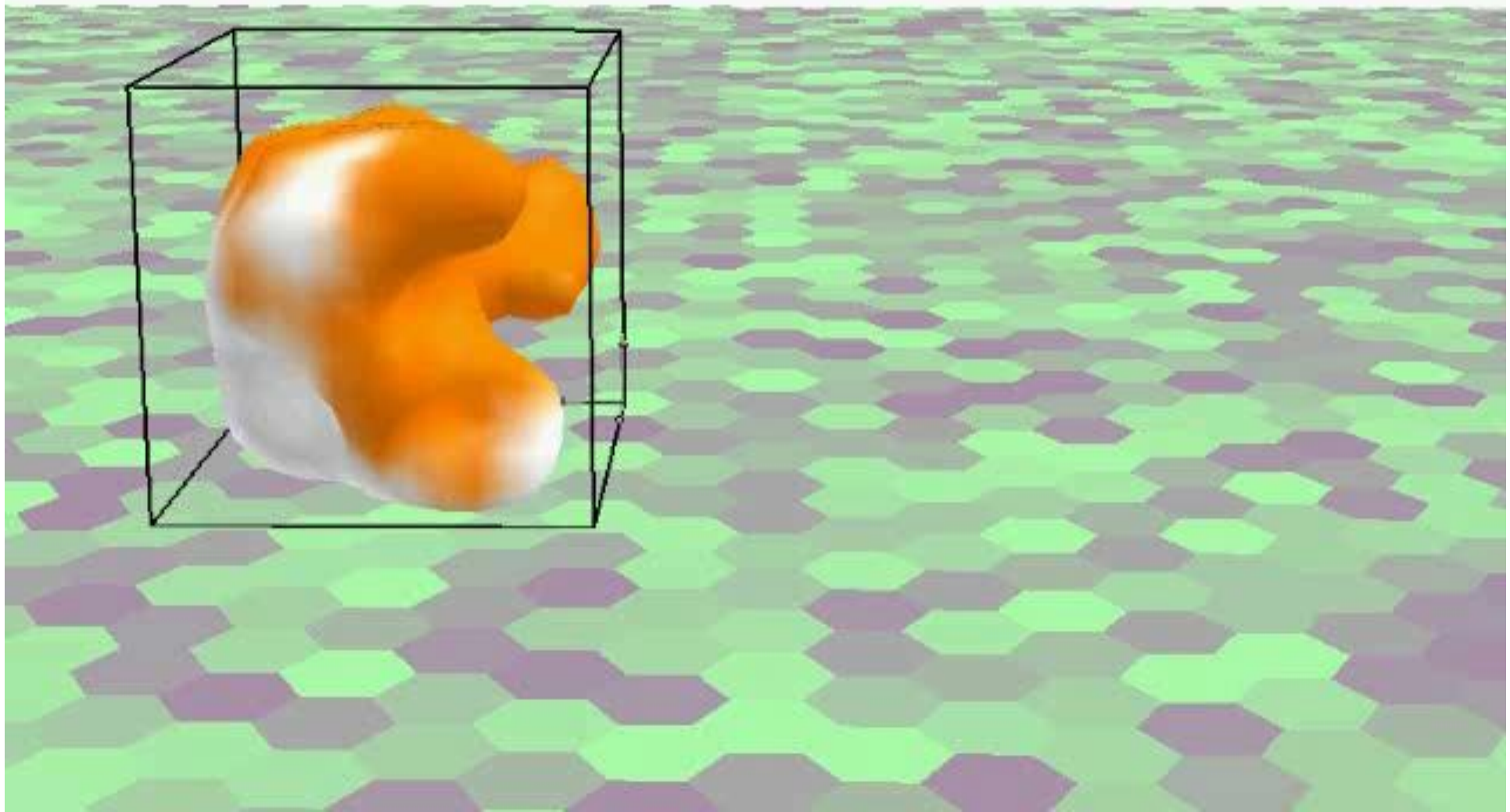
Tissue: soft support



Muscle2: expand then contract



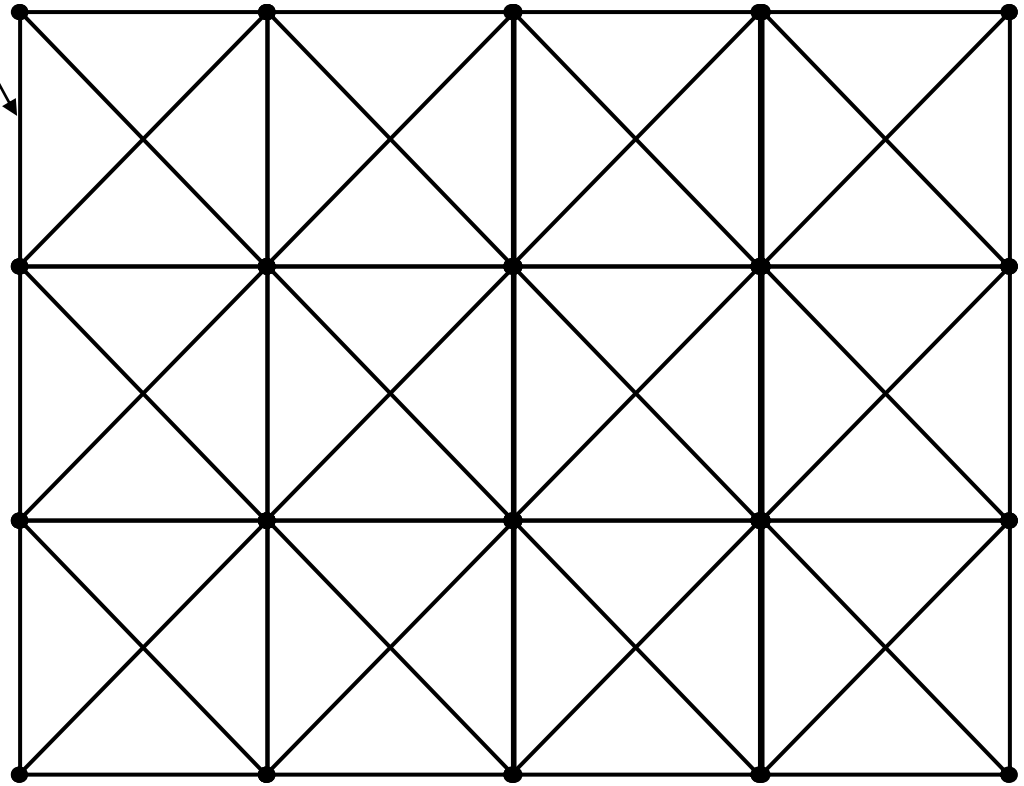
Bone: hard support



$L_0 = a+b*\sin(wt+c)$

$k=f_1(x,y,z)$
$b=f_2(x,y,z)$
$c=f_3(x,y,z)$

Evolve f_1, f_2, f_3



Flexible Muscle-Based Locomotion for Bipedal Creatures

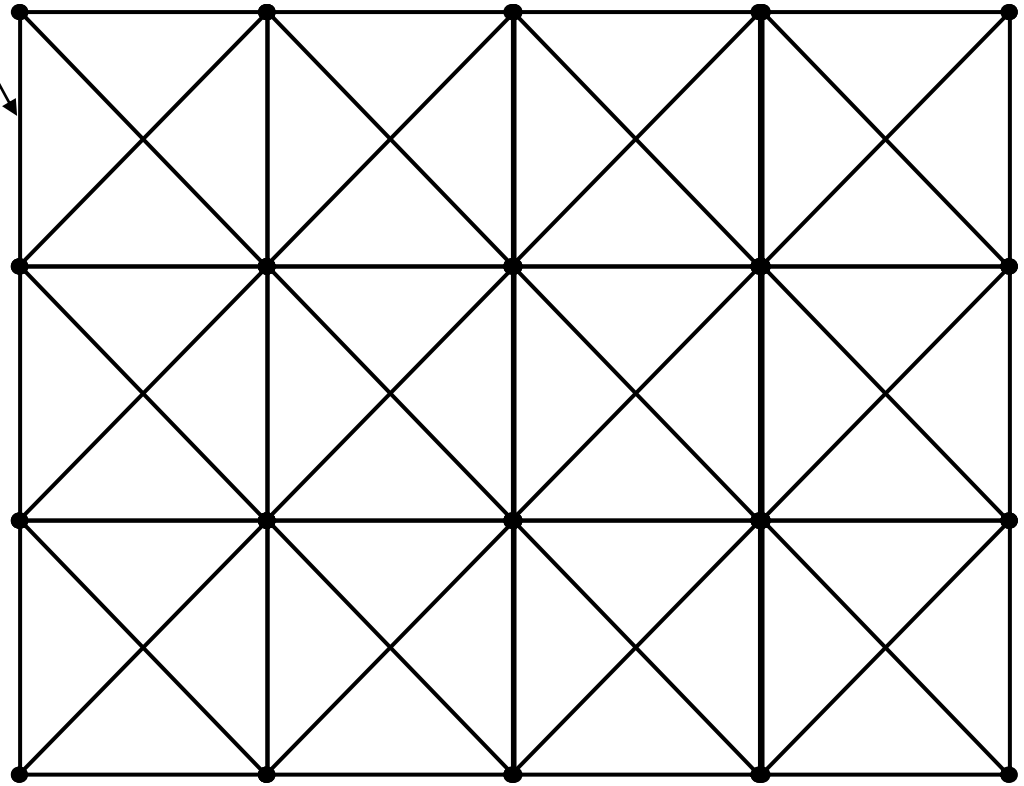
SIGGRAPH ASIA 2013

