A recording of a previous version of this talk is available on YouTube at this link.

The slides have been updated since that talk was recorded. I'll be recording another one shortly.

I'd love to know your thoughts! You can provide them here.

Natural Computing

Utilizing nature's untapped potential for computation, data storage, and data movement.

V. Hunter Adams

Last modified June 22, 2026

We can save the planet by turning it into a computer.

More precisely, by realizing that it already is one.

Any sufficiently advanced technology is indistinguishable from magic.

- Clarke's third law

Any sufficiently advanced ~~technology~~ computer is indistinguishable from ~~magic.~~ nature.

- Clarke's third law

Linked table of contents

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Humanity has a long history of using natural processes to produce **power**, but it has underutilized these processes for **computation**.

Can we unlock the latent computational potential in nature, and change the relationship between nature and machines?

This isn’t a research talk.

It’s a “should this be researched?” talk.

Computation is the *useful transformation* of one quantity (or quantifiable system) into another quantity (or quantifiable system).

A **computer** is anything which does computation.

Utility is in the eye of the beholder. The answer to the question "is this a computer?" is **subjective**.

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Computation is the *useful transformation* of one quantity (or quantifiable system) into another quantity (or quantifiable system).

It may be desirable to explain, that by the word [computer] operation, we mean any process which alters the mutual relation of two or more things, be this relation of what kind it may. This is the most general definition, and would include all subjects in the universe.

- Ada Lovelace, *Notes on the Analytical Engine*

A **computer** is anything which does computation.

What is a computer?

Digital | Analog | Quantum | Natural

- Quantities are represented **symbolically** (by bits, beads, gear rotations, etc.).
- We transform the *representations* for these quantities, rather than the quantities themselves.
  - When you double a quantity in a digital computer, there isn't twice as much of anything in that computer. Instead, the symbol/representation for the quantity is transformed to the symbol/representation for twice that quantity.
- Digital electronic computers symbolically represent these quantities with bits, encoded as **binary voltages in latch circuits**.
  - Transformations of the quantities can thus be performed using logic circuits. Claude Shannon showed that that such circuits can solve any problem that Boolean algebra can solve, and thus any Boolean transformation of the quantity can be performed.
- This enables digital computers of two varieties: special purpose and general purpose

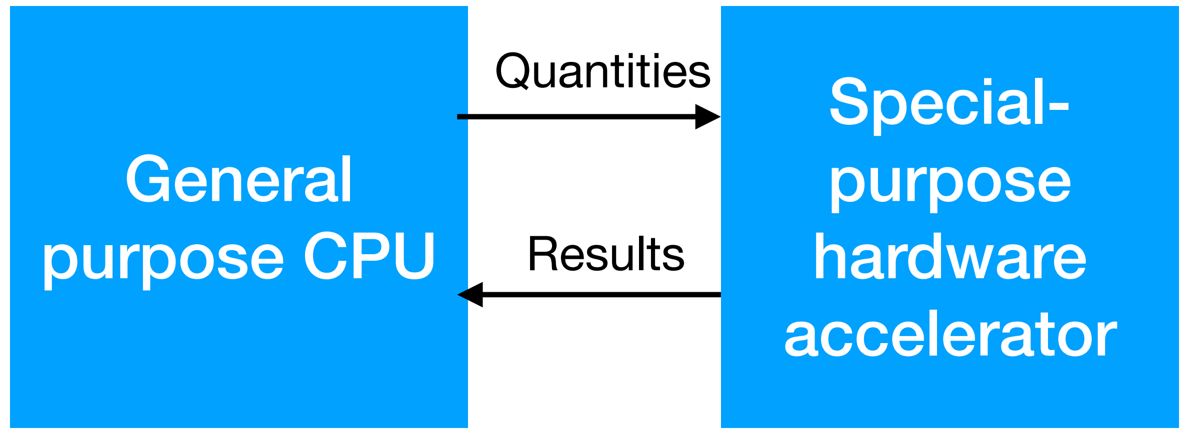
What is a computer?

Digital | Analog | Quantum | Natural

Special-purpose

We design a collection of circuits which implement Boolean algebra. The symbols for some number of quantities are communicated into these circuits as voltages, and the transformed quantities (the result of the operation which the circuits implement) come out as voltages on wires or in registers.

Think ASIC's, and **hardware accelerators**



Take 5760 to learn more!

Lattice-Boltzmann
Mandelbrot
2D Wave equation

General-purpose

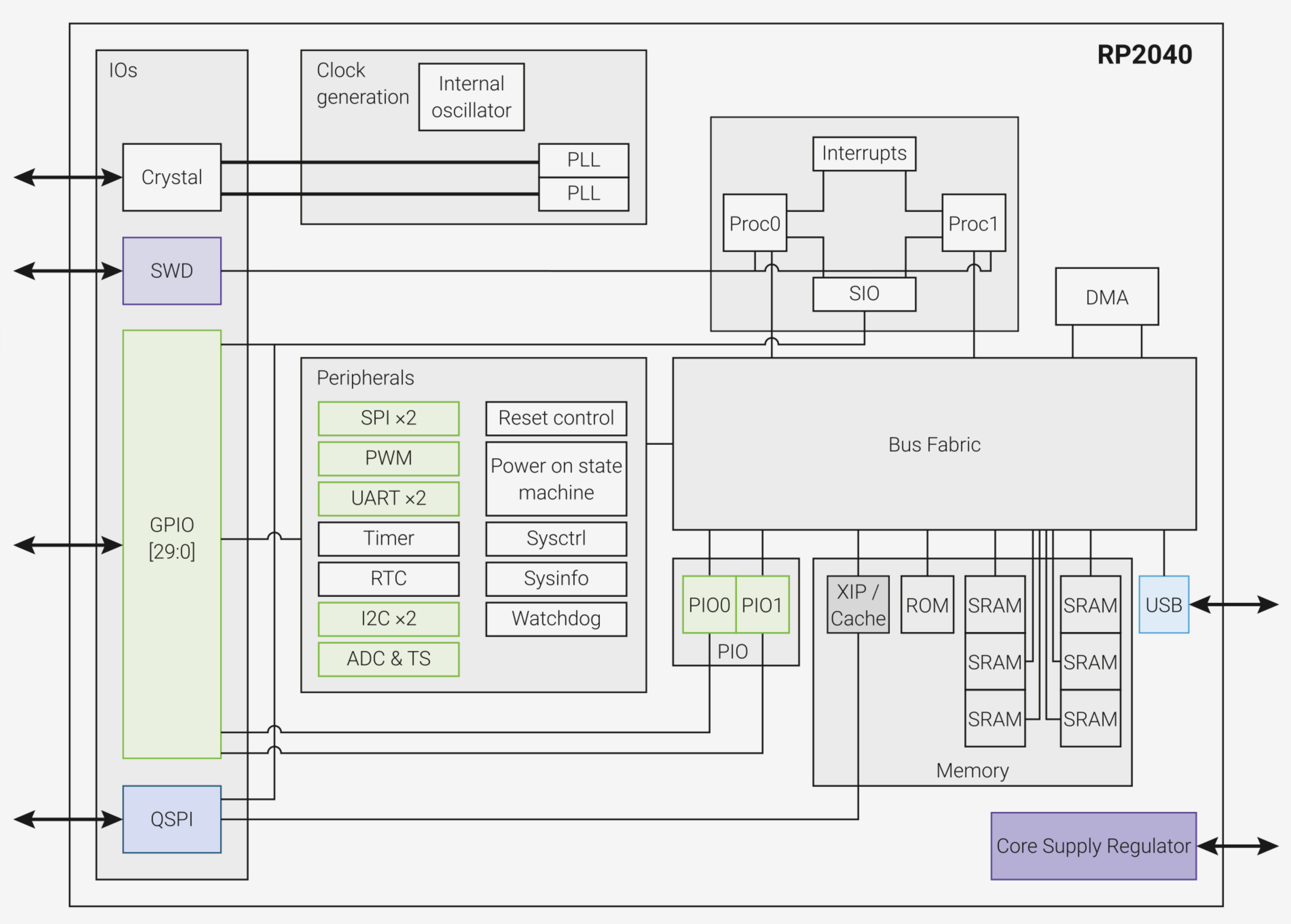
We implement and integrate some subsystems. To oversimplify, these include:

