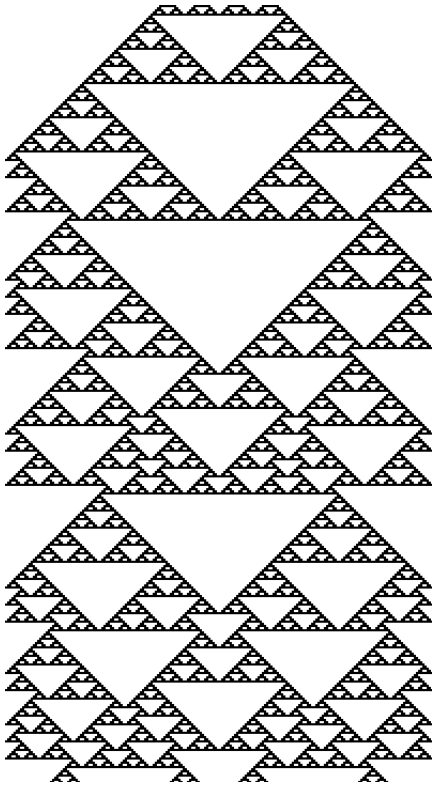
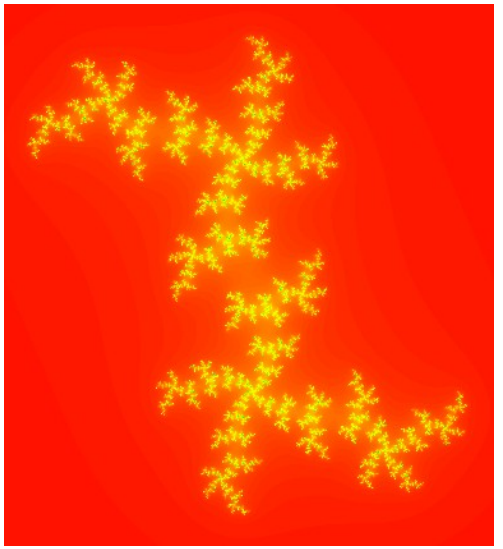
The Computational Beauty of Nature

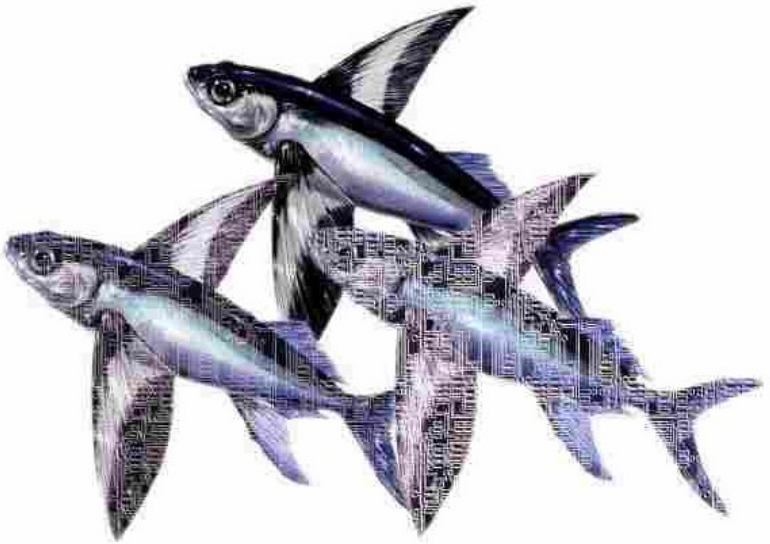
Professor Jim Marshall

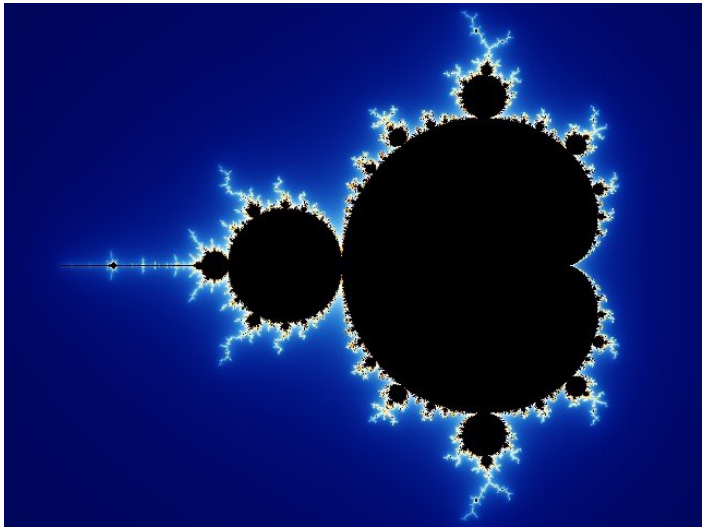
Spring 2020

Sarah Lawrence College









Administrivia

- Office: Science 100
  Phone: 2673
  Email: jmarshall@sarahlawrence.edu

- Class web page:
  http://science.slc.edu/jmarshall/cbn

- Check your SLC email (gm.slc.edu) every day

- Read the **Academic Honesty policy** on the class web page, as well as the other course policies

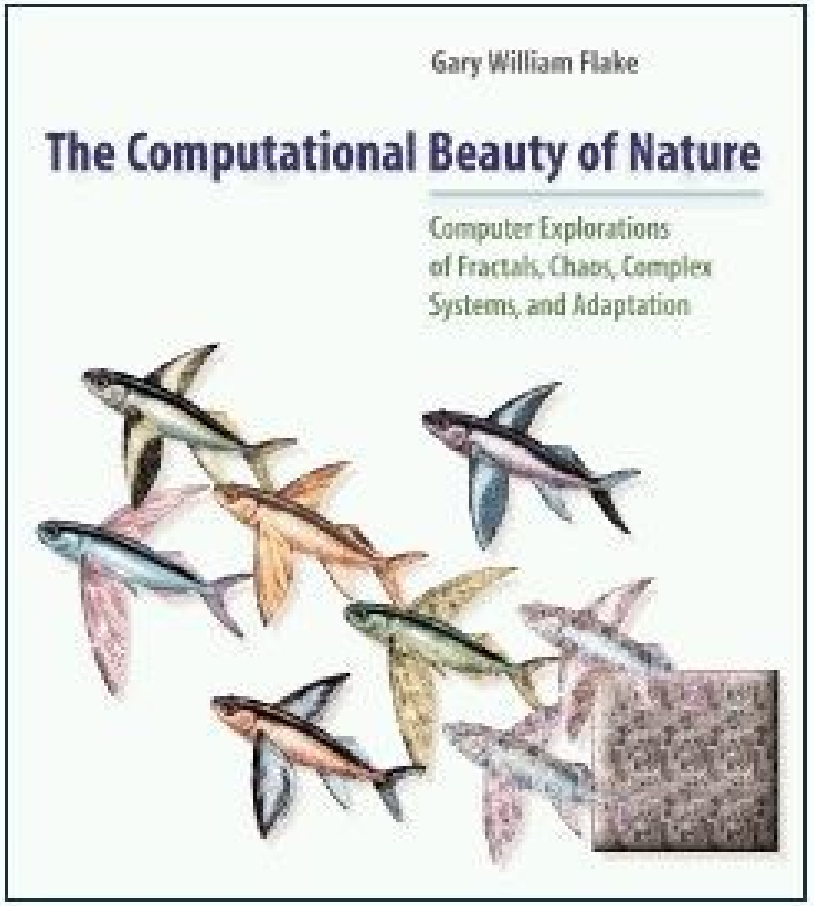
Administrivia

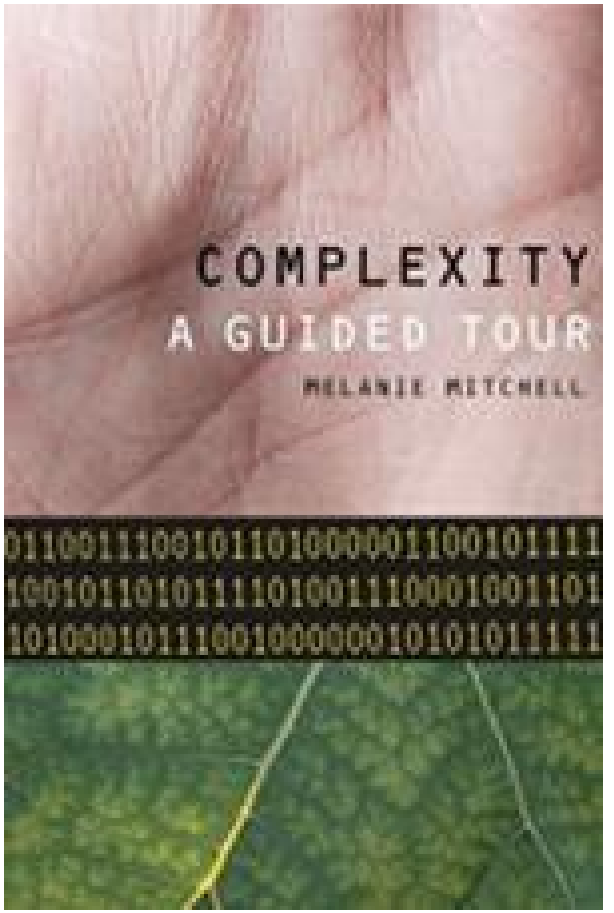
- **Class attendance**
  - please be on time
  - please notify me in advance if you need to miss class
  - more than 3 absences or more than 1 missed group conference may result in reduced course credit

- **Grading and evaluation**
  - weekly reading assignments
  - lab exercises, homework problem sets
  - in-class quizzes
  - research paper
  - attendance

