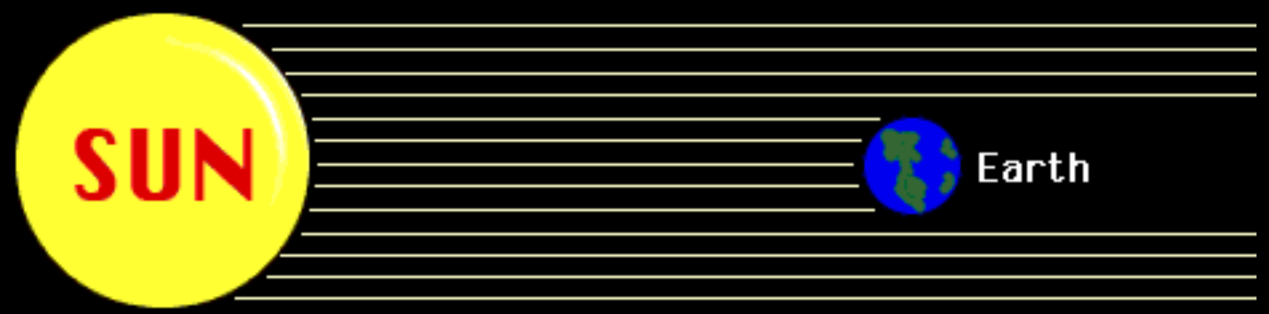
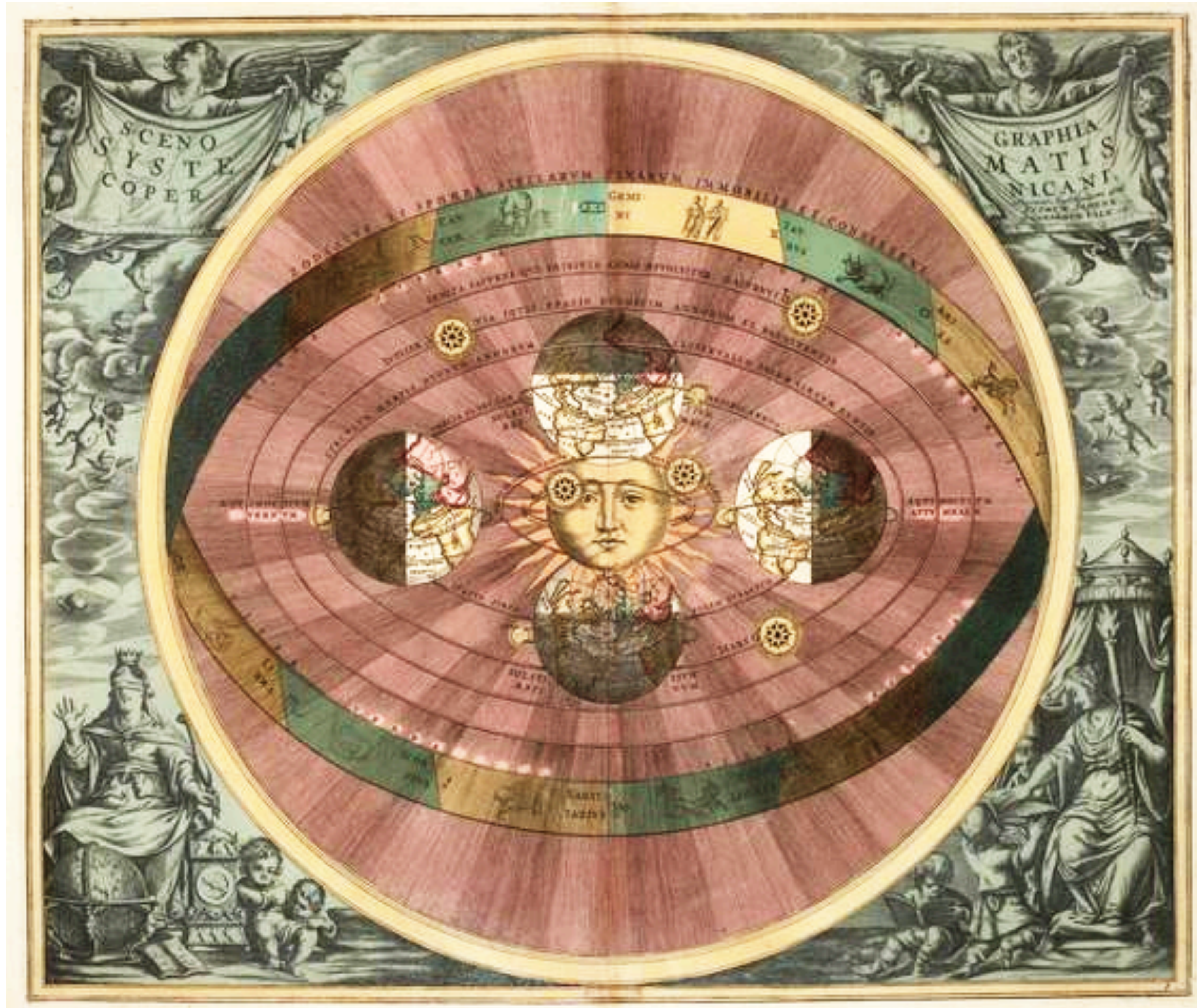
Introduction to Systems Theory

- Systems Theory
- Computation
- Cybernetics
- Equilibrium
- Feedback
- Complexity
- Adaptivity
- Emergence
- Robotics
- Algorithms: Fractals, L-Systems, Cellular Automata, Boids, BEAMS
- References

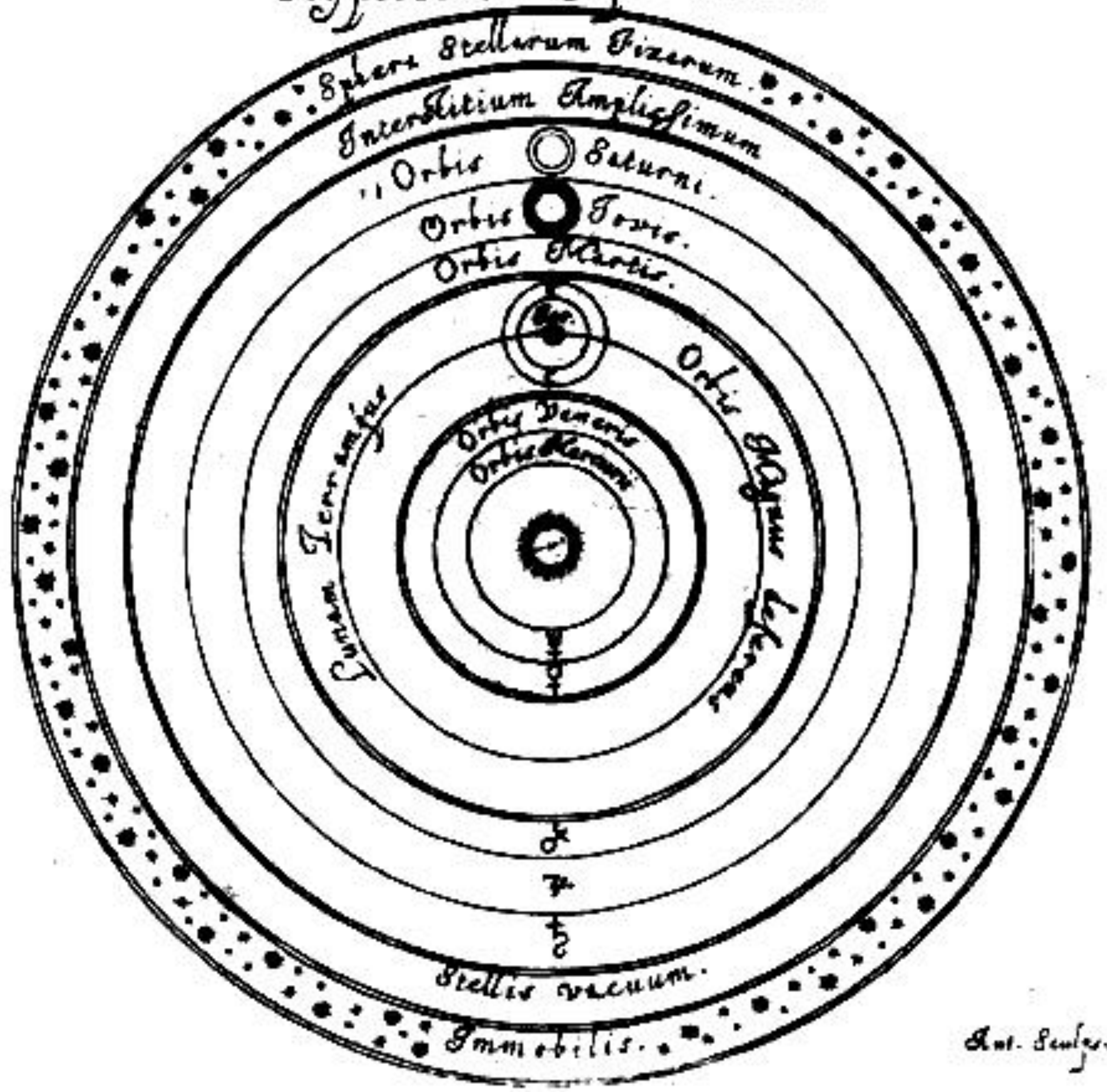
Systems Theory is the transdisciplinary study of the abstract organization of phenomena, independent of their substance, type, or spatial or temporal scale of existence. It investigates both the principles common to all complex entities, and the (usually mathematical) models which can be used to describe them.

The systems view was based on several fundamental ideas. First, all phenomena can be viewed as a web of relationships among elements, or asystem. Second, all systems, whether electrical, mechanical, biological, or social, have common patterns, behaviors, and properties that can be understood and used to develop greater insight into the behavior of complex phenomena and to move closer toward a unity of science. System philosophy, methodology and application are complementary to this science.


SUN
Earth


SCENO
SYSTE
COPER
GRAPHIA
MATIS
NICANI

Hypothesis Copernicana.



1. Systems have a structure that is defined by its parts and processes.
2. Systems are generalizations of reality.
3. Systems tend to function in the same way.
4. The various parts of a system have functional as well as structural relationships between each other.
5. The fact that functional relationships exist between the parts suggests the flow and transfer of some type of energy and/or matter.
6. Systems often exchange energy and/or matter beyond their defined boundary with the outside environment, and other systems, through various input and output processes.
7. Functional relationships can only occur because of the presence of a driving force.
8. The parts that make up a system show some degree of integration

Elements - are the kinds of parts (things or substances) that make up a system.

Attributes - are characteristics of the elements that may be perceived and measured.

Relationships - are the associations that occur between elements and attributes.

Isolated System - a system that has no interactions beyond its boundary layer.

Closed System - is a system that transfers energy, but not matter, across its boundary to the surrounding environment.

Open System - is a system that transfers both matter and energy can cross its boundary to the surrounding environment.

Morphological System - this is a system where we understand the relationships betweenelements and their attributes in a vague sense based only on measured features or correlations. In other words, we understand the form or morphology a system has based on the connections between its elements. We do not understand exactly how the processes work to transfer energy and/or matter through the connections between the elements.

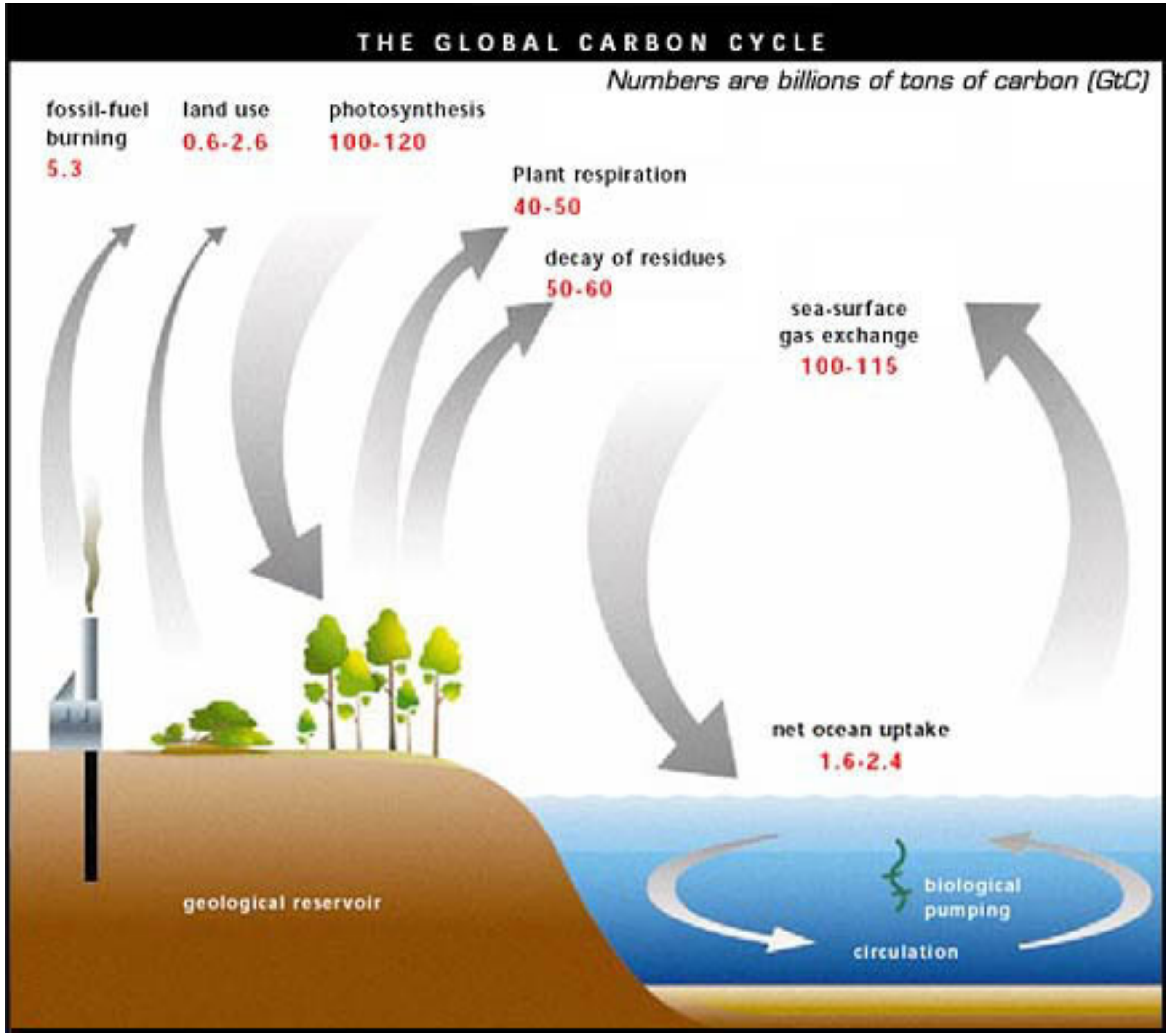
Cascading System - this is a system where we are primarily interested in the flow of energy and/or matter from one element to another and understand the processes that cause this movement. In a cascading system, we do not fully understand quantitative relationships that exist between elements related to the transfer of energy and/or matter.

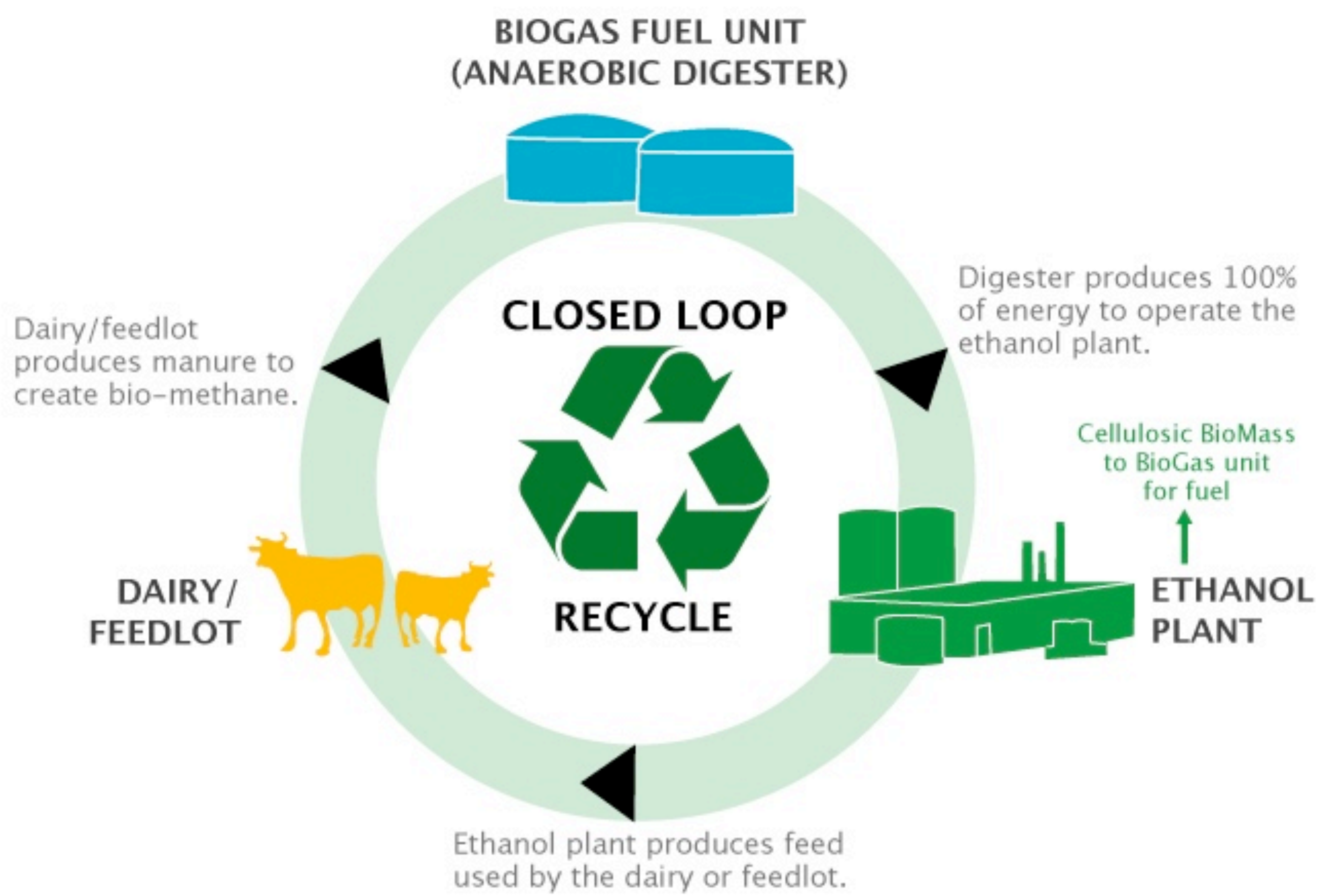
Process-Response System - this is a system that integrates the characteristics of both morphological and cascading systems. In a process-response system, we can model the processes involved in the movement, storage, and transformation of energy and/or matter between system elements and we fully understand how the form of the system in terms of measured features and correlations.

Control System - a system that can be intelligently manipulated by the action of humans.