Thomas Geijtenbeek
Michiel van de Panne
Frank van der Stappen

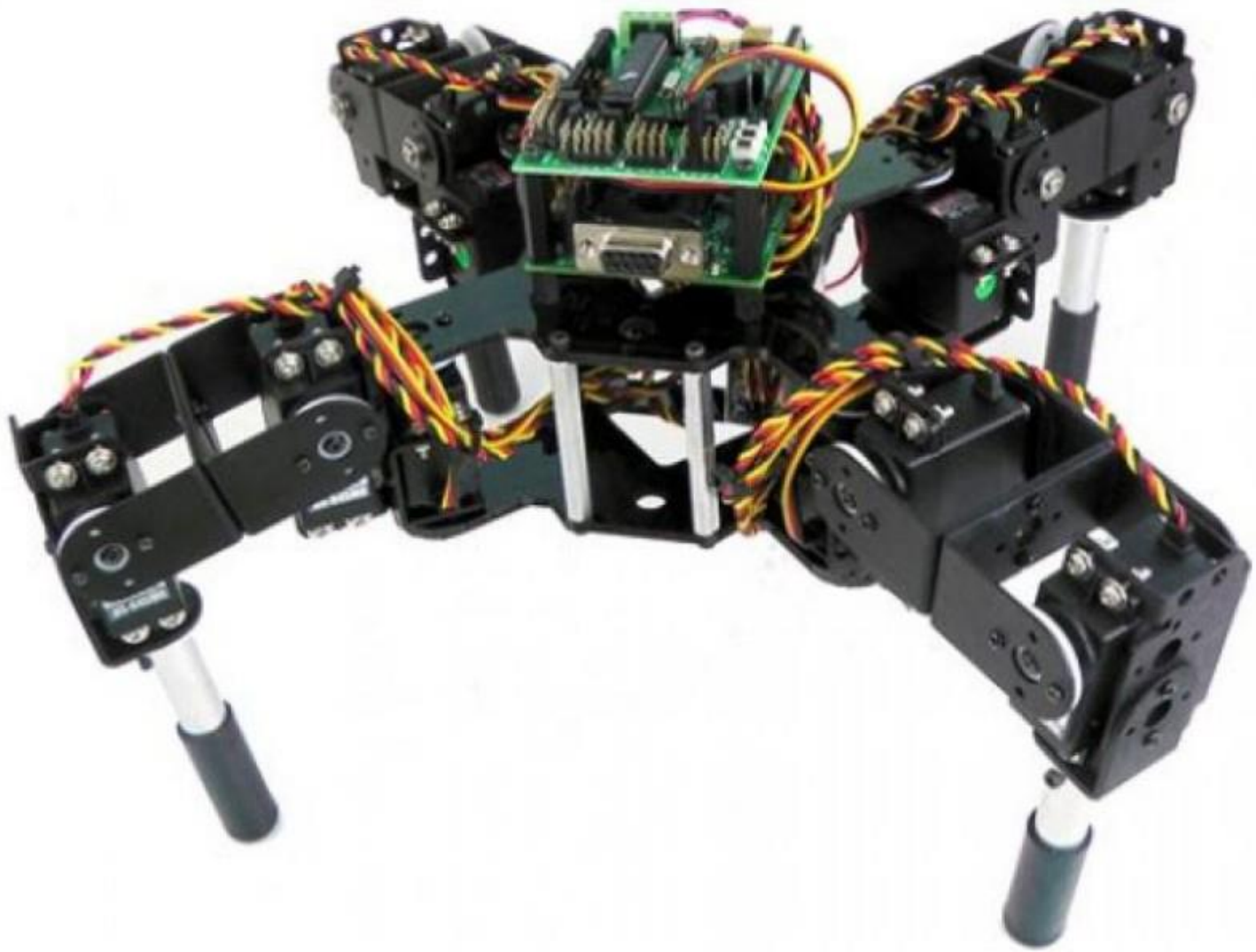
$L_0 = a + b*\sin(wt + c)$

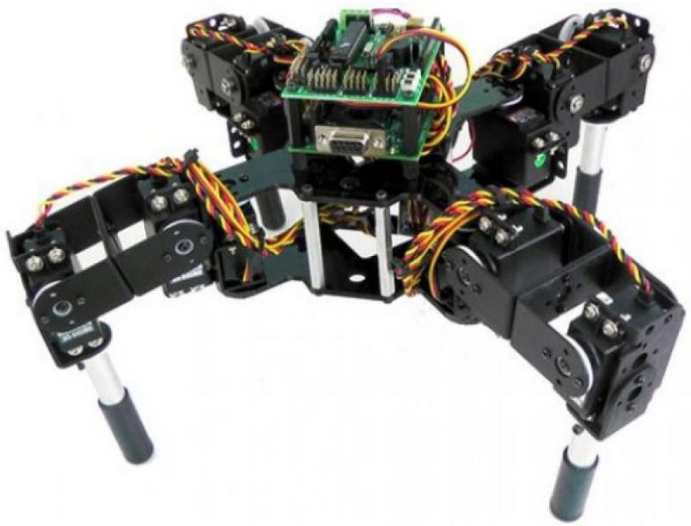
$L_0 = f(x,y,z,t)$

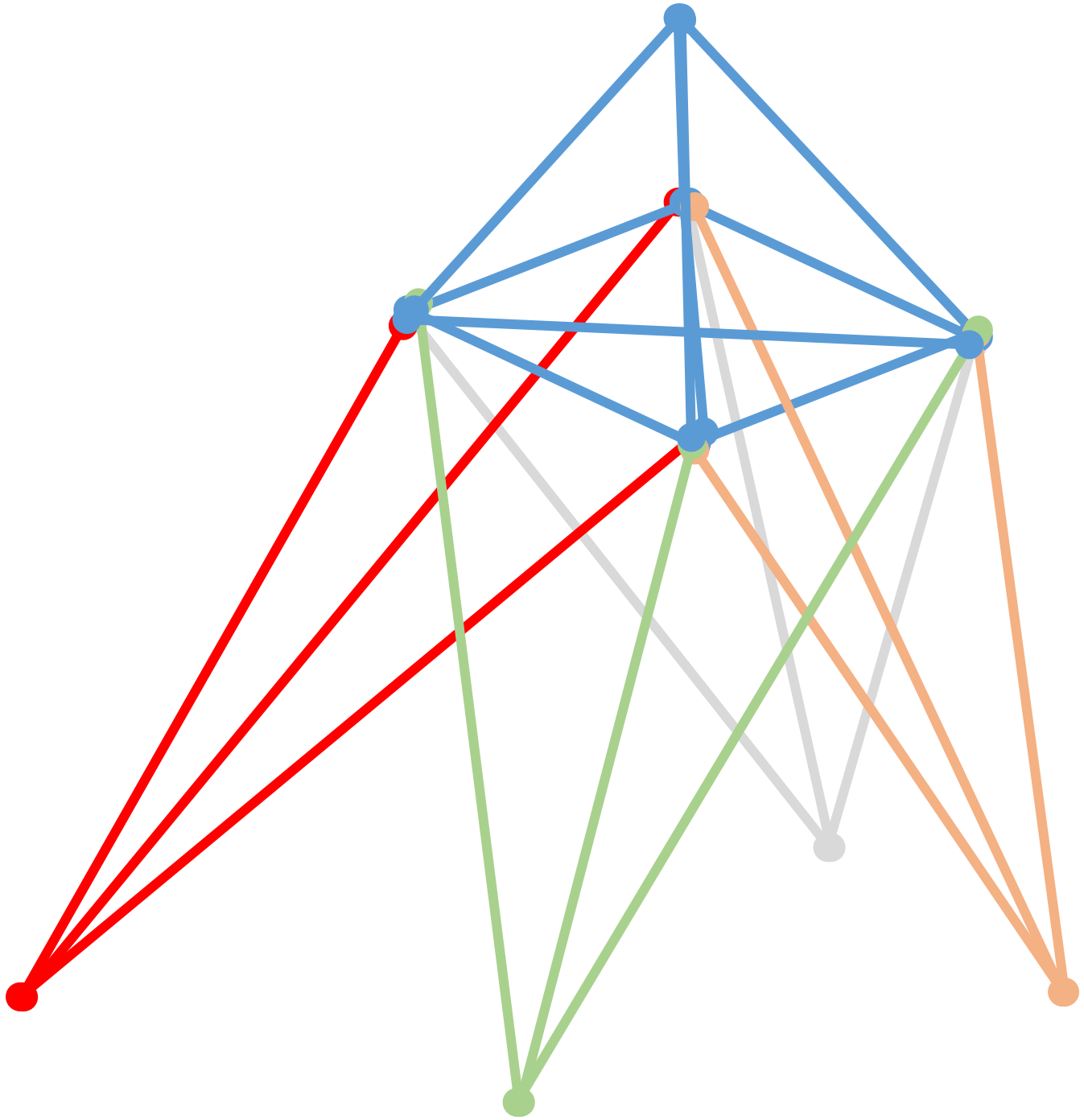
Evolve f

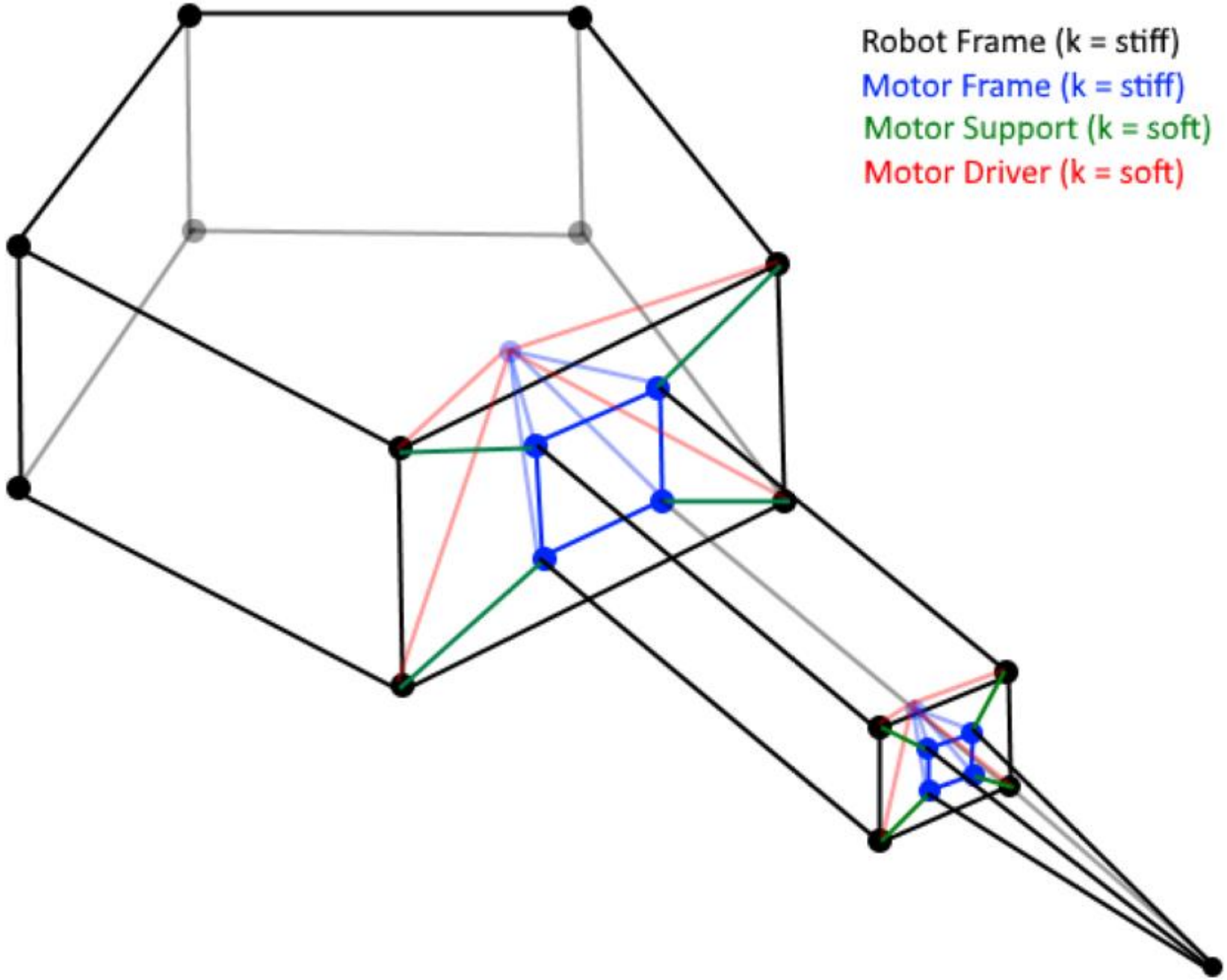


f(x,y,z,t) can be an analytical function or a neural network