Administrivia

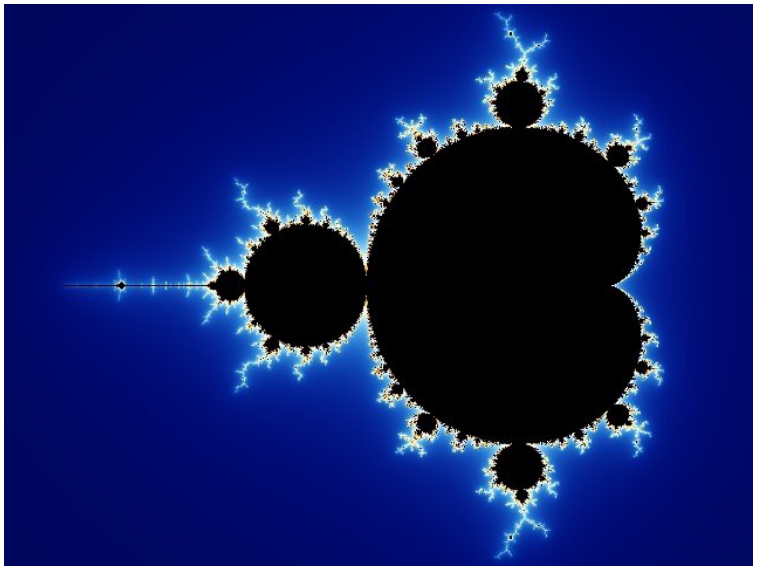
- **Books**

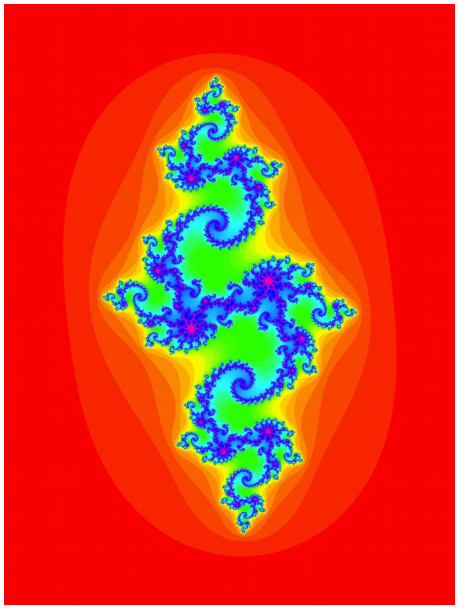


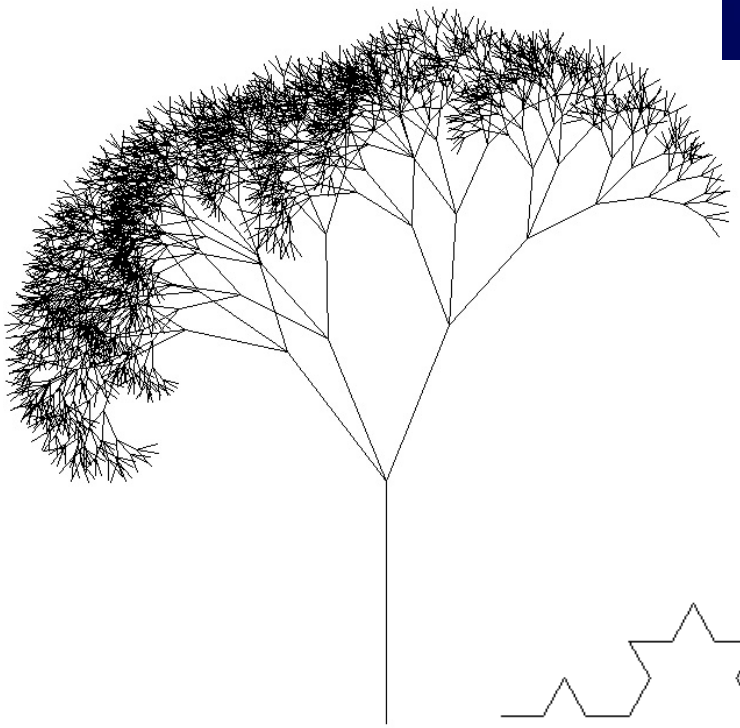


Topics: Fractals

- Self-similarity
- The Mandelbrot set
- Julia sets
- L-systems







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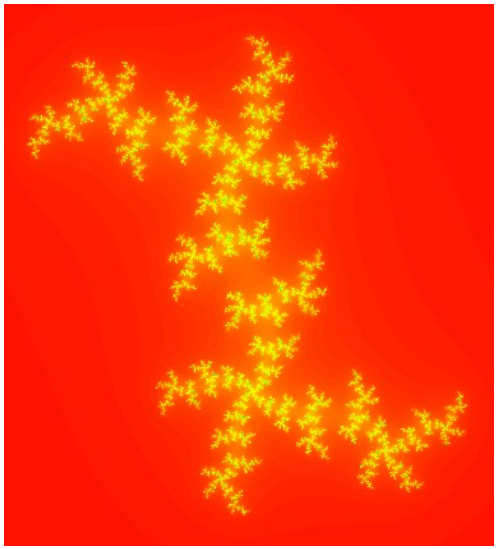
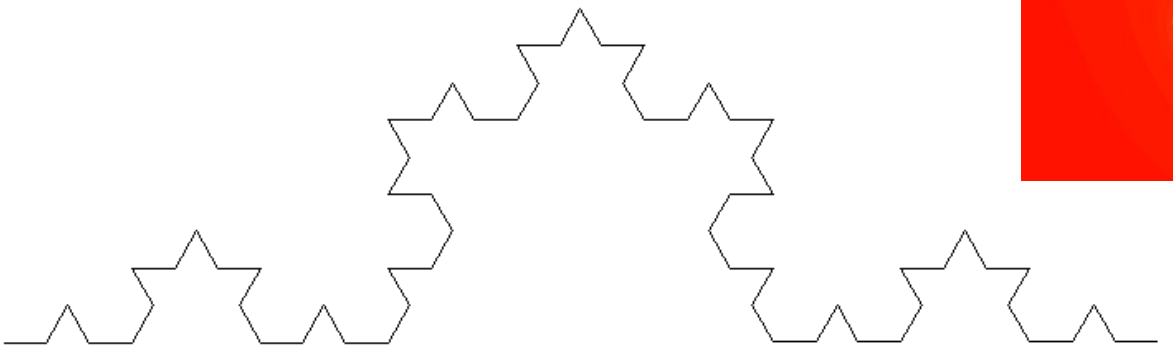
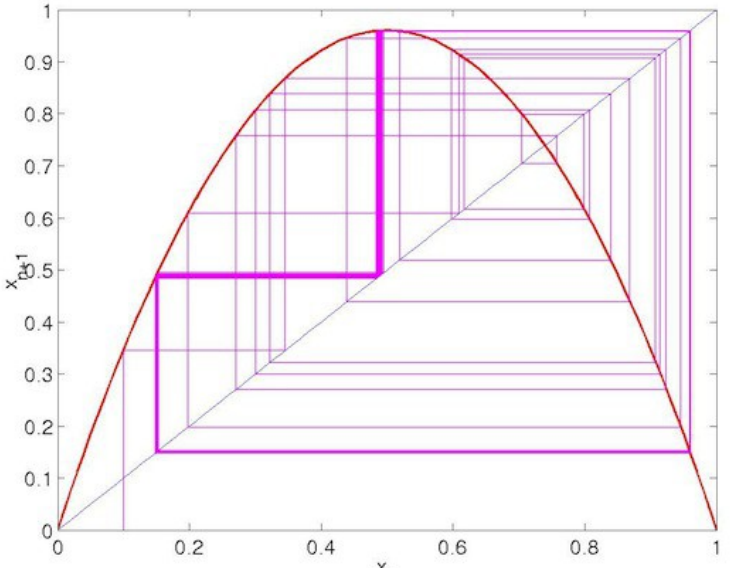


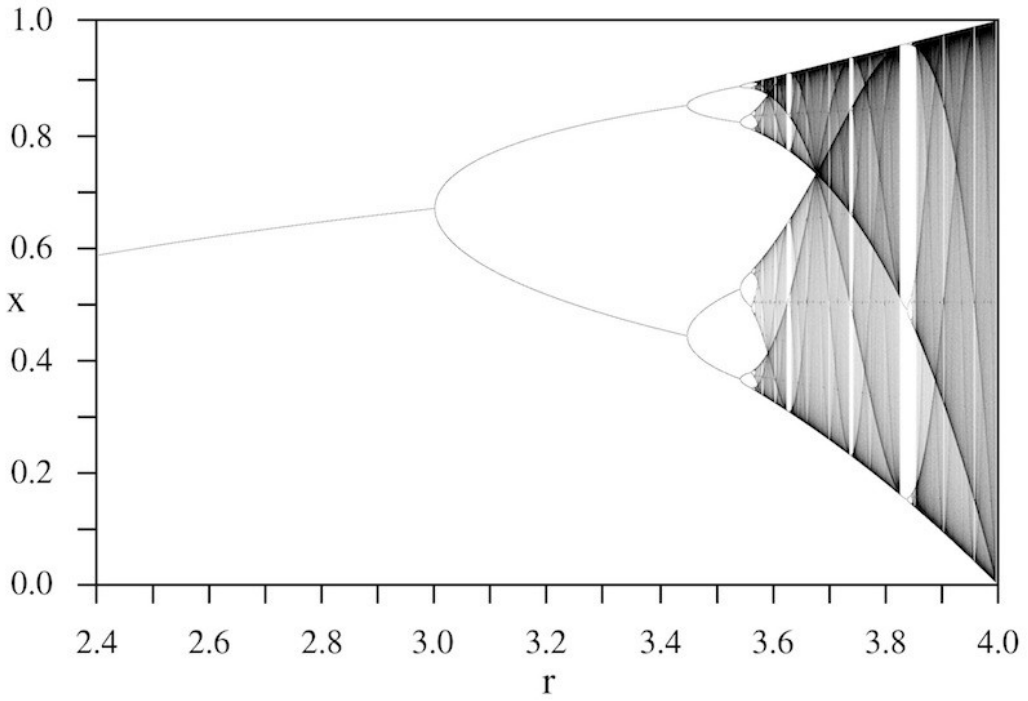


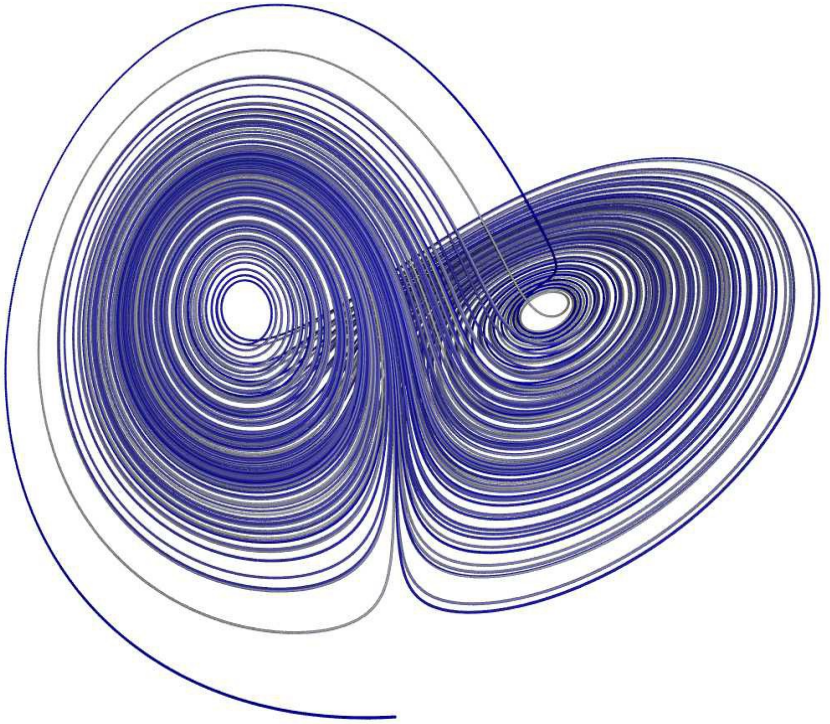
Topics: Chaos

- Nonlinear dynamics
- The logistic map
- Bifurcation diagrams
- Strange attractors

$$x_{t+1} = R\, x_t (1 - x_t)$$

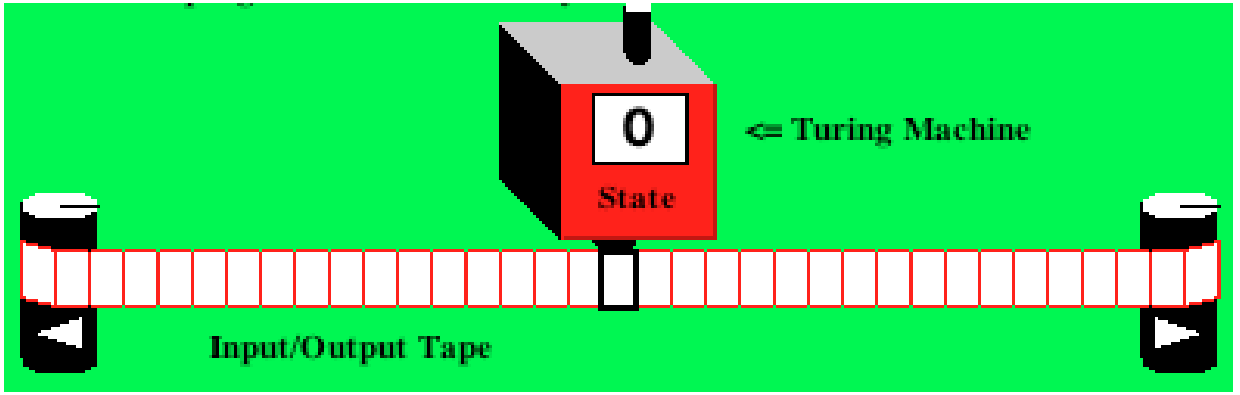


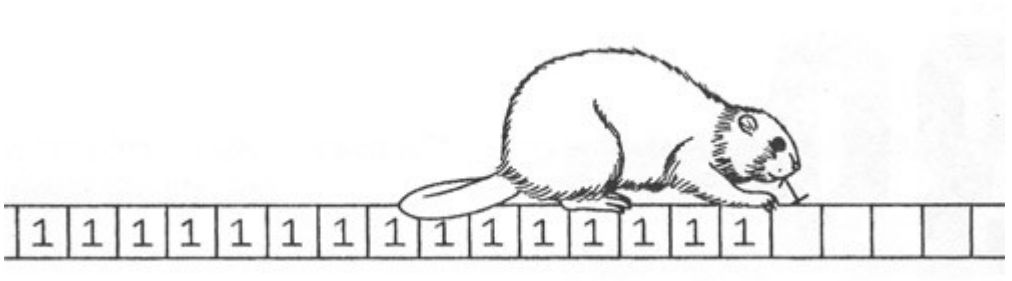




Topics: Computation

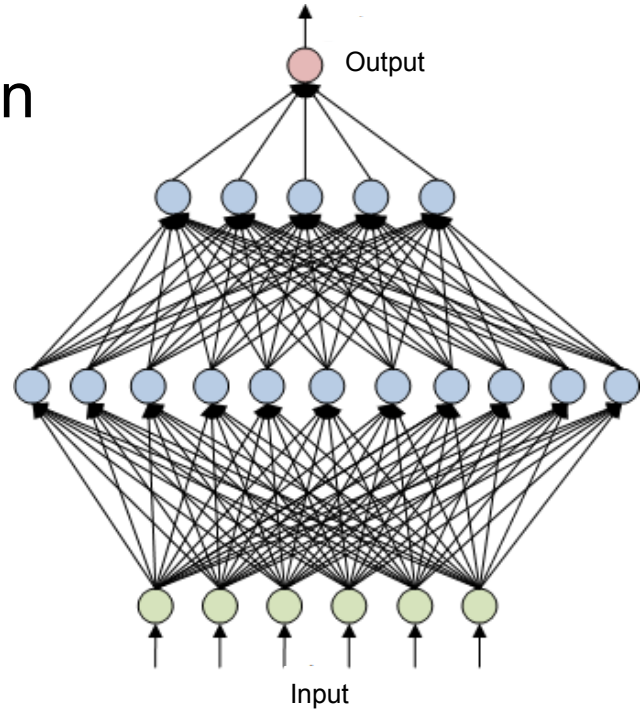
- Number systems and information
- Turing machines
- The limits of computation