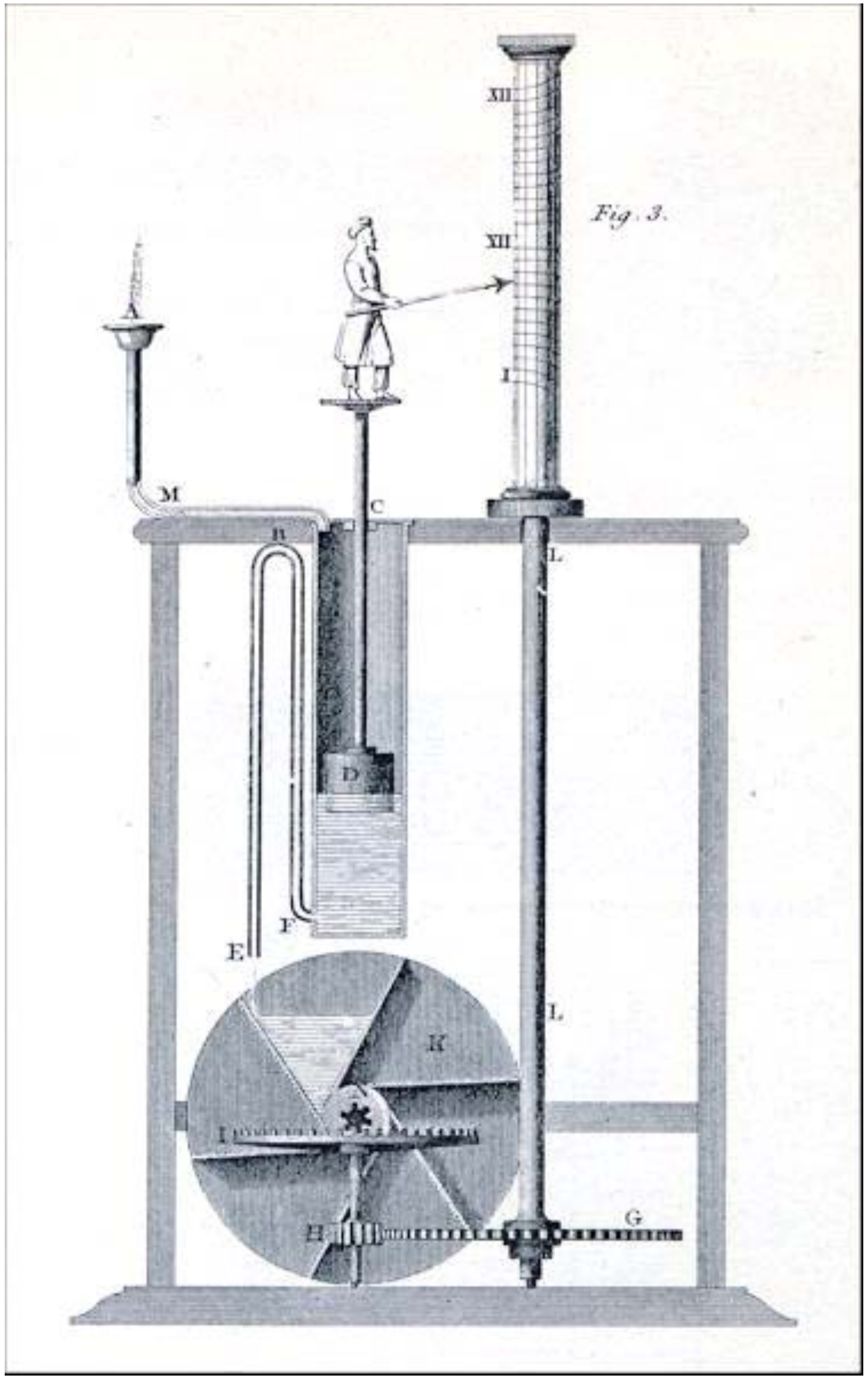
Ecosystem - is a system that models relationships and interactions between the various biotic and abiotic components making up a community or organisms and their surroundng physical environment.

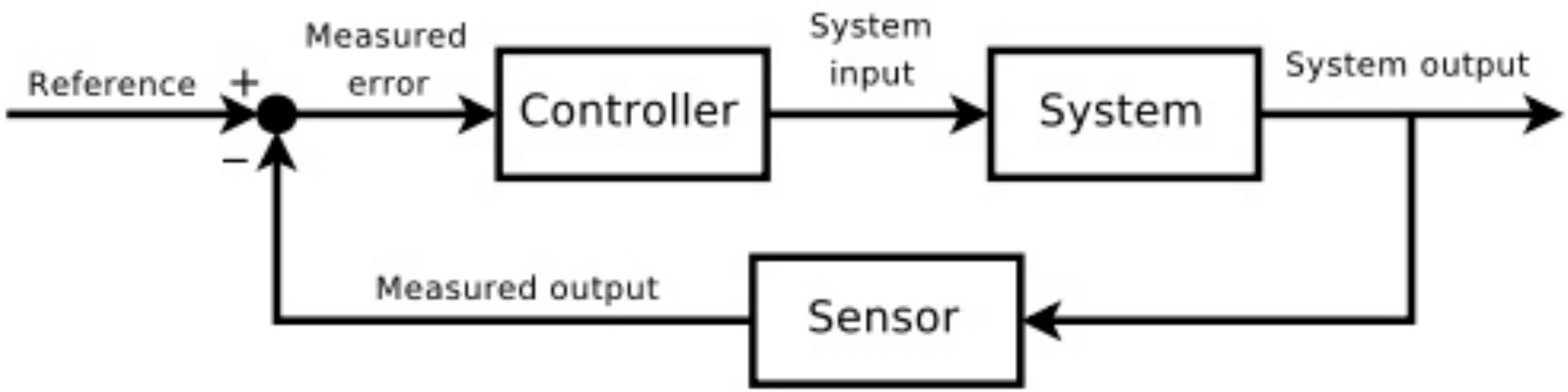
In this lecture the word *systems* is used to refer specifically to *self-regulating systems*, i.e. that are self-correcting through feedback. Self-regulating systems are found in nature, including the physiological systems of our body, in local and global ecosystems, and in climate.


THE GLOBAL CARBON CYCLE
Numbers are billions of tons of carbon (GtC)
fossil-fuel burning
5.3
land use
0.6-2.6
photosynthesis
100-120
Plant respiration
40-50
decay of residues
50-60
sea-surface gas exchange
100-115
net ocean uptake
1.6-2.4
geological reservoir
biological pumping
circulation

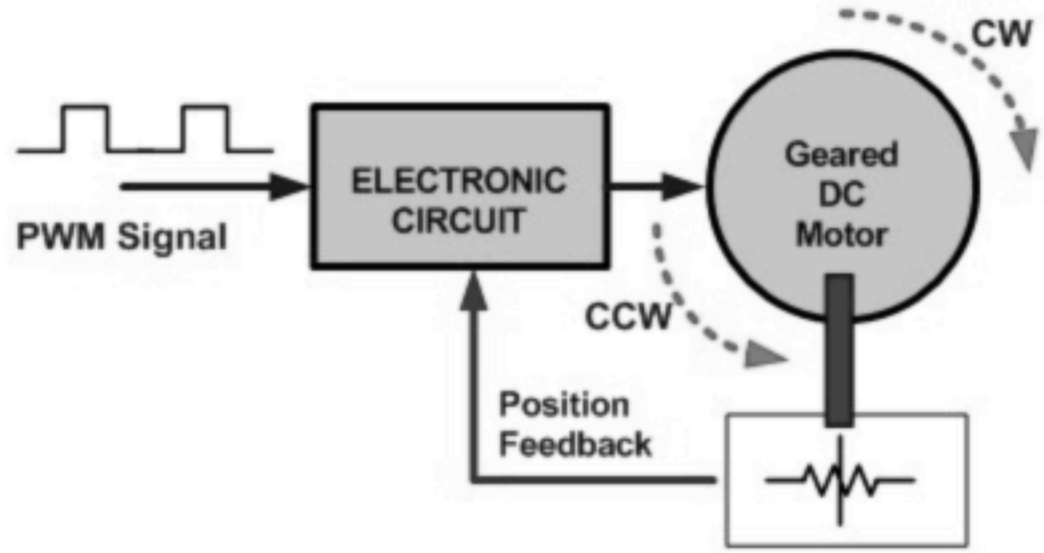

BIOGAS FUEL UNIT
(ANAEROBIC DIGESTER)
Digester produces 100% of energy to operate the ethanol plant.
CLOSED LOOP
Dairy/feedlot produces manure to create bio-methane.
Cellulosic BioMass to BioGas unit for fuel
DAIRY/ FEEDLOT
RECYCLE
ETHANOL PLANT
Ethanol plant produces feed used by the dairy or feedlot.

Feedback is a mechanism, process or signal that is looped back to control a system within itself. Such a loop is called a *feedback loop*. In systems containing an input and output, feeding back part of the output so as to increase the input is positive feedback (regeneration); feeding back part of the output in such a way as to partially oppose the input is negative feedback (degeneration).


XII
Fig. 3.
XII
I
A
M
C
B
L
D
E
F
L
K
I
H
G


Reference
+
−
Measured
error
Controller
System
input
System
System output
Measured output
Sensor

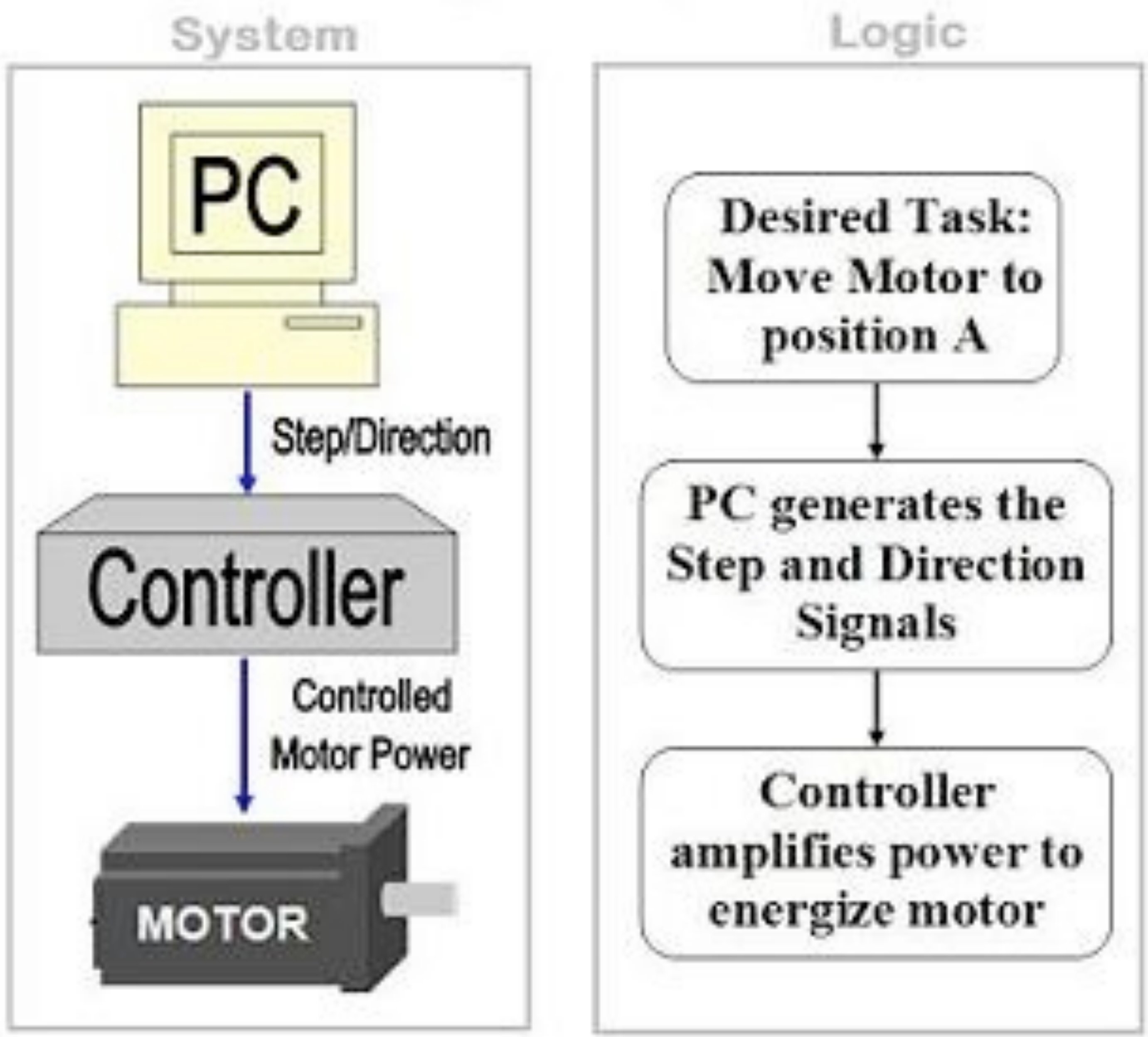
Typical Servo Motor



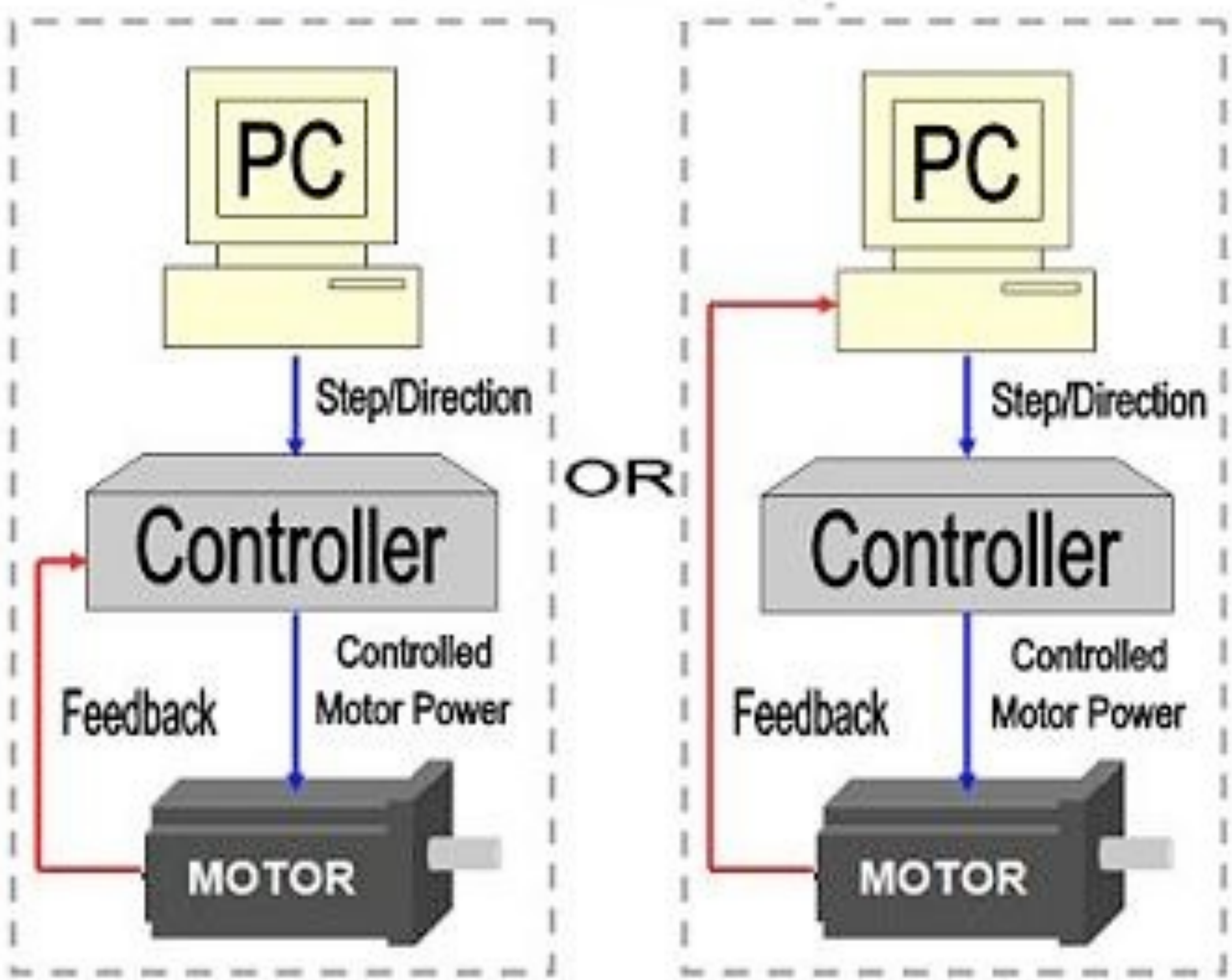
Servo Motor Block Diagram

The Servo Motor

Open Loop


System
Logic
PC
Step/Direction
Controller
Controlled
Motor Power
MOTOR
Desired Task:
Move Motor to
position A
PC generates the
Step and Direction
Signals
Controller
amplifies power to
energize motor

Closed Loop


PC
Step/Direction
Controller
Controlled
Motor Power
Feedback
MOTOR
OR
PC
Step/Direction
Controller
Controlled
Motor Power
Feedback
MOTOR

Cybernetics is most applicable when the system being analysed is involved in a *closed signal loop*; that is, where action by the system causes some change in its environment and that change is fed to the system via information (*feedback*) that causes the system to adapt to these new conditions: the system's changes affect its behavior. This *circular causal* relationship is necessary and sufficient for a cybernetic perspective

The roots of the application of control theory or feedback in engineering reach far back; so too, it was noticed by certain biologists that control or the maintenance of equilibrium is one of the basic properties of life. However, the unifying theory of control and communication as applicable both to living systems and to machines built by man was first generally recognized only in 1948 with the publication of Wiener's book *Cybernetics, or Control and Communication in the Animal and the Machine*.

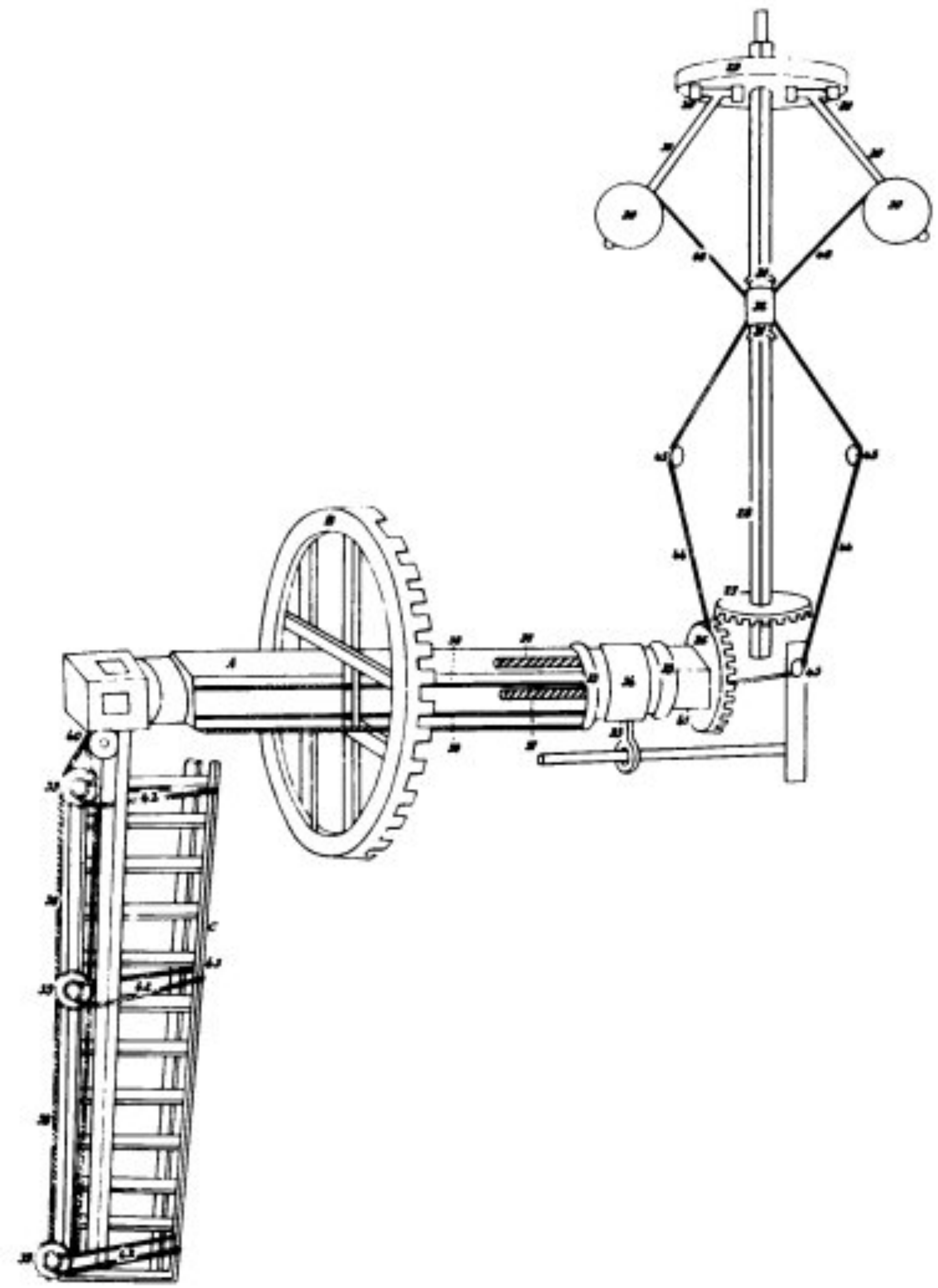


Fig. 1. Original figure from T. Mead, patent no. 1628,1787: ‘A regulator on a new principle for wind and other mills, for the better and more regular furling and unfurling of the sails on windmills without the constant attendance of a man, and for grinding corn and other grain, and dressing of flour and meal, superior in quality to the present practice, and for regulating all kind of machinery where the first power is unequal.’ Right up one sees a speed regulator. During rotation centrifugal forces will lift the two spherical weights. They pull on strings which then furl the sails so that the effective area exposed to the wind is reduced.