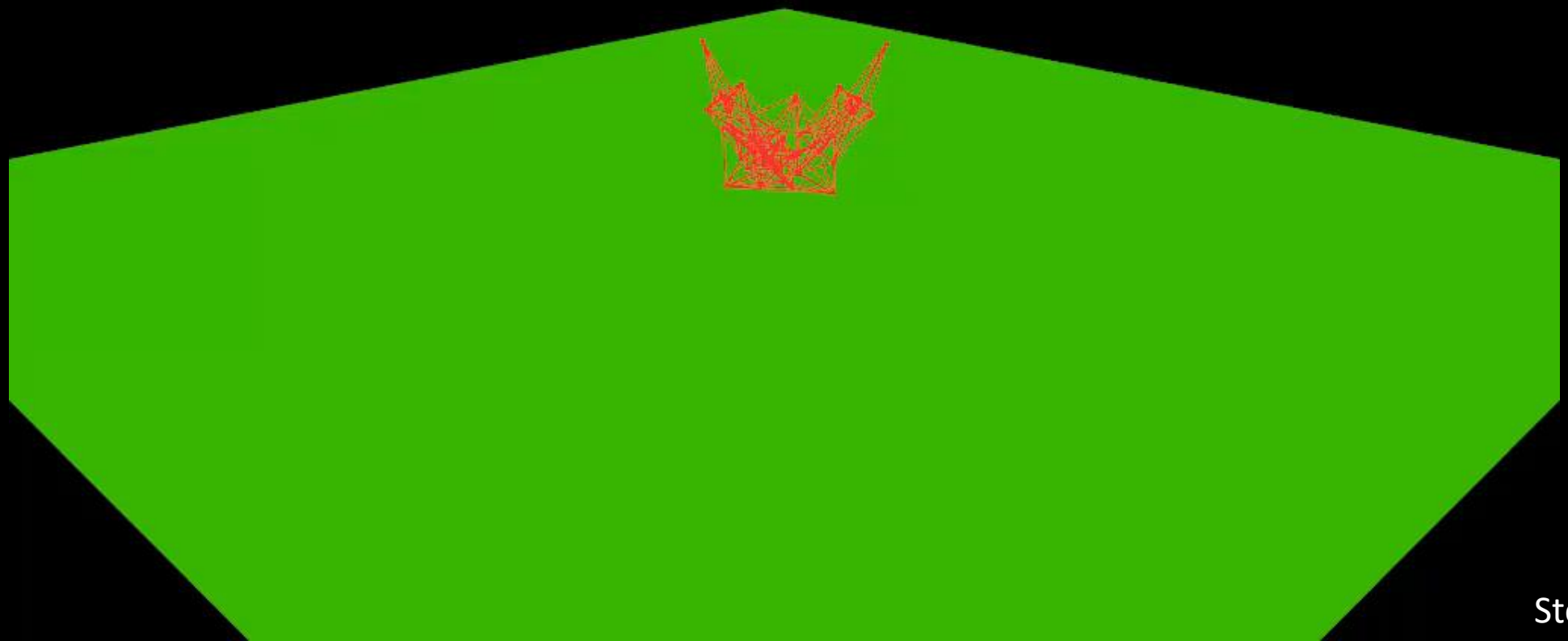




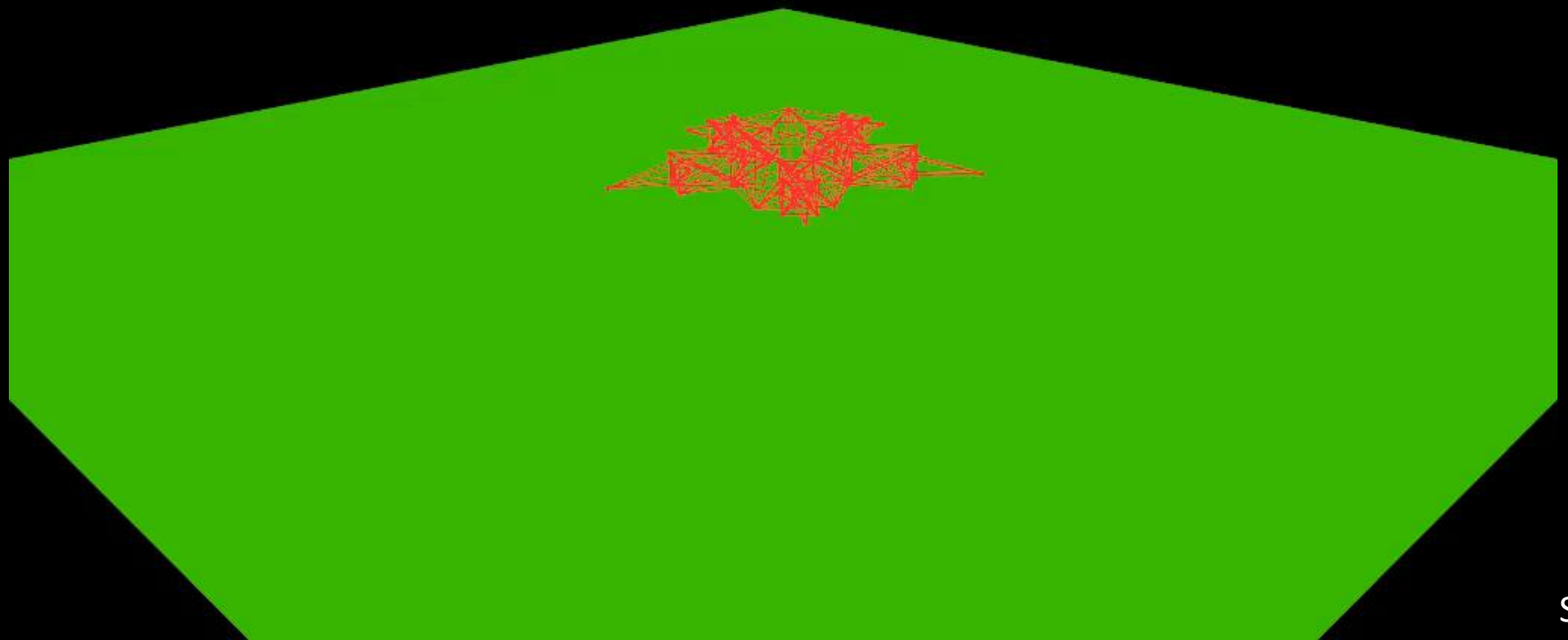




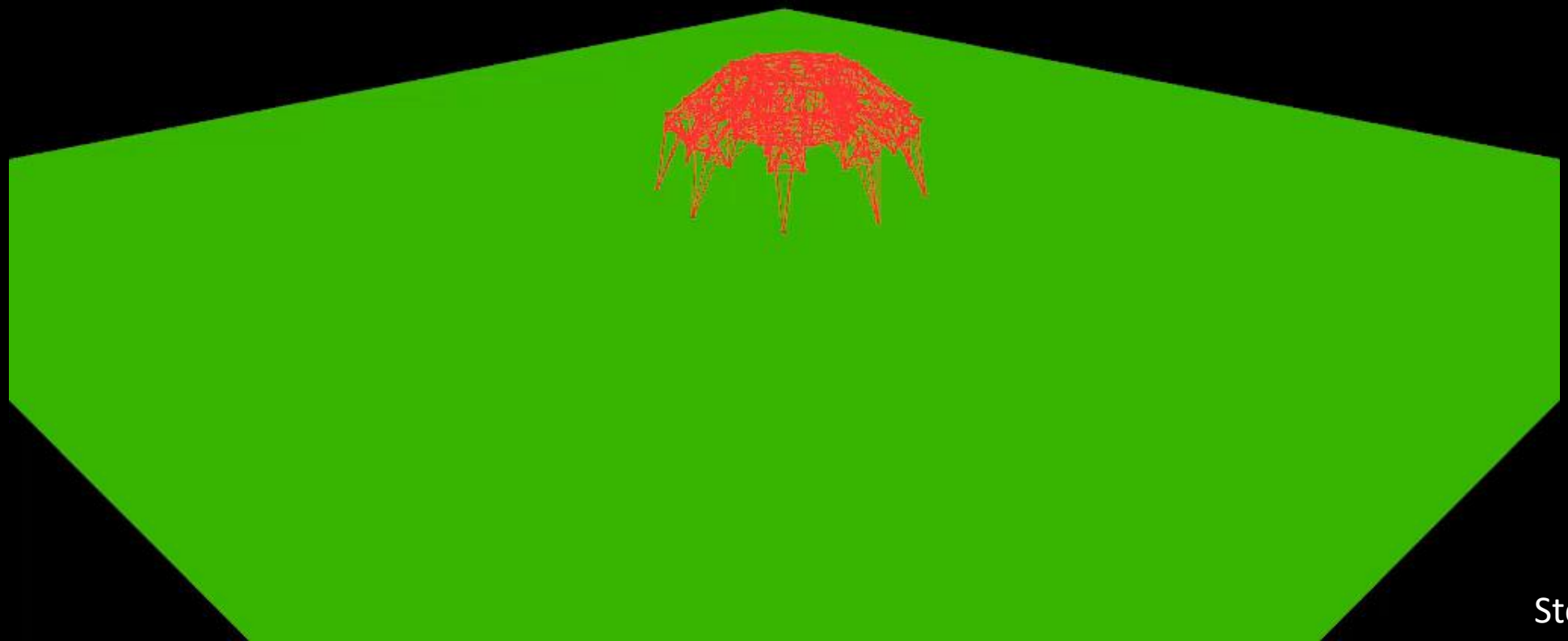
Steven Mazzola



Steven Mazzola



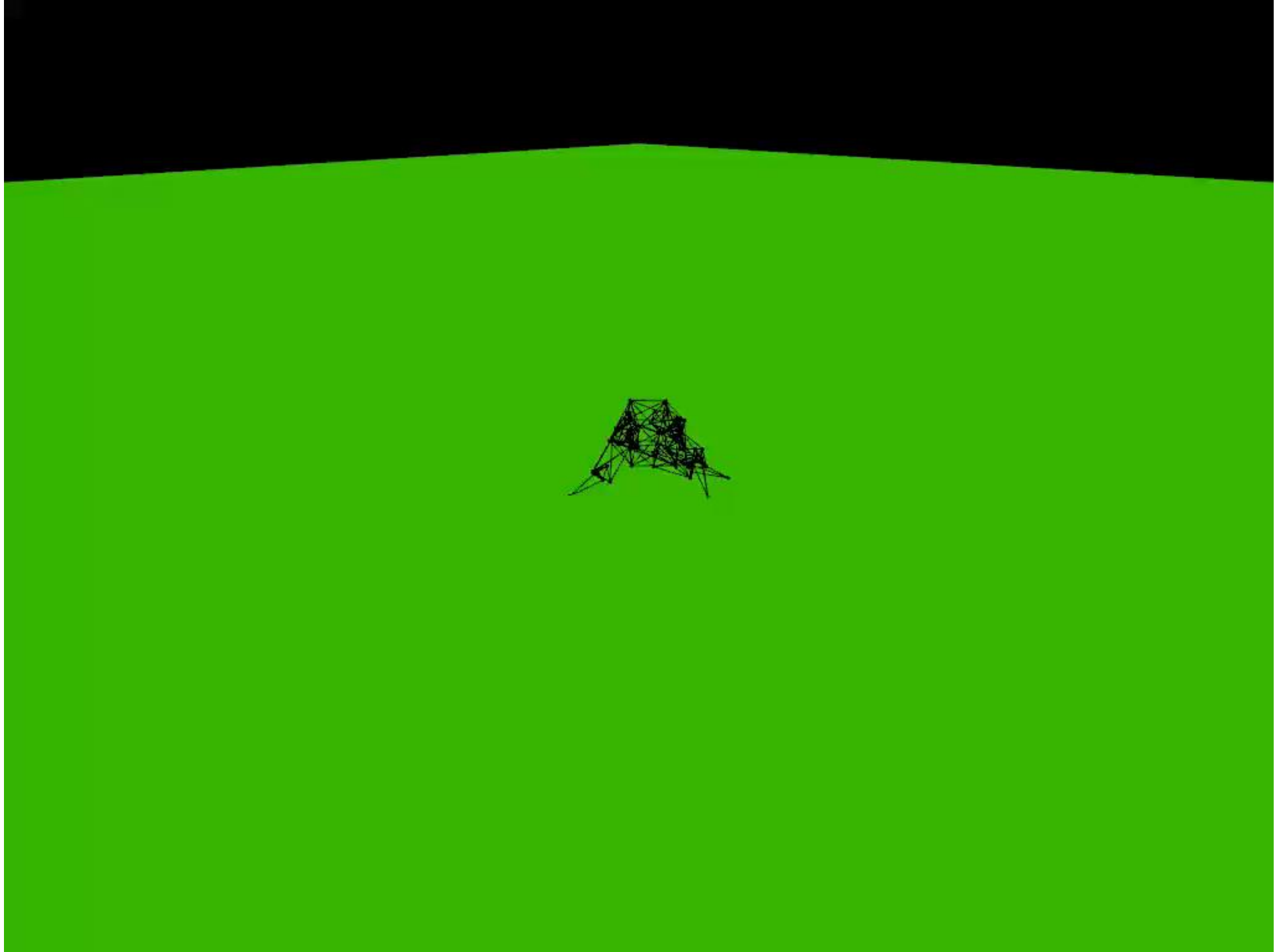
Steven Mazzola

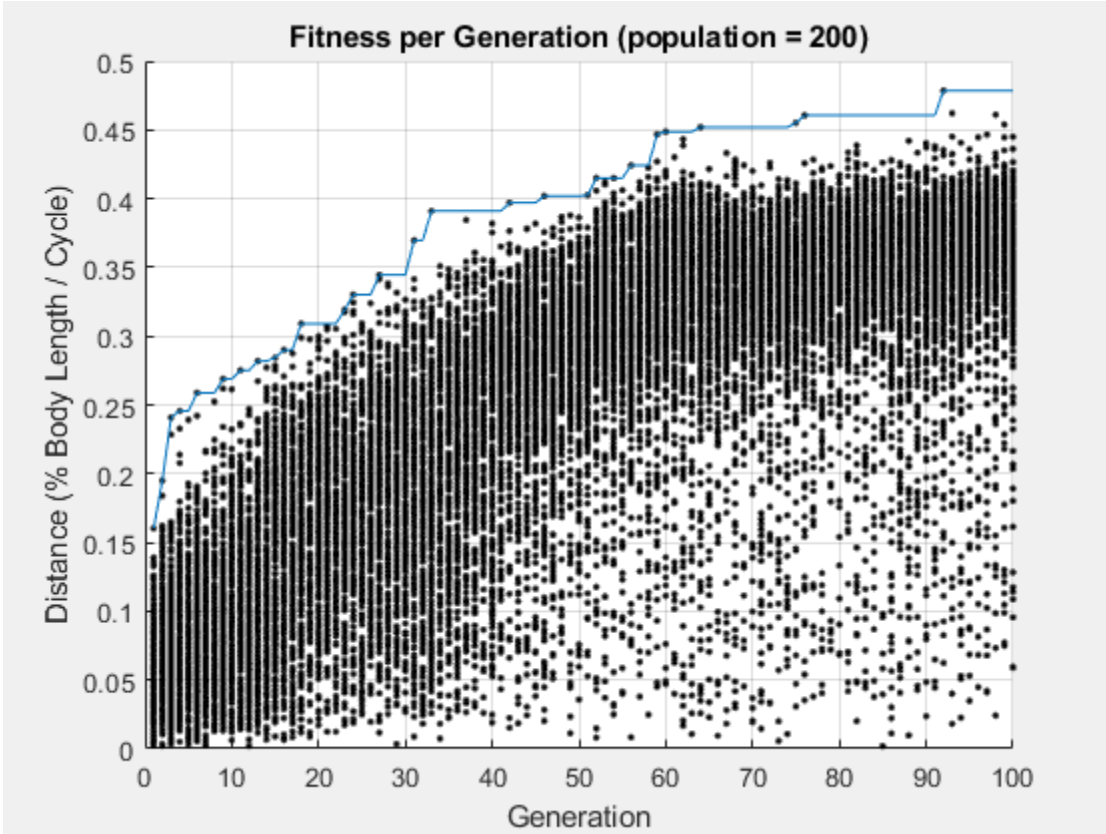


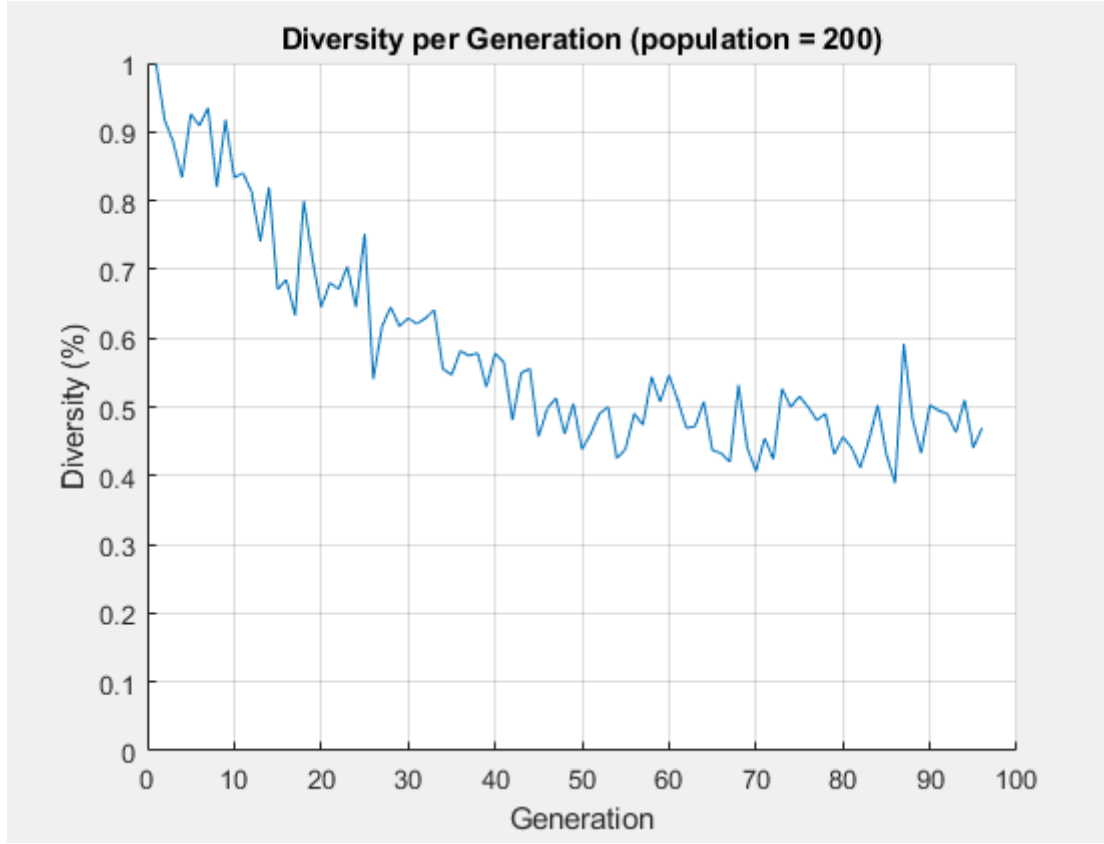
Steven Mazzola

300K Evaluations

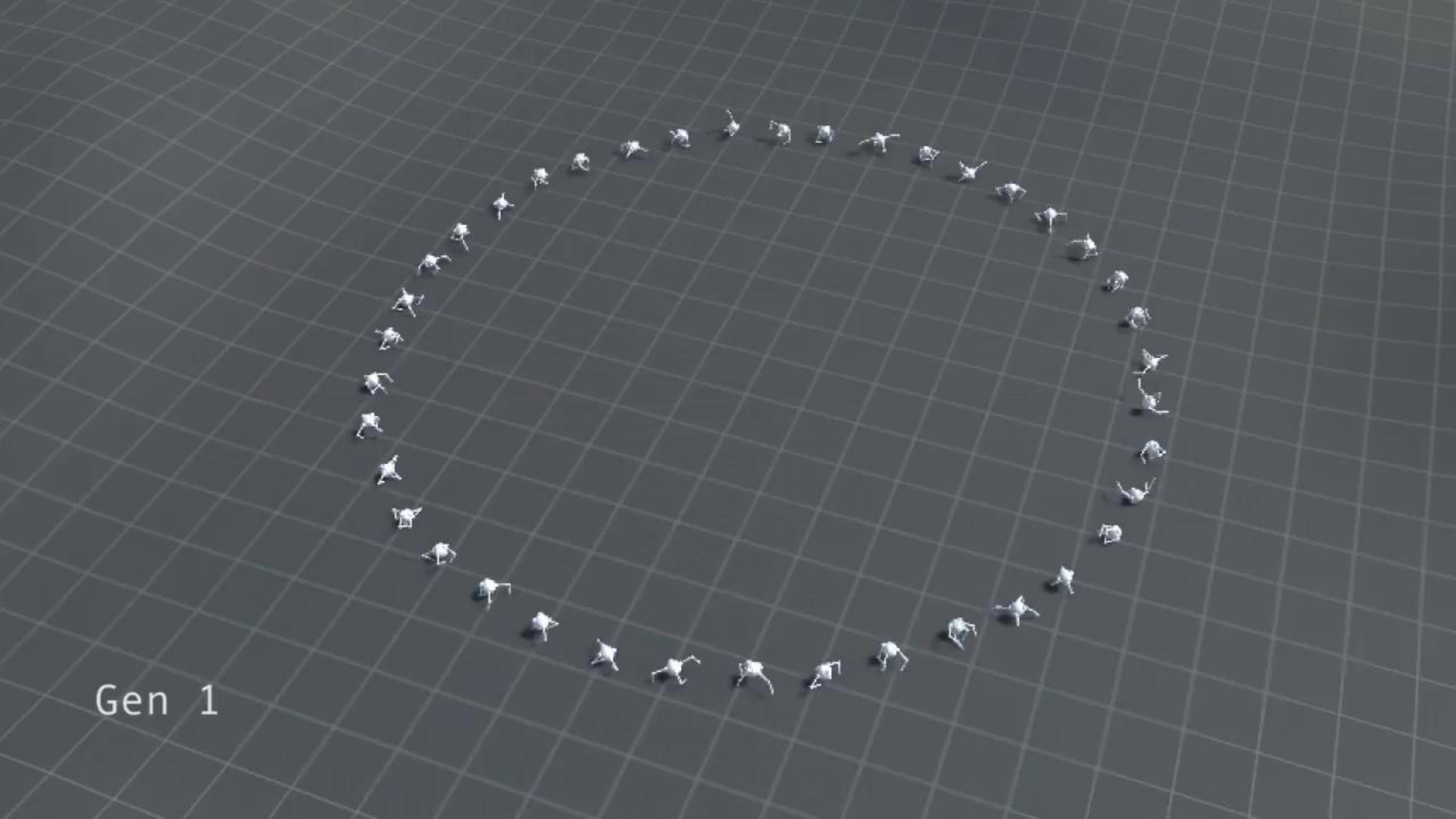
Steven Mazzola




Fitness per Generation (population = 200)
Distance (% Body Length / Cycle)
Generation
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
0.45
0.5
0
10
20
30
40
50
60
70
80
90
100


Diversity per Generation (population = 200)
Diversity (%)
Generation
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
0
10
20
30
40
50
60
70
80
90
100