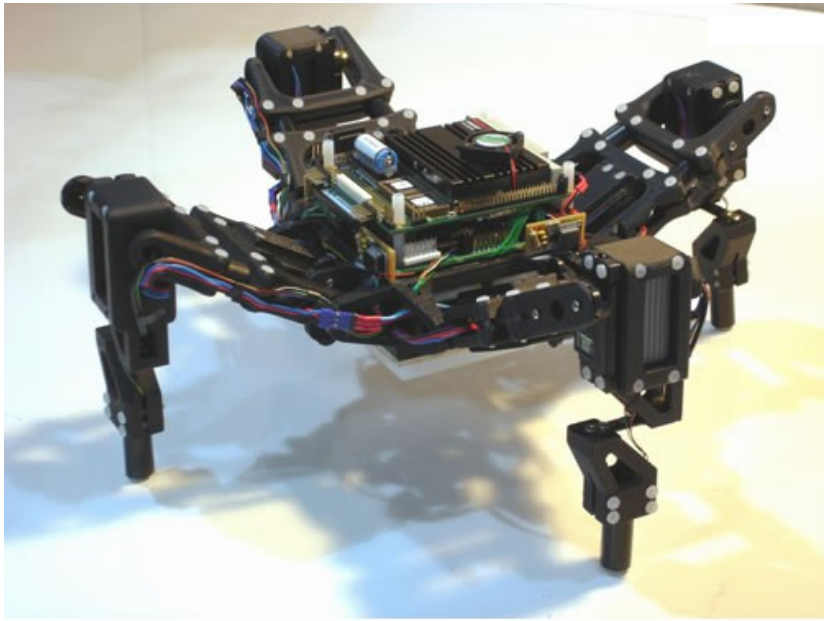


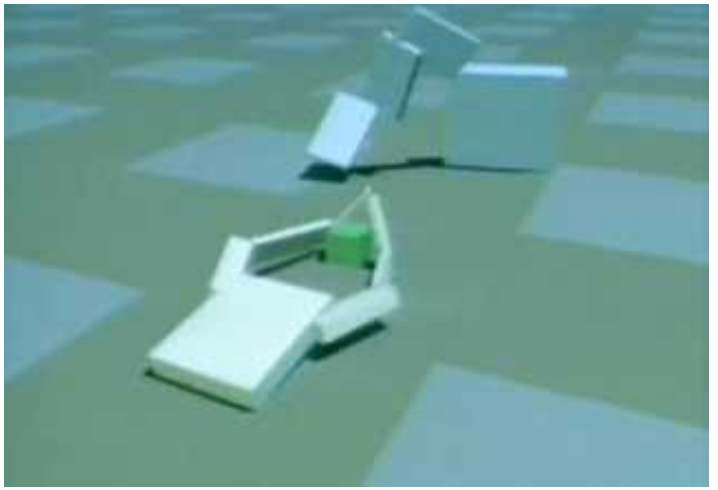


Topics: Adaptation

- Genetic algorithms and simulated evolution
- Artificial neural networks
- Evolving virtual creatures
- Evolutionary robotics

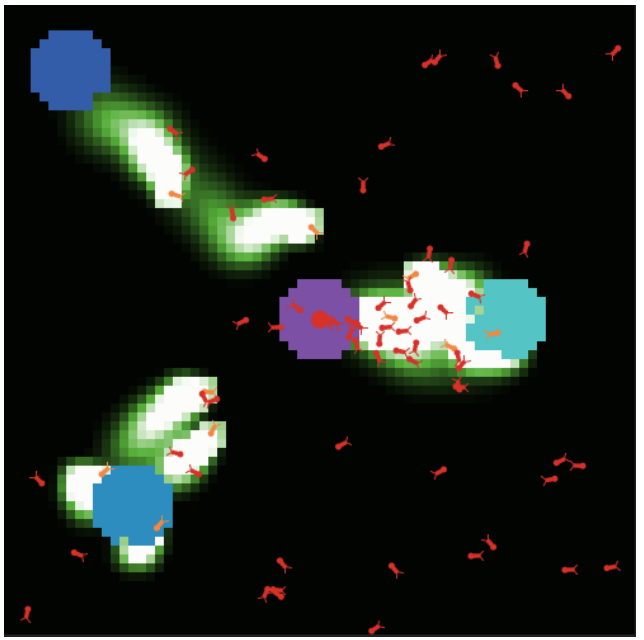


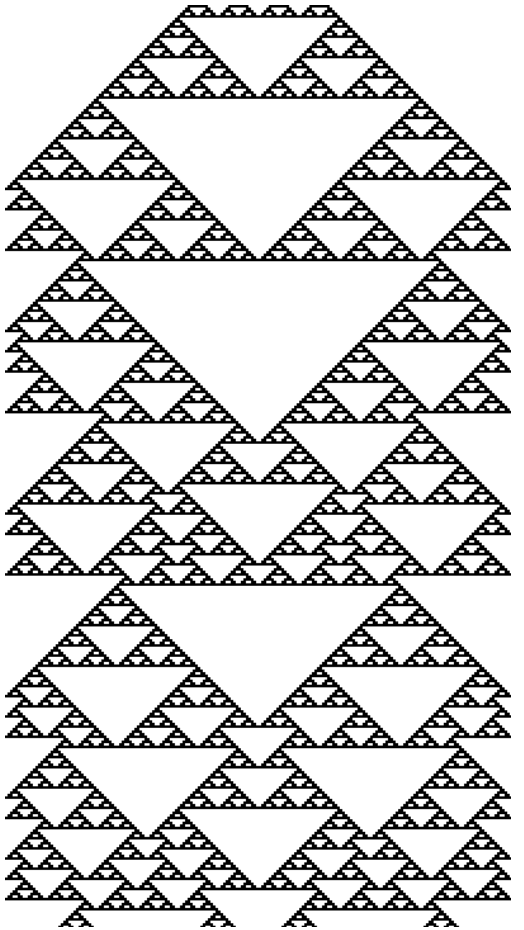


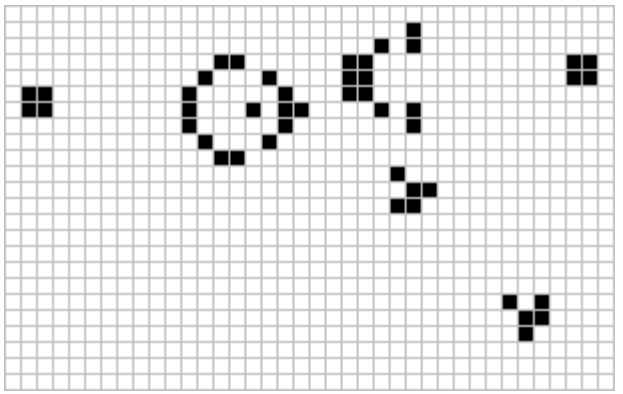


Topics: Emergence

- Cellular automata
- The “edge of chaos”
- The Game of Life
- Virtual ants and boids







NetLogo

What are complex systems?

- Networks of simple interacting components, which, following simple rules, produce **complex emergent** behavior
  - simple components with simple rules of operation
  - no central controller
  - limited communication among components
  - collective behavior emerges from interacting components
  - easy to understand the low-level component behavior
  - hard to predict the high-level emergent behavior

Ant colonies

“The solitary army ant is behaviorally one of the least sophisticated animals imaginable” —Nigel Franks

https://commons.wikimedia.org/wiki/File:Ant_on_leaf.jpg

Ant colonies

https://en.wikipedia.org/wiki/Army_ant

Ant colonies

https://en.wikipedia.org/wiki/Army_ant#/media/File:Dorylus.JPG

Ant colonies

https://en.wikipedia.org/wiki/Ant#/media/File:AntBridge_Crossing_03.jpg

Ant colonies

https://en.wikipedia.org/wiki/Ant#/media/File:AntBridge_Crossing_10.jpg

Ant colonies

https://danimaz.files.wordpress.com/2015/07/ponte-formiche.png

Ant colonies

https://www.youtube.com/watch?v=4BdjxYUdJS8

Termite mound

http://commons.wikimedia.org/wiki/File:Termite_mound_NT.jpg

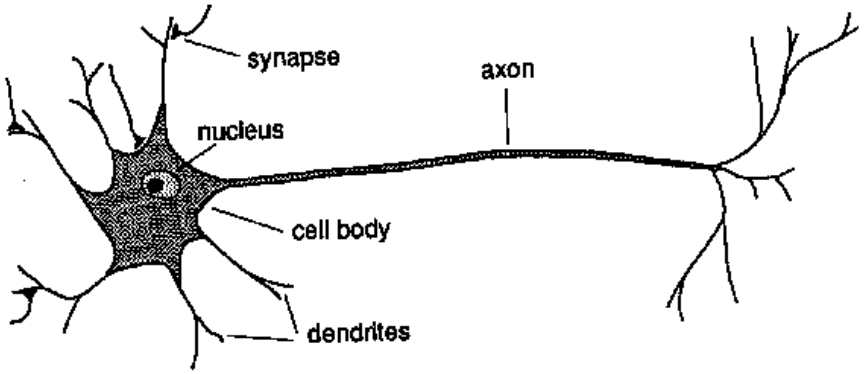
Ant videos

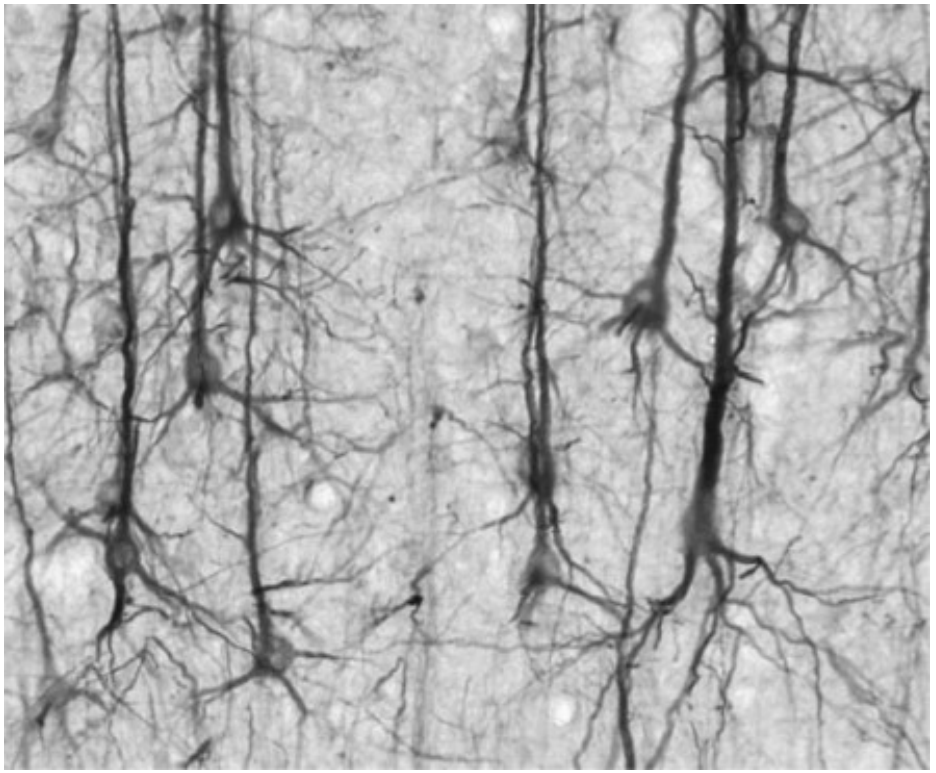
Army ants

Excavation of a giant anthill

http://www.youtube.com/watch?v=DXaaTQztoI0
http://www.youtube.com/watch?v=lFg21x2sj-M