Memory, to hold data and instructions.

A processing unit, to execute the instructions (transformations) that quantities in the instruction memory represent. These transformations act on data from elsewhere in memory, or from an input mechanism.

A bus, for moving data between subsystems.

Peripherals. These are special-purpose subsystems (a timer, a serializer/deserializer, a DMA channel, etc.) which do a limited number of things efficiently, and communicate with the CPU over the bus.



System architecture for RP2040 microcontroller. This is one level of abstraction up from the computer architecture.

Top

What is a computer?

Digital | Analog | Quantum | Natural

Special-purpose

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Think ASIC's, and **hardware accelerators**.

Put a pin in these ideas.

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What is a computer?

Digital | **Analog** | Quantum | Natural

- Quantities are represented **physically** (i.e., with physics) by position, analog voltage, etc..
- If we'd like to model/predict the degrees of freedom of some system (tides, movement of planets, etc.), we build an ***analog****ous* analog computer which contains the same number of degrees of freedom, and the same equations for describing how those degrees of freedom change with time.
  - When you double a quantity in an analog computer, something inside the computer doubles!
- Analog computers use physics to understand one system with another system. They do so by **changing the units of the quantities being transformed**, but keeping those transformations identical between systems.
  - The position of a planet may be modeled as the voltage from an operational amplifier, or the angular position of a rotating gear.
- Analog computers tend to be **special purpose**, but they can be extremely fast and power efficient as compared to digital electronic computers.

What is a computer?

How do you design an analog computer?

First:

Generate an understanding of the system which you'd like to model (what are the degrees of freedom, and what are the equations which describe how those degrees of freedom change with time?).

→

Then:

Build a separate system which contains the same number of degrees of freedom, and the same equations which describe how those degrees of freedom change with time.

You have control over this system! You can make it run faster, slower, forward, backward, and you can change parameter values.

What is a computer?

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Put a pin in this idea too.

What is a computer?

Digital | Analog | **Quantum** | Natural

- Quantities are represented **symbolically** by the probability amplitudes of finding a *qubit* in one of two possible quantum states. A qubit can exist in a superposition of these two states, but chooses one (based on those probability amplitudes) upon observation. We never observe the superposition, only the classical bit which results from the observation.

- Because all of our qubits are entangled (their probability amplitudes are correlated), each additional qubit **doubles** the dimension of the state space. The size of the state space for a quantum computer with 300 qubits is 2^{300}, greater than the number of atoms in the universe.

- Quantum computers transform the representations for these quantities (the probability amplitudes) by means of **quantum logic gates**, which are analogous to classical logic gates in digital computers.
  - These gates logically modify the probability amplitudes for the qubits, potentially conditioned on the probability amplitudes of other qubits.
  - Because an observation collapses these probability amplitudes, we defer observation to the *end* of the quantum computation. This observation collapses the system to classical bits, which we interpret as the output of our calculation.

- The power of these computers is **parallelism**. The transformations encoded by the quantum logic gates occur for all values in the (potentially massive) superposition state space in parallel. The resulting output encodes the transformation as applied to all values in the superposition. This collapses upon observation, suggesting that quantum computers do not *replace* other computers, but accelerate particular kinds of algorithms.

What is a computer?

Digital | Analog | **Quantum** | Natural

How do you use a quantum computer?

1. Initialize the probability amplitudes for all of your qubits to describe an initial superposition.
2. Setup your quantum logic gates such that they implement your algorithm of interest.
3. Allow for these quantum logic gates to transform your qubit probability amplitudes.
4. Measure the system, which collapses the qubits to classical bits according to their updated probability amplitudes.
5. Treat the resulting collection of classical bits as the result of your computation.

For example . . .

What is a computer?

Digital | Analog | **Quantum** | Natural

RSA public key N (product of two big prime numbers) → **Quantum computer**

Find a number, r, which is likely to share a prime factor with N → Run Euclid's algorithm to find the greatest common factor between N and r, then use that factor (likely to be one of the prime factors of N) to find the other. → Now you have the RSA private key.

What is a computer?

Digital | Analog | **Quantum** | Natural

RSA public key N (product of two big prime numbers) →

Quantum computer

Find a number, r, which is likely to share a prime factor with N

→ Run Euclid's algorithm to find the greatest common factor between N and r, then use that factor (likely to be one of the prime factors of N) to find the other.

→ Now you have the RSA private key.

uh-oh!

What is a computer?

Digital Analog Quantum Natural

The quantum computer behaves like a **physics-based accelerator** for a digital electronic computer. By interfacing the digital electronic computer with a separate computing device which is based on *completely different* underlying mechanisms for computation, we improve the speed with which that digital electronic computer can compute certain algorithms.

This idea has been extended into . . .

- **Reservoir computing**: Use the intrinsic properties of a material (e.g. twisted magnets, ferroelectrics, memresistors, or a bucket of water) to do computation. This removes the separation between processing and memory units, and the computation being performed can be adjusted by adjusting the properties of the material.
    - Lee, Oscar, et al. "Task-adaptive physical reservoir computing." Nature Materials (2023): 1-9.
    - Duport, F., Schneider, B., Smerieri, A., Haelterman, M. & Massar, S. All-optical reservoir computing. Opt. Express 20, 22783–22795 (2012).
    - Grollier, J. et al. Neuromorphic spintronics. Nat. Electron. 3, 360–370 (2020).
    - Fernando, C. & Sojakka, S. Pattern recognition in a bucket. In Proc. ECAL 2003: Advances in Artificial Life (eds Banzhaf, W. et al.) 588–597 (Springer, 2003).
- **Physical computing:** Implement deep-learning accelerators that use physics (optics, mechanics, etc.) to generate neural networks.
    - Wright, Logan G., et al. "Deep physical neural networks trained with backpropagation." Nature 601.7894 (2022): 549-555.
    - Lee, Ryan H., Erwin AB Mulder, and Jonathan B. Hopkins. "Mechanical neural networks: Architected materials that learn behaviors." Science Robotics 7.71 (2022): eabq7278.