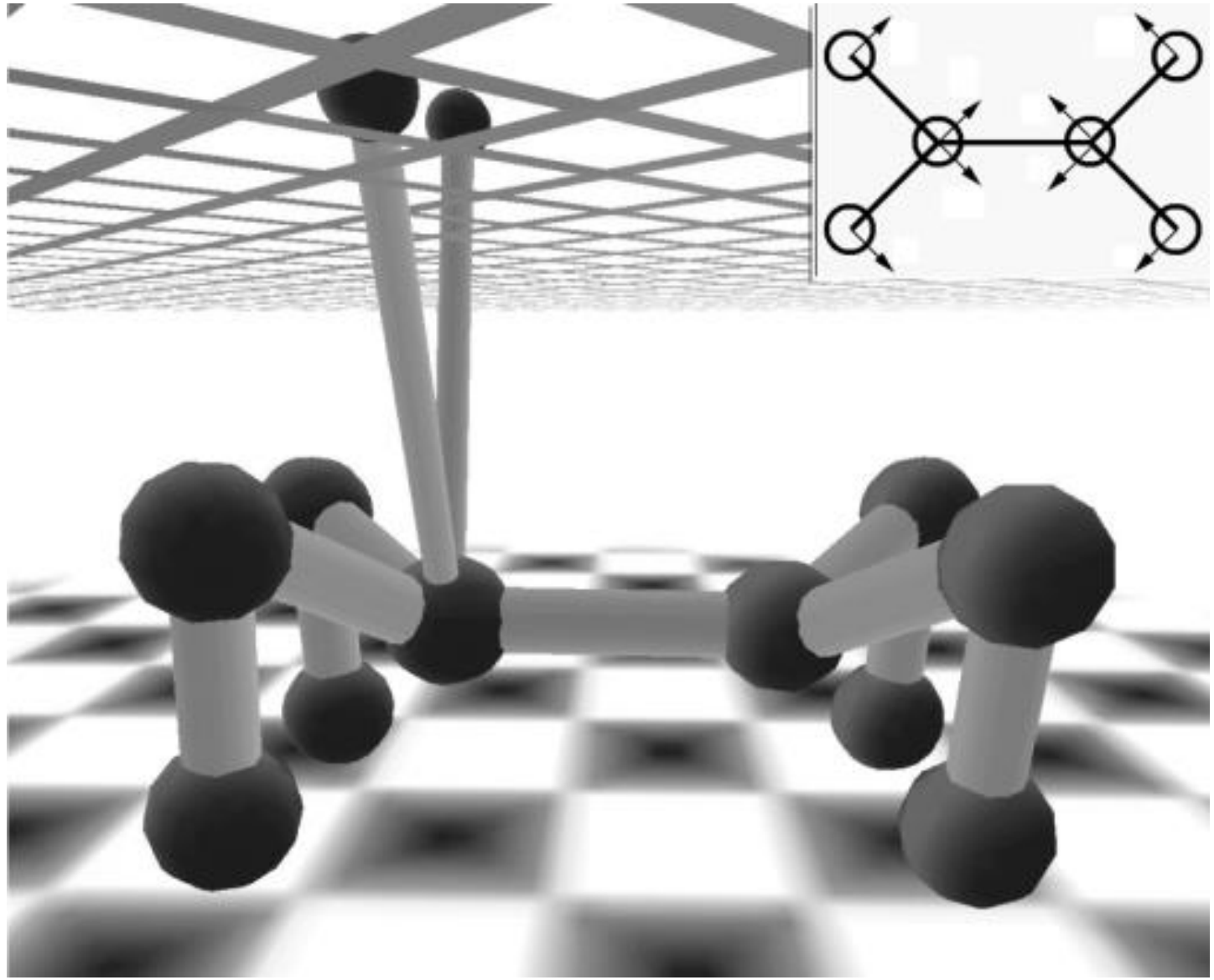
Many robots in one world

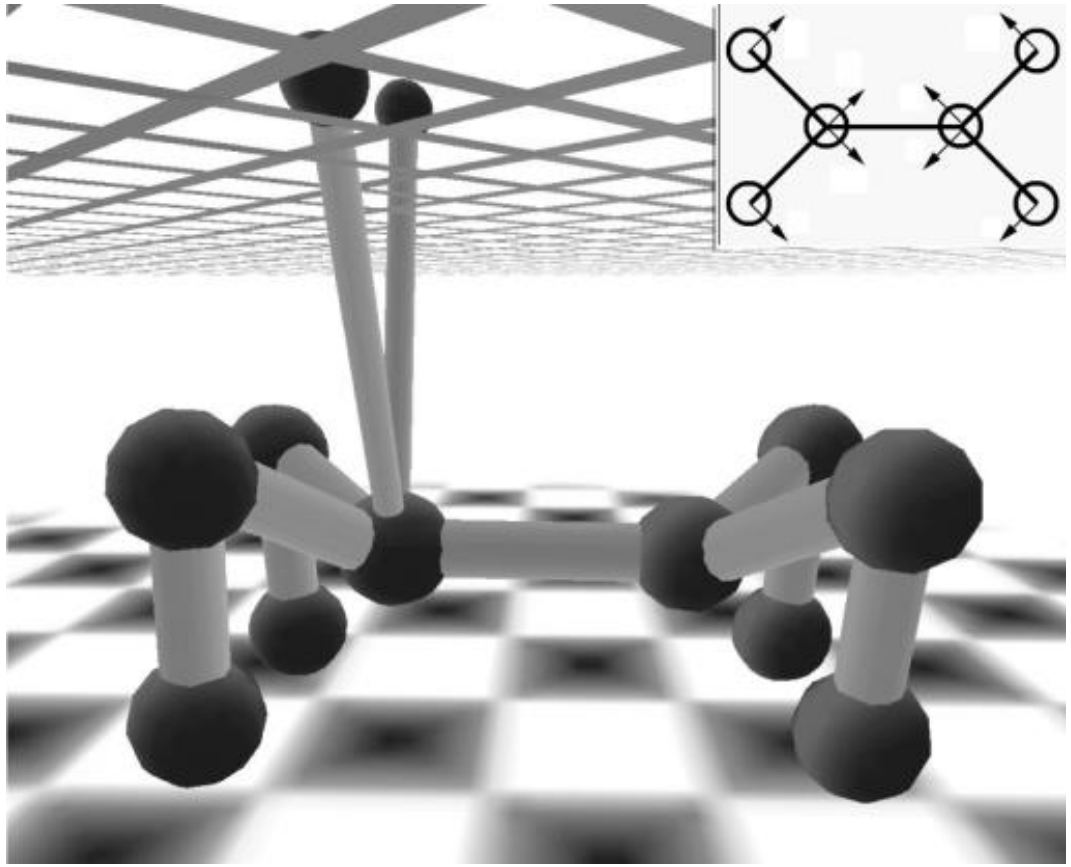

Gen 1

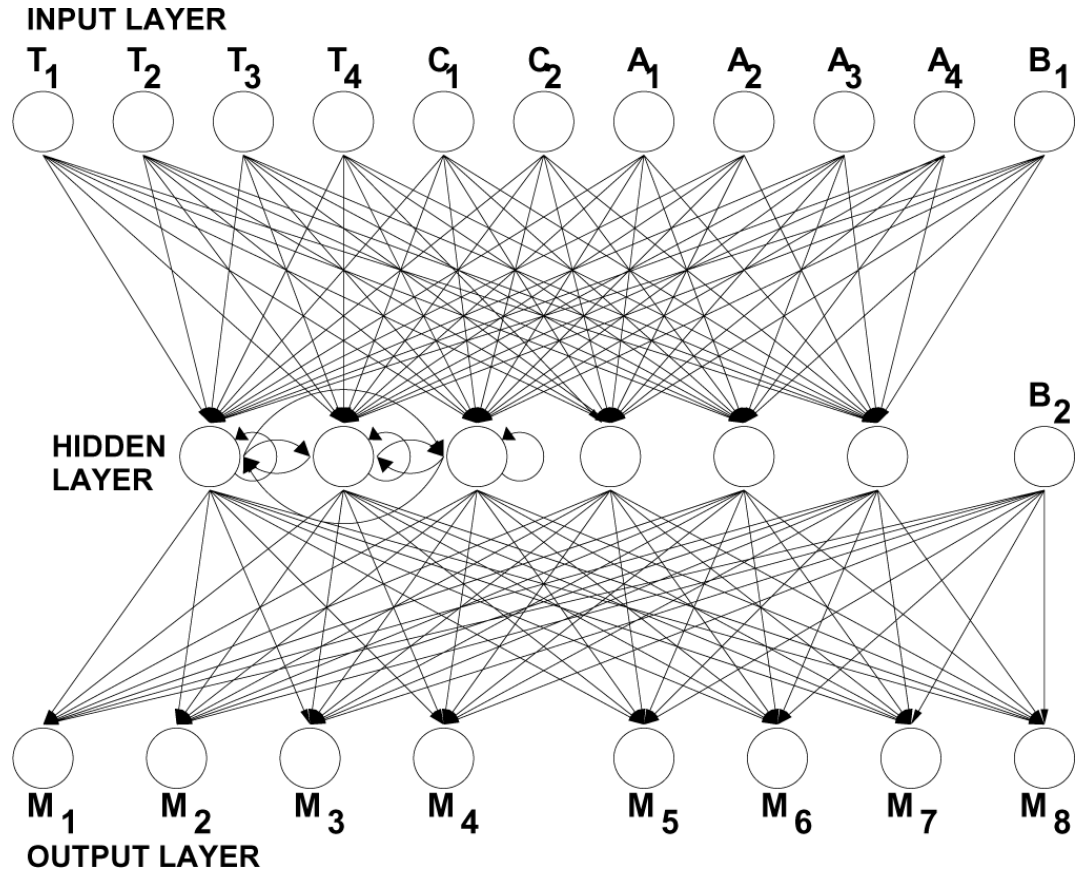
Huy Ha

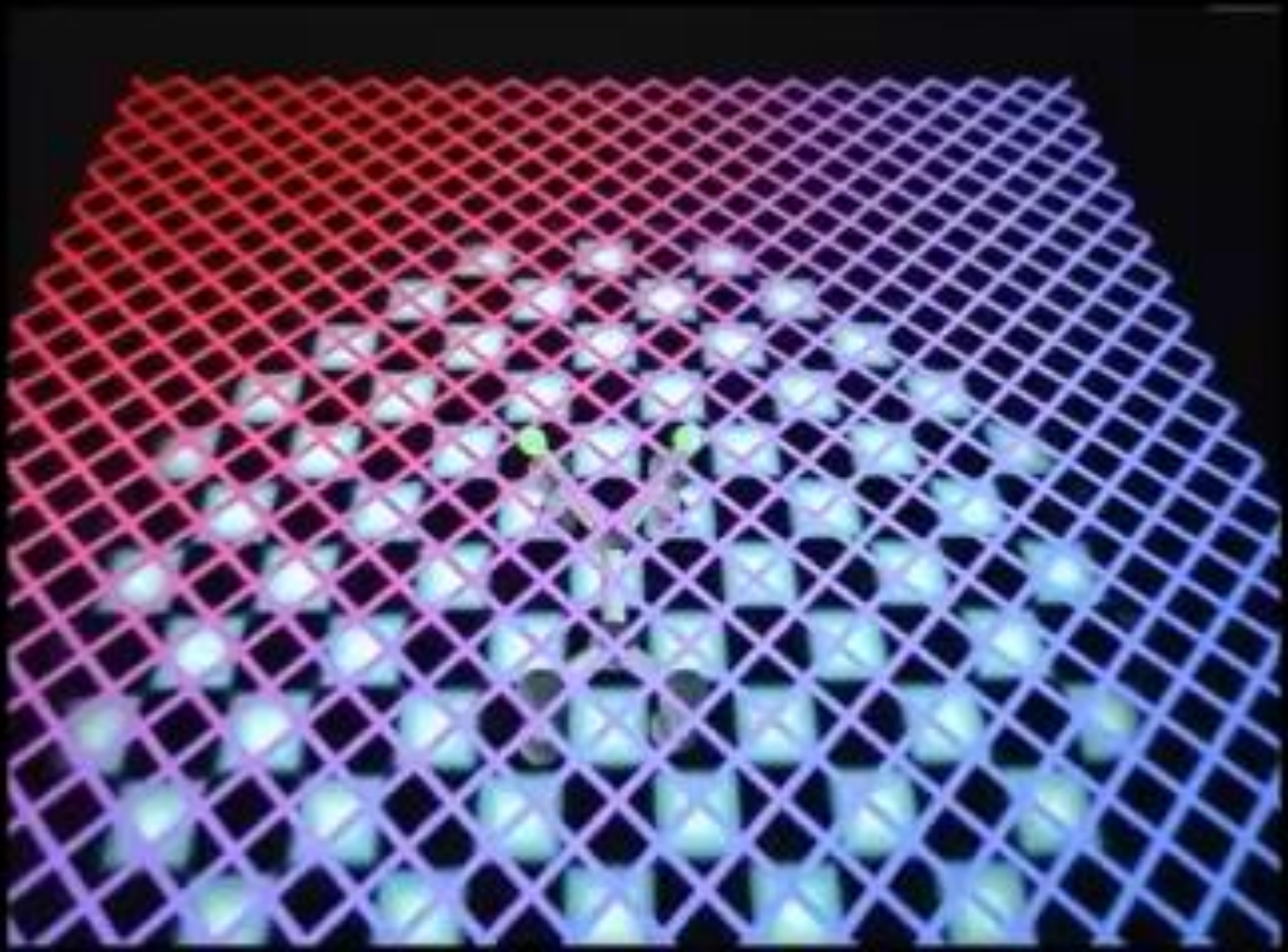
Incorporating Sensors

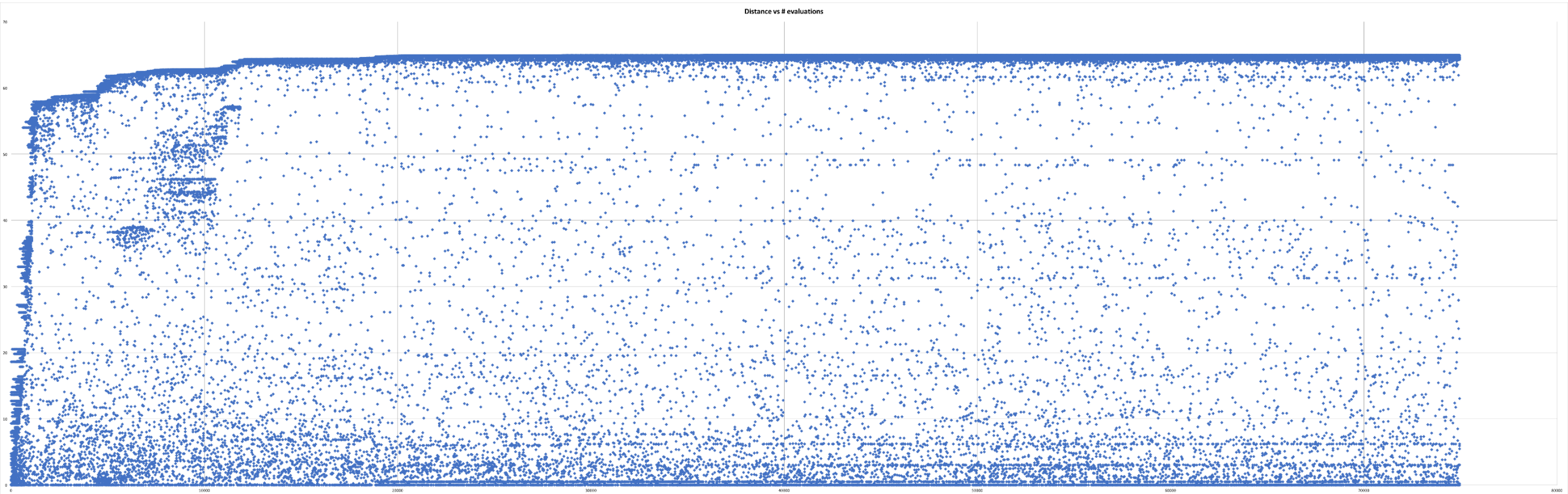
- You can change the length L0 of springs also as function of sensors
- Sensor types:
  - External, e.g.
    - light level
    - Distance to goal
  - Internal (proprioceptive)
    - Actual length of spring
    - Ground force (Whether mass is on or below ground)
    - Speed
    - …






INPUT LAYER
T1 T2 T3 T4 C1 C2 A1 A2 A3 A4 B1
B2
HIDDEN LAYER
M1 M2 M3 M4 M5 M6 M7 M8
OUTPUT LAYER




Distance vs # evaluations
70
60
50
40
30
20
10
0
0
10000
20000
30000
40000
50000
60000
70000
80000

More complex functions

- $L_0 = a+b*\sin(\omega t+c)$
- $L_0 = a+b*\sin(\omega t+c)+d*\sin(2\omega t+e)$
- $L_0 = a+b*\sin(\omega t+c)+d*\sin(2\omega t+e)+f*\sin(3\omega t+g)$
- …
- $L_0 = f(\sin(\omega t))$ ← Evolve *f* directly