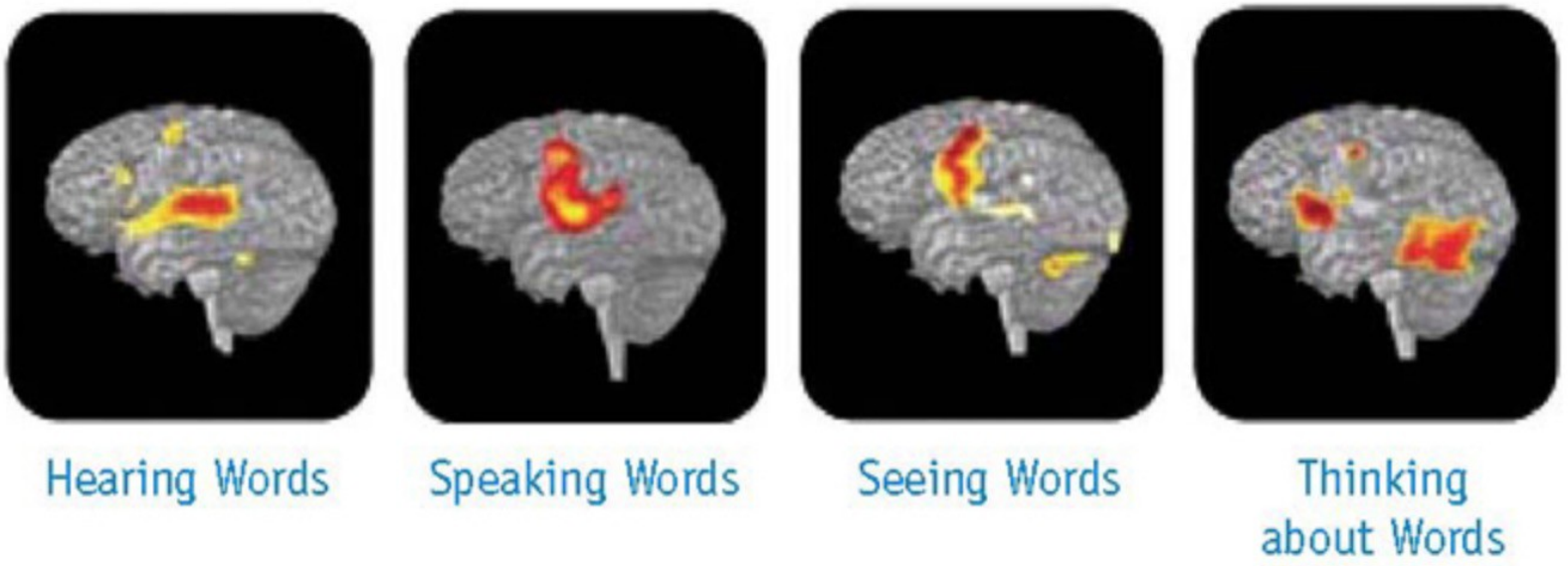
Brains

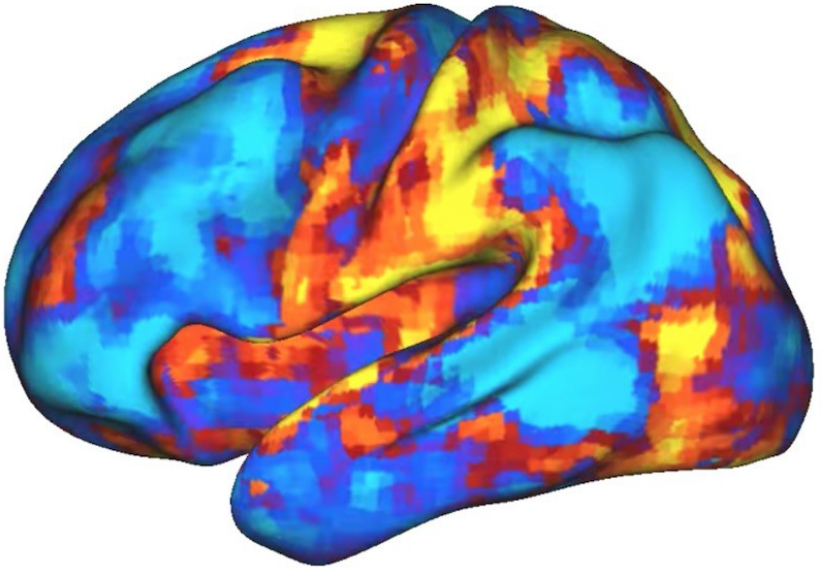




https://commons.wikimedia.org/wiki/File:MRI_brain.jpg

Brains



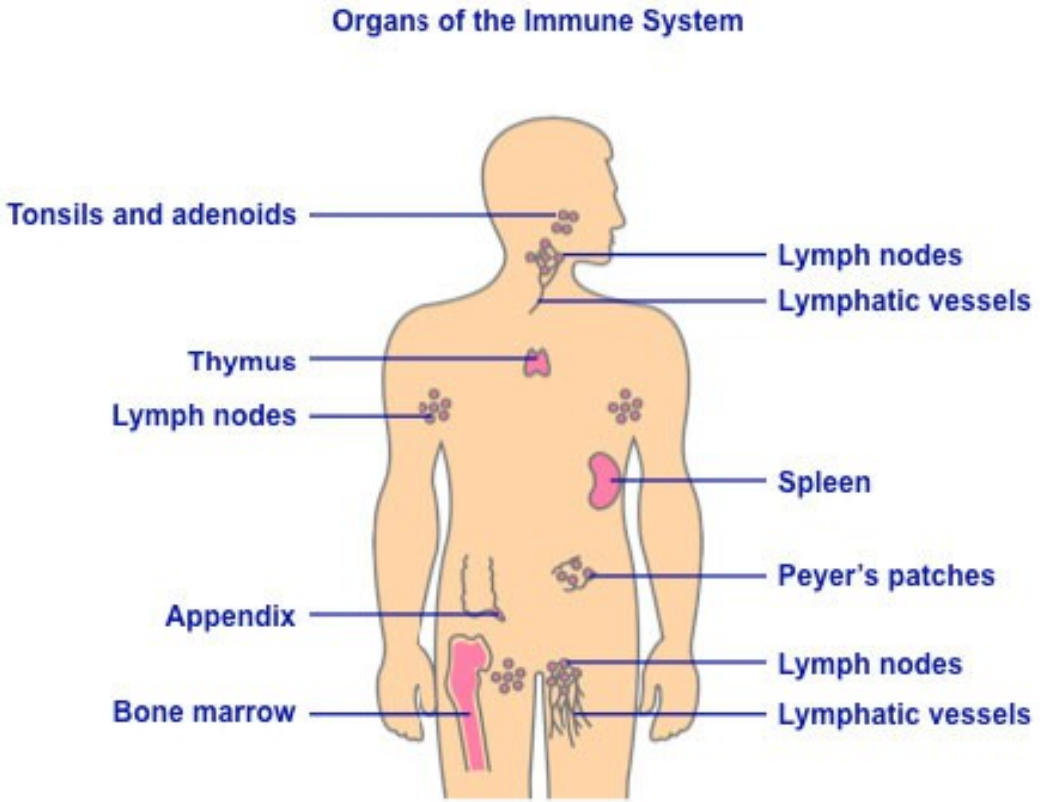


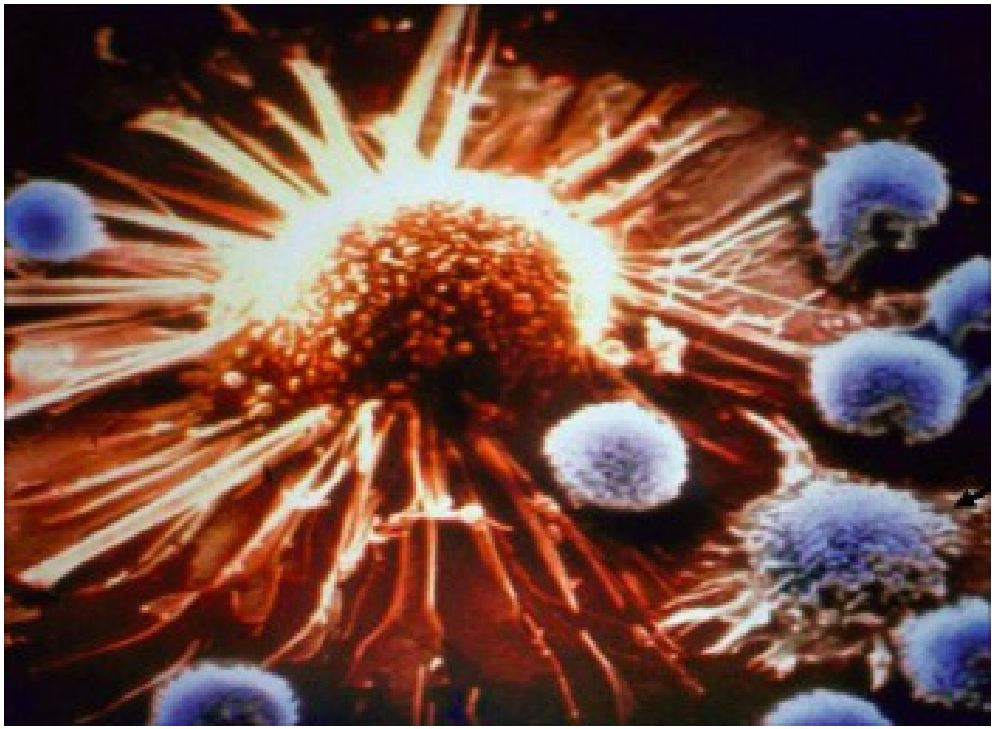
https://www.youtube.com/watch?v=VaQ66IDZ-08

Bird flocking

https://www.youtube.com/watch?v=DmO4EIlgmd0

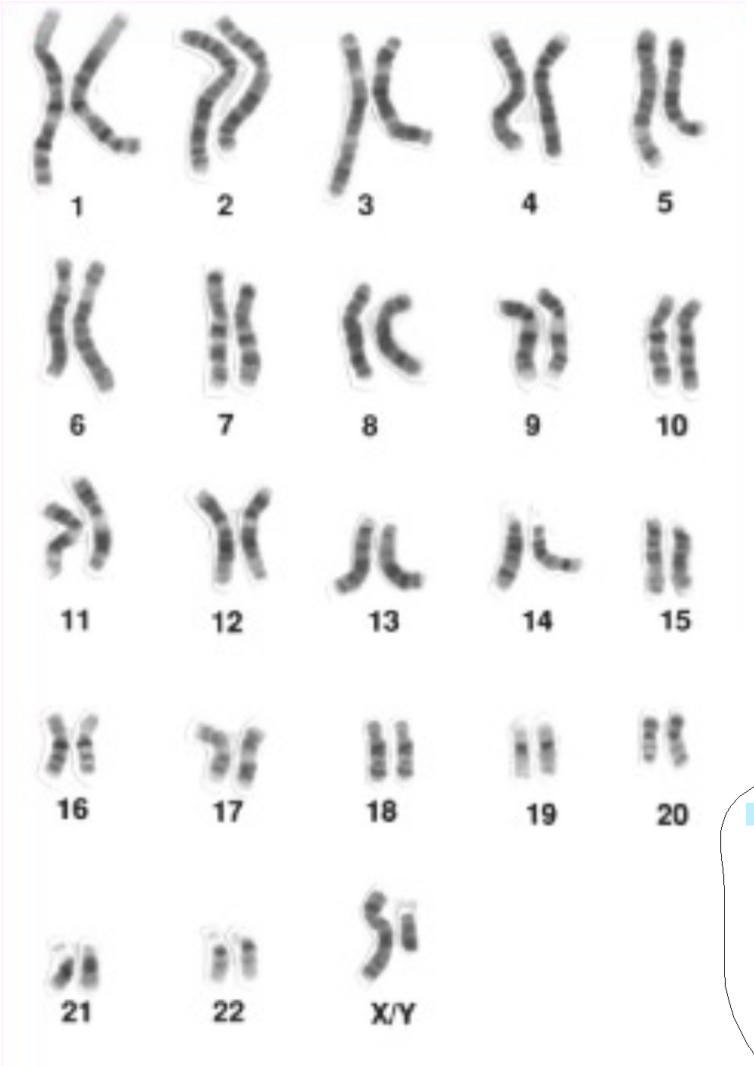
The immune system

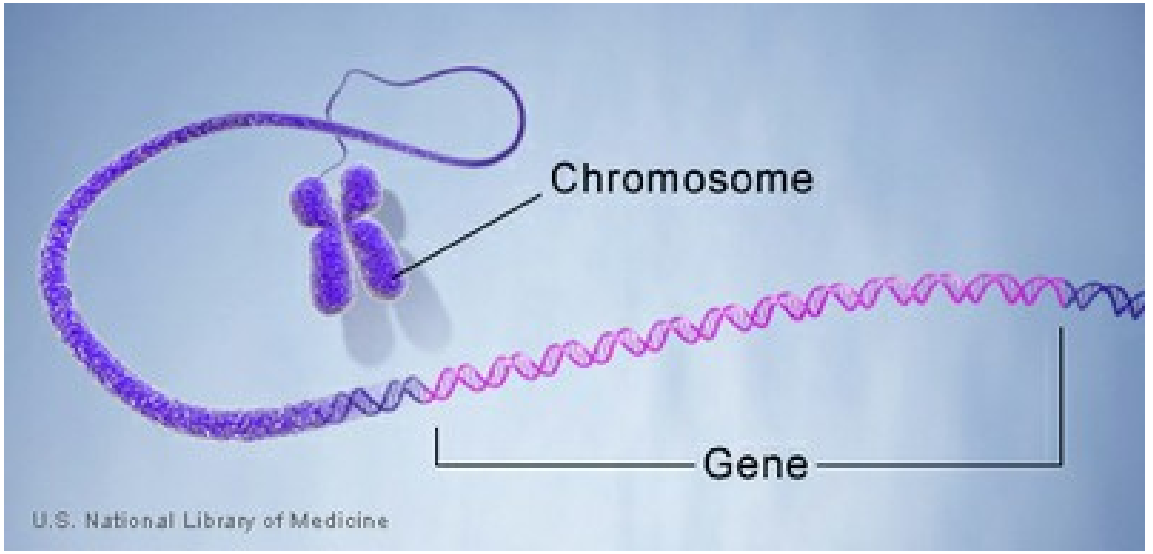


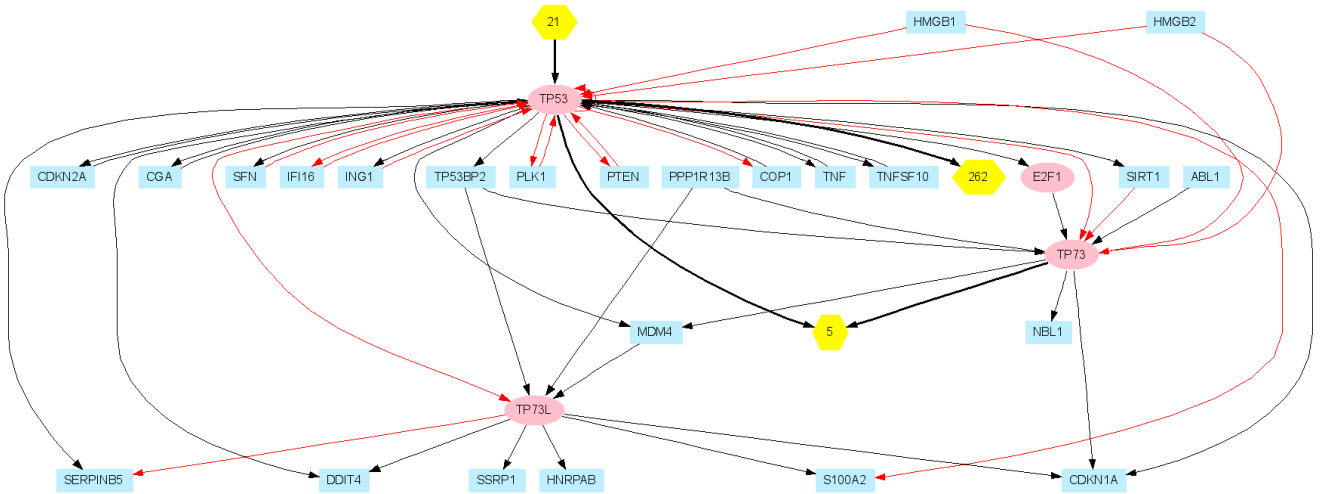


https://5nrrbodysystems.weebly.com/immune-system.html
https://home.ccr.cancer.gov/inthejournals/dev/itj-therapy.asp