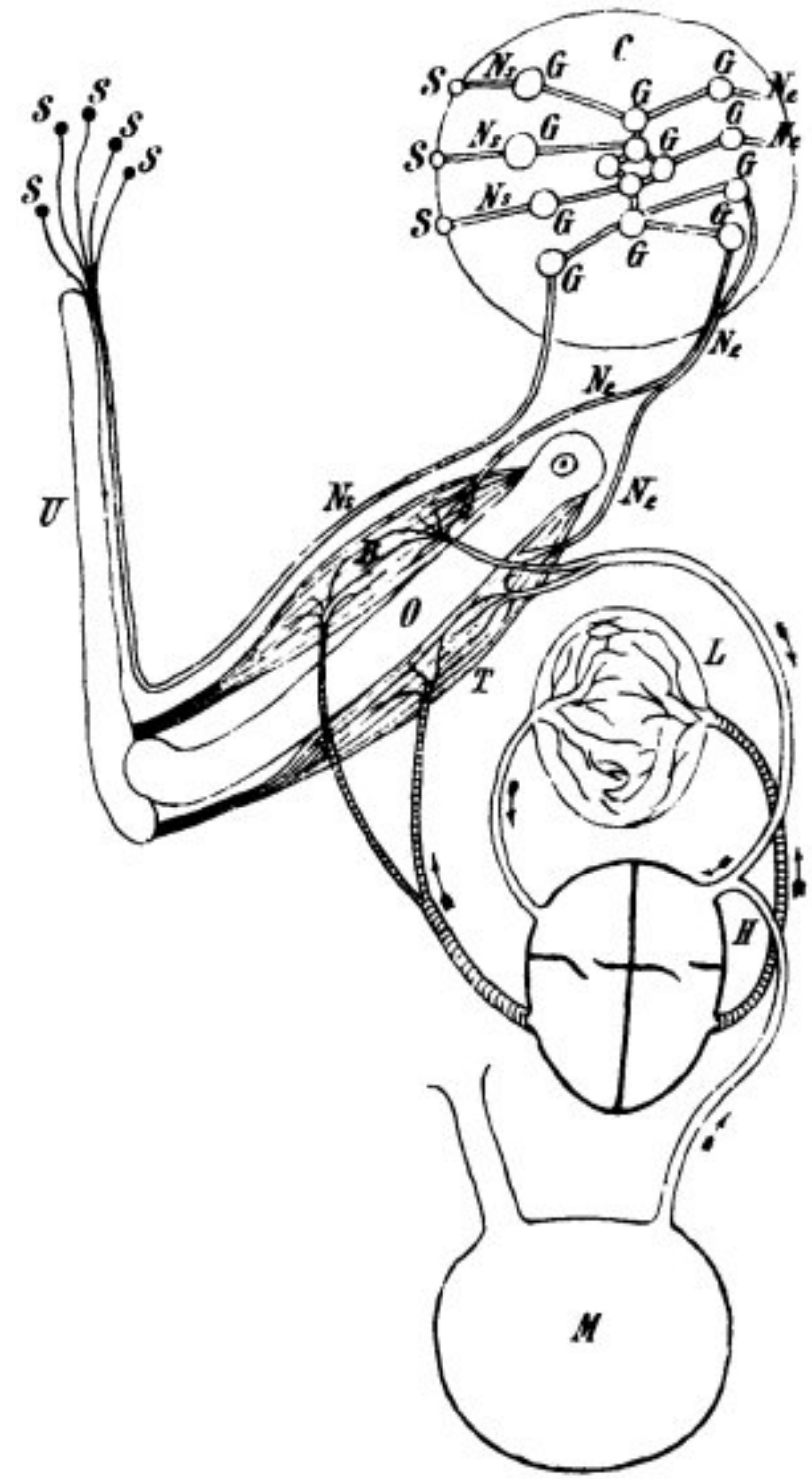
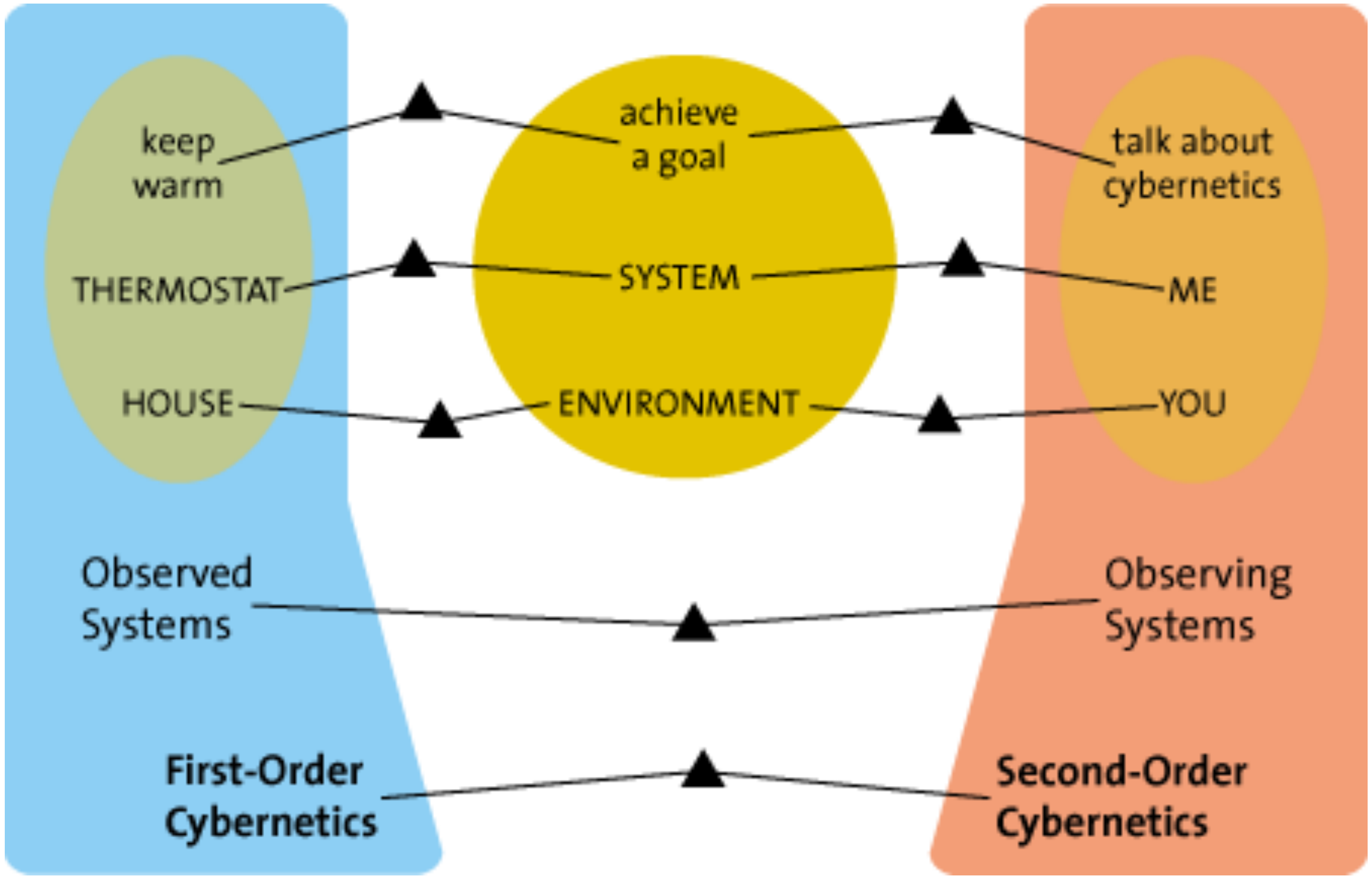
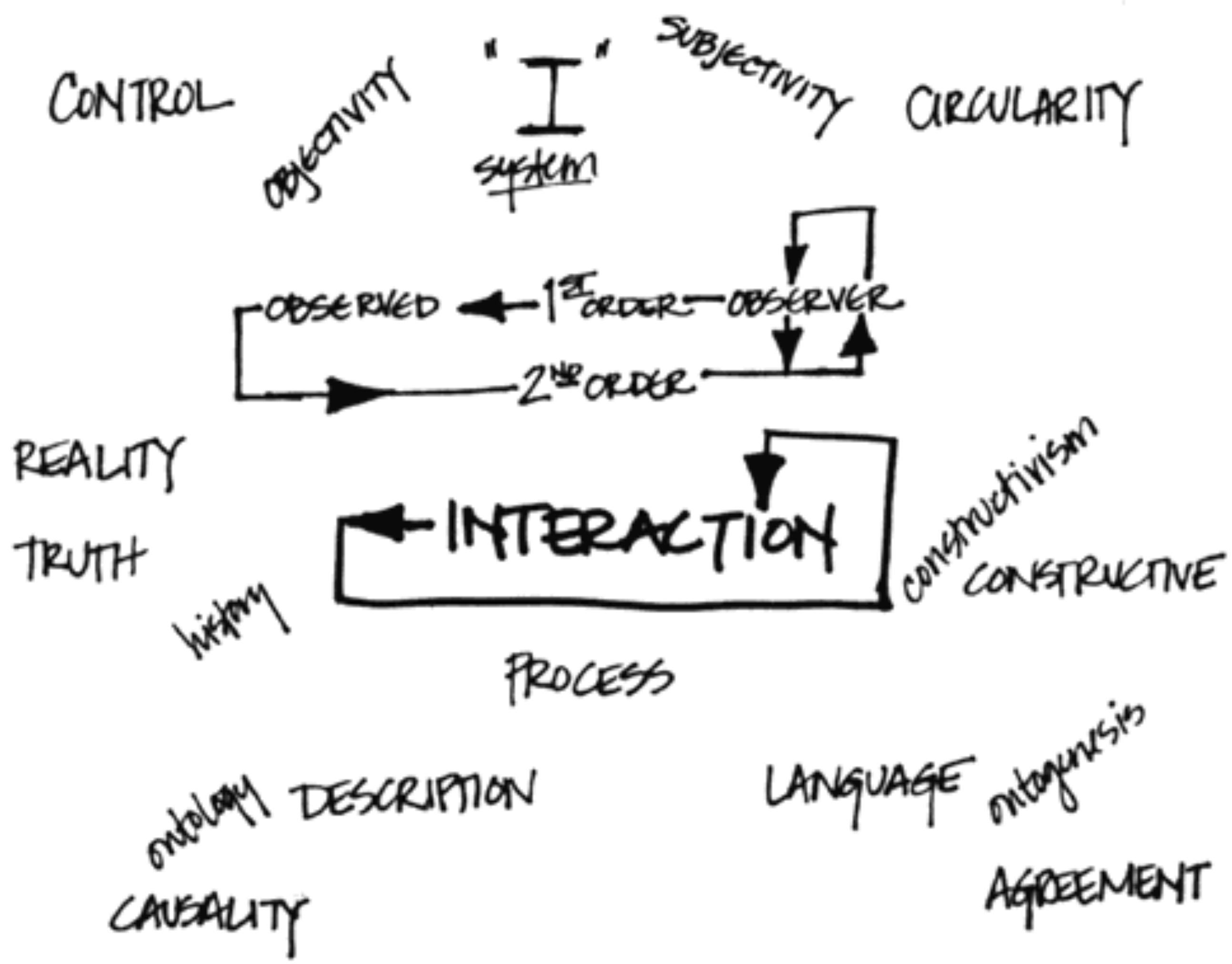


Fig. 2. Original figure from F. Lincke: 'Das mechanische Relais' (the mechanical relay), ***VDI Zeitschrift***, 23, 509–24, 577–616 (1879). The 'indicators' are sensory nerves (***S***, ***Ns***), the 'executive' organ (motor nerves ***Ne*** and muscle ***B***), the 'transmitter' (brain with ganglion cells ***G***), and the 'motor' (stomach ***M***, heart ***H***, lung ***L***). 'The activity we use to direct our human "machine" to its goal results from the difference between the will and the observed or imagined reality, i.e. the difference between the intention and the result of the execution.'


keep warm
THERMOSTAT
HOUSE
achieve a goal
SYSTEM
ENVIRONMENT
talk about cybernetics
ME
YOU
Observed Systems
Observing Systems
First-Order Cybernetics
Second-Order Cybernetics


CONTROL
OBJECTIVITY
"I"
system
SUBJECTIVITY
CIRCULARITY
OBSERVED
1ST ORDER
OBSERVER
2ND ORDER
REALITY
TRUTH
history
INTERACTION
constructivism
CONSTRUCTIVE
PROCESS
ontology
DESCRIPTION
LANGUAGE
ontogenesis
CAUSALITY
AGREEMENT

Equilibrium describes the average condition of a system, as measured through one of its elements or attributes, over a specific period of time. There are six types of equilibrium:

(1) Steady state equilibrium is an average condition of a system where the ***trajectory*** remains unchanged in time.

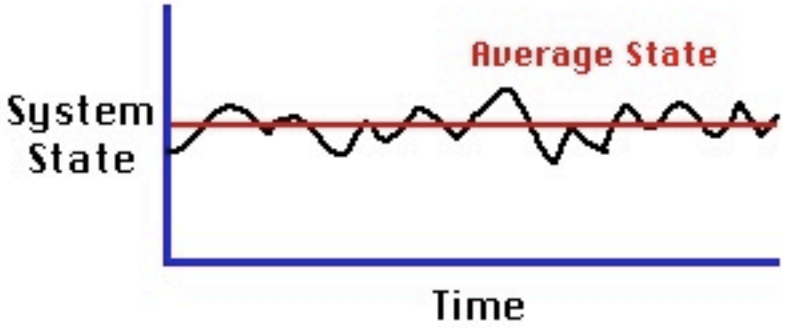


Figure 4f-1: Example of the state of a steady state equilibrium over time.

(2) Thermodynamic equilibrium describes a condition in a system where the distribution of mass and energy moves towards maximum **entropy**.

Figure 4f-2: Example of the state of a thermodynamic equilibrium over time.

(3) A **dynamic equilibrium** occurs when there are unrepeated average states through time.

Figure 4f-3: Example of the state of a dynamic equilibrium over time.

(4) Static equilibrium occurs where force and reaction are balanced and the properties of the system remain unchanged over time.

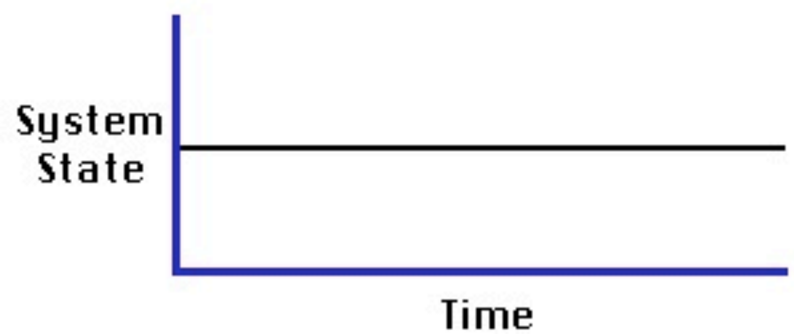


Figure 4f-4: Example of the state of a static equilibrium over time.

(5) In a **stable equilibrium** the system displays tendencies to return to the same equilibrium after **disturbance**.

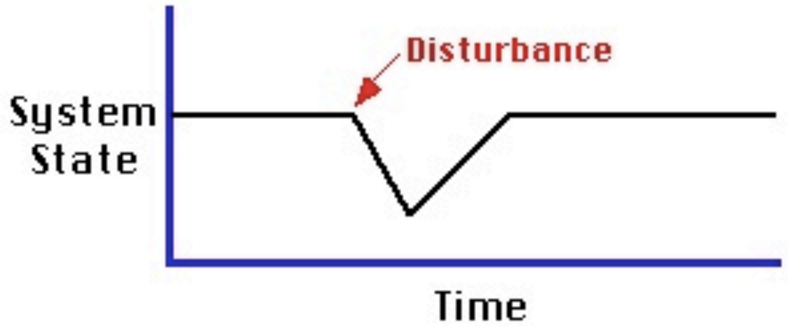


Figure 4f-5: Example of the state of a stable equilibrium over time.

(6) In an **unstable equilibrium** the system returns to a new equilibrium after **disturbance**.

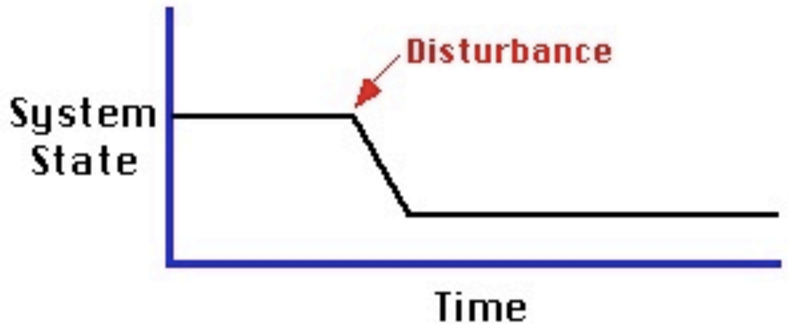


Figure 4f-6: Example of the state of an unstable equilibrium over time.

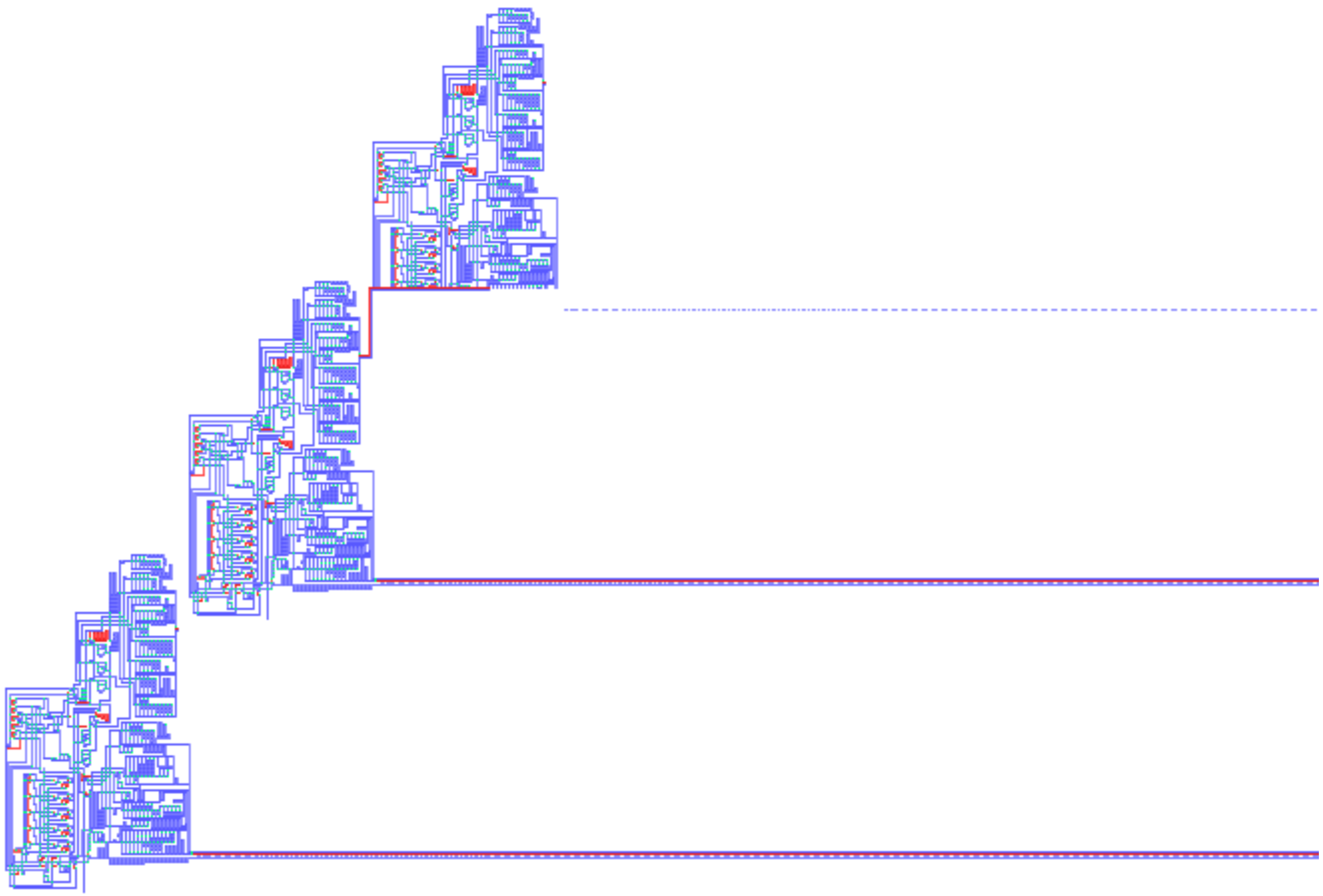
A *complex system* is a system composed of interconnected parts that as a whole exhibit one or more properties (behavior among the possible properties) not obvious from the properties of the individual parts.