But can we **find** these computers rather than **engineer** them?

What is a computer?

Digital | Analog | Quantum | **Natural**

In the near-term . . .

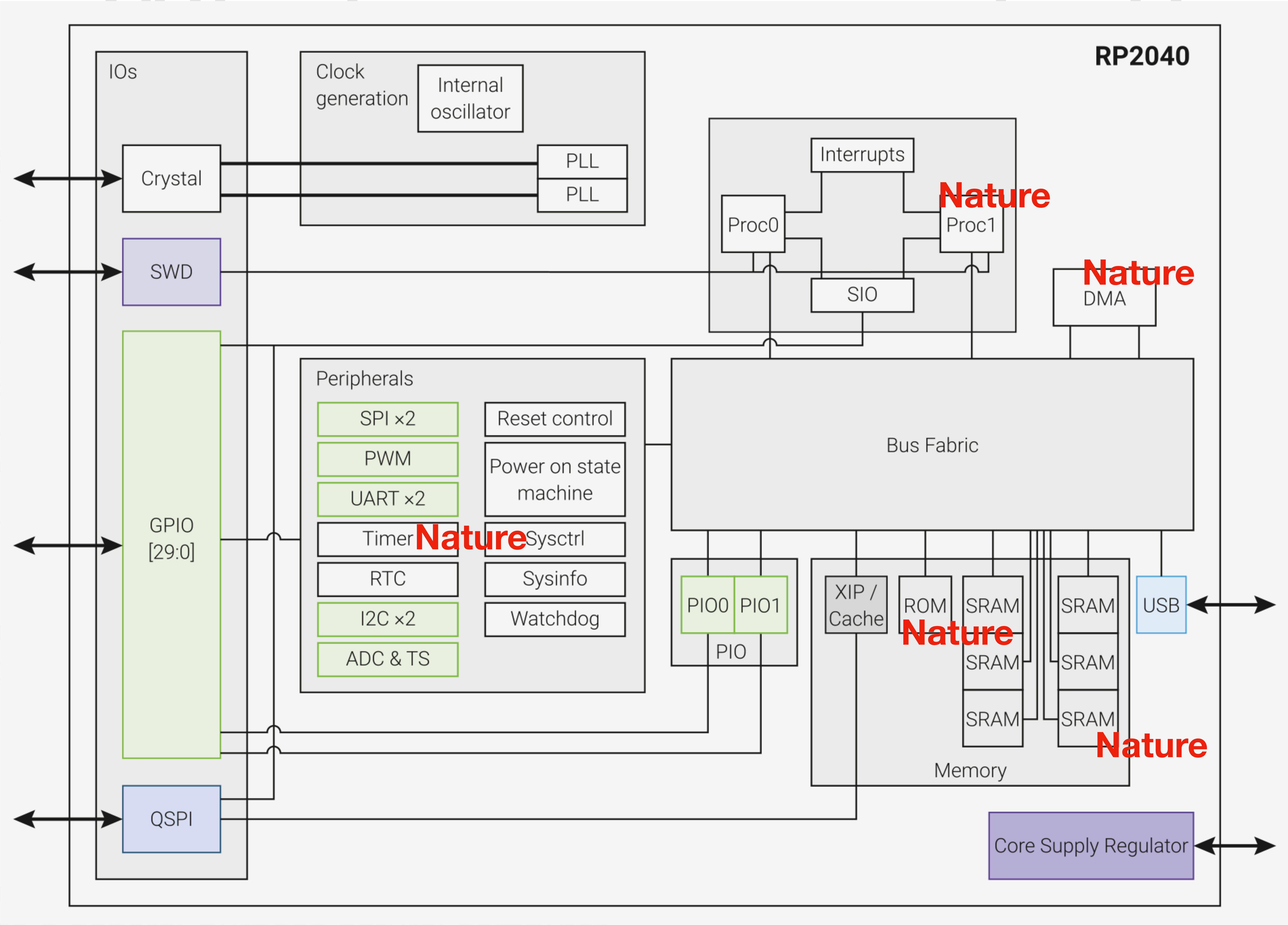
- Nature is replete with processes which transform one set of quantities into another. To the extent that these transformations are **useful**, then these are examples of **natural computation**. If we can interface these natural sources of computation with our digital electronic computers, they can be used as **natural accelerators** (as opposed to hardware accelerators).
- Nature is replete with **repositories for data**. If we can interface these natural repositories for data with our digital electronic computers, they can be used as **natural memory**.
- Nature offers mechanisms for **moving data**, *en masse*, from one place to another. If we can interface this natural movement of data with our digital electronic computers, they can be used for **natural data transfer.**

In the limit . . .

- We can piece together these natural accelerators, natural memory, and natural mechanisms for data transfer into a general-purpose natural computer.

Digit ... tural

- Nature is r ... xtent that these tran ... n interface these natu ... d as **natural accelerat**
- Nature is r ... data with our digital
- Nature off ... interface this natural mo ... **l data transfer.**



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What is a computer?

Digital | Analog | Quantum | **Natural**

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- Nature offers mechanisms for **moving data**, *en masse*, from one place to another. If we can interface this natural movement of data with our digital electronic computers, they can be used for **natural data transfer.**

Let us consider **natural computation**, **natural memory**, and **natural data transfer** in turn

In the limit . . .

- We can piece together these natural accelerators, natural memory, and natural mechanisms for data transfer into a general-purpose natural computer.

Nature and computing

Natural computation | Natural memory | Natural data transfer

How does one implement a natural computational accelerator?

1. Engage in **computational naturalism**, through which one searches in nature for examples of **algorithmic processes** through which quantities are being transformed into other quantities.
2. Develop a model for this system which describes that transformation of inputs to outputs, in detail or in a blackbox fashion.
3. Develop a system by which a digital electronic computer can affect the inputs to the system and observe the outputs, and then use that system as an **accelerator** for that particular algorithm.

Rather than **building** analog computers, we are **finding** analog computers, understanding the transformations that they perform, and plugging them into our digital electronic computers as accelerators. There is evidence that this works . . .

Nature and computing

Natural computation | Natural memory | Natural data transfer

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This relates to Wolfram's Principle of Computational Equivalence. Every process (from simple cellular automata, to physics, to brains) can be thought of as *computational* (transforming inputs to outputs). The Principle of Computational Equivalence states that, above a low threshold, all these processes correspond to computations of equivalent sophistication.