Genetic regulatory networks

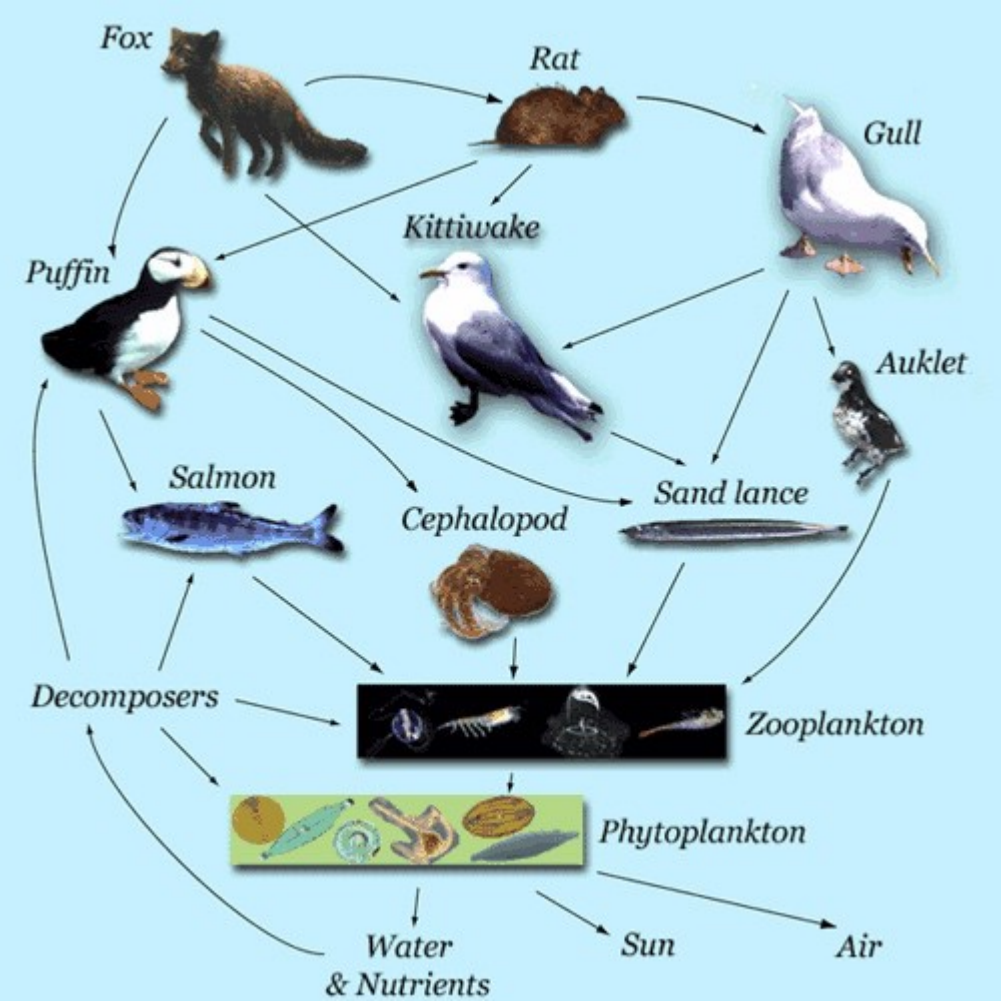


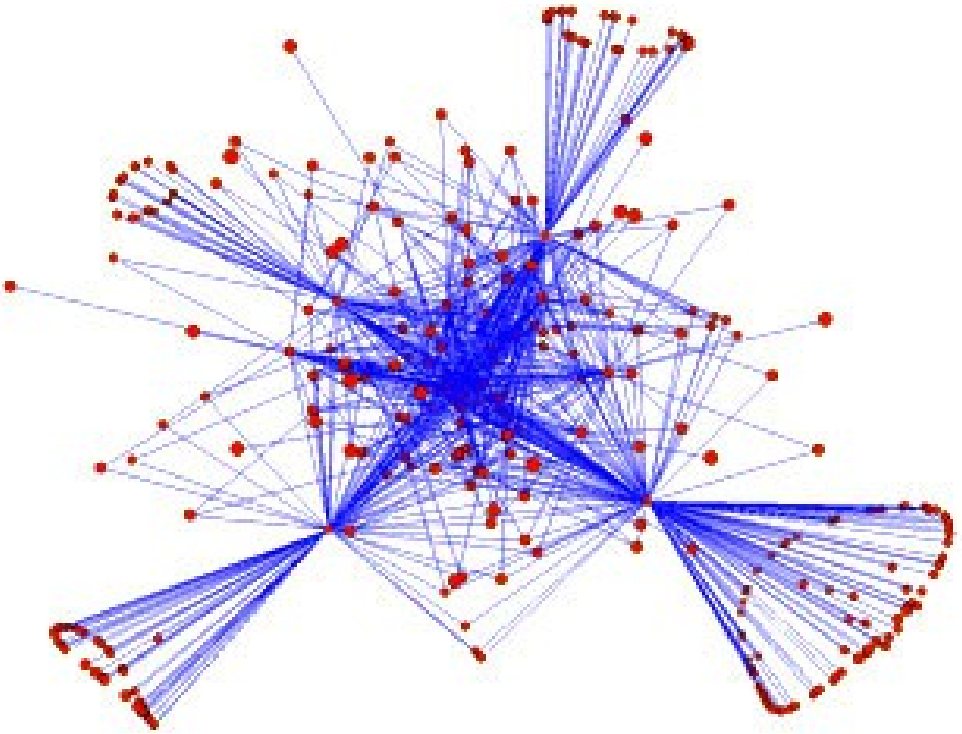




http://rulai.cshl.edu/TRED/GRN/p53.htm
https://www.ncbi.nlm.nih.gov/books/NBK22266
https://www2.le.ac.uk/projects/vgec/geneticsall/genes-chromosomes

Food webs

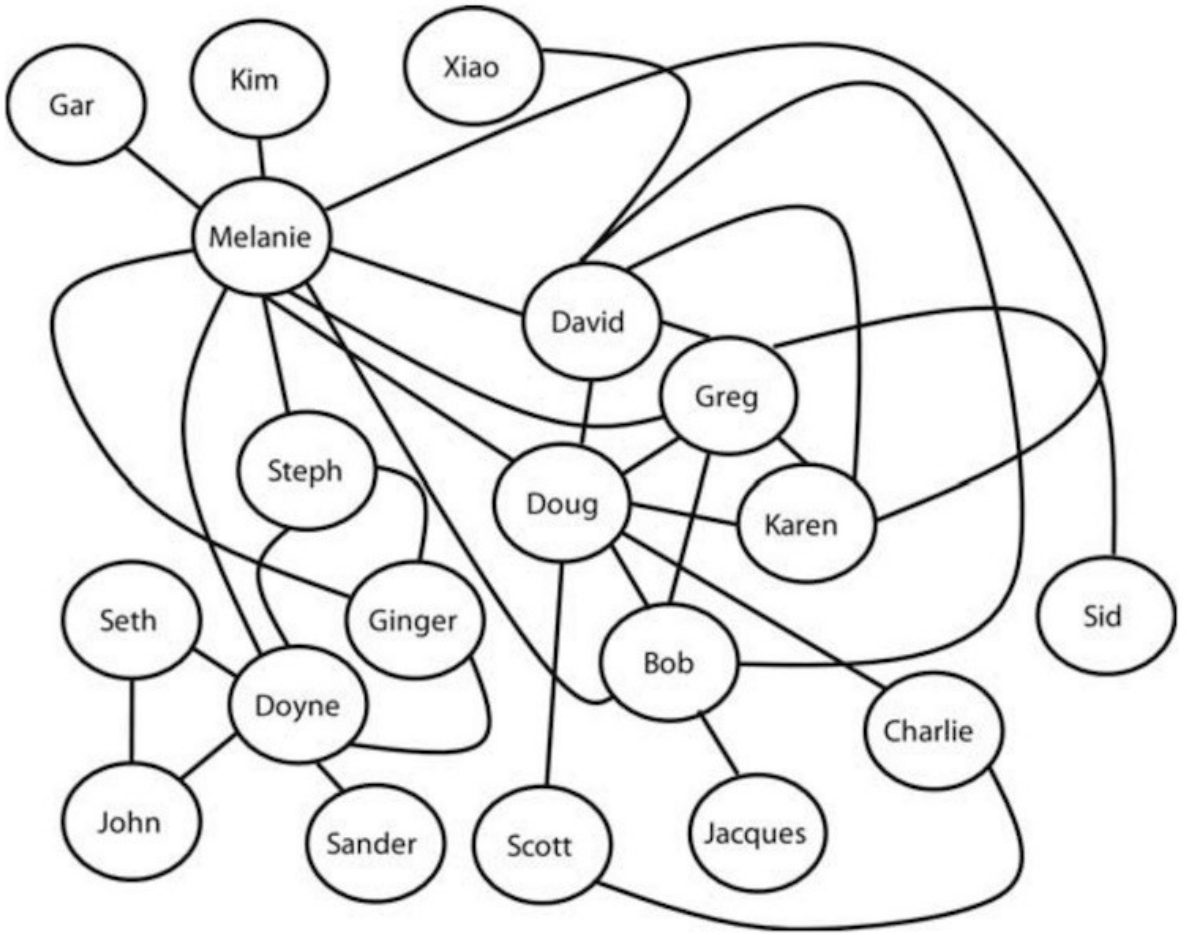




Alaskan marine food web

http://www.afsc.noaa.gov/Quarterly/jas2006/images/Gaichas_Feature.jpg
http://alaska.usgs.gov/science/biology/seabirds_foragefish/marinehabitat/images/Food_Web3.jpg

Social networks

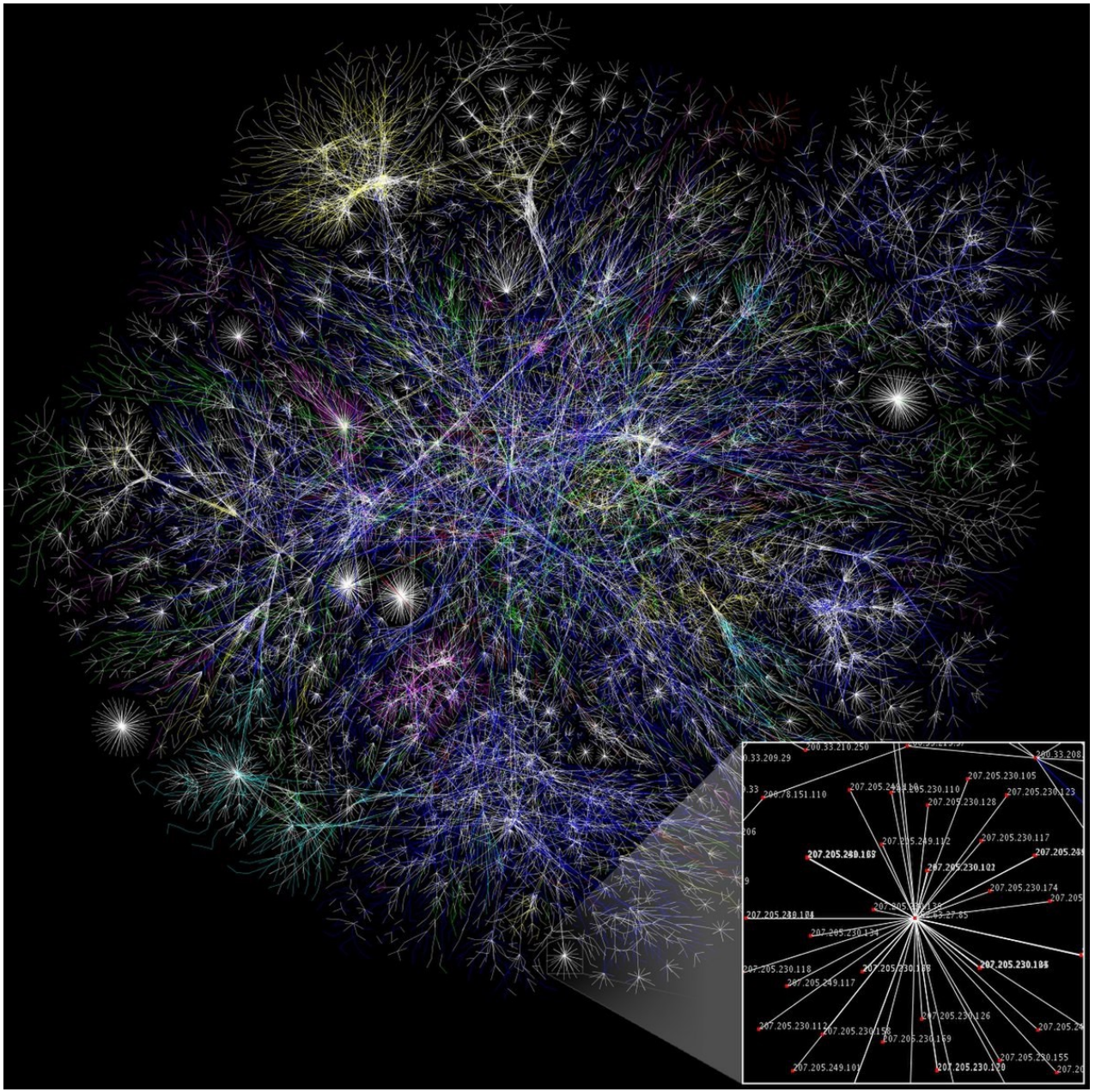


Social networks

Facebook “friend” links

www.facebook.com/note.php?note_id=469716398919

Map of the Internet (2005)