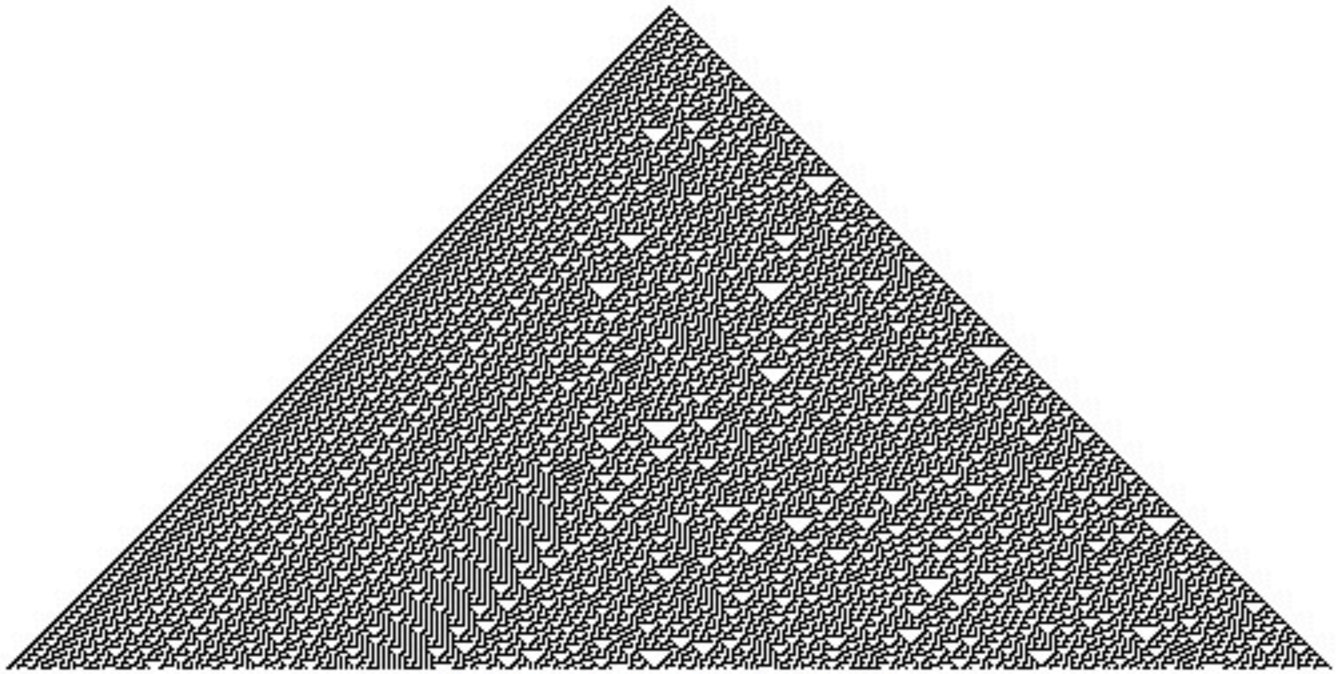
A system's complexity may be of one of two forms: *disorganized complexity* and *organized complexity*. In essence, disorganized complexity is a matter of a very large number of parts, and organized complexity is a matter of the subject system (quite possibly with only a limited number of parts) exhibiting emergent properties.

In philosophy, systems theory, science, and art, *emergence* is the way complex systems and patterns arise out of a multiplicity of relatively simple interactions. Emergence is central to the theories of integrative levels and of complex systems.

Emergent properties are collective properties, which means they are properties of collections, not properties of individual parts. The cause can often be traced back to the interactions between the parts of which a system is made. Often the nature of those interactions is more important than the identity of the parts. This concept has found a use in the computer science world where swarm intelligence, a type of artificial intelligence, is used to control flocks, or swarms, of robots.

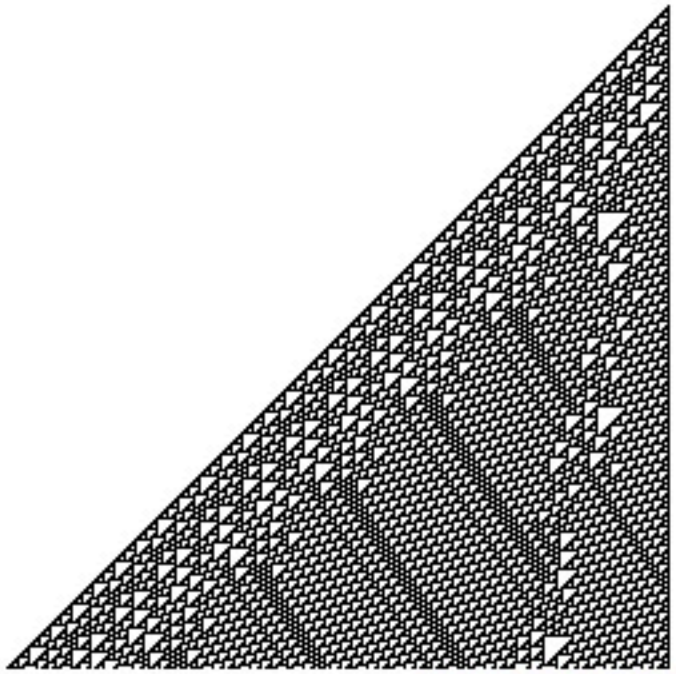
Cellular Automaton





Rule 30 cellular automaton

current pattern	111	110	101	100	011	010	001	000
new state for center cell	0	0	0	1	1	1	1	0



Rule 110 cellular automaton

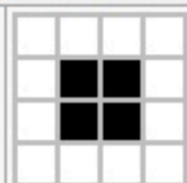
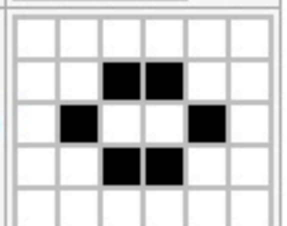
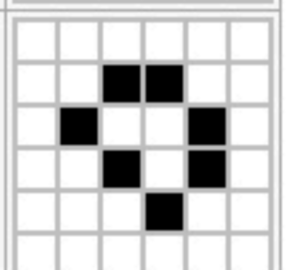
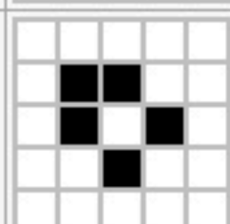
Game of Life

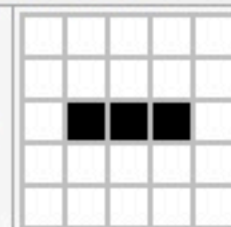
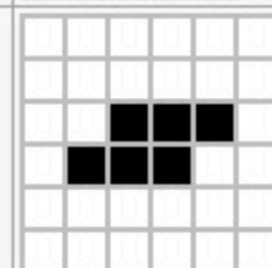
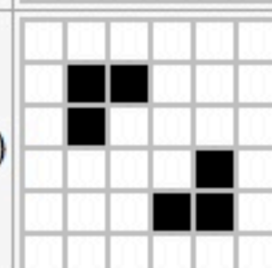
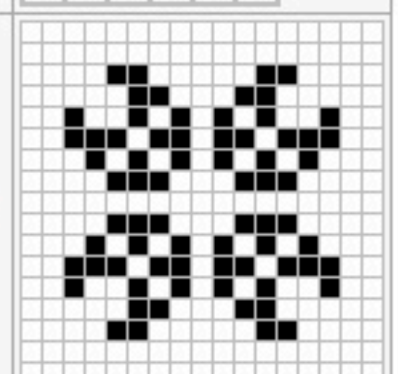
· Any live cell with fewer than two live neighbours dies, as if caused by under-population.

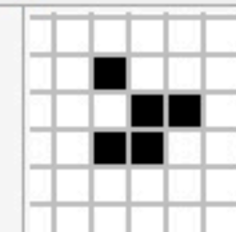
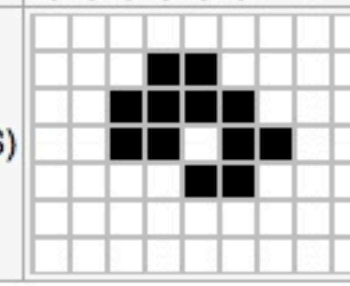
· Any live cell with two or three live neighbours lives on to the next generation.

· Any live cell with more than three live neighbours dies, as if by overcrowding.

· Any dead cell with exactly three live neighbours becomes a live cell, as if by reproduction.

Still lives	
Block	
Beehive	
Loaf	
Boat	

Oscillators	
Blinker (period 2)	
Toad (period 2)	
Beacon (period 2)	
Pulsar (period 3)	

Spaceships	
Glider	
Lightweight spaceship (LWSS)	

Paskian Environments

In the late 1950's Gordon Pask constructed several electrochemical devices having emergent sensory capabilities. These control systems possessed the ability to adaptively construct their own sensors, thereby choosing the relationship between their internal states and the world at large. Devices were built that evolved through sensitivity to sound or magnetic fields. Pask's devices have far-reaching implications for artificial intelligence, self-constructing devices, theories of observers and epistemically-autonomous agents, theories of functional emergence, machine creativity, and the limits of contemporary machine learning paradigms.

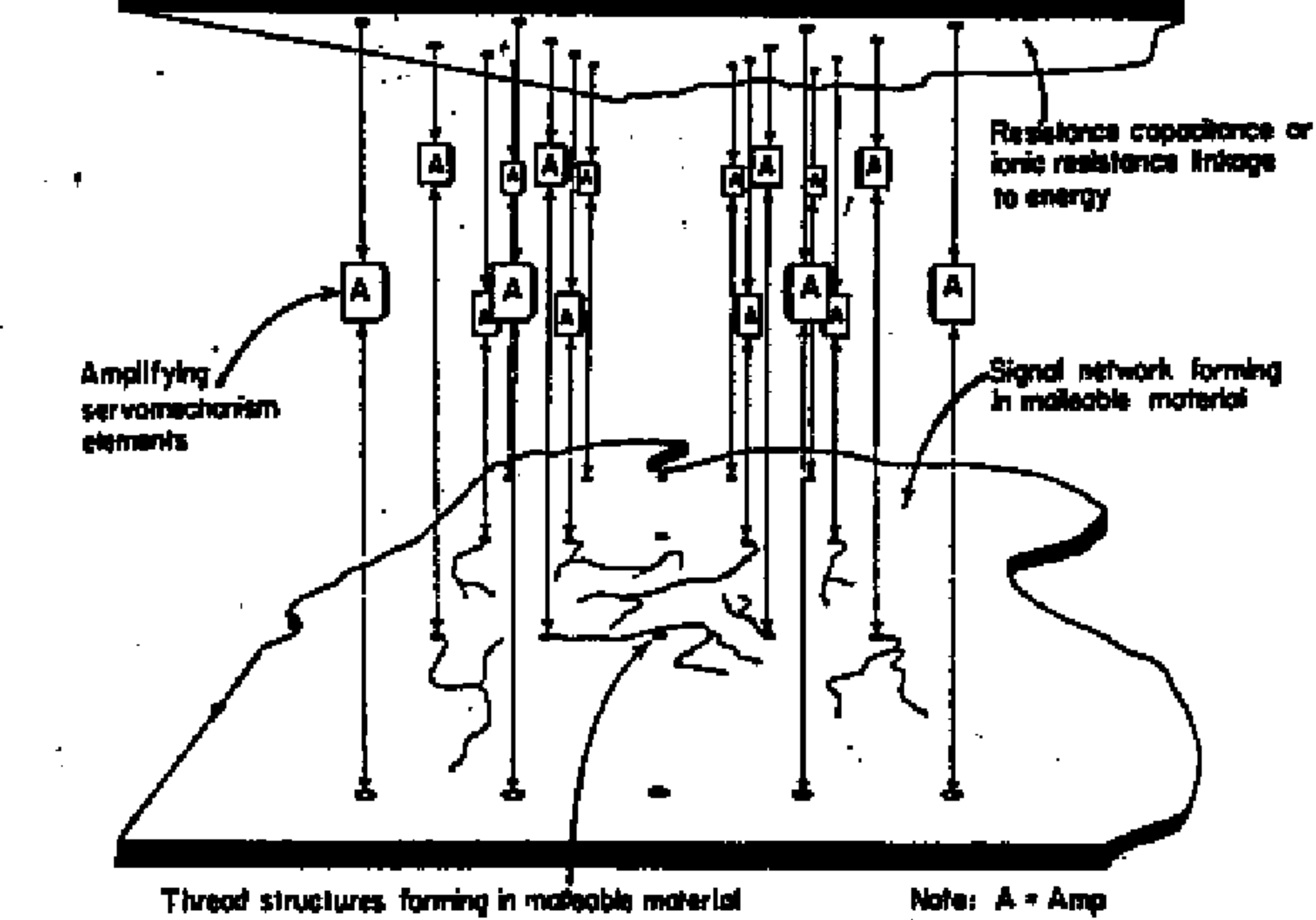


Figure 1. Pask's schematic indicating the relationship between the electrode array and the ferrous sulphate medium. From [28].

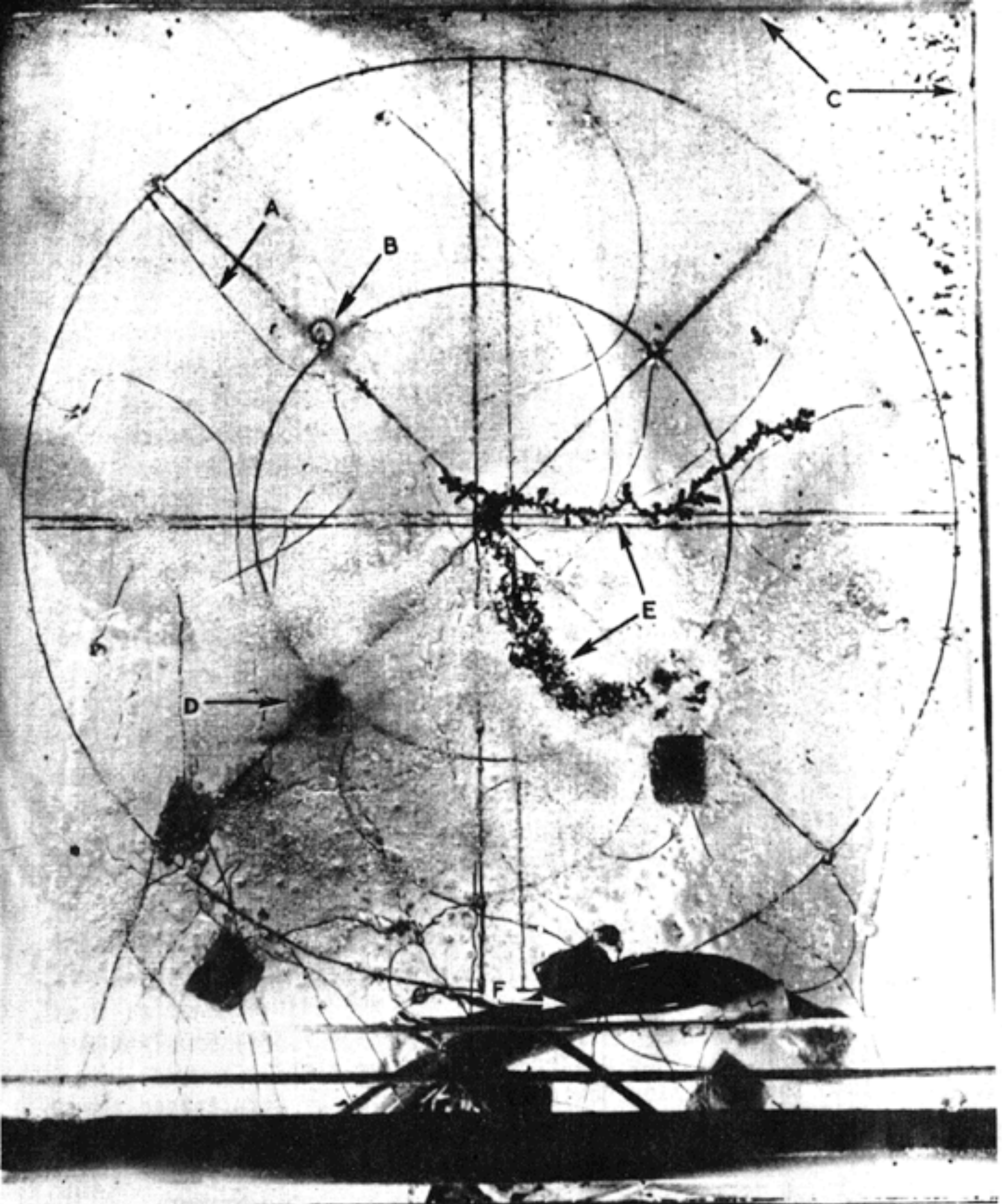
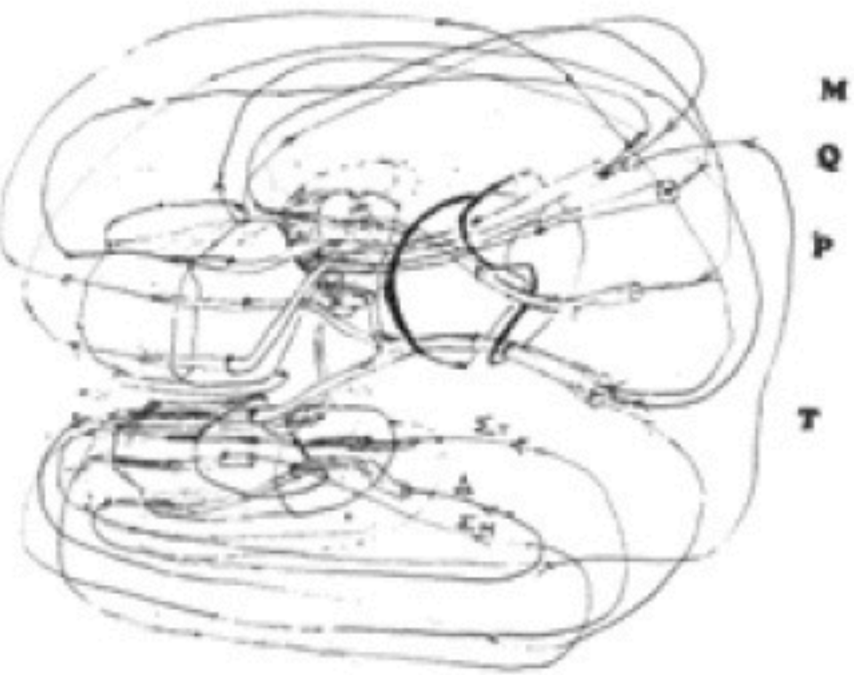
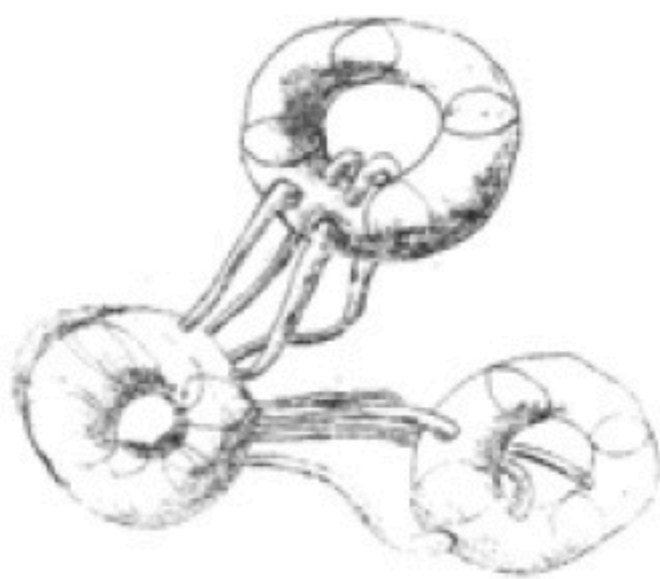
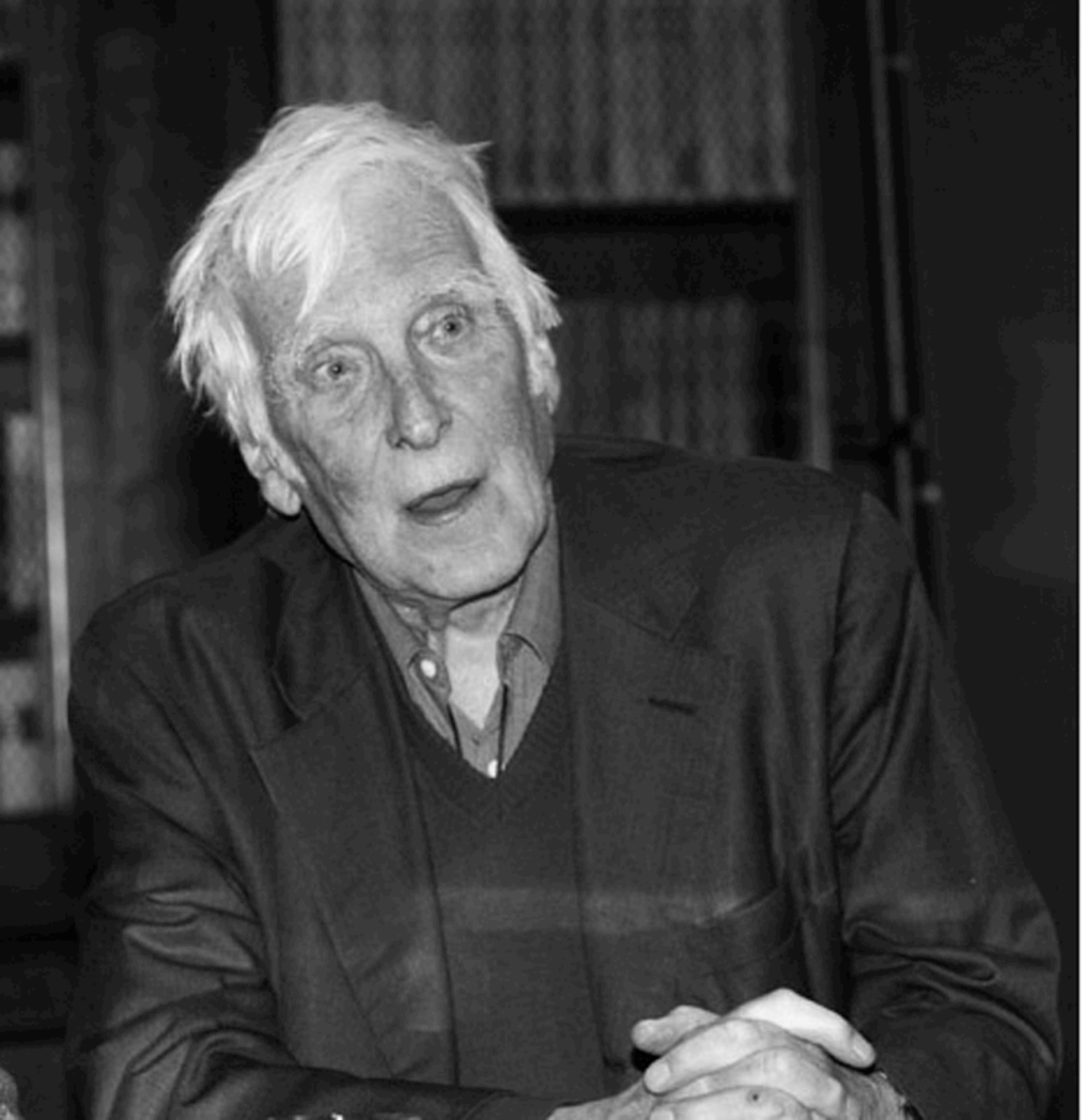