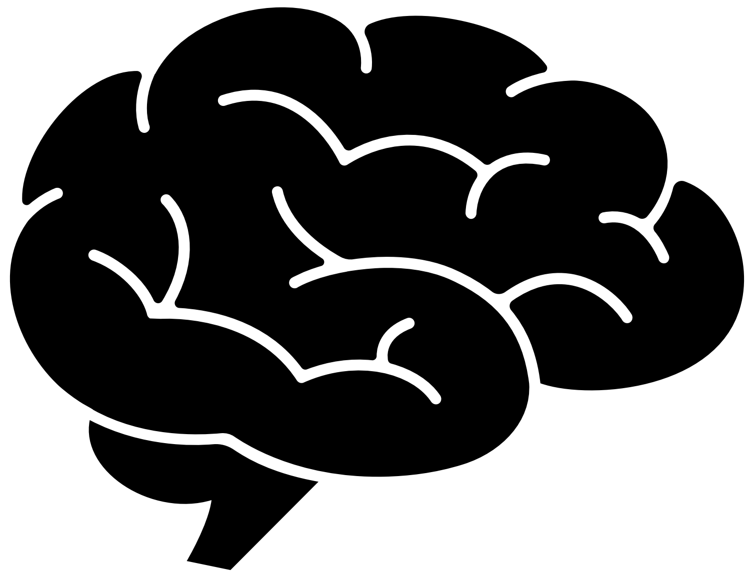
But can these computations be ***used***?

Nature and computing

Natural computation | Natural memory | Natural data transfer

How do we know that this works, in principle?

1. Our **brains** are natural accelerators for our **digital electronic computers**.
2. Our brains are better than our computers at certain algorithms.
3. We interface our brains with digital electronic computers by means of keyboards, mice, screens, microphones, and speakers. Our computers can thereby use our brains as accelerators, offloading work to our brains by providing an input to the brain, and then prompting for the output from the brain.



An example of a natural accelerator

Nature and computing

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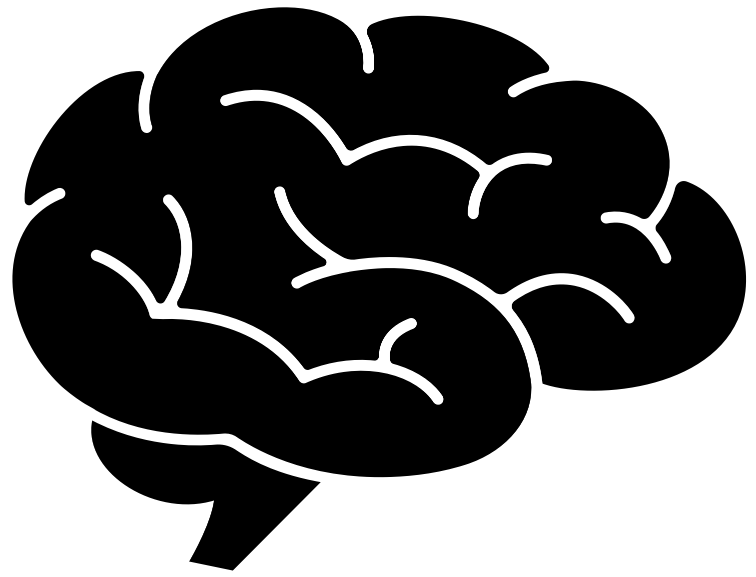

An example of a natural accelerator

But there are more examples!

Nature and computing

Natural computation | Natural memory | Natural data transfer

Low-hanging fruit

1. Nature excels at **generating randomness**. We might develop a natural random number generator:
    - Use galactic cosmic rays (or high-energy particles from a small piece of radioactive material) as bus-masters. Build radiation-softened memory to increase the rate of single-event upsets in a section of memory, and use those single-event upsets as a source of entropy.
2. Nature offers **periodic processes**, which might be used as natural timer peripherals in event-driven systems.
    - Synchronization occurs all over the place in nature! Can we sync our computers with these natural oscillators?
    - Extend battery life in your IoT device by turning it **off** with a latching circuit (consumes ~0W), and using a stochastic natural process (wind blowing on a piezo, a bird pecking a vibration sensor, etc.) to wake the system at some rate.

Strogatz, Steven H., and Ian Stewart. "Coupled oscillators and biological synchronization." Scientific american 269.6 (1993): 102-109.

Nature and computing

Natural computation | Natural memory | Natural data transfer

Let's prove this concept

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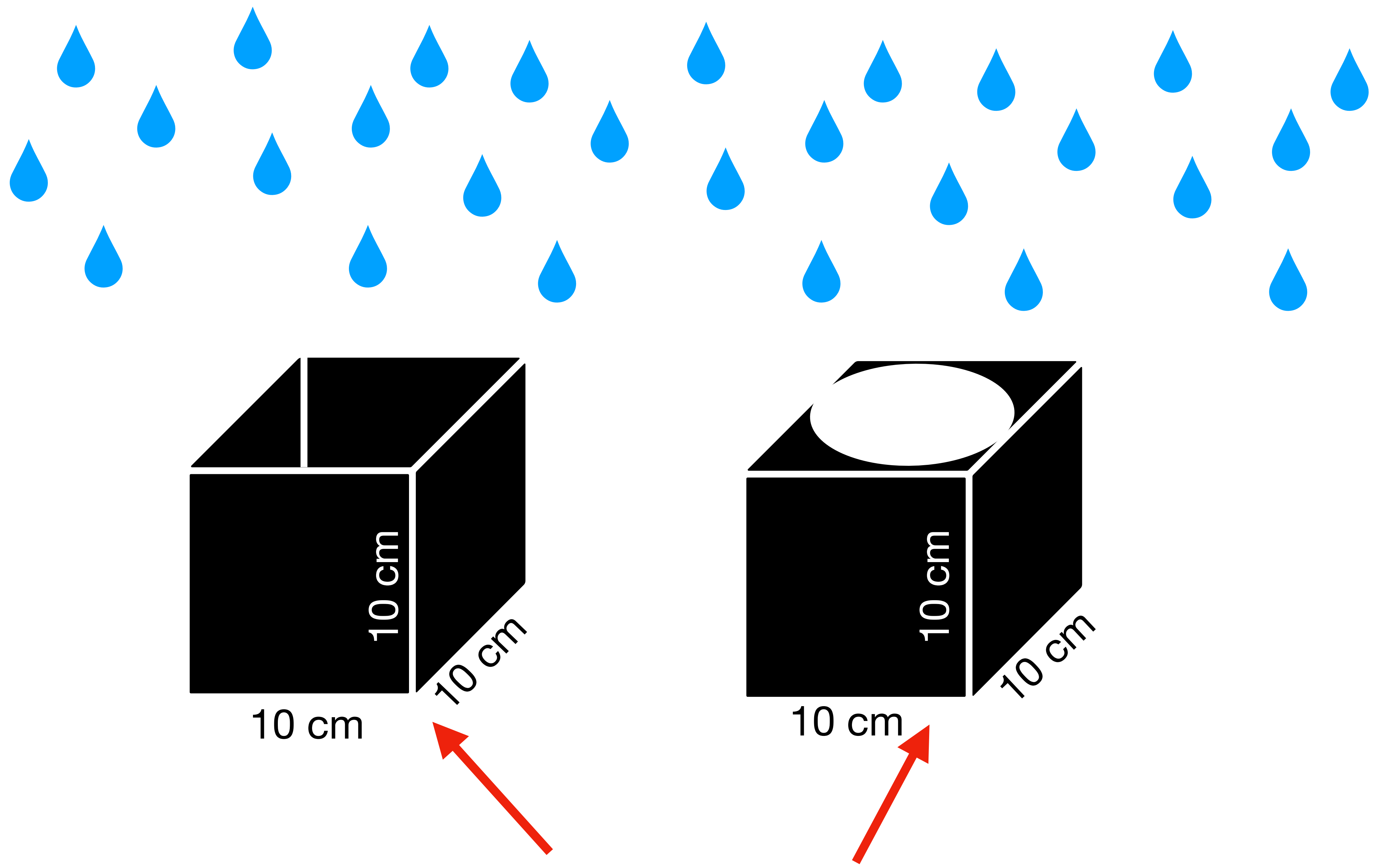
Nature and computing