https://en.wikipedia.org/wiki/File:Internet_map_1024.jpg

How can we understand complex systems?

$$\nabla \cdot \mathbf{E} = 4\pi\rho$$

$$\nabla \times \mathbf{E} = -\frac{1}{c}\frac{\partial \mathbf{B}}{\partial t}$$

$$\nabla \cdot \mathbf{B} = 0$$

$$\nabla \times \mathbf{B} = \frac{4\pi}{c}\mathbf{J} + \frac{1}{c}\frac{\partial \mathbf{E}}{\partial t}$$

Theory

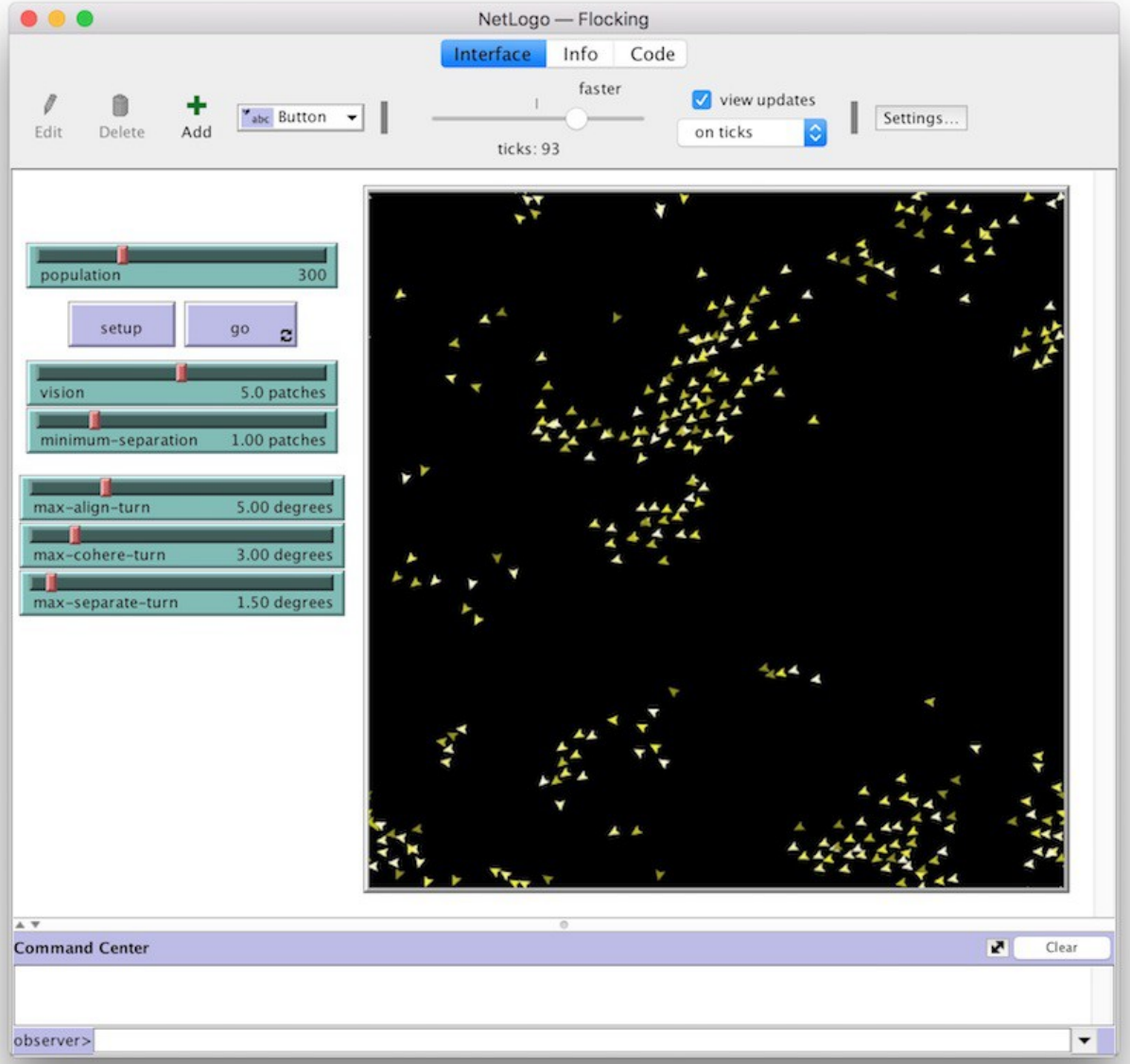
Observation and experiments

Computer modeling

How can we understand complex systems?

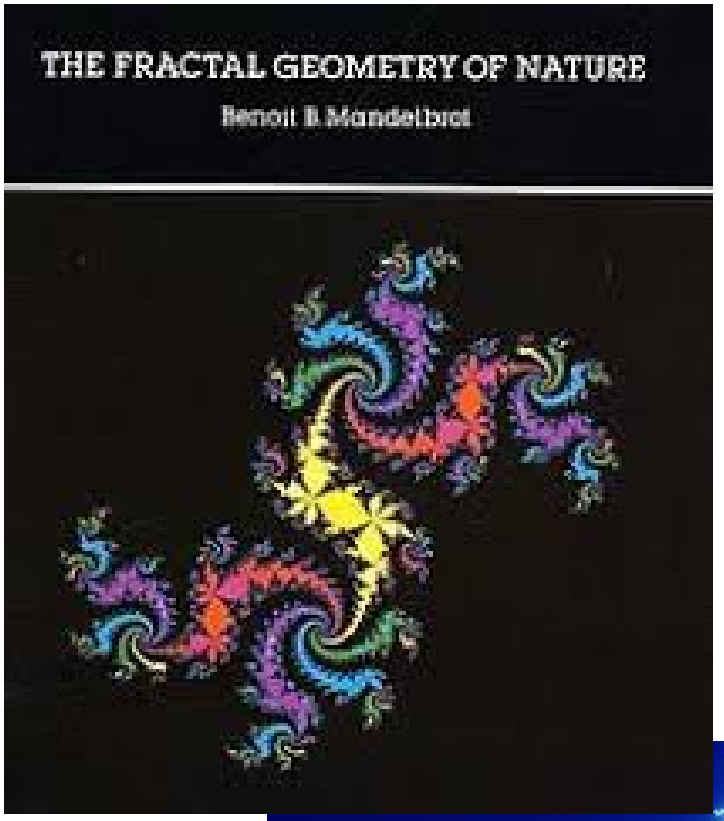
- **Reductionism**
  - Linear systems
  - Can be understood by analyzing each part in isolation
  - “The whole is equal to the sum of its parts”
  - Long tradition in Western science
- **Holism**
  - Nonlinear systems
  - “The whole is greater than the sum of its parts”

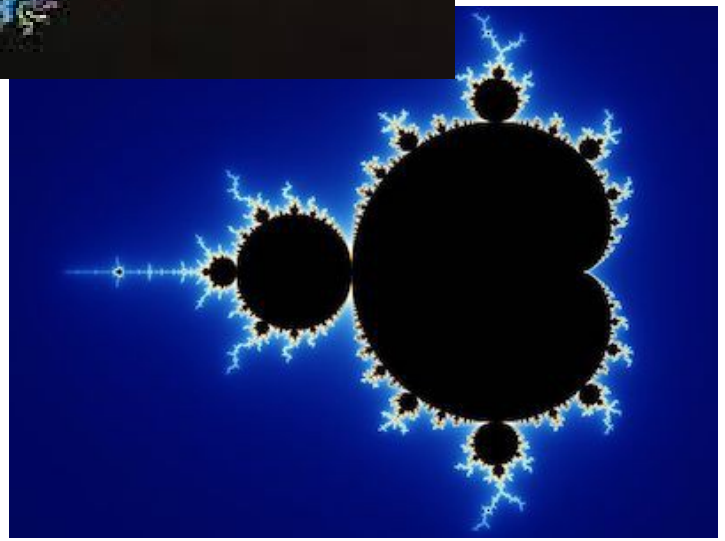
Computational modeling



NetLogo

Mathematical modeling





Benoit Mandelbrot (1924-2010)

“Clouds are not spheres, mountains are not cones, coastlines are not circles, and bark is not smooth, nor does lightning travel in a straight line.”

—Benoit Mandelbrot

“Clouds are not spheres, mountains are not cones, coastlines are not circles, and bark is not smooth, nor does lightning travel in a straight line.”

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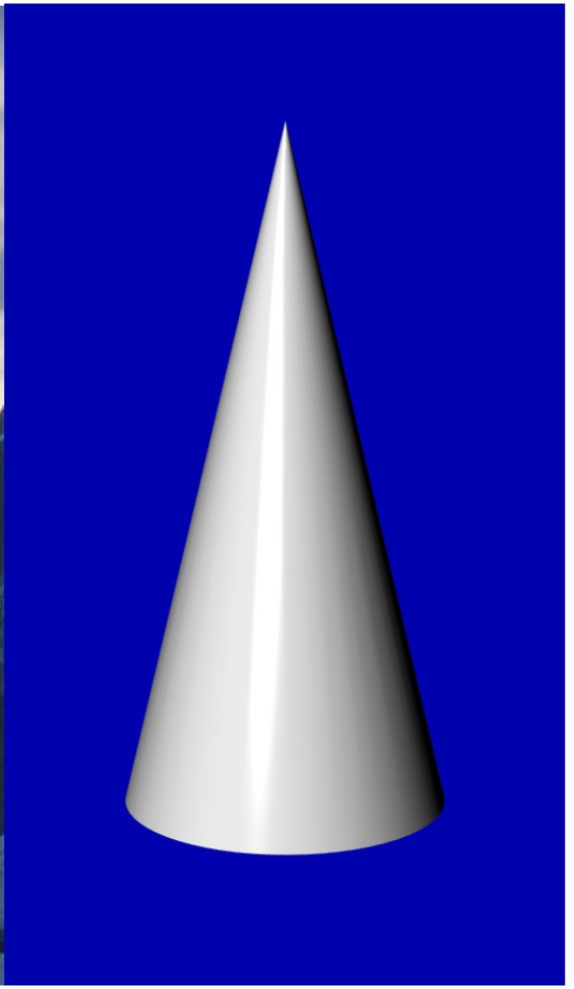