Assignment 3c

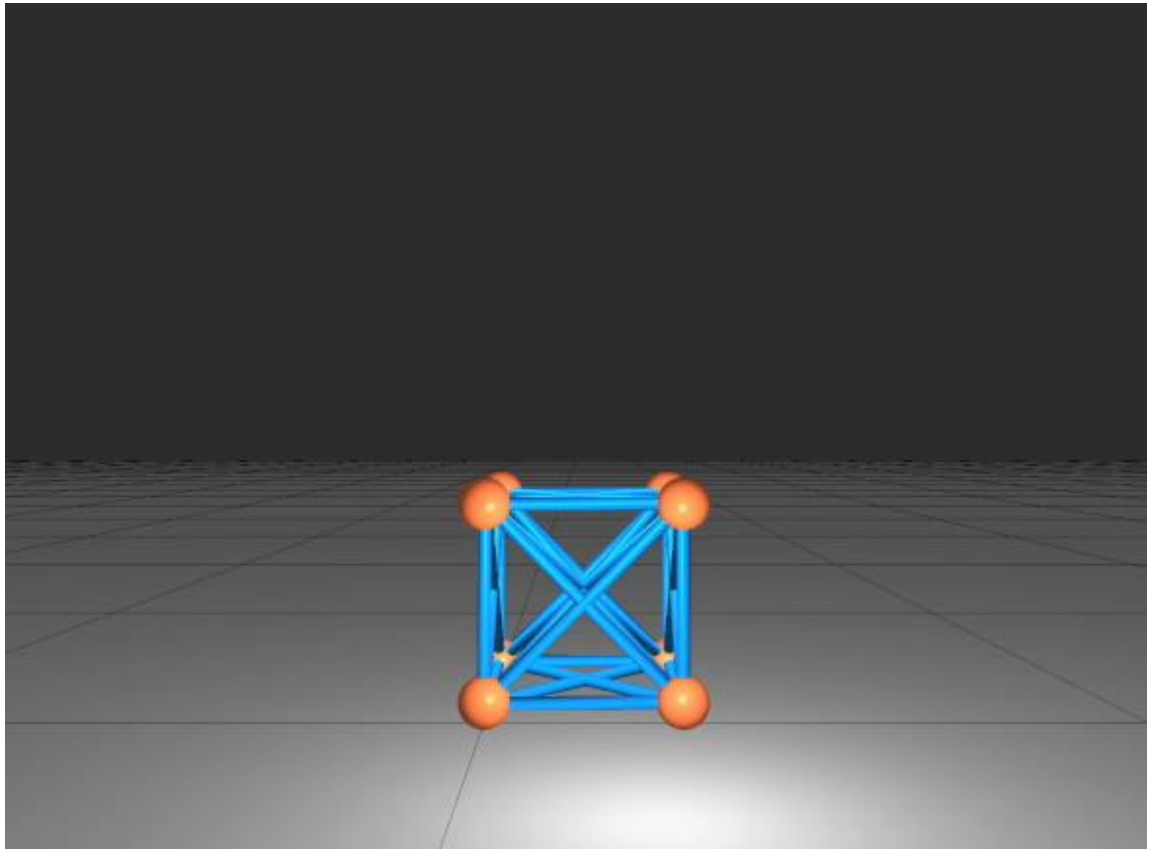
Evolve a robot with a variable morphology

Evolve a robot with a variable morphology

1. Cover page includes all information
2. General quality of the report (grammar, layout)
3. Video of fastest robot with at least three cycles shown
4. Video of fastest robot bouncing on the ground
5. Robot zoo – images of nine different robots (in a 3x3 panel)
6. Nice rendering of the robot (bars, spheres, ground grid, shaded faces)
7. Multiple robots showed in a single video
8. Description of all simulation parameters
9. Description of all robot parameters
10. Description of all evolutionary parameters
11. Learning curve with error bars
12. Populating dot plot
13. Populating Diversity chart
14. Discussion of what works and did not work
15. Performance (speed of robot) in robot maximum diameter per cycle.
16. Innovative robot(s) shown
17. Alternative representations tried
18. Post video of robot on piazza (provide screenshot and link)

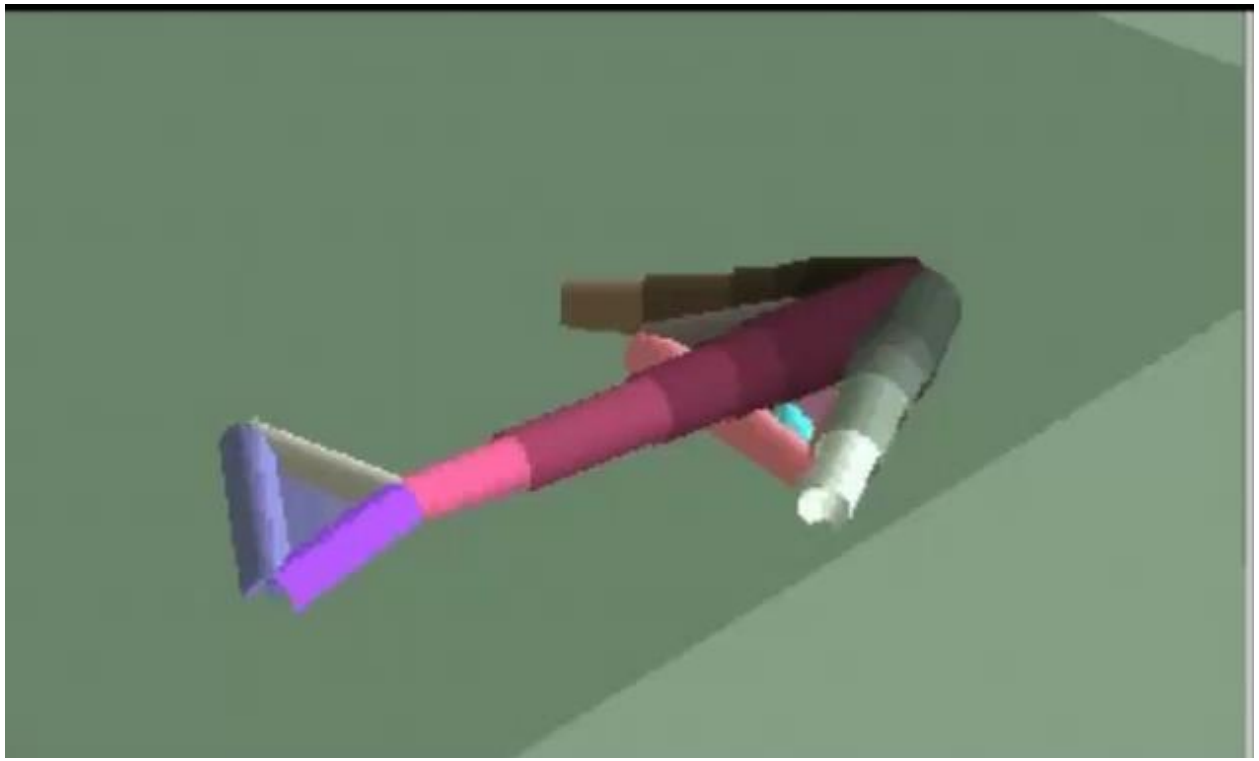
Assignment 3c

- Evolve morphology

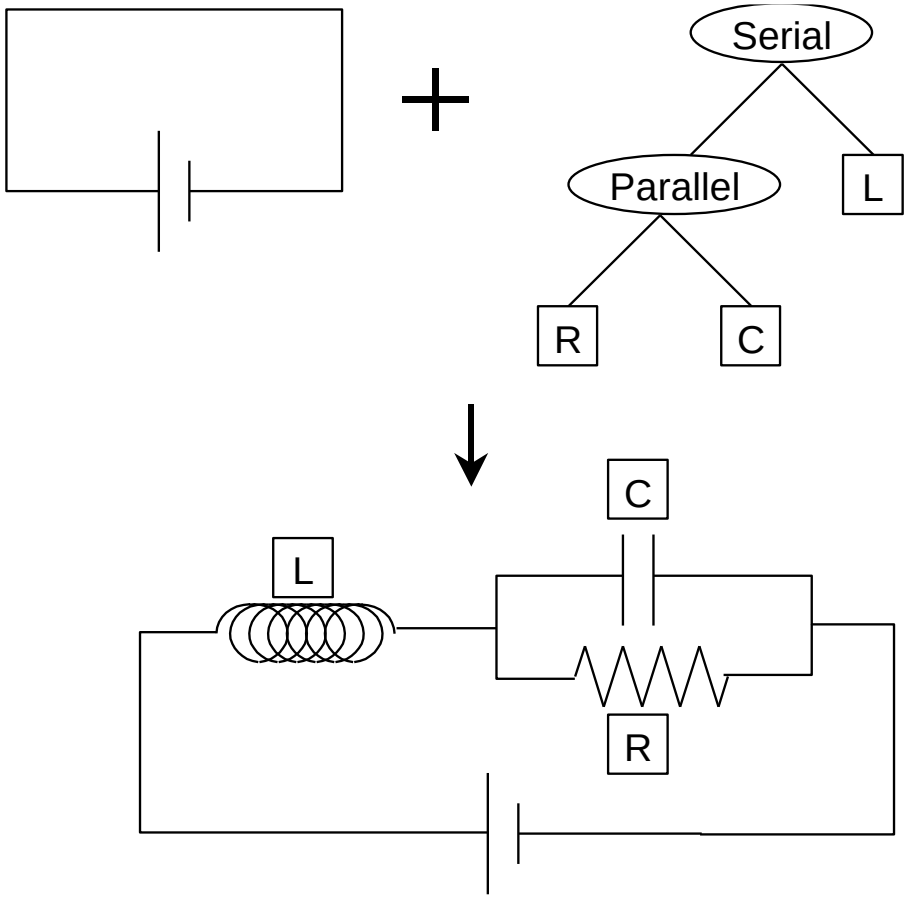


Direct morphological operators

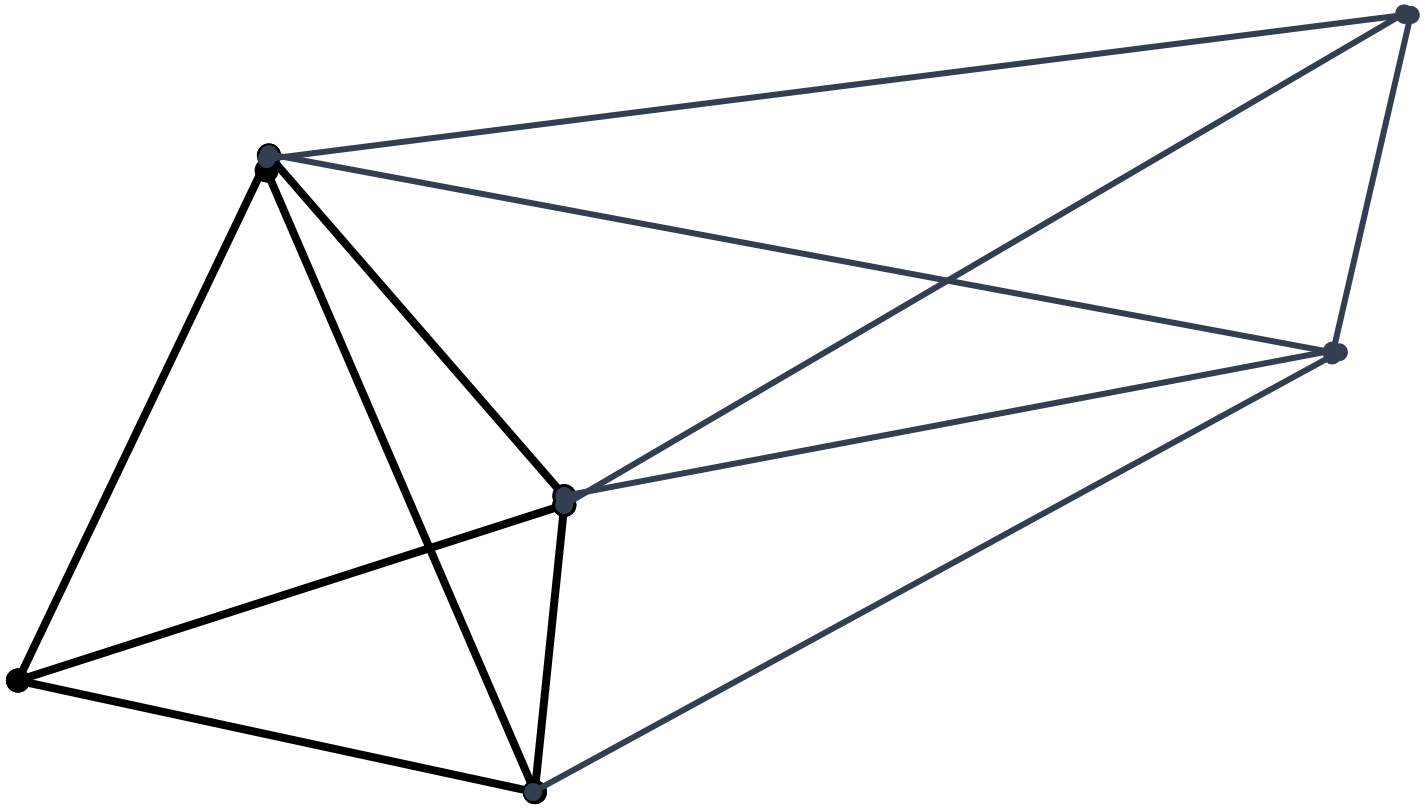
- Control changes
  - Change actuation parameters a,b,c,k
- Morphological changes
  - Add/remove spring between two exiting masses
  - Add/remove mass
  - Change mass distribution (but keep total mass constant)
  - Change rest length of existing spring
- Some operators require “cleanup” and bookkeeping
  - For example, after removing a mass you may need to remove dangling springs and update indices of other masses