Natural computation | Natural memory | Natural data transfer

Monte Carlo integration by rain

1. Manufacture a 10cm x 10cm x 10cm vessel, which will hold precisely 1L of water (1kg). This vessel should have an open top.
2. Lasercut the curve which you would like to integrate (e.g., a circle) out of a 10cm x 10cm acrylic sheet. Use this as the lid a separate vessel of the same size
3. Place both vessels in the rain until the open-top vessel fills
4. Mass the other vessel. The area of the curve in square cm is $(100 \times \text{mass of water in kg})$



When this fills, mass this.

Multiply mass (kg) by 100 to get area of curve in cm^2.

(Assumes uniform distribution of equal-volume raindrops)

Nature and computing

Natural computation | Natural memory | Natural data transfer

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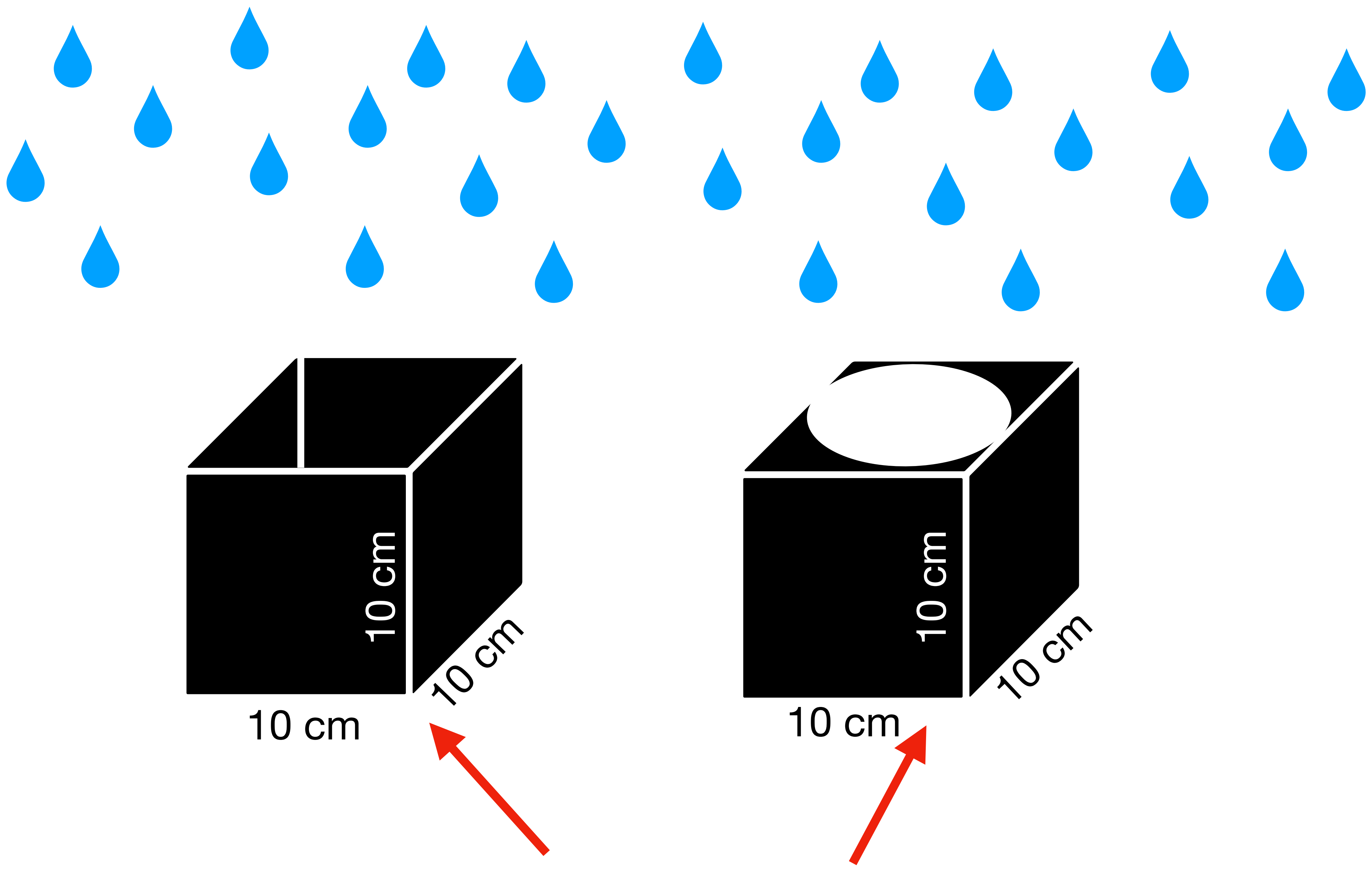


Multiply mass (kg) by 100 to get area of curve in cm^2.

(Assumes uniform distribution of equal-volume raindrops)

A very similar setup could use snow or bubbles rather than rain.