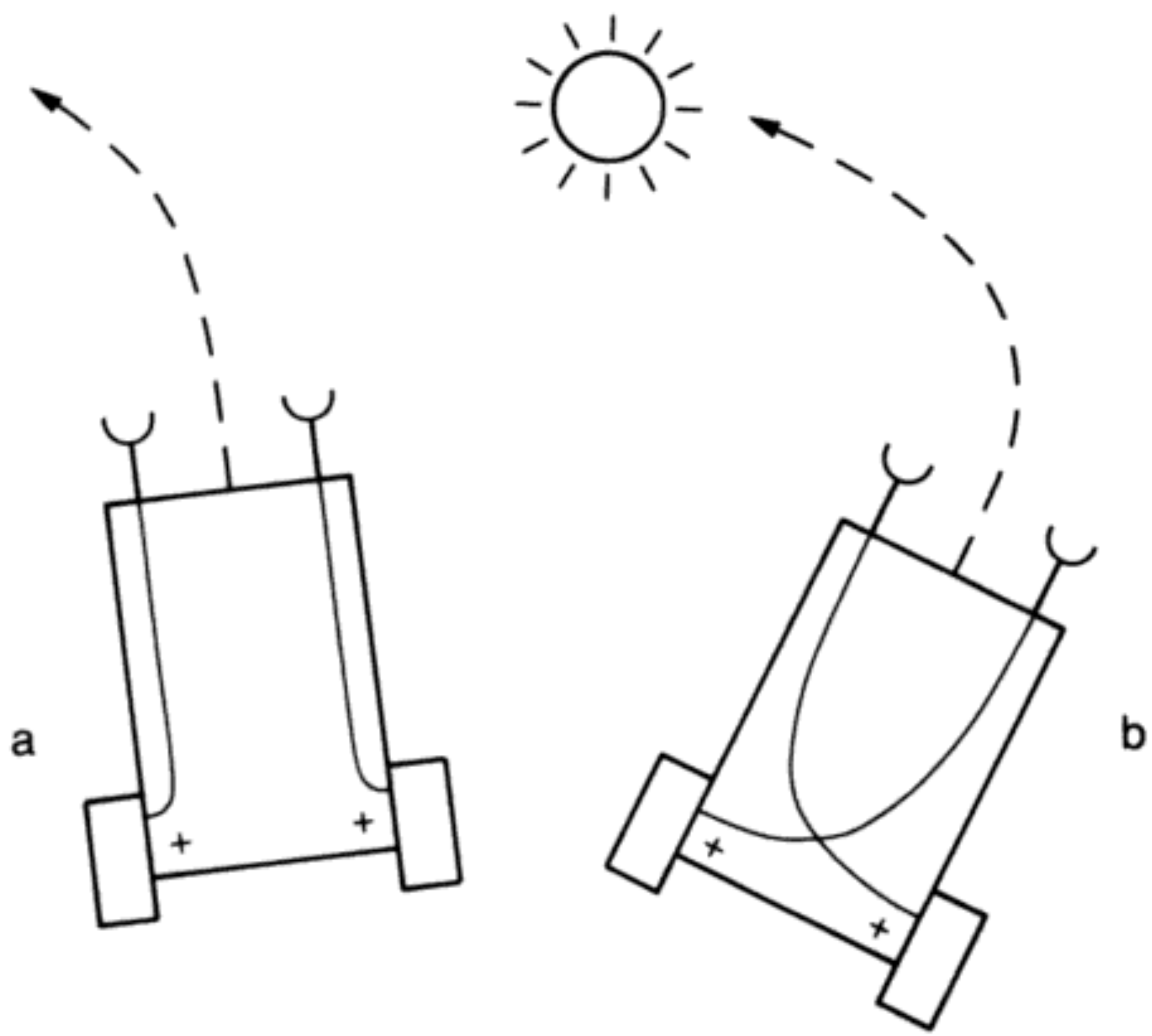
Figure 2. Photograph of Pask's electrochemical assemblage. The electrodes run perpendicular to the page. The circular wires are a support frame. Two dendritic iron thead structures can be seen in the righthand quadrants. The large dark area in the lower left quadrant is undissolved ferrous sulphate. From [27].


M
Q
P
T



Braitenberg's Vehicles




a
b
+
+
+
+

In the book *Vehicles: Experiments in Synthetic Psychology*, Valentino Braitenberg describes a series of thought experiments in which “vehicles” with simple internal structure behave in unexpectedly complex ways. He describes simple control mechanisms that generate behaviors that, if we did not already know the principles behind the vehicles' operation, we might call aggression, love, foresight and even optimism. Braitenberg gives this as evidence for the “law of uphill analysis and downhill invention,” meaning that it is much more difficult to try to guess internal structure just from the observation of behavior than it is to create the structure that gives the behavior.

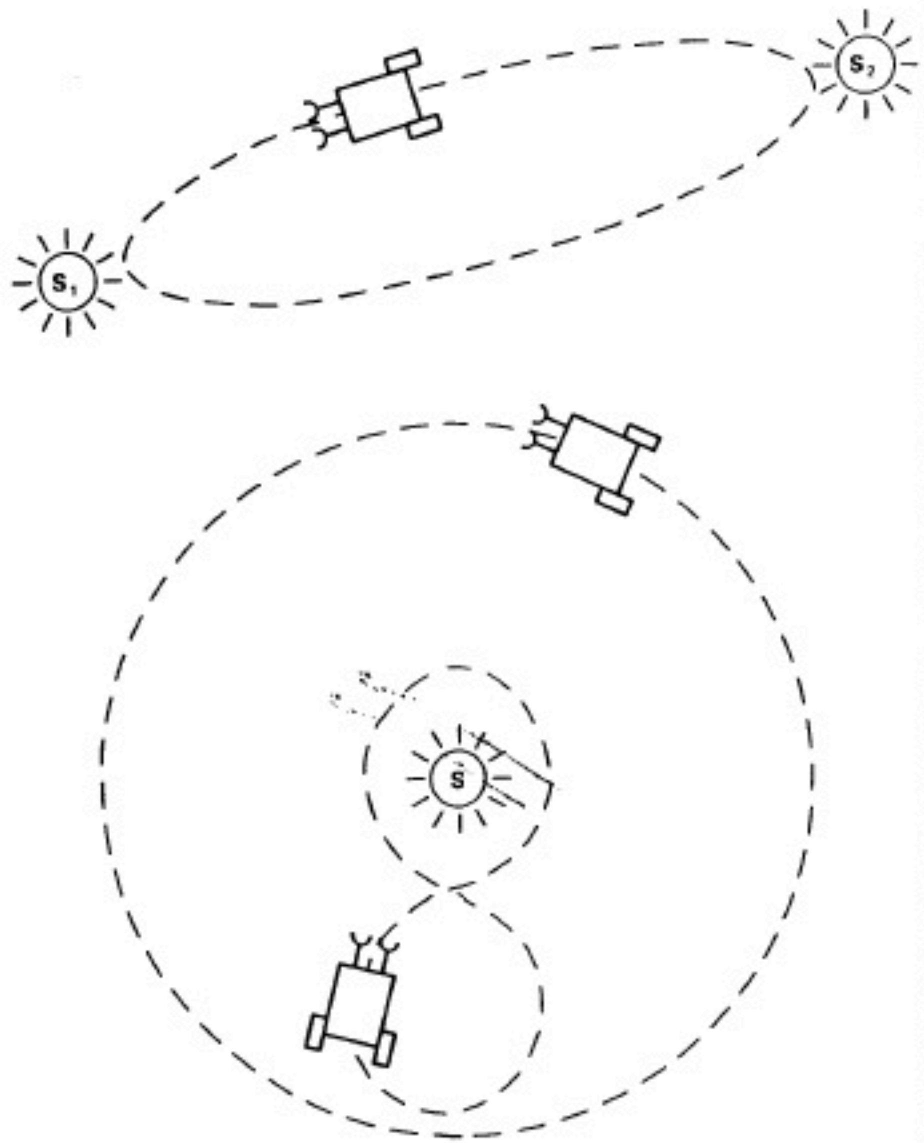


Figure 7
Trajectories of vehicles of brand 4a around or between sources.

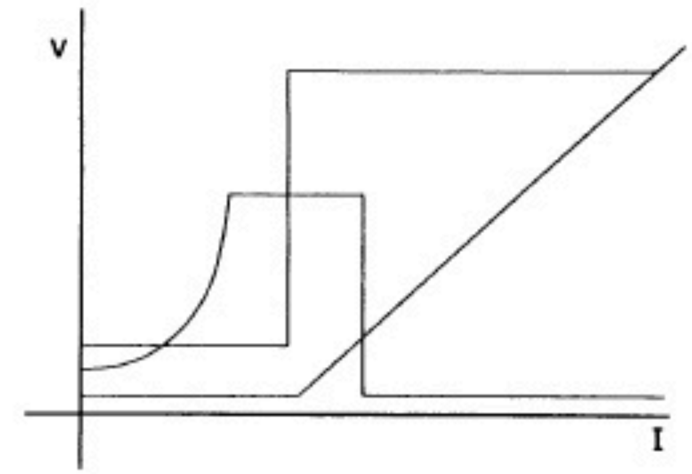
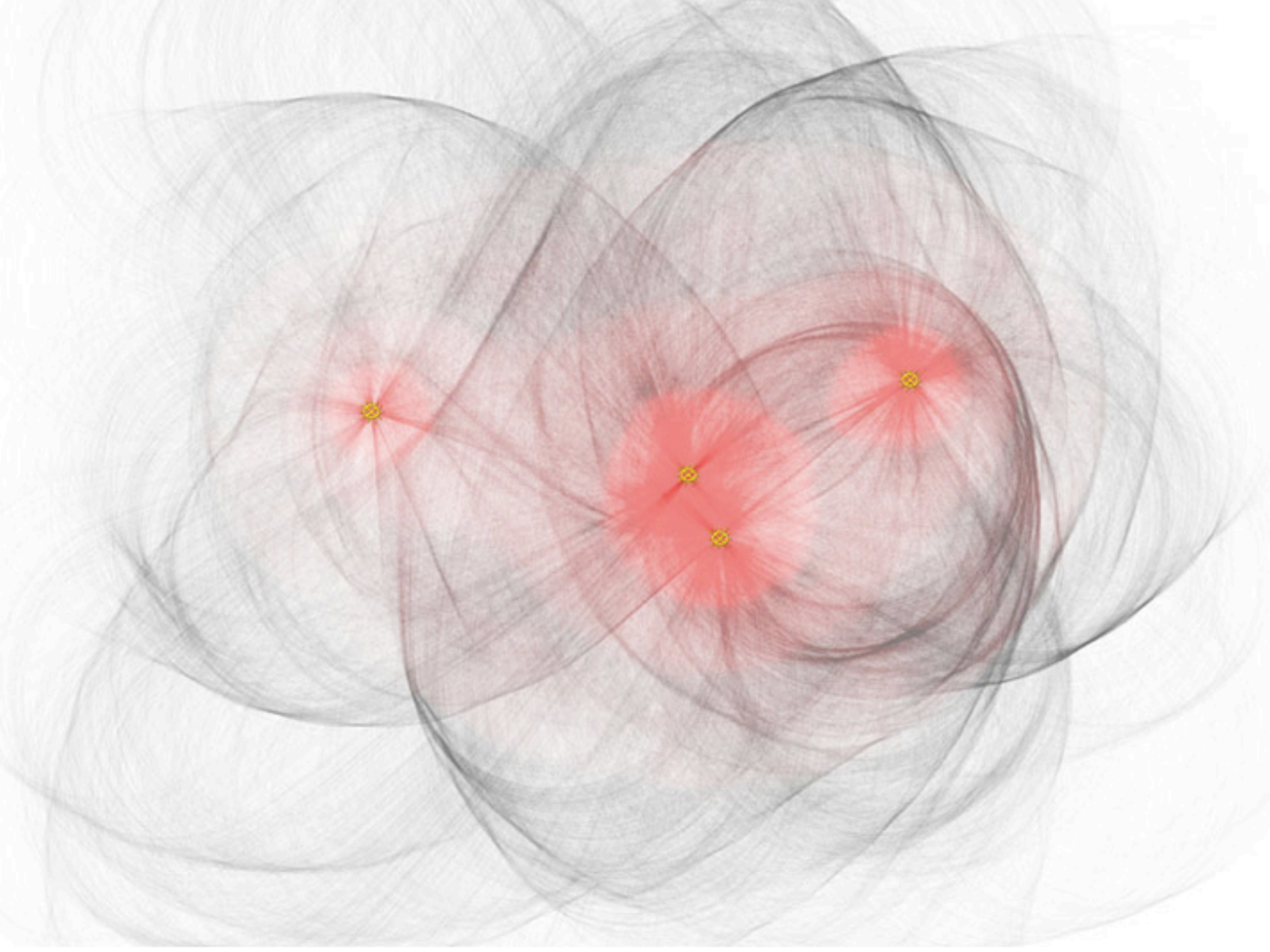
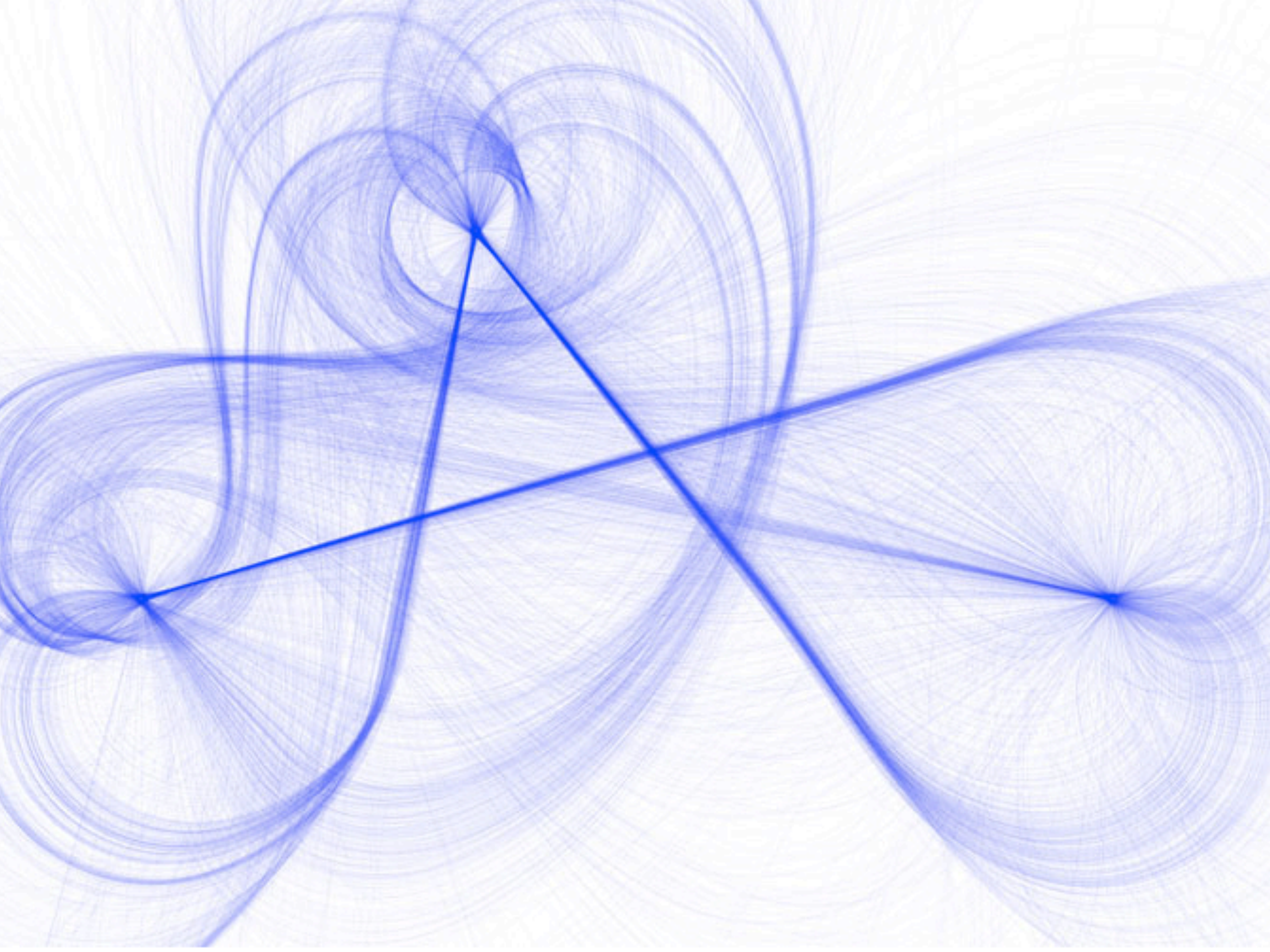


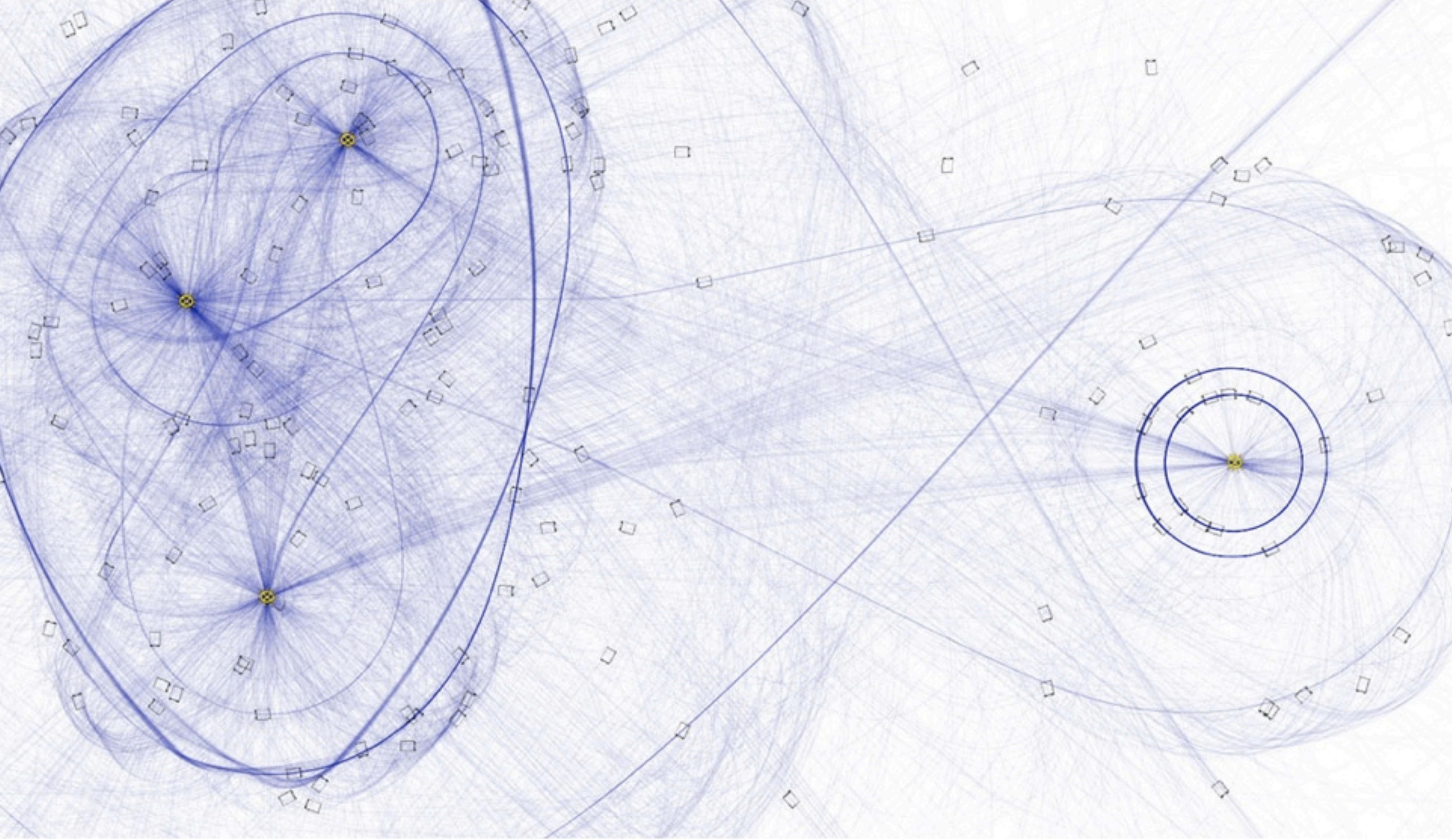
Figure 8
Various bizarre kinds of dependence of the speed of the motor (ordinate) on the intensity of stimulation (abscissa) in Vehicle 4b.