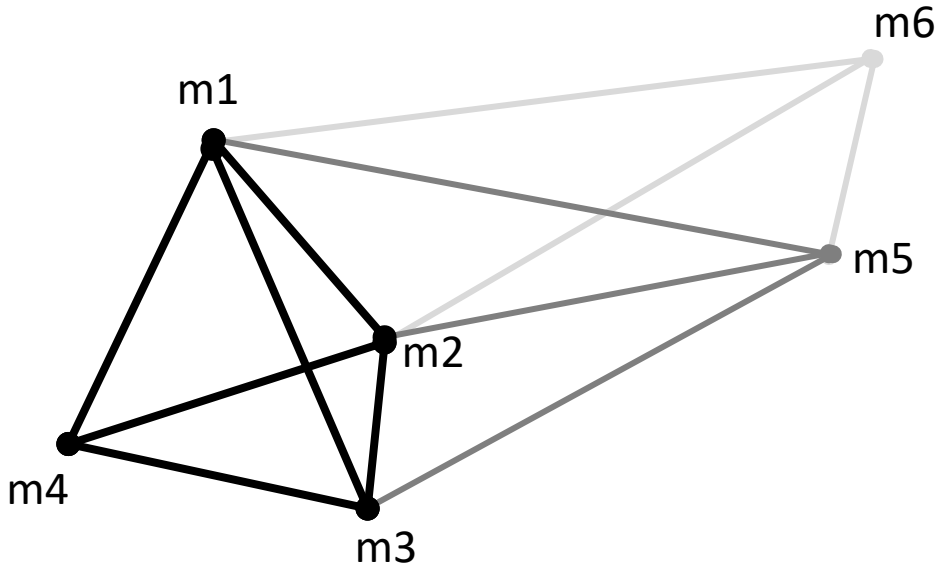


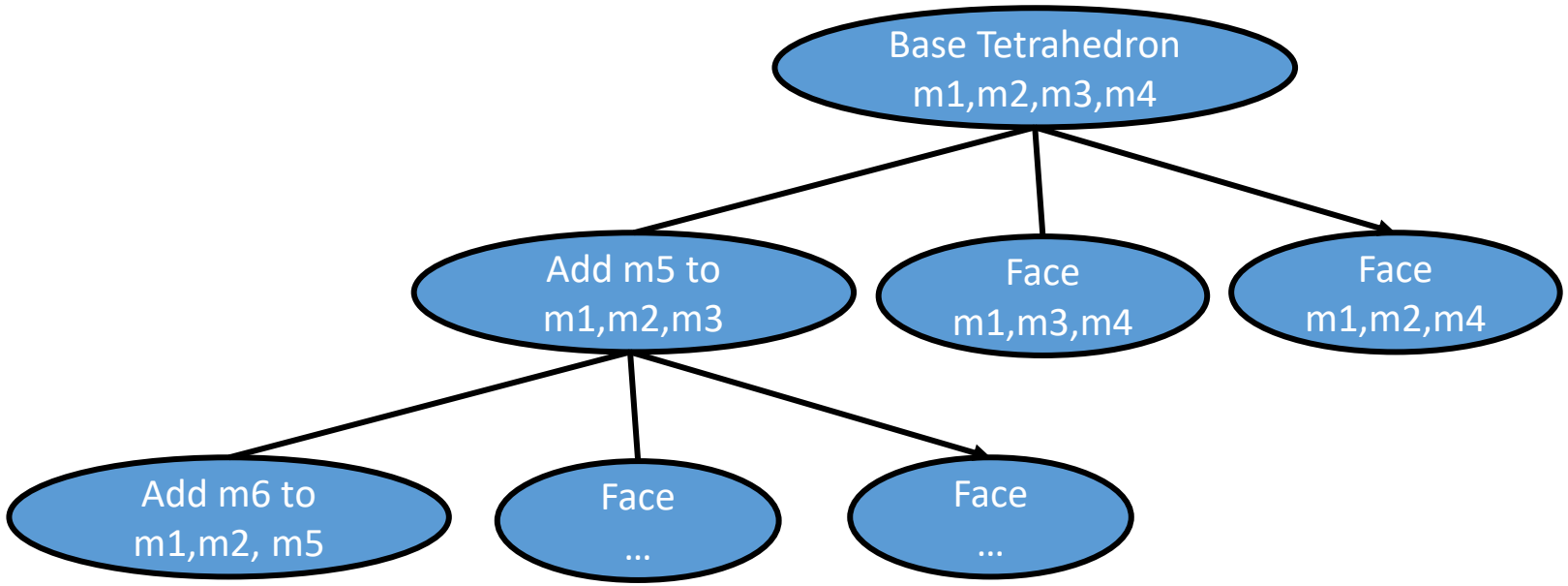
Developmental encoding



Developmental encodings

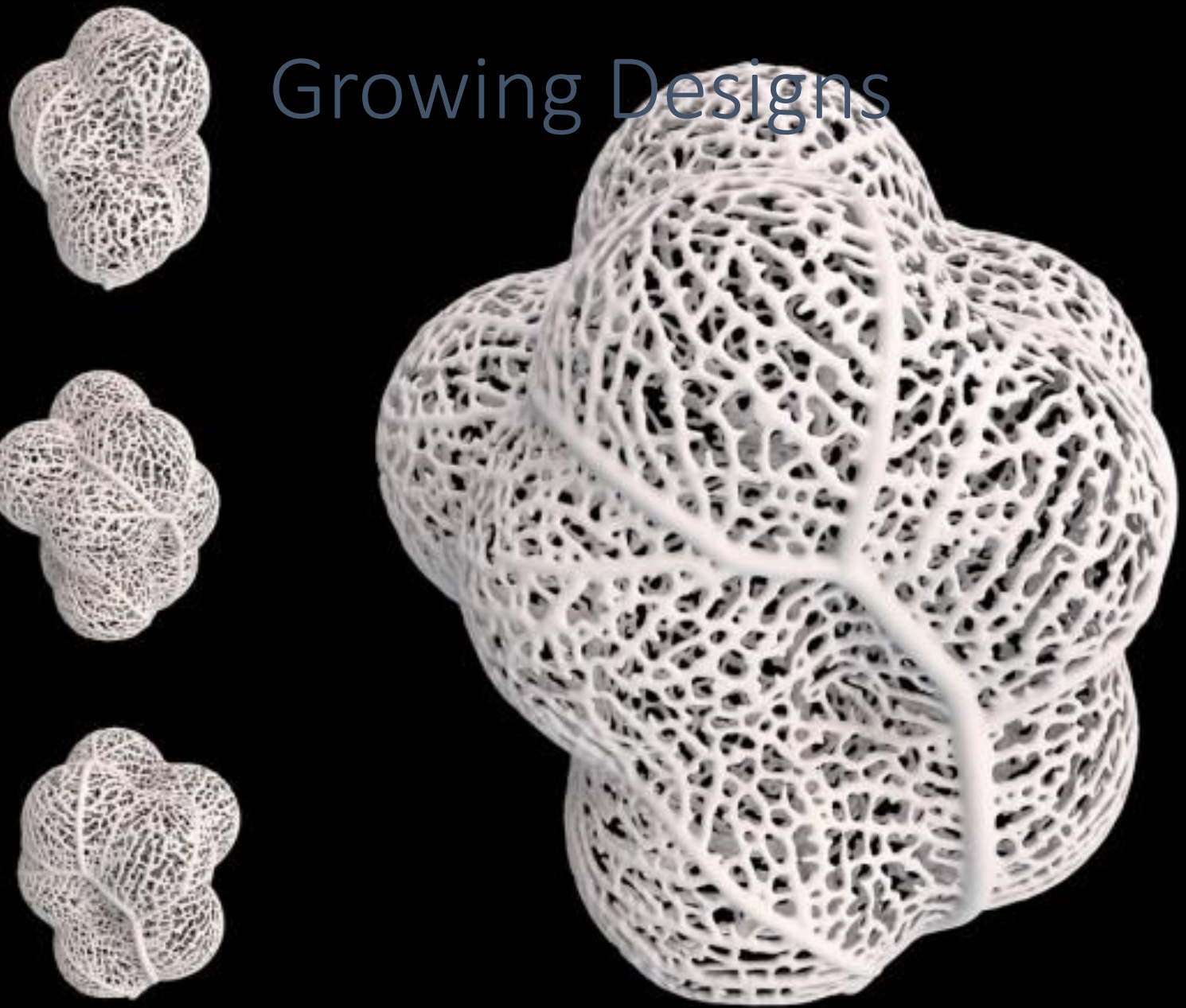



m6
m1
m5
m2
m4
m3


Base Tetrahedron
m1,m2,m3,m4
Add m5 to
m1,m2,m3
Face
m1,m3,m4
Face
m1,m2,m4
Add m6 to
m1,m2, m5
Face
…
Face
…

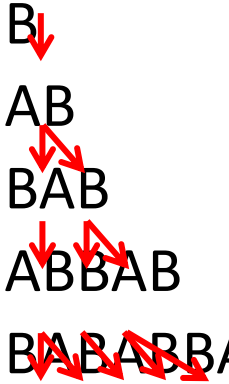
RoboGrammar: Graph Grammar for Terrain-optimized Robot Design