Nature and computing

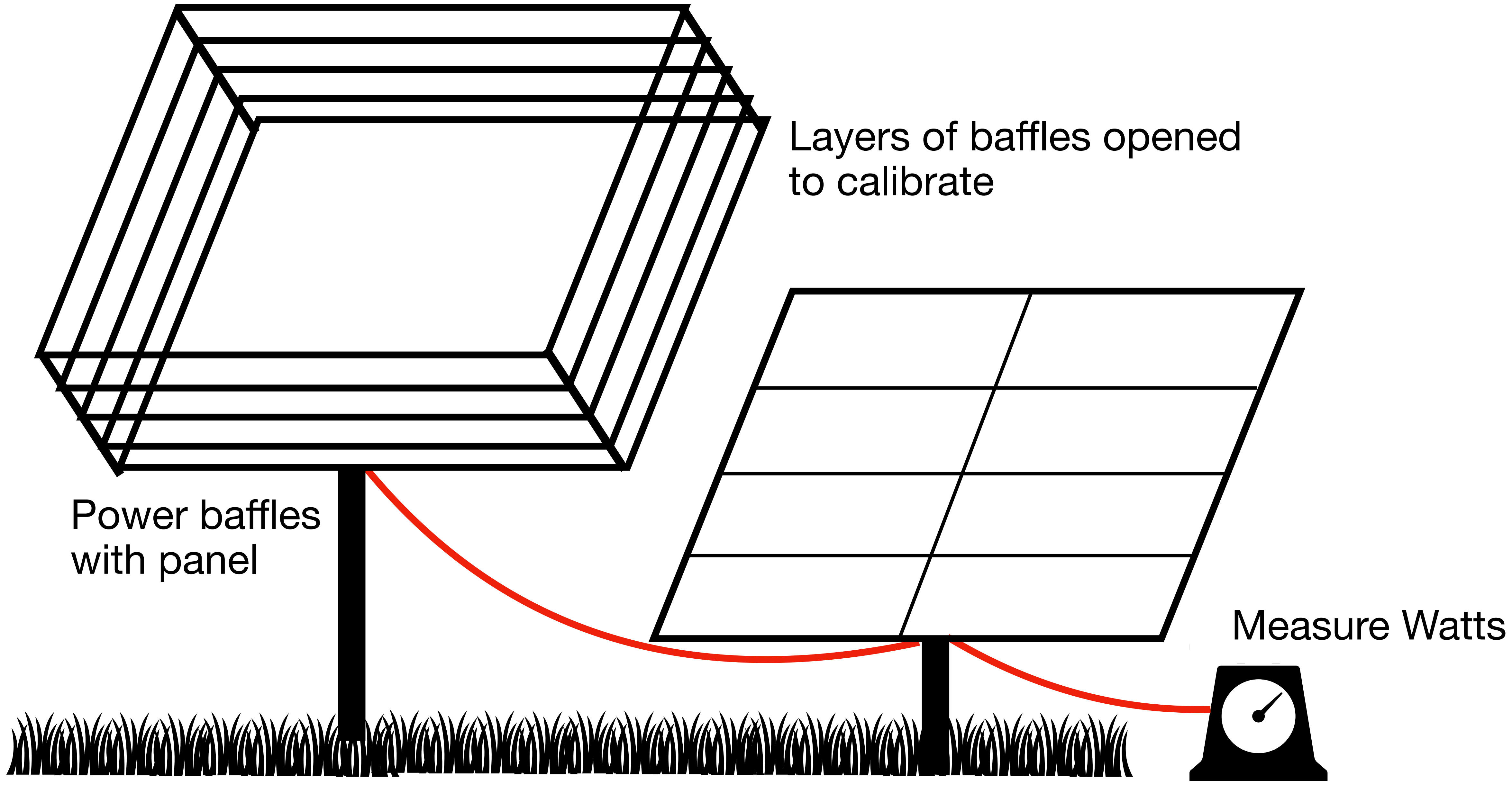
Natural computation | Natural memory | Natural data transfer

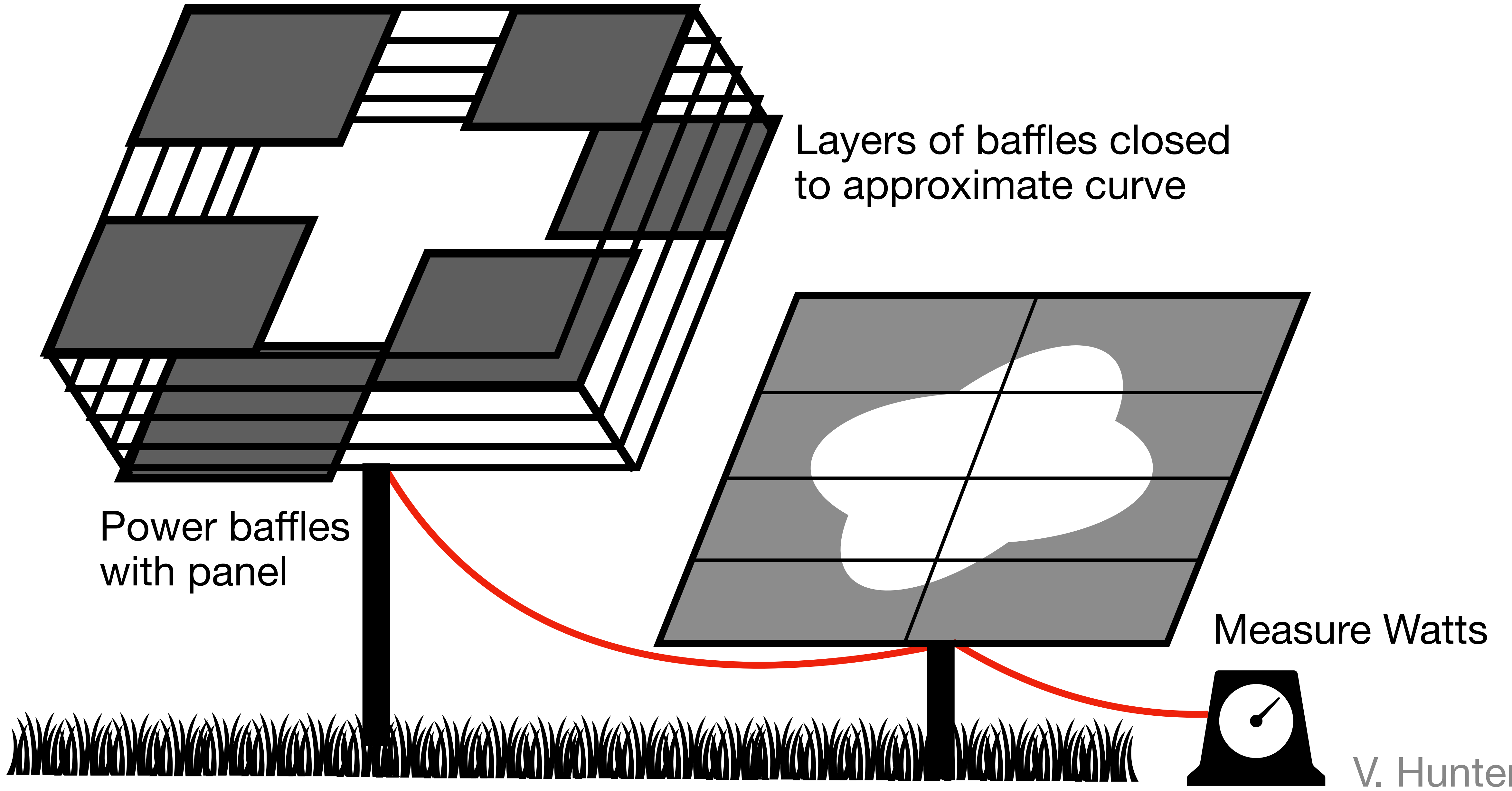
Monte Carlo integration by sunshine

Known

(~~Local solar irradiance~~) x (~~panel efficiency~~) x (panel area unbaffled)
——————————————————————————— = Measured watts unbaffled / Measured watts baffled
(~~Local solar irradiance~~) x (~~panel efficiency~~) x (panel area baffled)