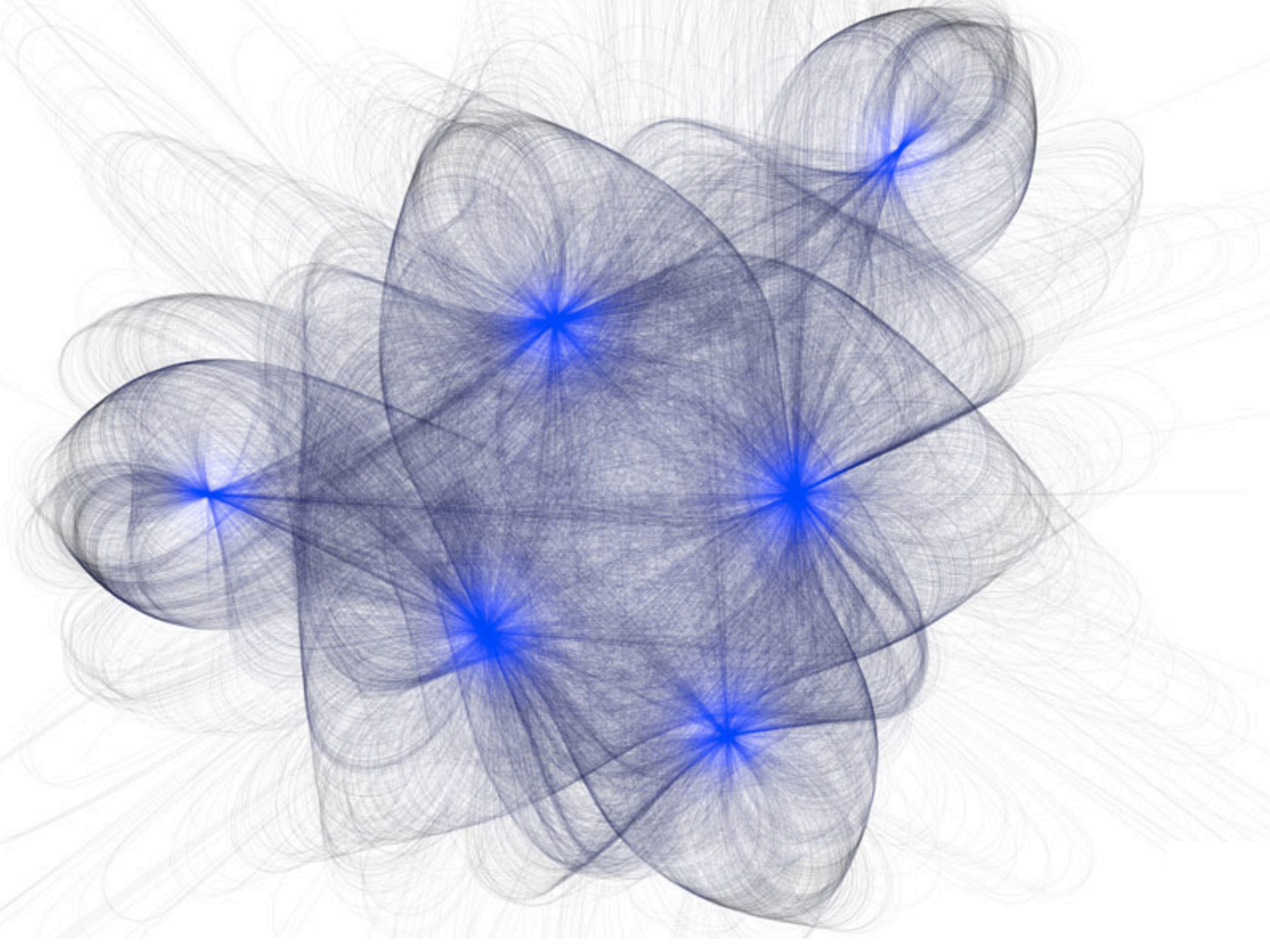
ing, continuous. Moreover, if friction plays a role, as we have already decided it should, thresholds in motor activation would ensue naturally: the vehicle will start moving only when the force exerted by the motor exceeds a certain value, sufficient to overcome the initial friction.

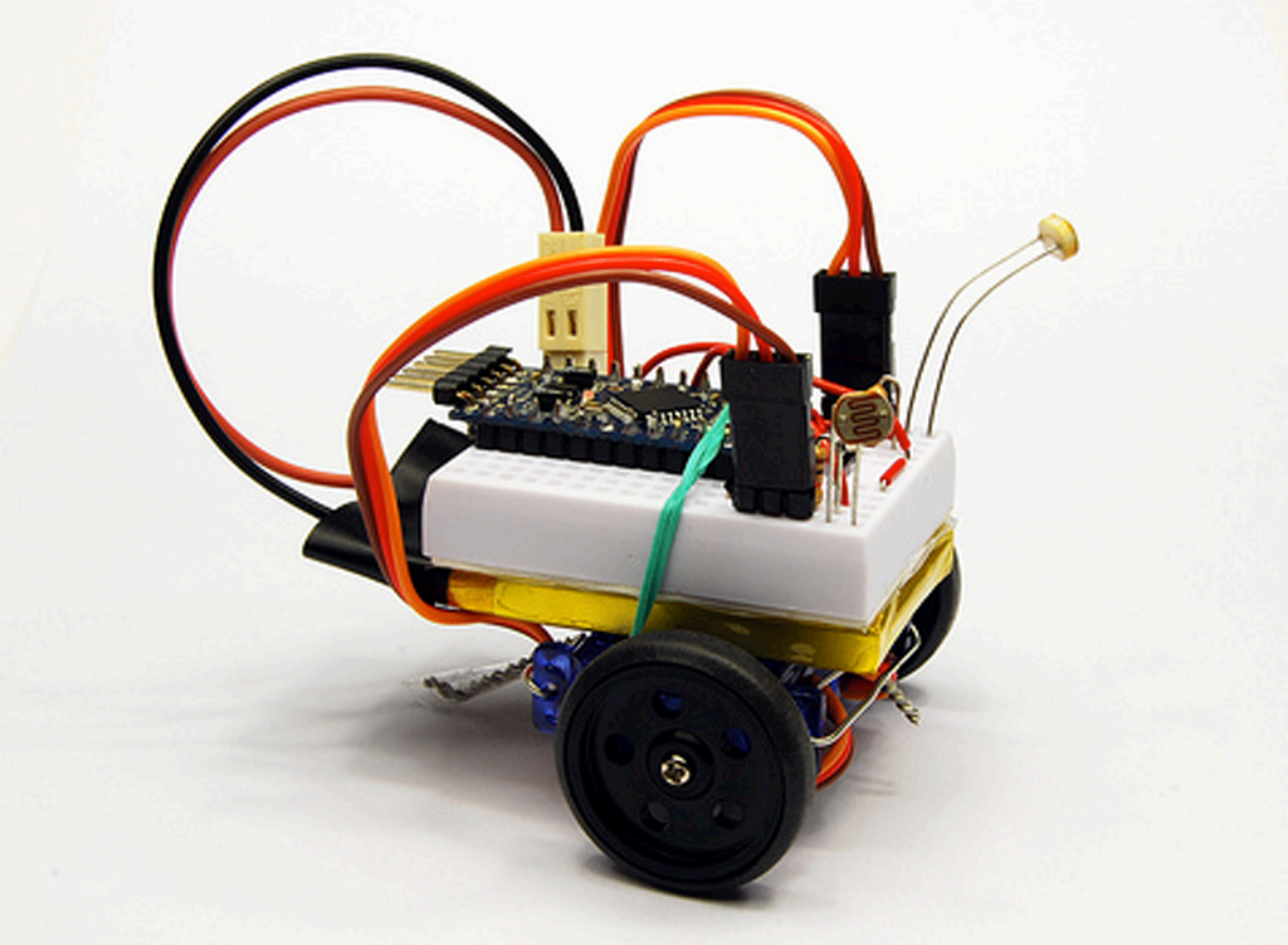
Whatever their origin, thresholds in some behavior patterns make a lot of difference in the eye of the observer. These creatures, the observer would say, ponder over their DECISIONS. When you come close to them with a lure, it takes them some time to get going. Yet once they have decided, they can act quite quickly. They do indeed seem to act in a spontaneous way: none of this passive being attracted one way or the other that was so obvious in the vehicles of the more lowly types. You would almost be tempted to say: where decisions are being made, there must be a WILL to make them. Why not? For all we know, this is not the worst criterion for establishing the existence of free will.











Boids

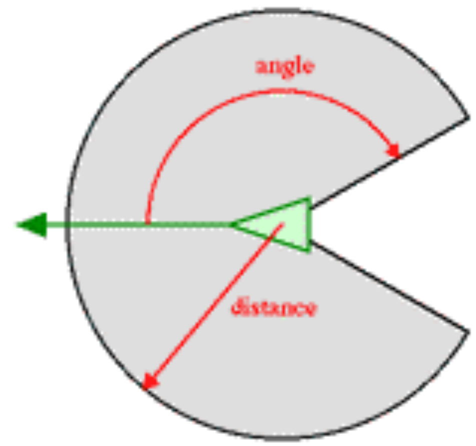
Boids is an artificial life program, developed by Craig Reynolds in 1986, which simulates the flocking behaviour of birds. His paper on this topic was published in 1987 in the proceedings of the ACM SIGGRAPH conference. The name refers to a *bird-like object*, but its pronunciation evokes that of *bird* in a stereotypical New York accent. As with most artificial life simulations, Boids is an example of emergent behavior; that is, the complexity of Boids arises from the interaction of individual agents (the boids, in this case) adhering to a set of simple rules.

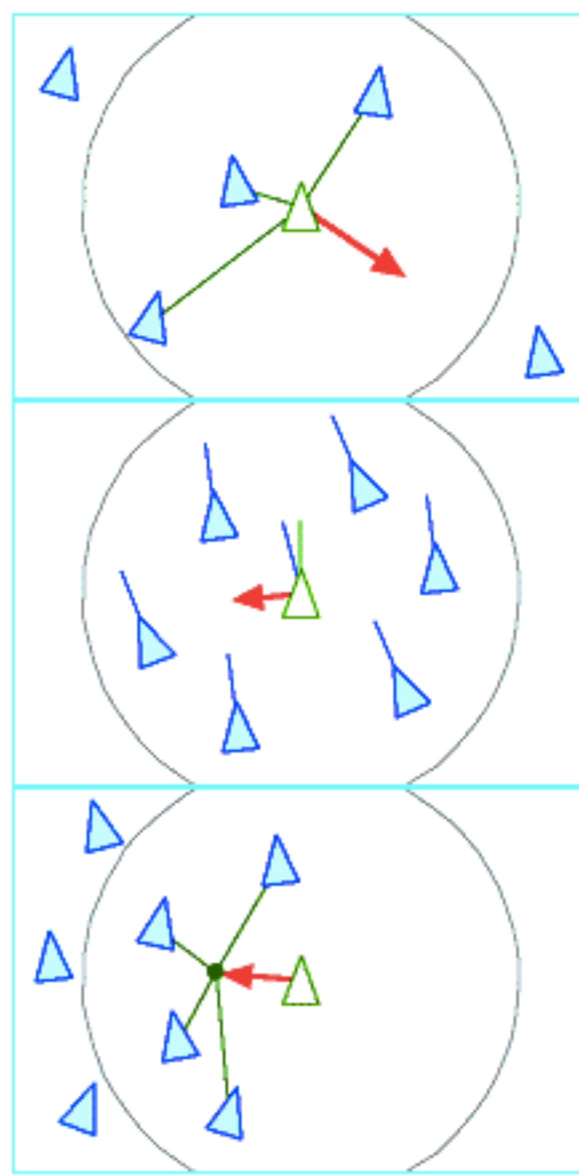
COURSE: 07

COURSE ORGANIZER: DEMETRI TERZOPOULOS

"BOIDS DEMOS"

CRAIG REYNOLDS
SILICON STUDIOS, MS 3L-980
2011 NORTH SHORELINE BLVD.
MOUNTAIN VIEW, CA 94039-7311

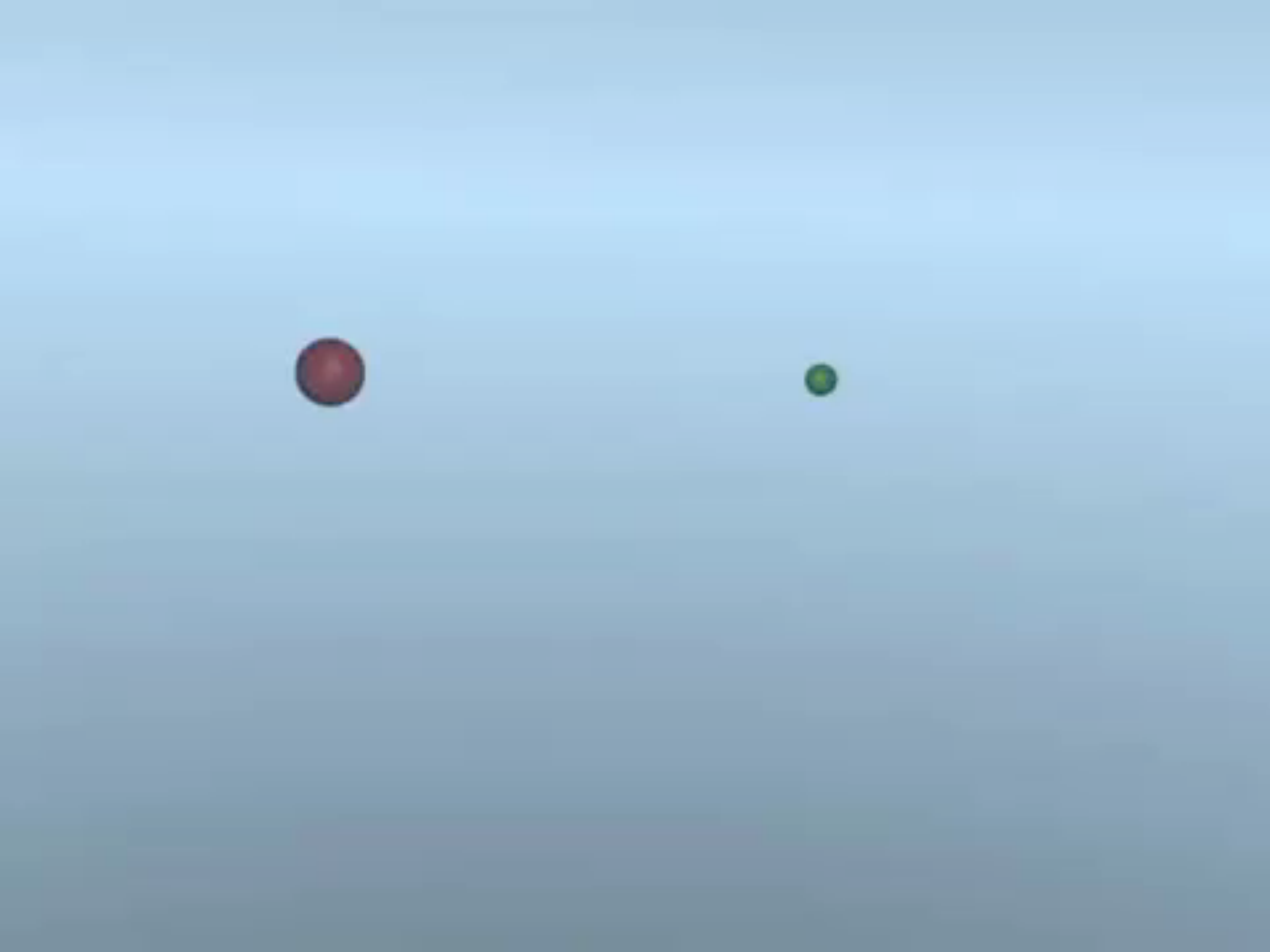




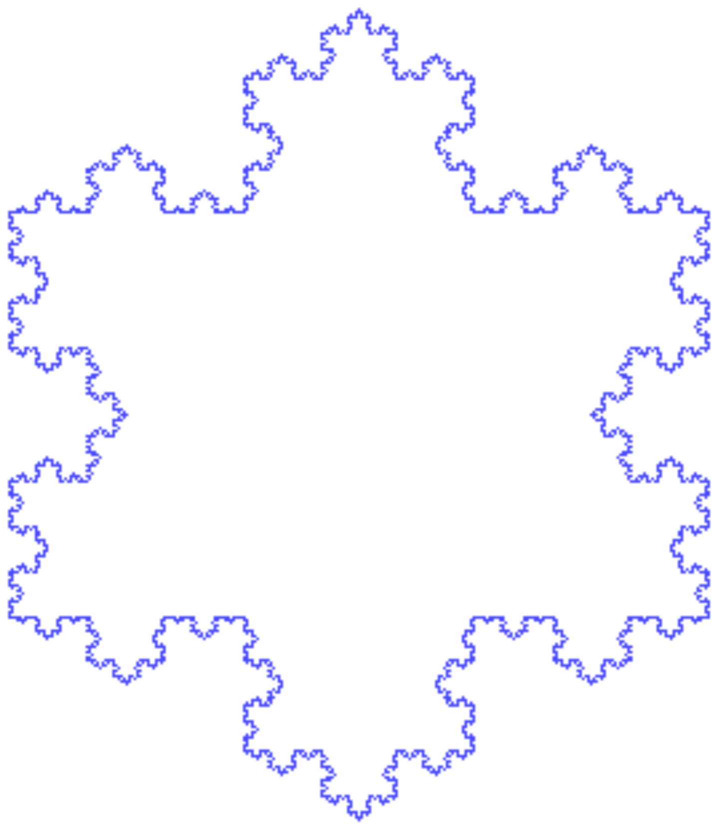
Separation: steer to avoid crowding local flockmates

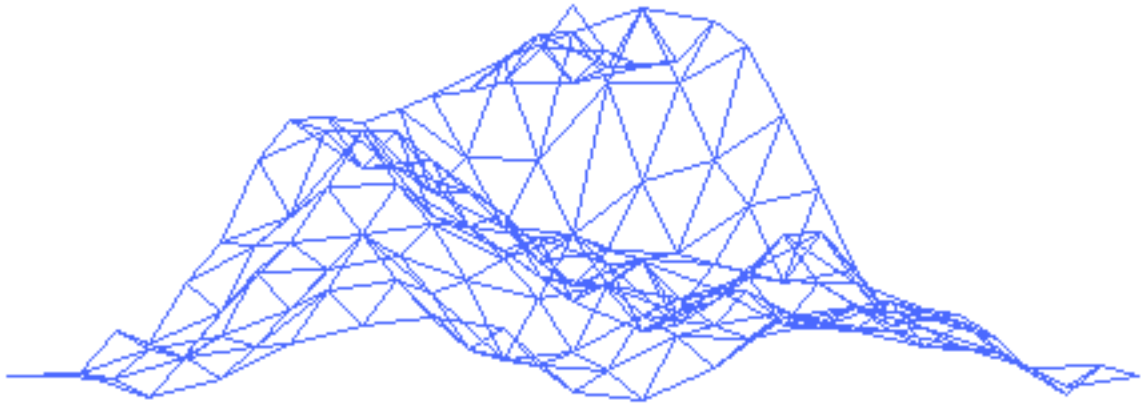
Alignment: steer towards the average heading of local flockmates