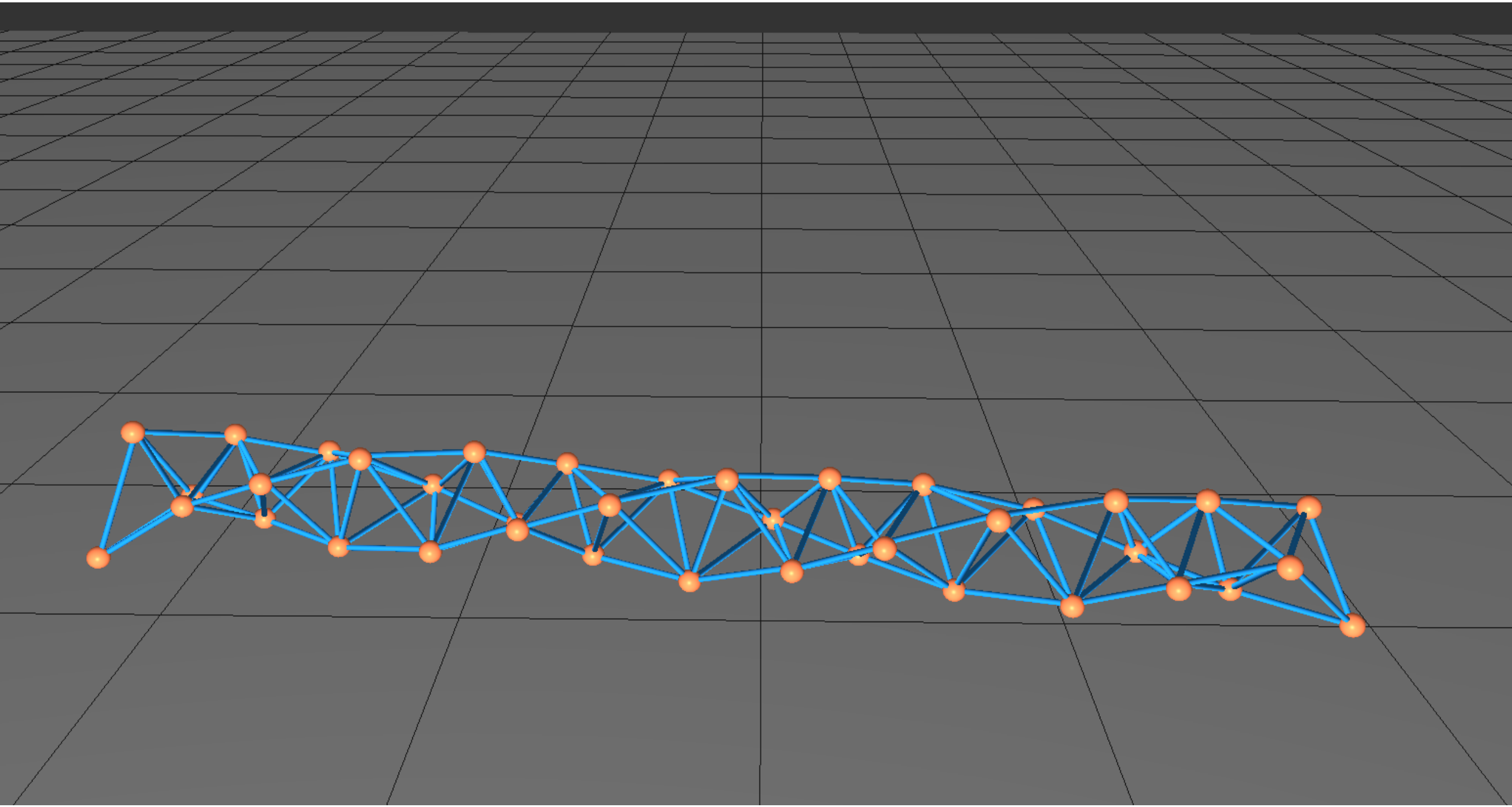
Growing Designs



Generative Blueprints

- A→B B→AB
  - A
  - B
  - AB
  - BAB
  - ABBAB
  - BABABBAB
  - ABBABBABABBAB

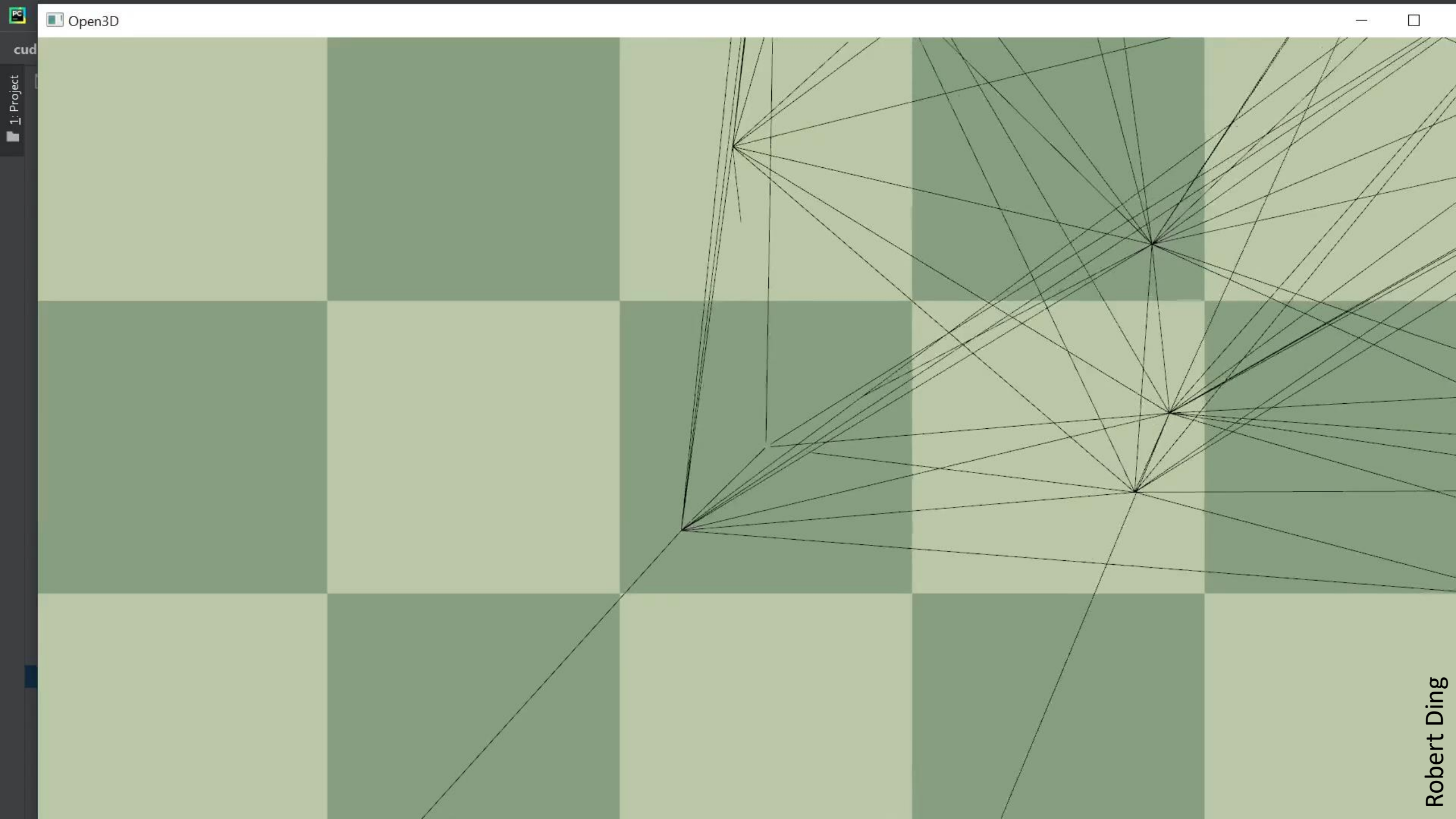


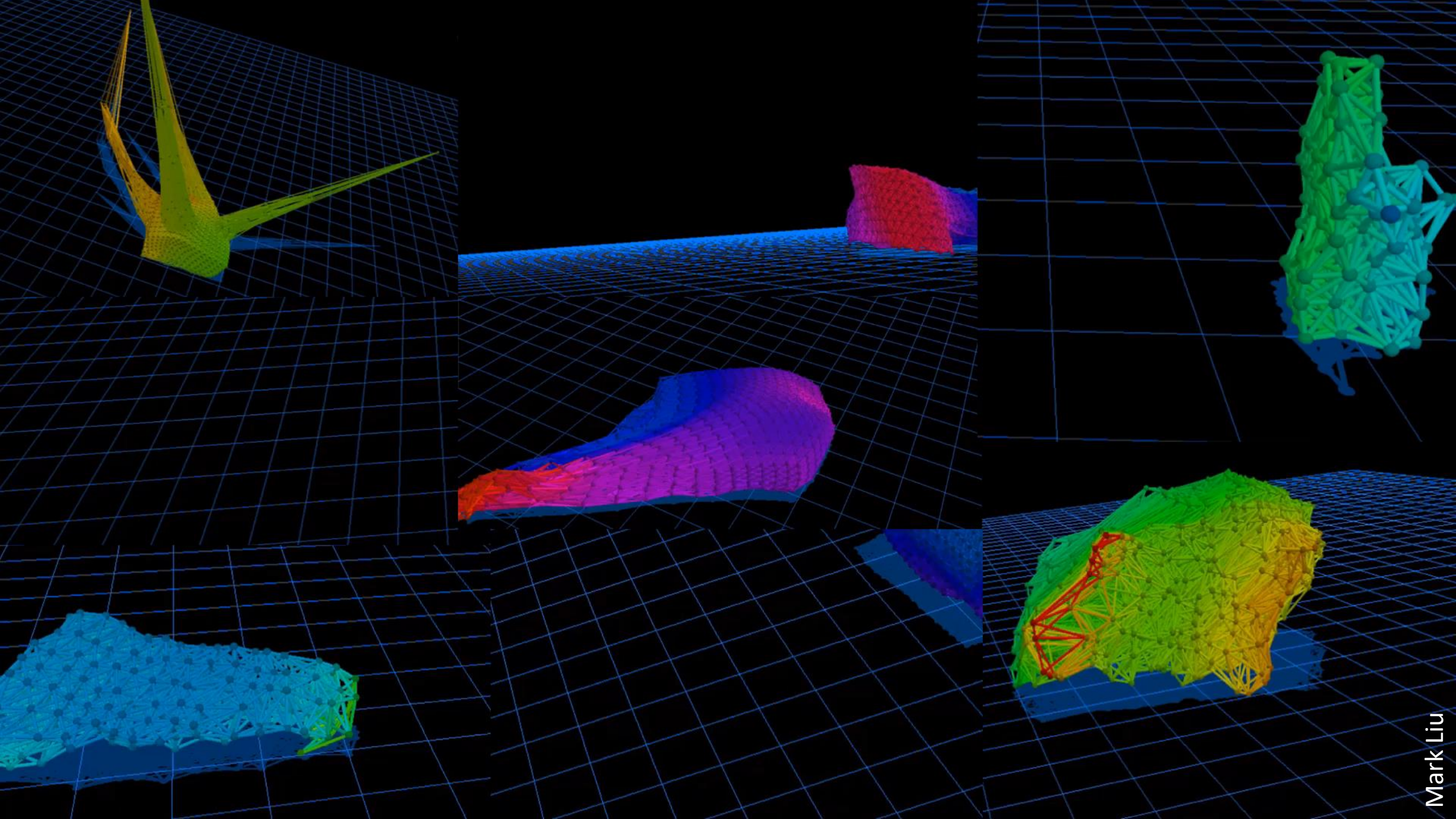


Huy Ha

Elizabeth Ayton, Max Segan

Elizabeth Ayton, Max Segan


Open3D
cud
1: Project
Robert Ding


Mark Liu

Final Presentation

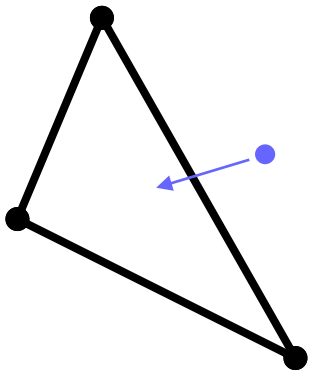
1. Cover page includes all information
2. Video of best robot shown
3. Multiple robot videos shown
4. Single video with multiple robot is shown
5. Robot zoo – images of nine different robots (in a 3x3 panel)
6. Nice rendering of the robot (bars, spheres, ground grid, shaded faces)
7. Post video of robot on your online portfolio (provide screenshot and link)

Extra

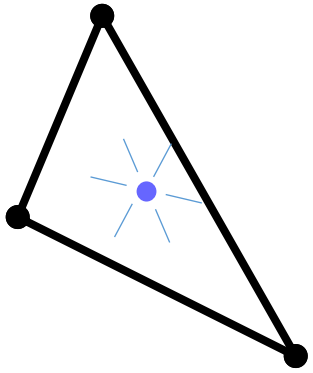
Types of collisions

- Must be handled
  - Mass with triangle
  - Edge with edge
- Can be ignored:
  - Mass with mass
  - Mass with edge
  - Edge with triangle
  - triangle with triangle

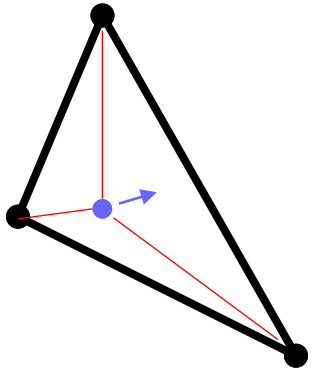
Mass-Triangle Collision



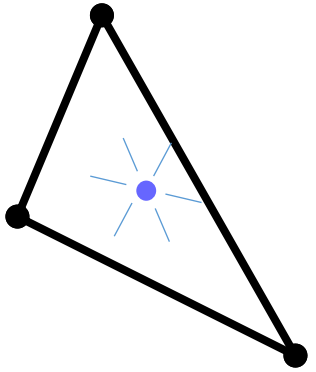
Before collision



Collision moment
Temporary springs added

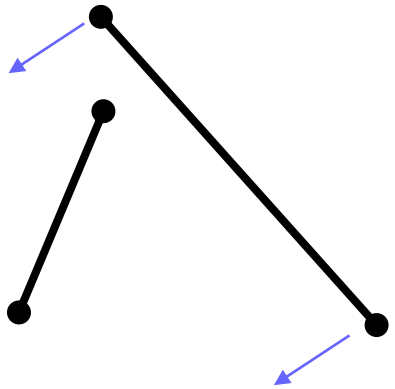


Springs take care
of impact dynamics

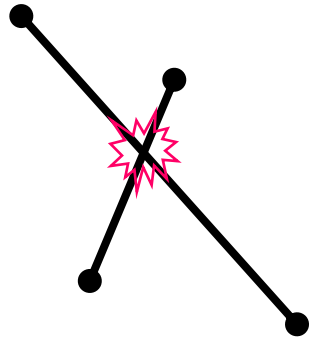


When mass exits
Temporary springs removed

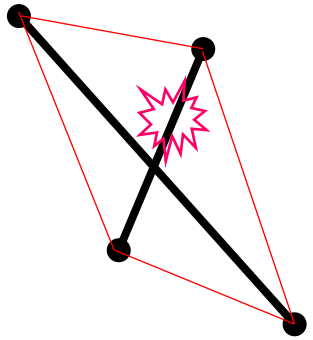
Edge-Edge Collision



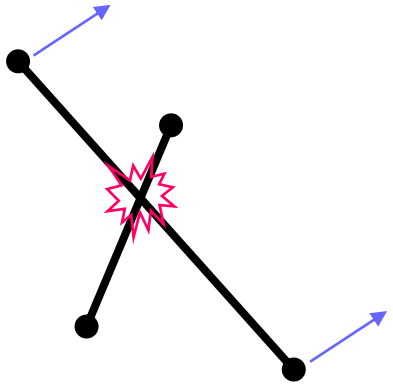
Before collision



Collision moment
Temporary springs added



Springs take care
of impact dynamics



When edge exits
Temporary springs removed