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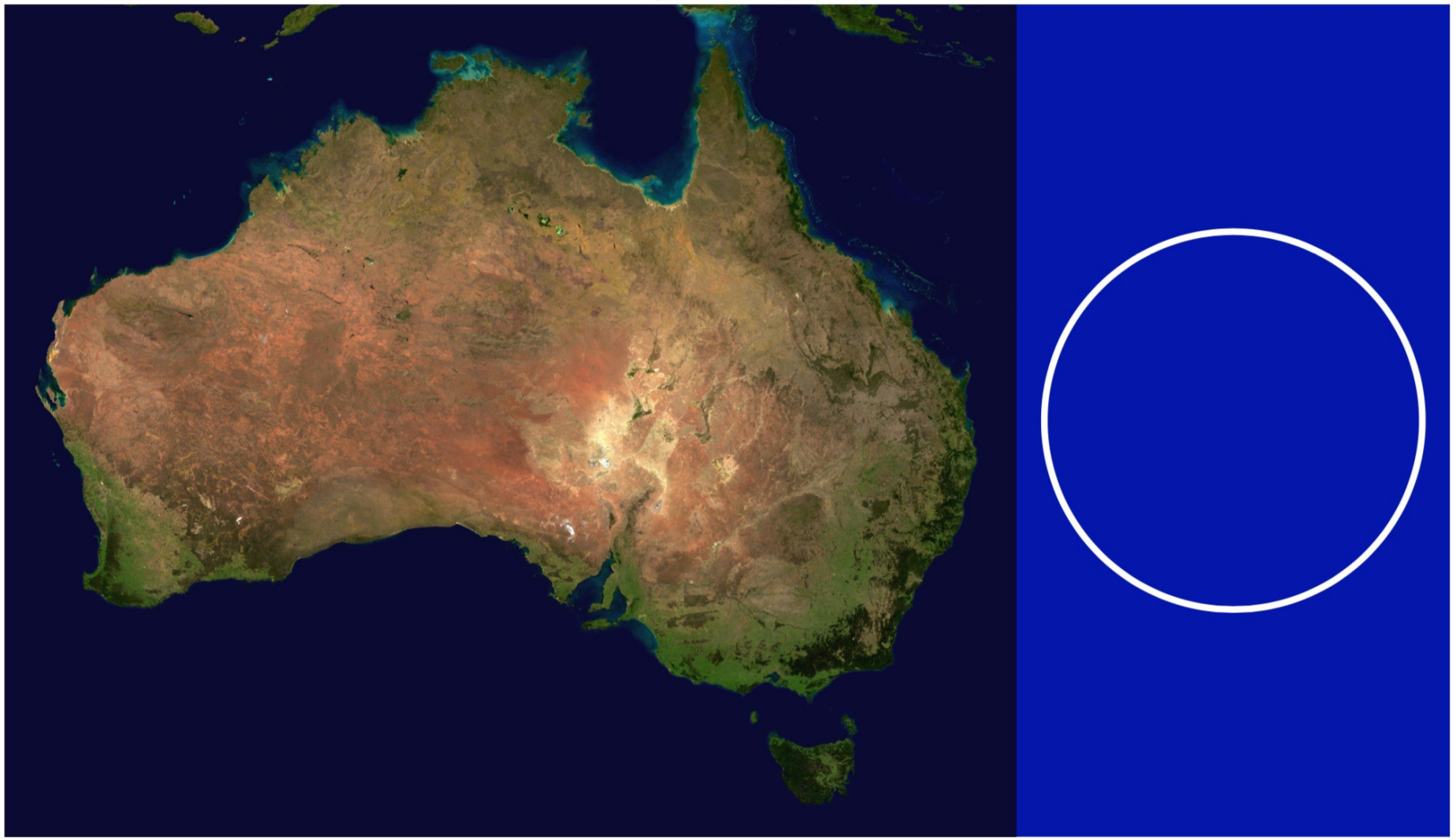

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“Clouds are not spheres, mountains are not cones, coastlines are not circles, and bark is not smooth, nor does lightning travel in a straight line.”

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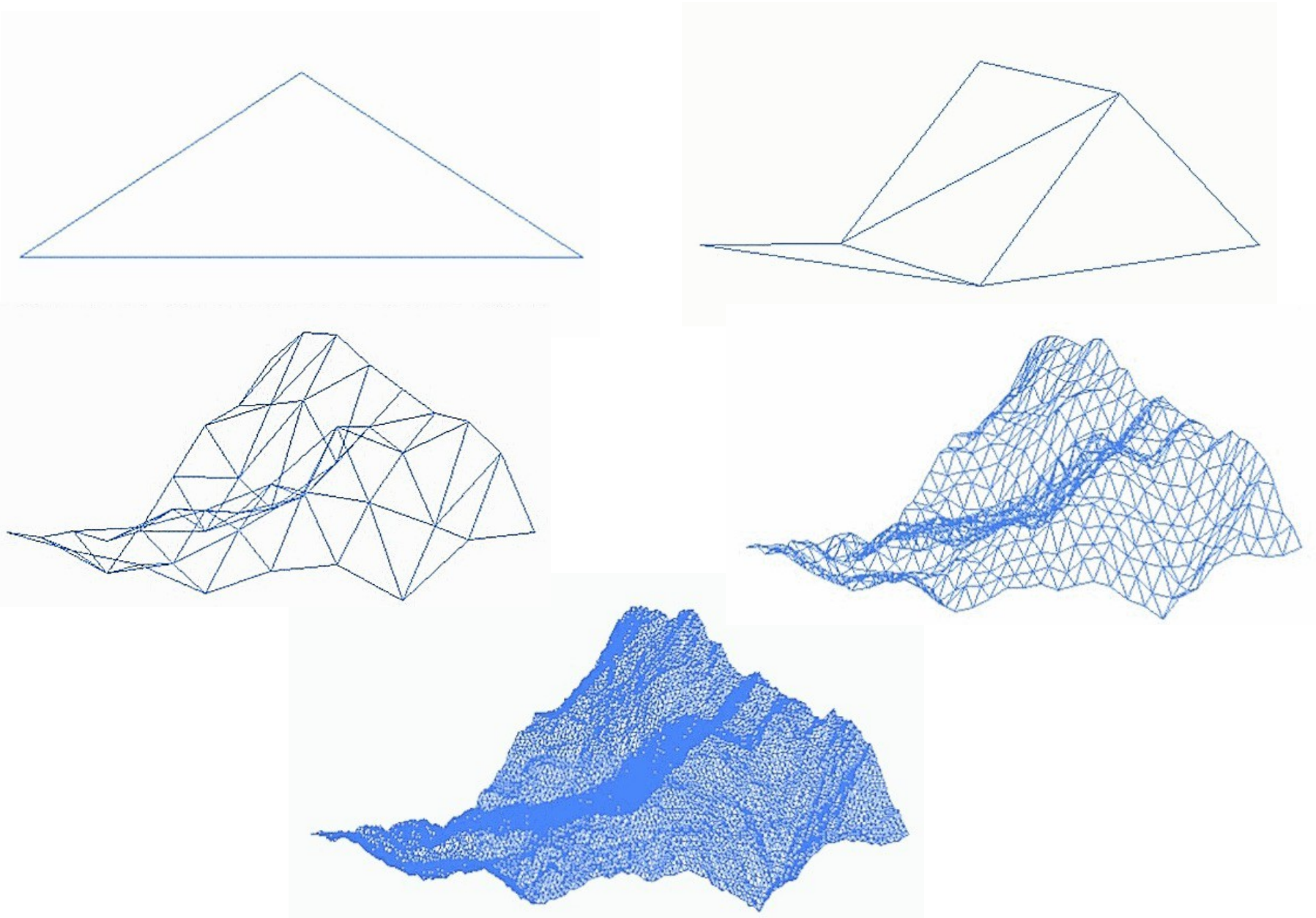
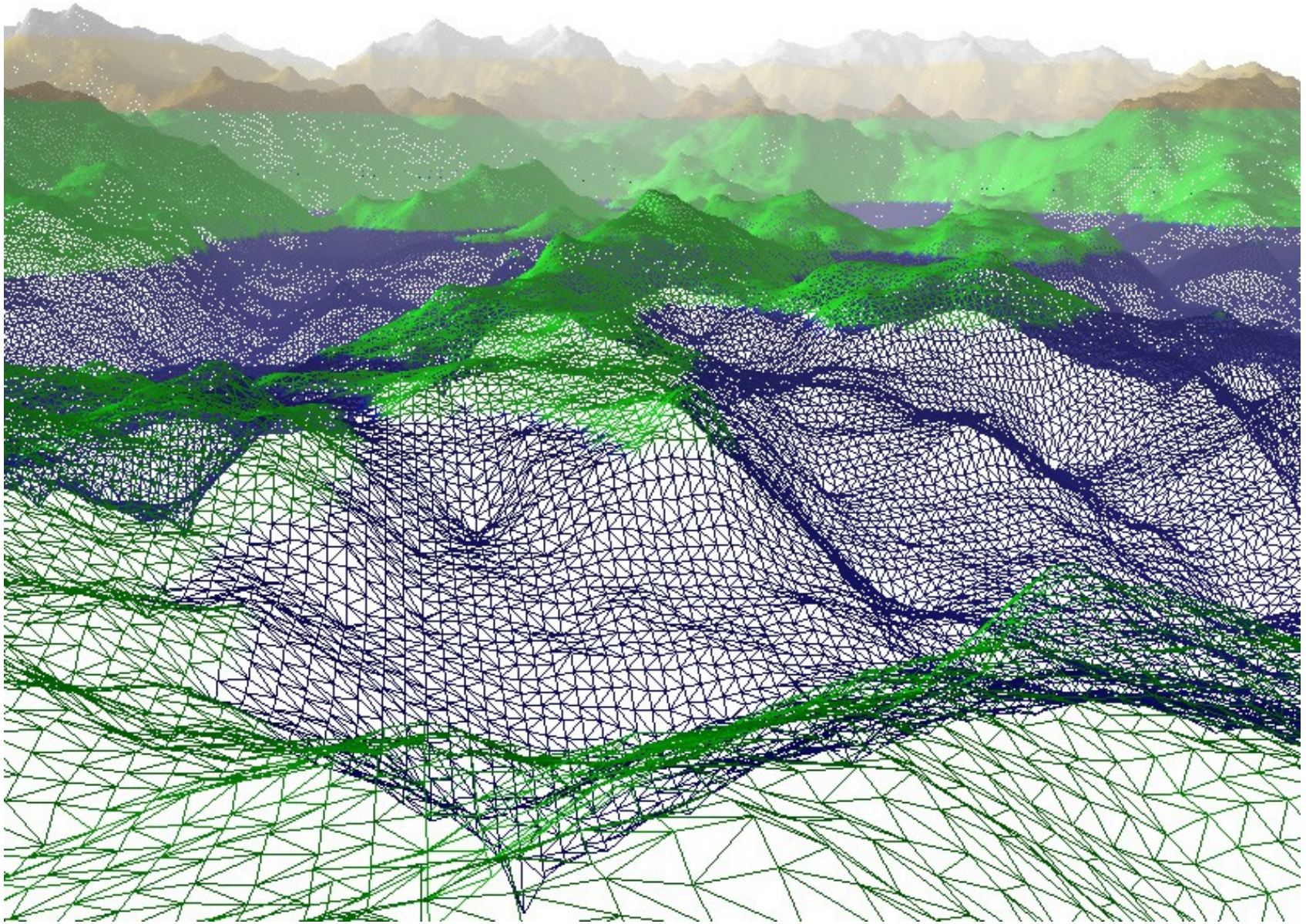
Fractal Geometry



https://en.wikipedia.org/wiki/Fractal_landscape#/media/File:Animated_fractal_mountain.gif