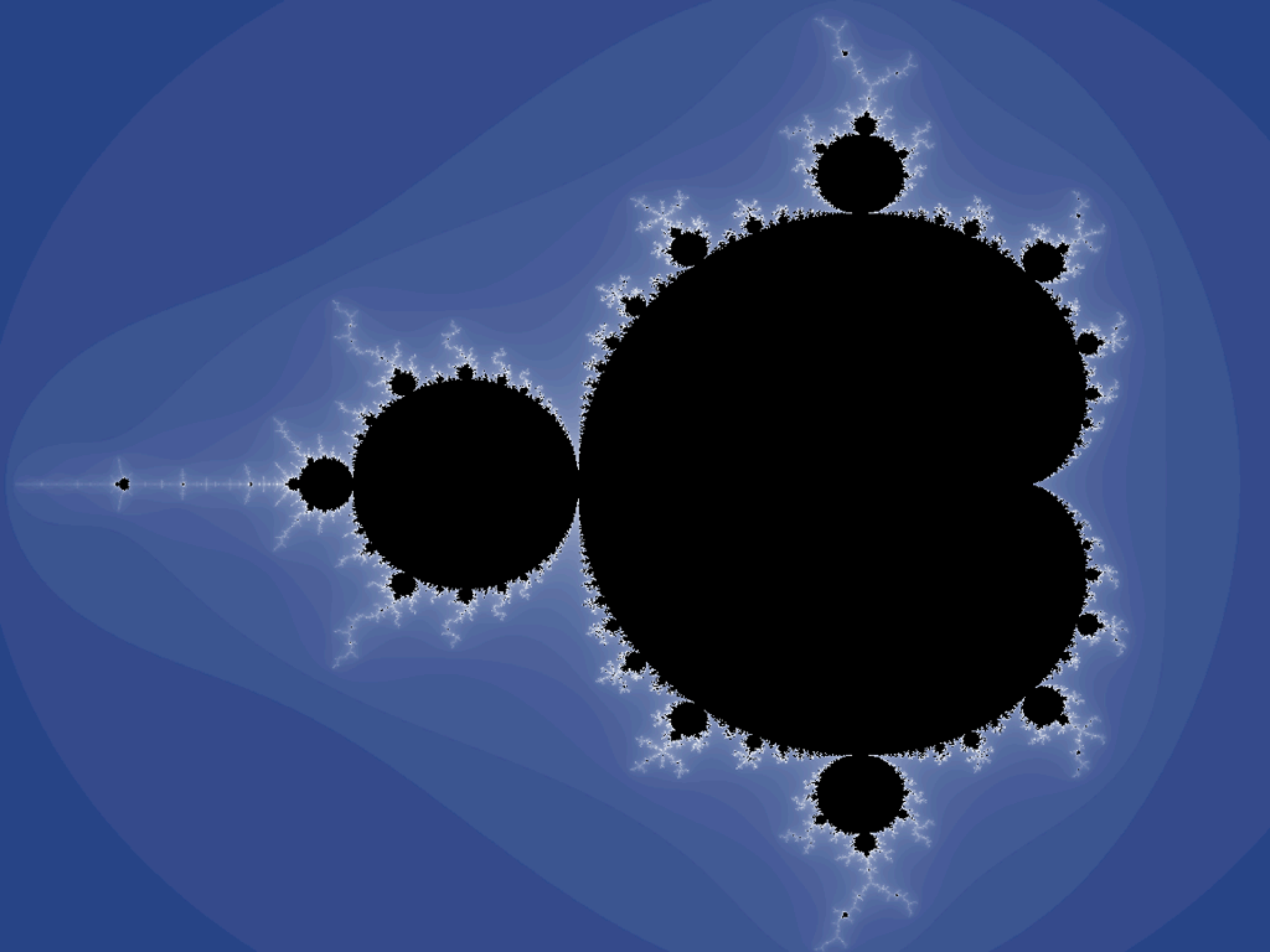
Cohesion: steer to move toward the average position of local flockmates

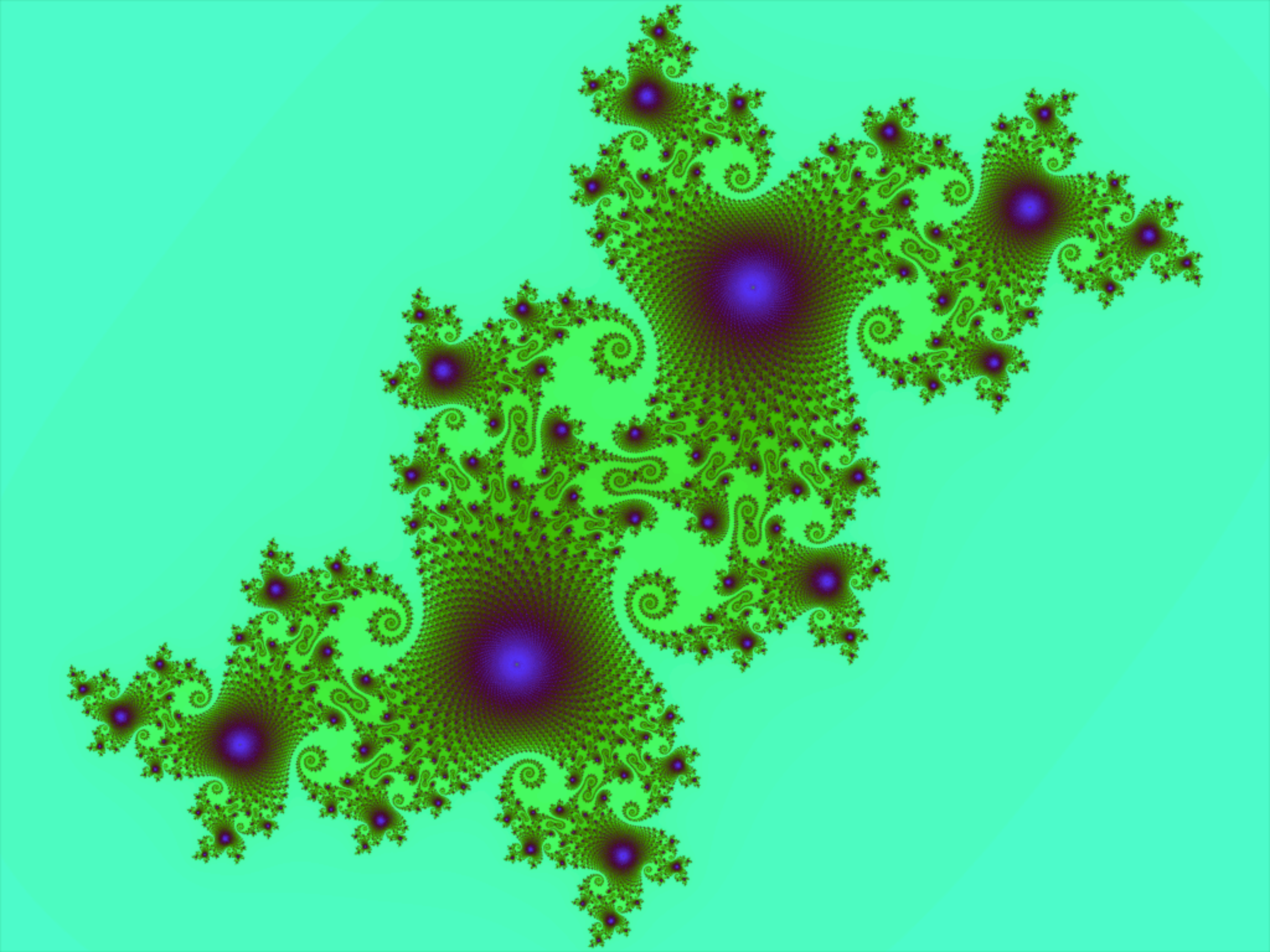


Mandelbrot Set









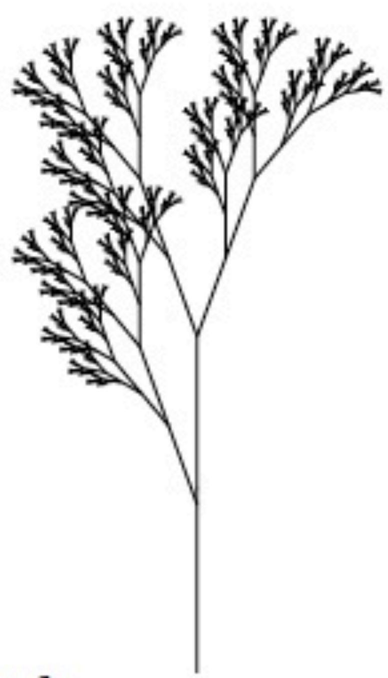
L-Systems

An *L-system* or *Lindenmayer system* is a parallel rewriting system, namely a variant of a formal grammar, most famously used to model the growth processes of plant development, but also able to model the morphology of a variety of organisms. L-systems can also be used to generate self-similar fractals such as iterated function systems.

a
n=5, δ=25.7°
F
F →F[+F]F[-F]F

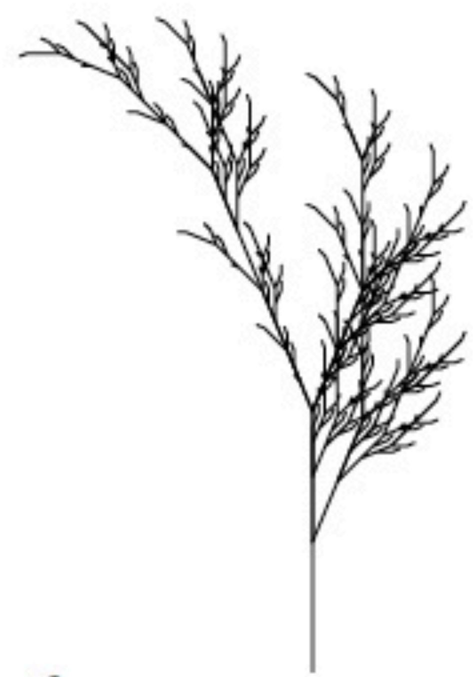
b
n=5, δ=20°
F
F →F[+F]F[-F][F]

c
n=4, δ=22.5°
F
F →FF-[-F+F+F]+
[+F-F-F]



d
n=7, δ=20°
X
X →F[+X]F[-X]+X
F →FF

e
n=7, δ=25.7°
X
X →F[+X][-X]FX
F →FF



f
n=5, δ=22.5°
X
X →F-[[X]+X]+F[+FX]-X
F →FF

Example 1: Algae

Lindenmayer's original L-system for modelling the growth of algae.

variables : A B

constants : none

start : A

rules : (A → AB), (B → A)

which produces:

n = 0 : A

n = 1 : AB

n = 2 : ABA

n = 3 : ABAAB

n = 4 : ABAABABA

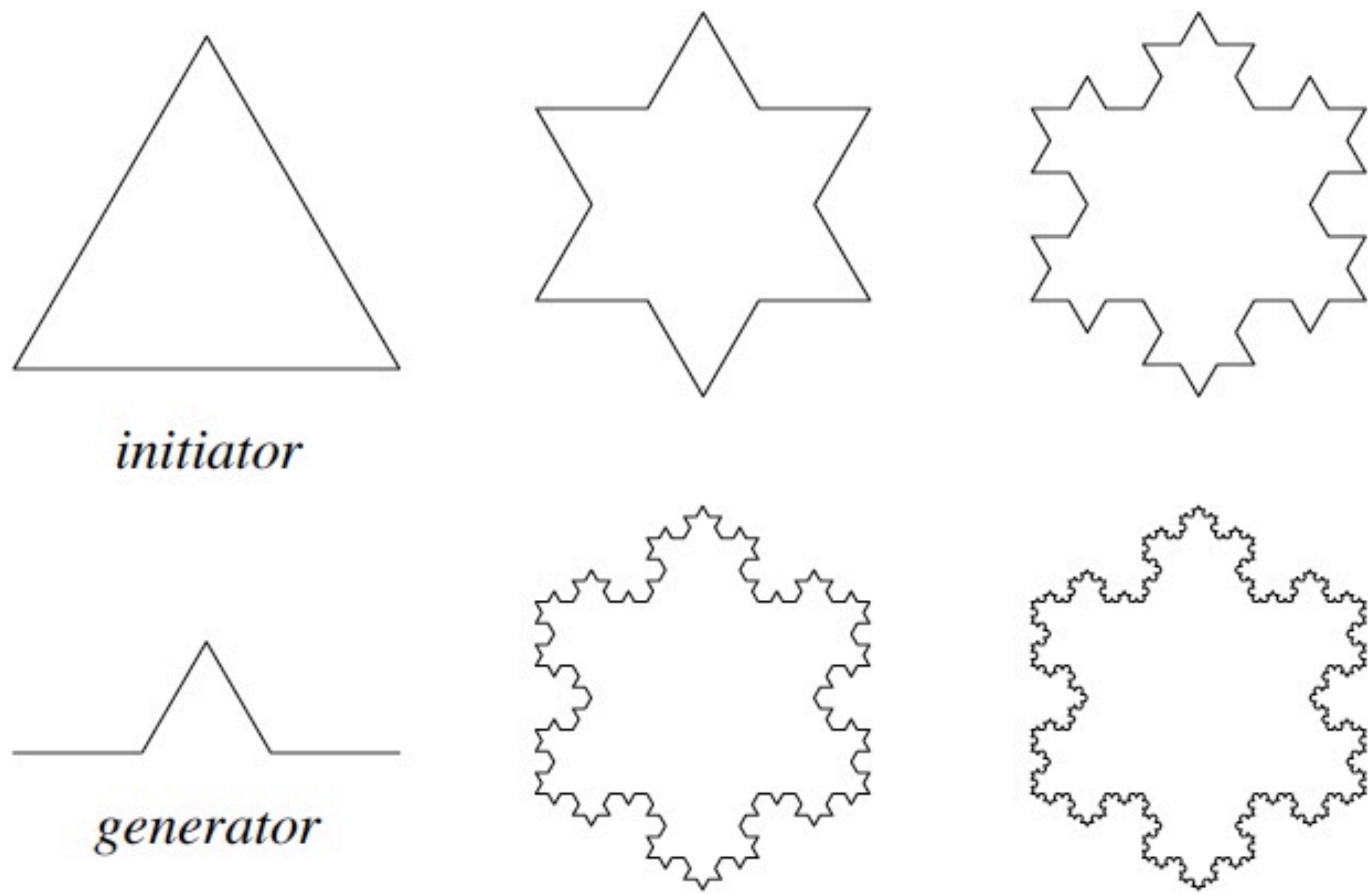
n = 5 : ABAABABAABAAB

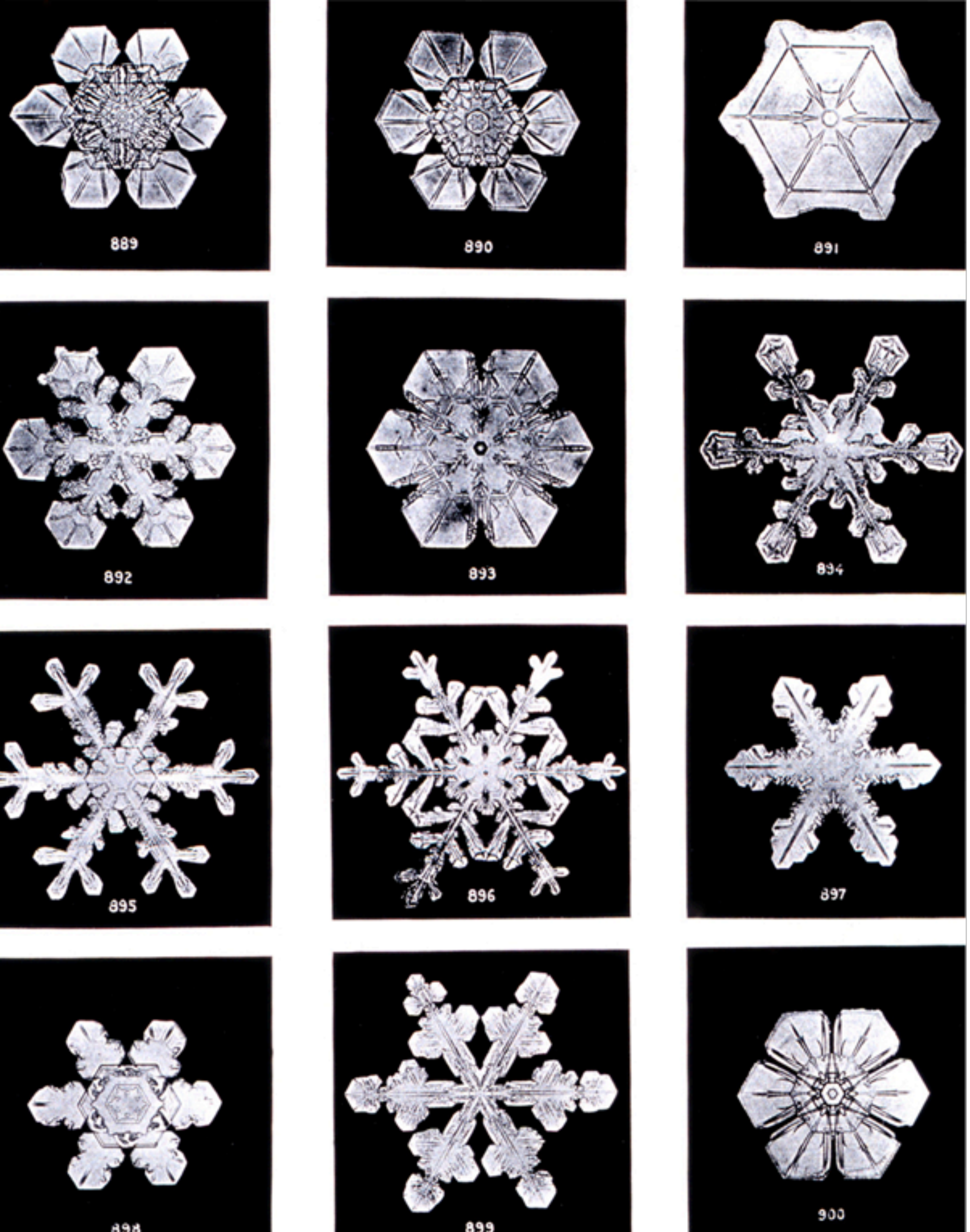
n = 6 : ABAABABAABAABABAABABA

n = 7 : ABAABABAABAABABAABABAABAABABAABAAB

Example 1: Algae, explained

```
n=0:         A           start (axiom/initiator)
            / \
n=1:       A   B         the initial single A spawned into AB by rule (A → AB), rule (B → A) couldn't be applied
          /|    \
n=2:     A B     A       former string AB with all rules applied, A spawned into AB again, former B turned into A
        /| |     |\
n=3:   A B A     A B     note all A's producing a copy of themselves in the first place, then a B, which turns ...
      /| | |\    |\ \
n=4: A B A A B   A B A   ... into an A one generation later, starting to spawn/repeat/recurse then
```


initiator
generator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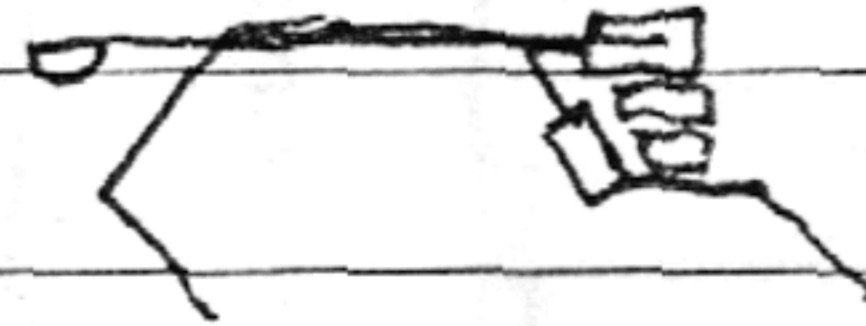
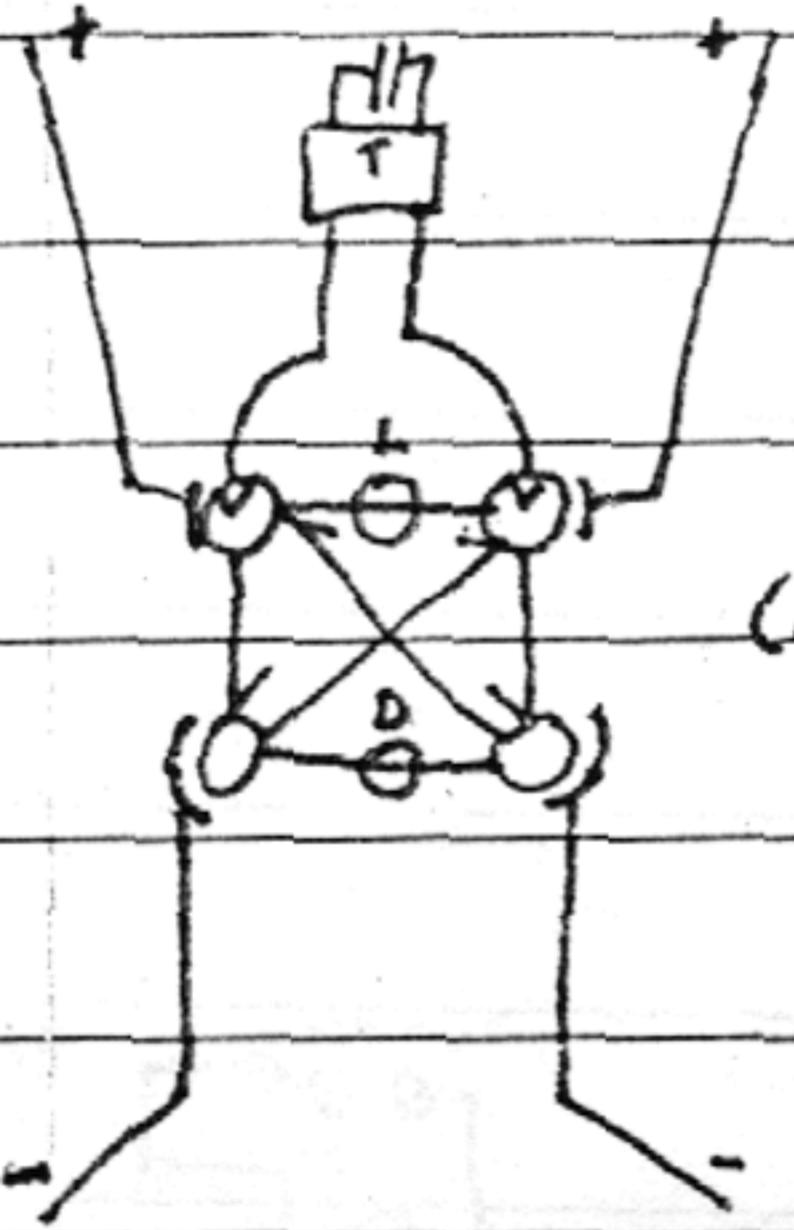
BEAM robotics