Unknown





Nature and computing

Natural computation | Natural memory | Natural data transfer

Monte Carlo integration by sunshine

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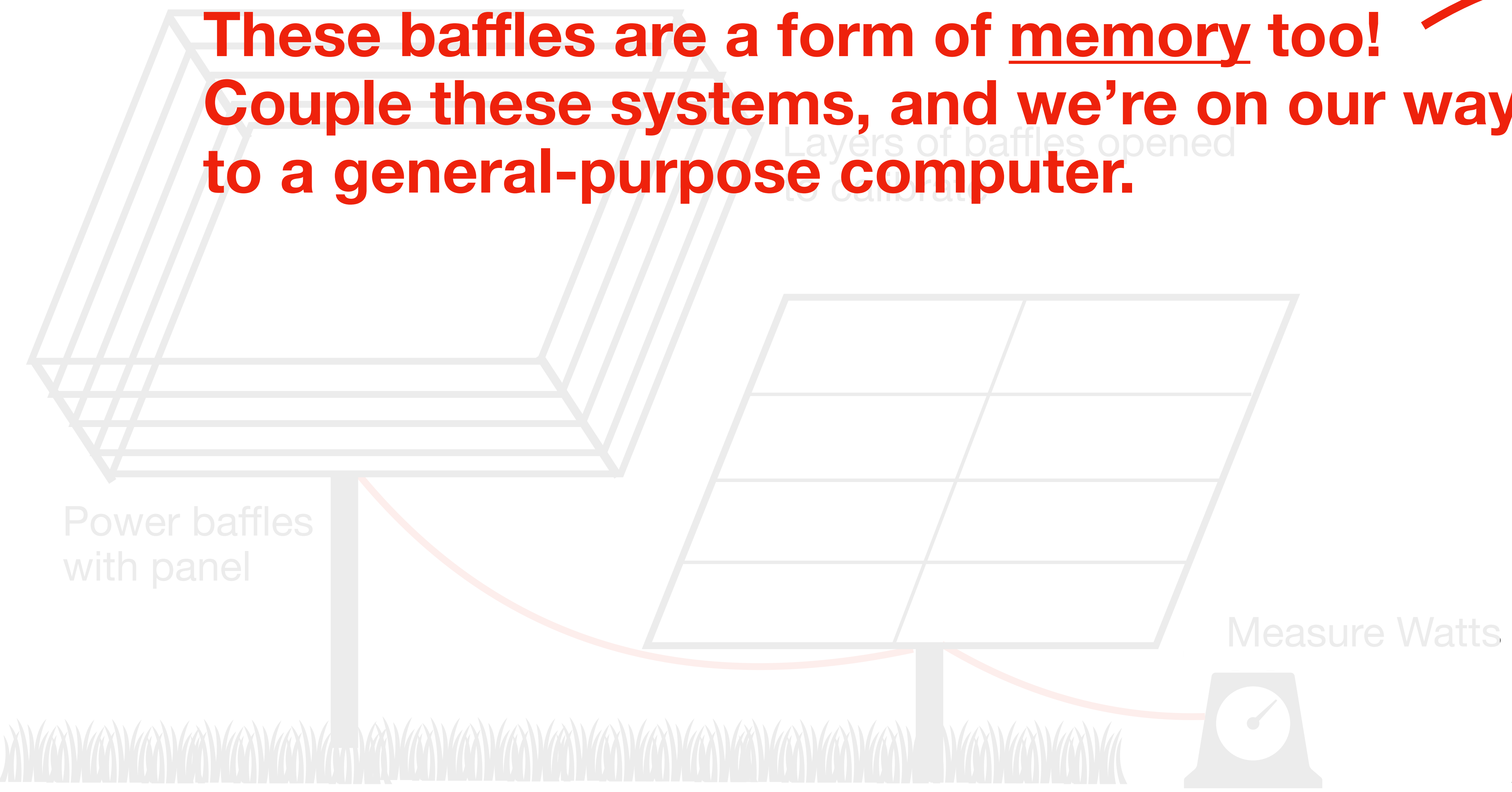
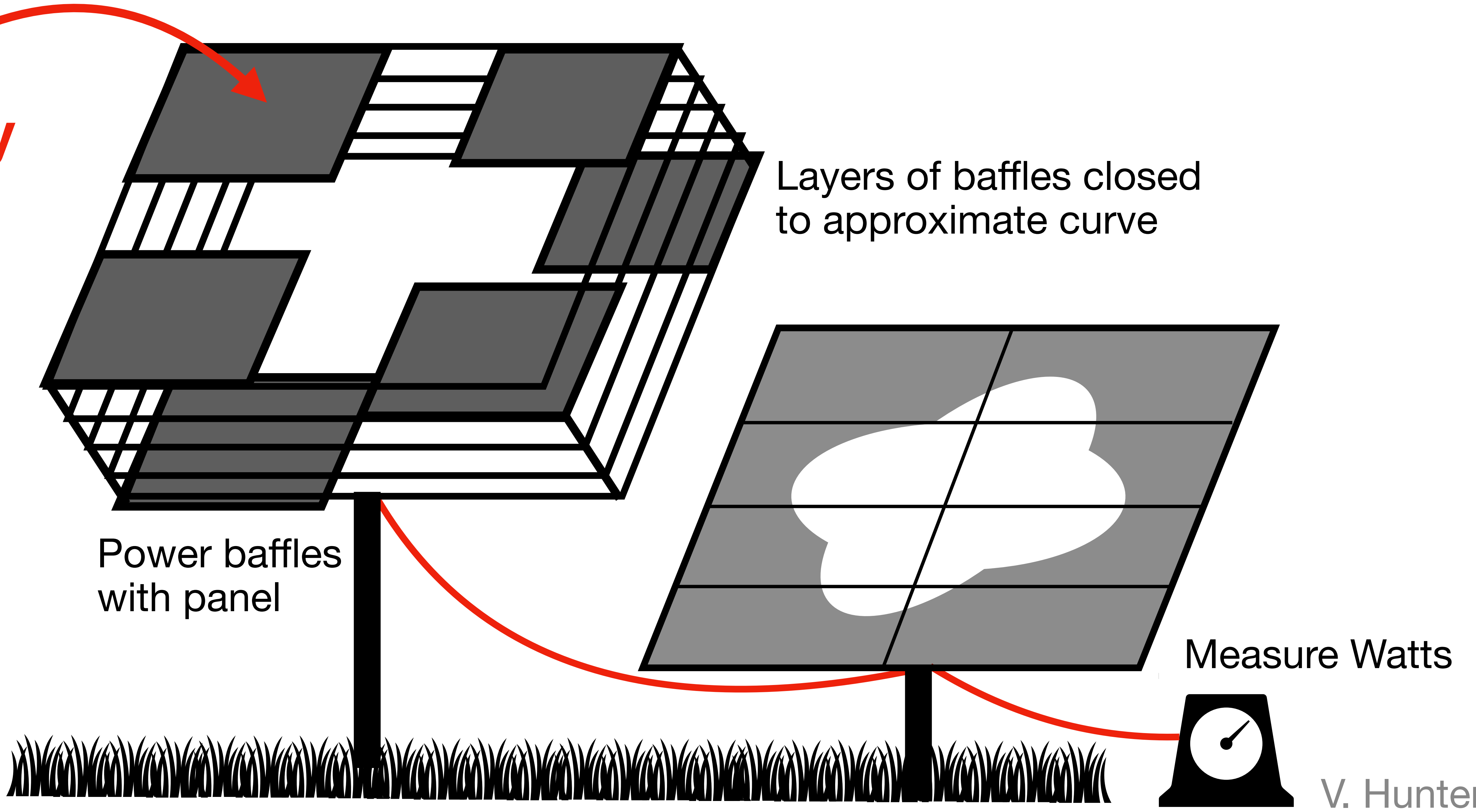
(~~Local solar irradiance~~) x (~~panel efficiency~~) x (panel area unbaffled) / (~~Local solar irradiance~~) x (~~panel efficiency~~) x (panel area baffled) = Measured watts unbaffled / Measured watts baffled