Fractal Geometry



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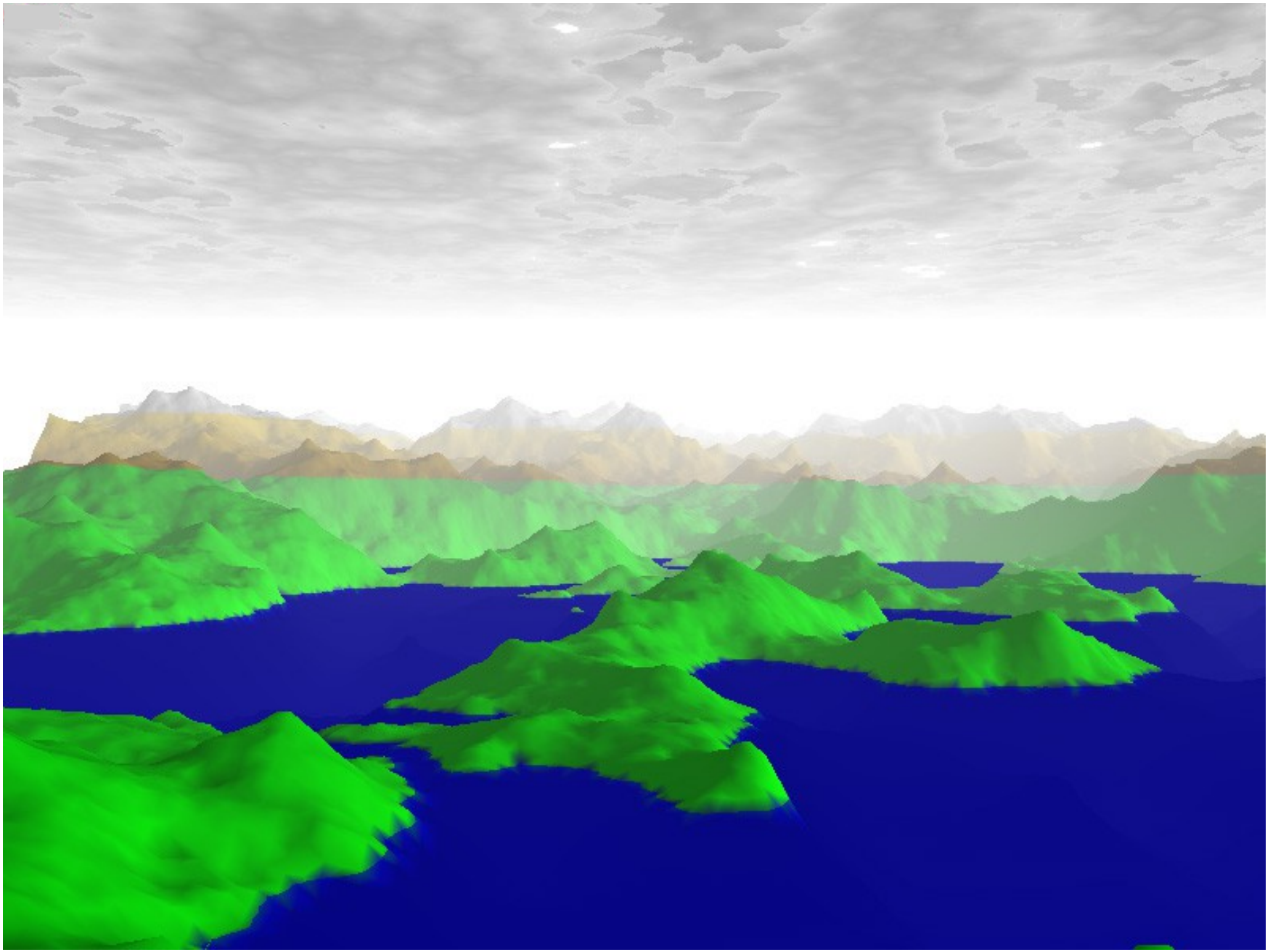
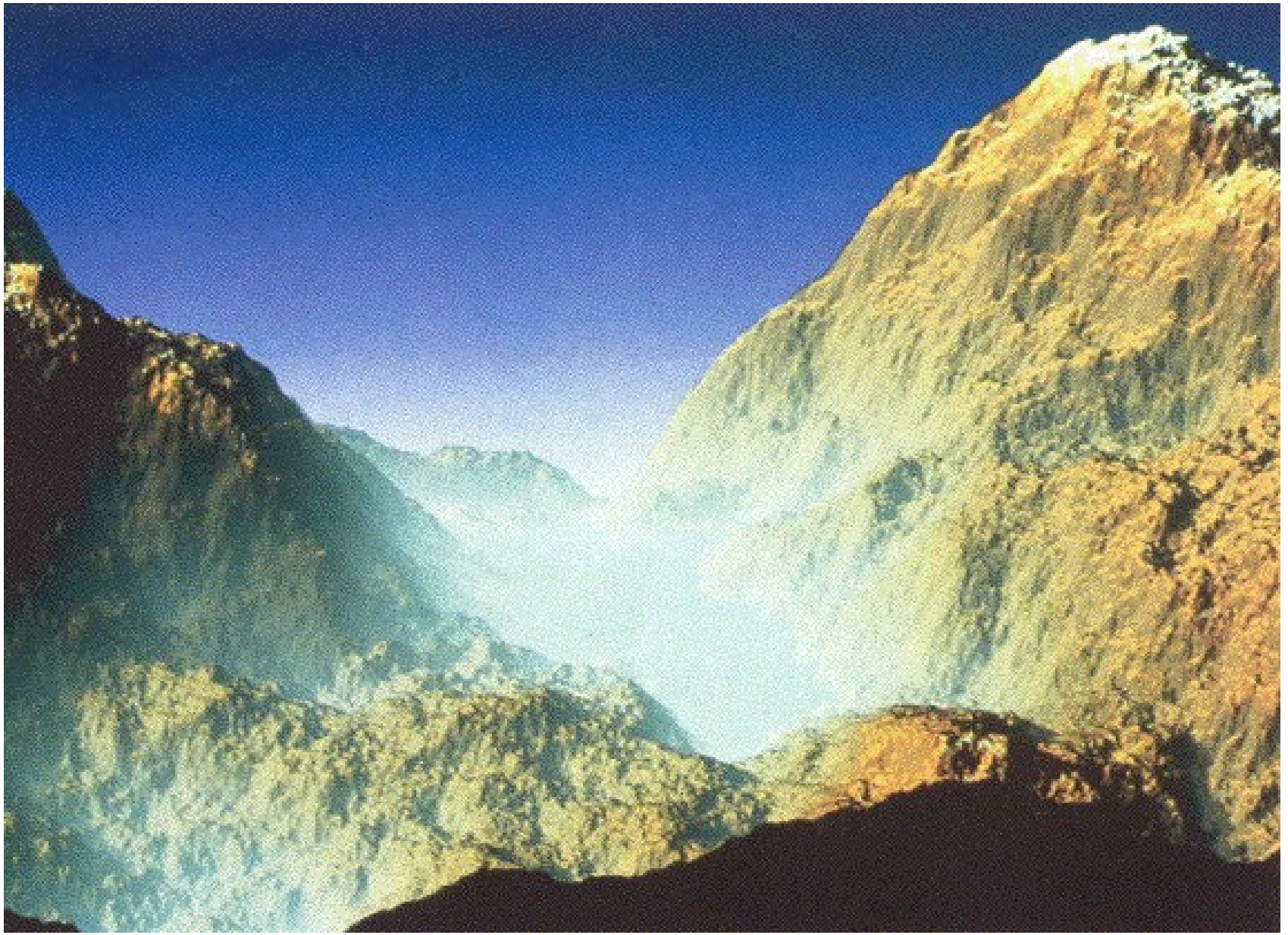
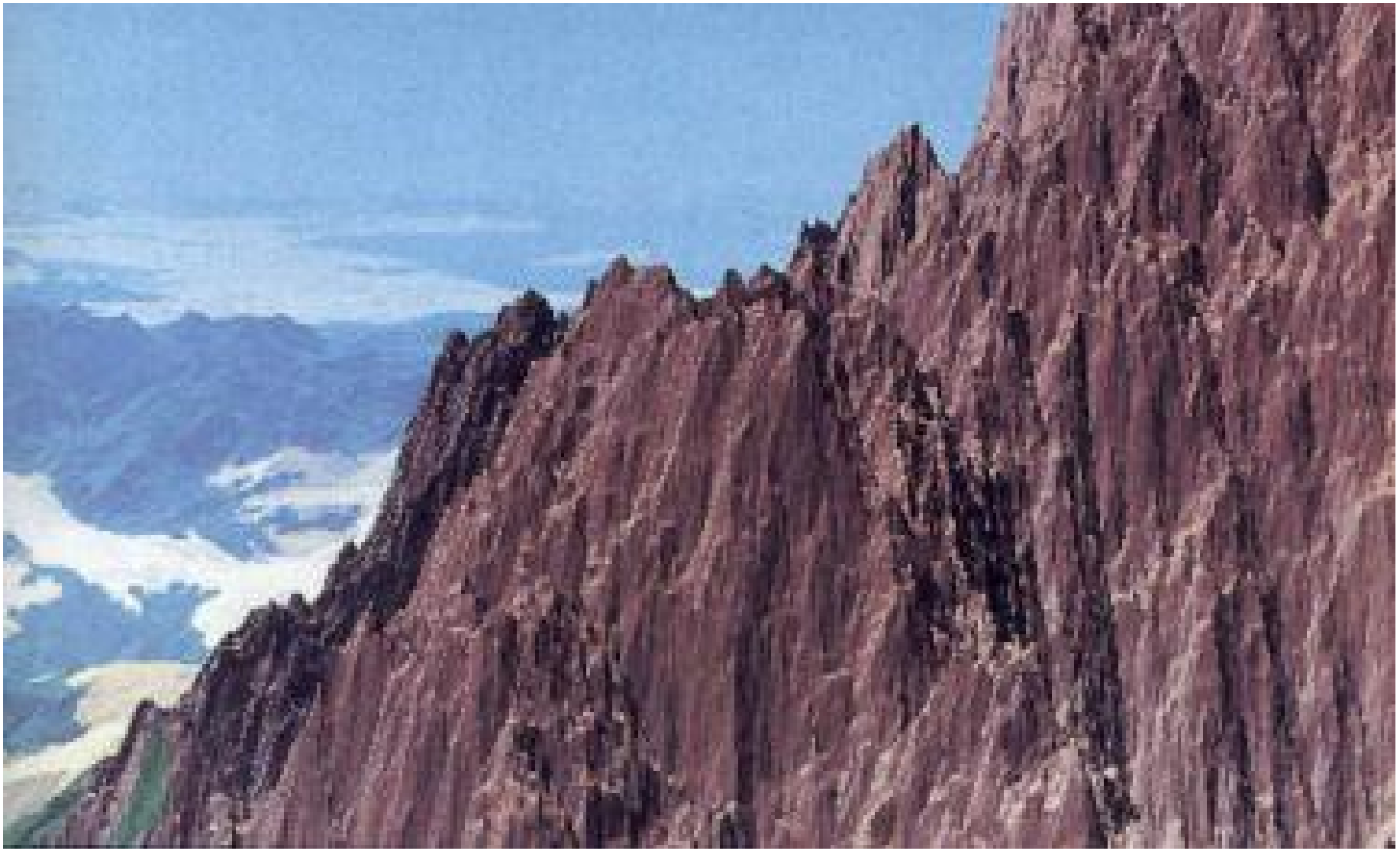


Fractal Geometry



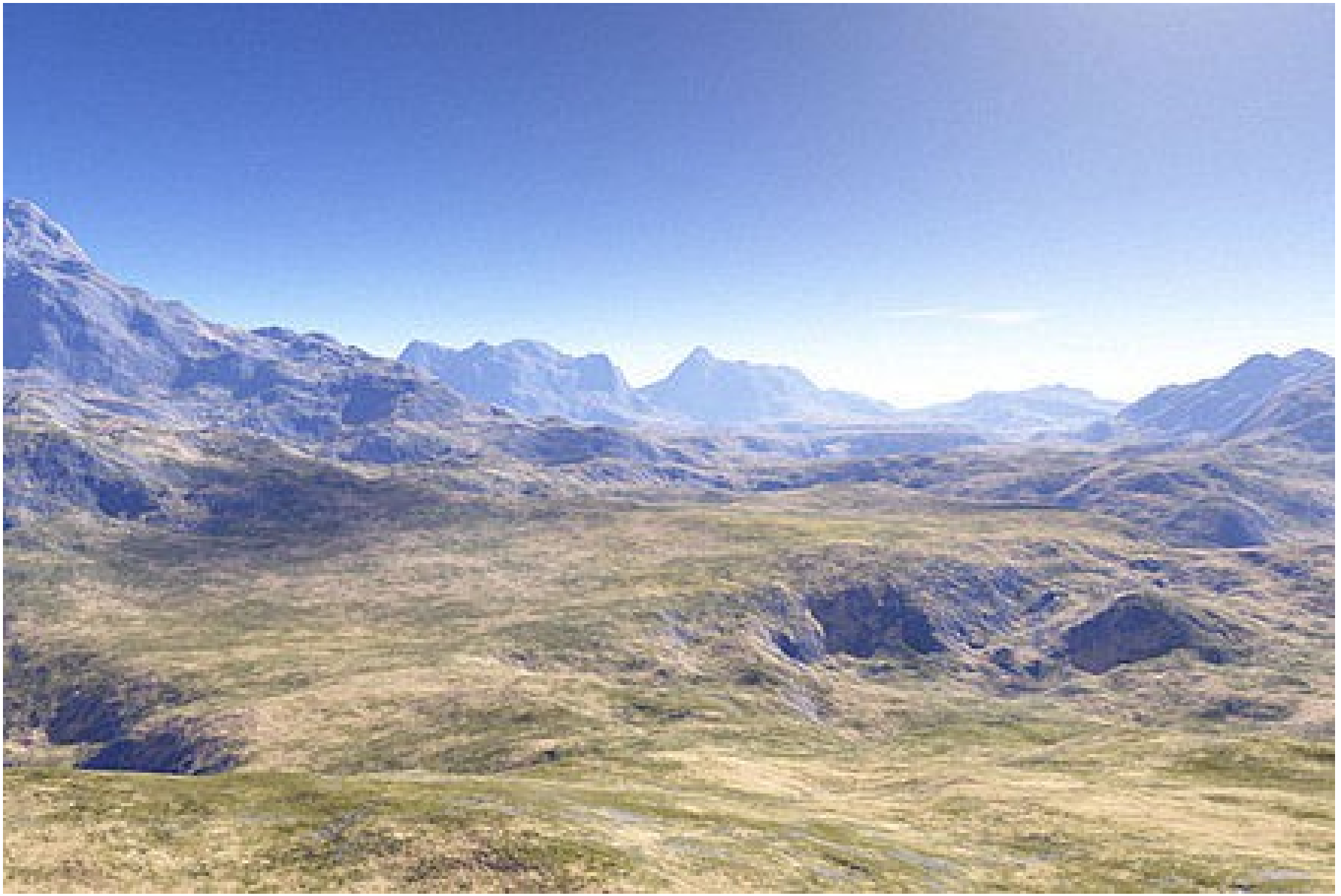
Fractal Geometry



Fractal Geometry

https://en.wikipedia.org/wiki/Fractal_landscape#/media/File:Fractal_terrain_texture.jpg

Fractal Geometry



https://en.wikipedia.org/wiki/Fractal_landscape#/media/File:FractalLandscape.jpg

Reading Assignment for Thursday

- **Preface** and **Chapter 1** of *Complexity: A Guided Tour*
- **Preface** and **Introduction (Chapter 1)** of *The Computational Beauty of Nature*
- Both books will be on reserve at the library
- No lab this week