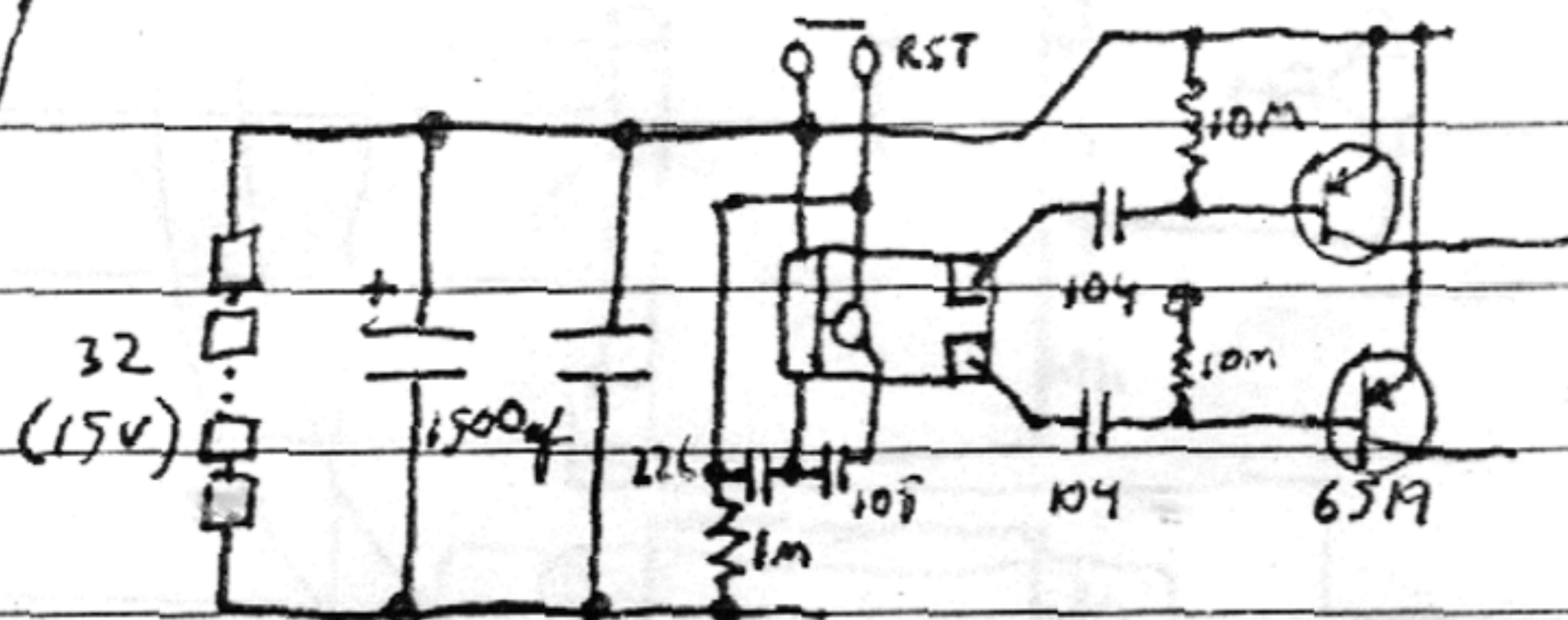
The word BEAM in the context of robotics is an acronym for Biology, Electronics, Aesthetics, and Mechanics. This is a term that refers to a style of robotics that primarily uses simple analogue circuits, such as comparators, instead of a microprocessor in order to produce an unusually simple design (in comparison to traditional mobile robots) that trades flexibility for robustness and efficiency in performing the task for which it was designed. Exceptions to the convention of using only analog electronics do exist and these are often colloquially referred to as *mutants*. BEAM robots typically consist of a set of the aforementioned analog circuits (mimicking biological neurons) which facilitate the robot's response to its working environment.

1. Use the lowest number possible of electronic elements
2. Recycle and reuse technoscrap
3. Use radiant energy (such as solar power)

VBUG 1.6 - Solar:



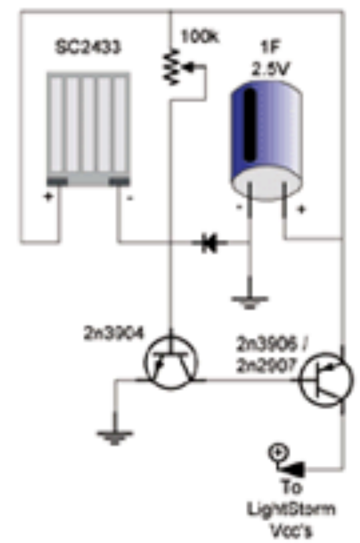




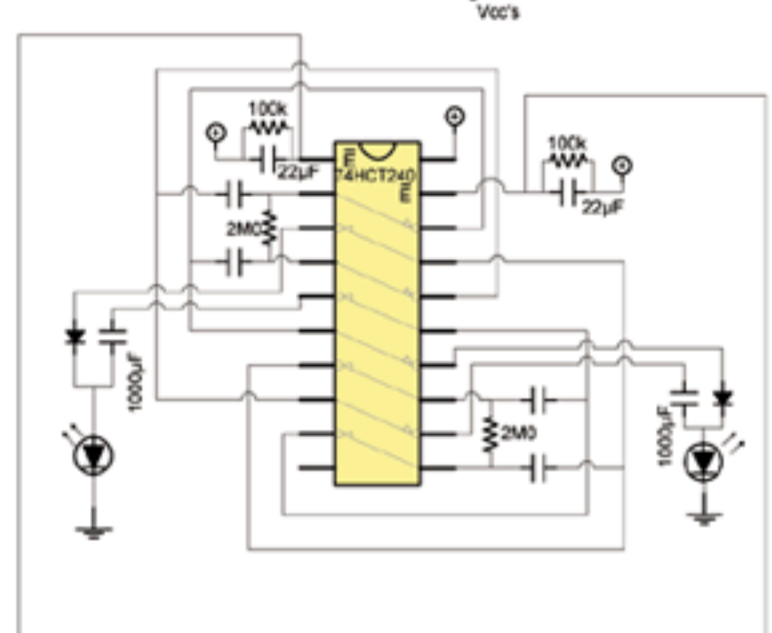
- COUNTERSINK SOLAR CELL HOLES
- SPREAD PINS UNDER PRESSURE from centre
- ALIGN & solder.

~INCEPT: THURS, APR 21, 1994, 7:06 PM MT

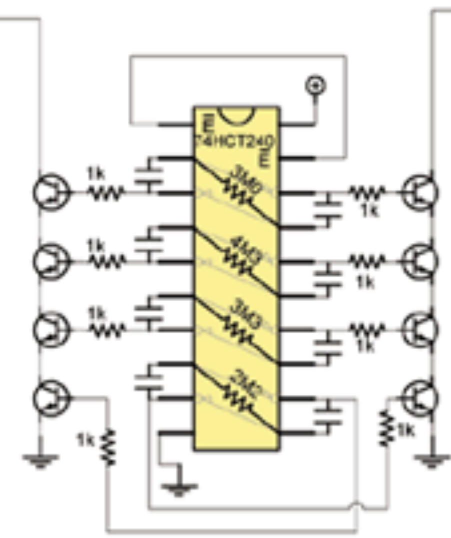
SOLARBOTICS Ltd



Dark Turn-on Circuit



Dual Pummer Circuit

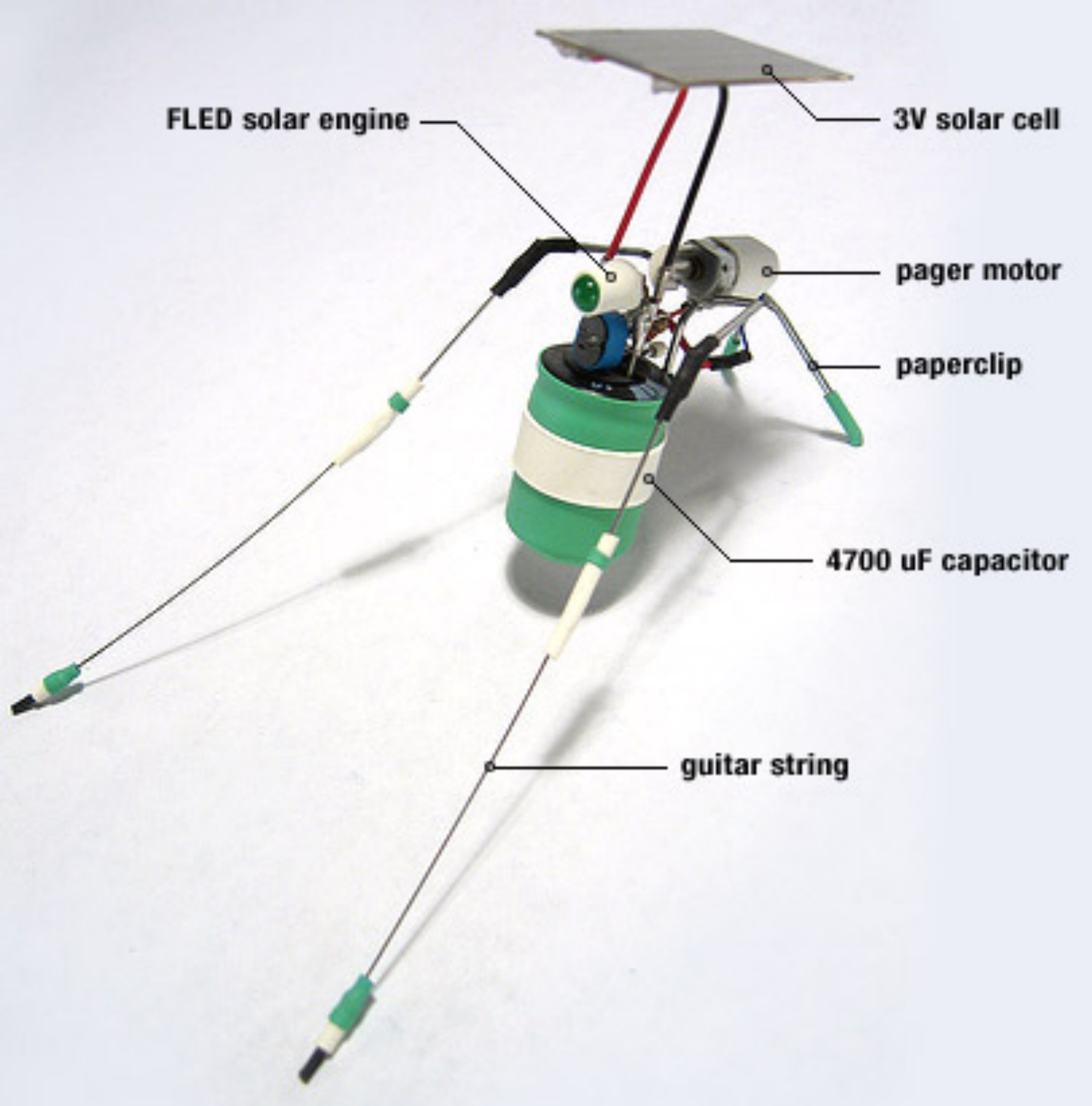


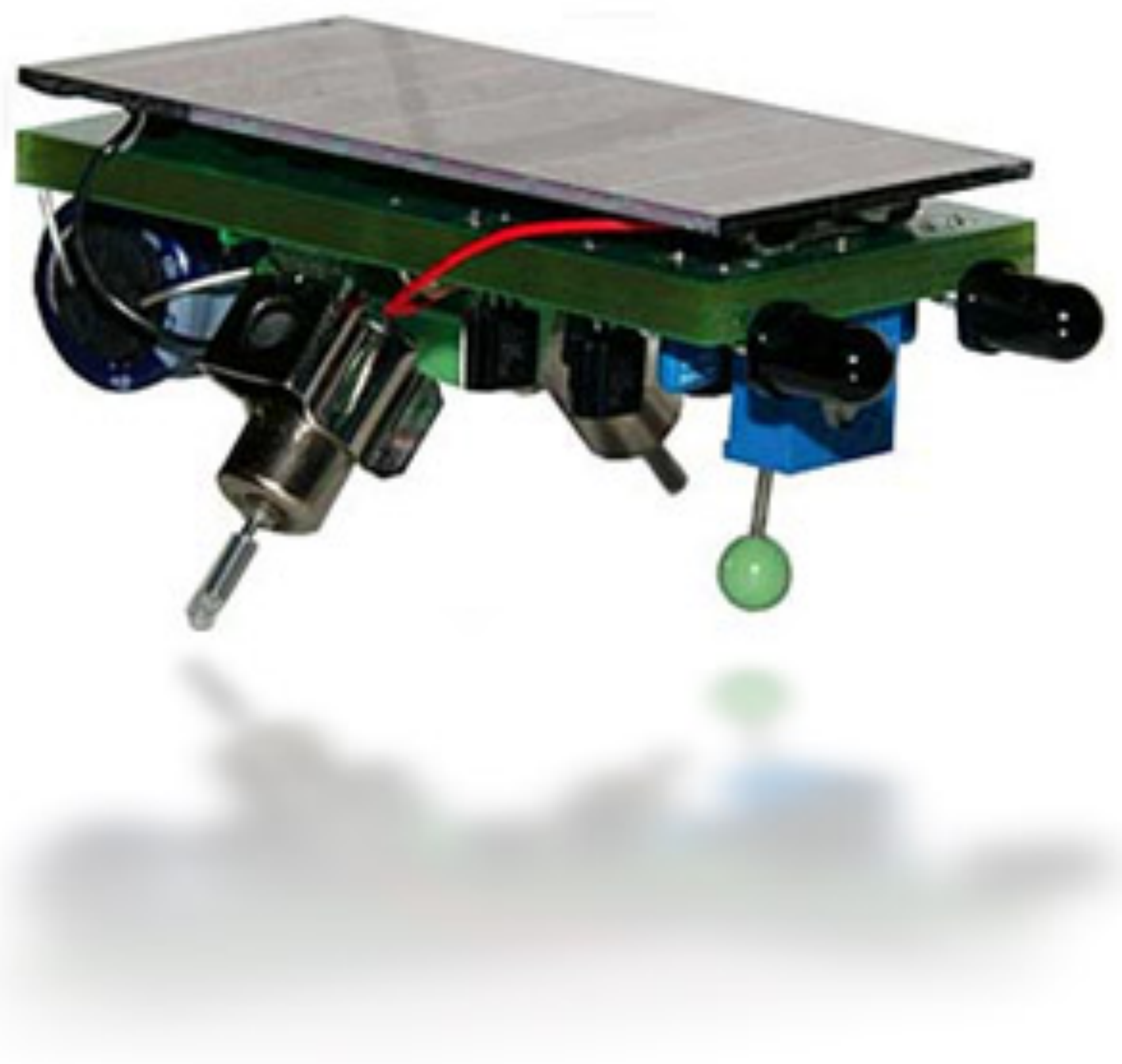
All capacitors are 0.22µF unless otherwise noted

NPN Transistors (3904/2n2222)

Dual QuadCore with 4-input AND Gate Pseudo-Random Chaos Generator

Note: Use germanium diodes for best performance


FLED solar engine
3V solar cell
pager motor
paperclip
4700 uF capacitor
guitar string



Audiotropes react to sound sources.

- Audiophiles go towards sound sources.
- Audiophobes go away from sound sources.

Phototropes ("light-seekers") react to light sources.

- Photophiles (also Photovores) go toward light sources.
- Photophobes go away from light sources.

Radiotropes react to radio frequency sources.

- Radiophiles go toward RF sources.
- Radiophobes go away from RF sources.

Thermotropes react to heat sources.

- Thermophiles go toward heat sources.
- Thermophobes go away from heat sources.

Sitters: Unmoving robots that have a physically passive purpose.

Beacons: Transmit a signal (usually a navigational blip) for other BEAMbots to use.

Pummers: Display a "light show".

Ornaments: A catch-all name for sitters that are not beacons or pummers.

Squirmers: Stationary robots that perform an interesting action (usually by moving some sort of limbs or appendages).

Magbots: Utilize magnetic fields for their mode of animation.

Flagwavers: Move a display (or "flag") around at a certain frequency.

Heads: Pivot and follow some detectable phenomena, such as a light (These are popular in the BEAM community. They can be stand-alone robots, but are more often incorporated into a larger robot.).

Vibrators: Use a small pager motor with an off-centre weight to shake themselves about.

Sliders: Robots that move by sliding body parts smoothly along a surface while remaining in contact with it.

Snakes: Move using a horizontal wave motion.

Earthworms: Move using a longitudinal wave motion.

Crawlers: Robots that move using tracks or by rolling the robot's body with some sort of appendage. The body of the robot is not dragged on the ground.

Turbots: Roll their entire bodies using their arm(s) or flagella.

Inchworms: Move part of their bodies ahead, while the rest of the chassis is on the ground.

Tracked robots: Use tracked wheels, like a tank.

Jumpers: Robots which propel themselves off the ground as a means of locomotion.

Vibrobots: Produce an irregular shaking motion moving themselves around a surface.

Springbots: Move forward by bouncing in one particular direction.

Rollers: Robots that move by rolling all or part of their body.

- Symets: Driven using a single motor with its shaft touching the ground, and moves in different directions depending on which of several symmetric contact points around the shaft are touching the ground.
- Solarrollers: Solar-powered cars that use a single motor driving one or more wheels; often designed to complete a fairly short, straight and level course in the shortest amount of time.
- Poppers: Use two motors with separate solar engines; rely on differential sensors to achieve a goal.
- Miniballs: Shift their centre of mass, causing their spherical bodies to roll.

Walkers: Robots that move using legs with differential ground contact.

- Motor Driven: Use motors to move their legs (typically 3 motors or less).
- Muscle Wire Driven: Utilize Nitinol (nickel - titanium alloy) wires for their leg actuators.

Swimmers: Robots that move on or below the surface of a liquid (typically water).

- Boatbots: Operate on the surface of a liquid.
- Subbots: Operate under the surface of a liquid.

Fliers: Robots that move through the air for sustained periods.

- Helicopters: Use a powered rotor to provide both lift and propulsion.
- Planes: Use fixed or flapping wings to generate lift.
- Blimps: Use a neutrally-buoyant balloon for lift.

Climbers: Robot that moves up or down a vertical surface, usually on a track such as a rope or wire.

In 1999 I started experimenting with basic electronic analogue circuits, which led me develop simple miniature robots. All modules get their energy from solar cells and can thus work autonomously, producing variable tiny sounds and movements. Their aesthetic is determined by the functional electronic components. My interest lies not so much in the individual output of his miniature robots but in their interaction with each other. The focus is on the space, formed by the linked modules and on the developed sculptural and acoustic fields.