Unknown

These baffles are a form of <u>memory</u> too!
Couple these systems, and we're on our way to a general-purpose computer.





V. Hunter Adams

Nature and computing

Natural computation | Natural memory | Natural data transfer

Low-hanging does not mean low-impact!

Low-hanging fruit:

What fraction of total global compute is devoted to Monte Carlo analysis? What fraction of all of the instructions being executed each second by all the CPU's on the planet is devoted to generating pseudorandom numbers? How much energy would be saved by utilizing natural random number generators?

1. Nature excels at **generating randomness**. We might develop a natural random number generator:
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    - Extend battery life in your IoT device by turning it **off** with a latching circuit (consumes ~0W), and using a stochastic natural process (wind blowing on a piezo, a bird pecking a vibration sensor, etc.) to wake the system at some rate.

Nature and computing

Natural computation | Natural memory | Natural data transfer

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   Let's prove this concept

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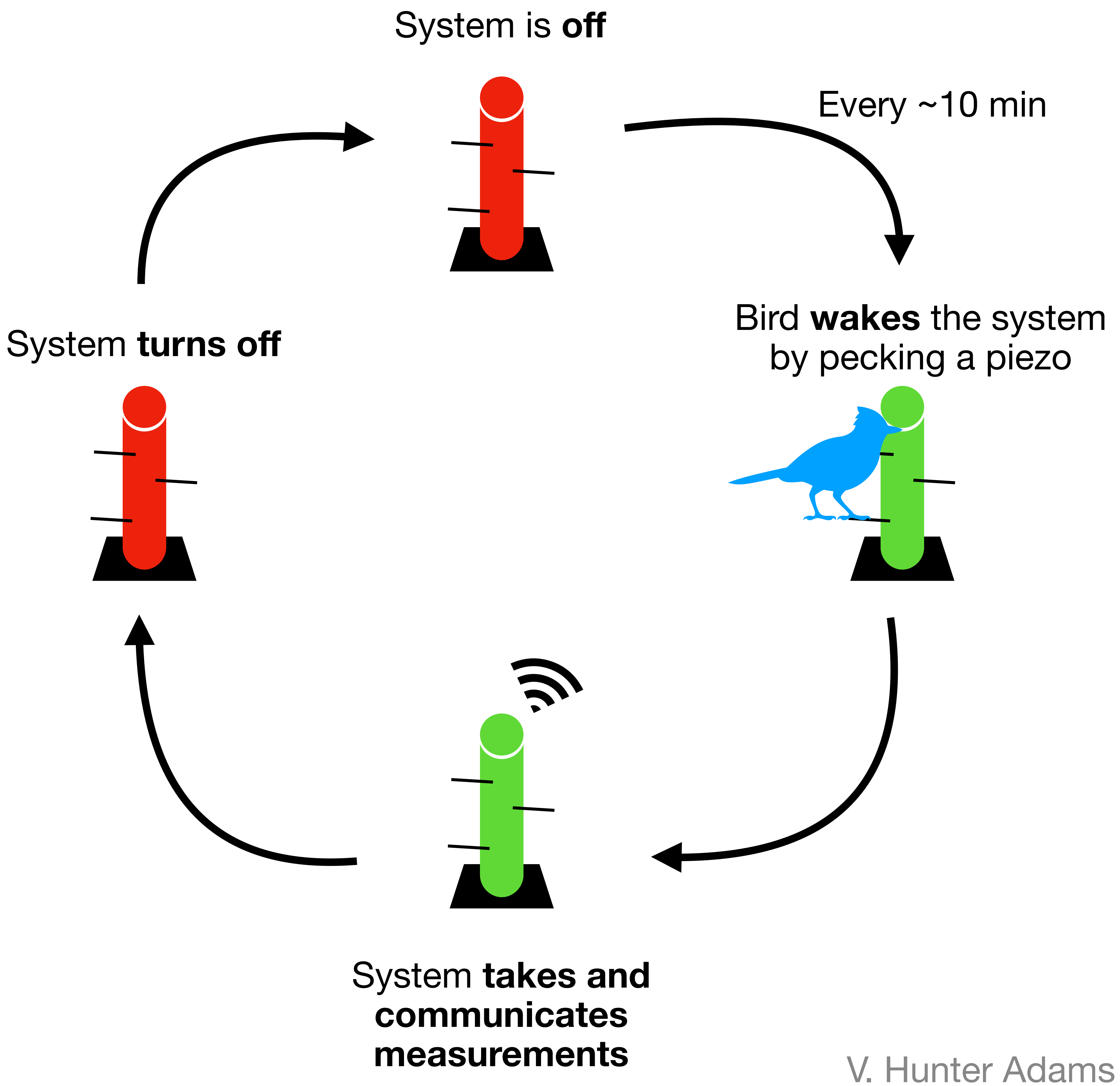
Nature and computing

Natural computation | Natural memory | Natural data transfer

Birds as timers in IoT systems

1. In digital agriculture applications, we generally don't require high-speed or high-precision timing in our measurements (temperature, humidity, etc. don't change that quickly)
2. To save battery, we want to sleep the system as much as possible and only wake when it's time to take a measurement. But how do we know when it's time to take a measurement?
3. We have two options:
    1. Keep a timer on (which consumes power)
    2. Allow for *some natural periodic process* to wake our system. Like, for instance, birds visiting a bird feeder!



Nature and computing

Natural computation | Natural memory | Natural data transfer

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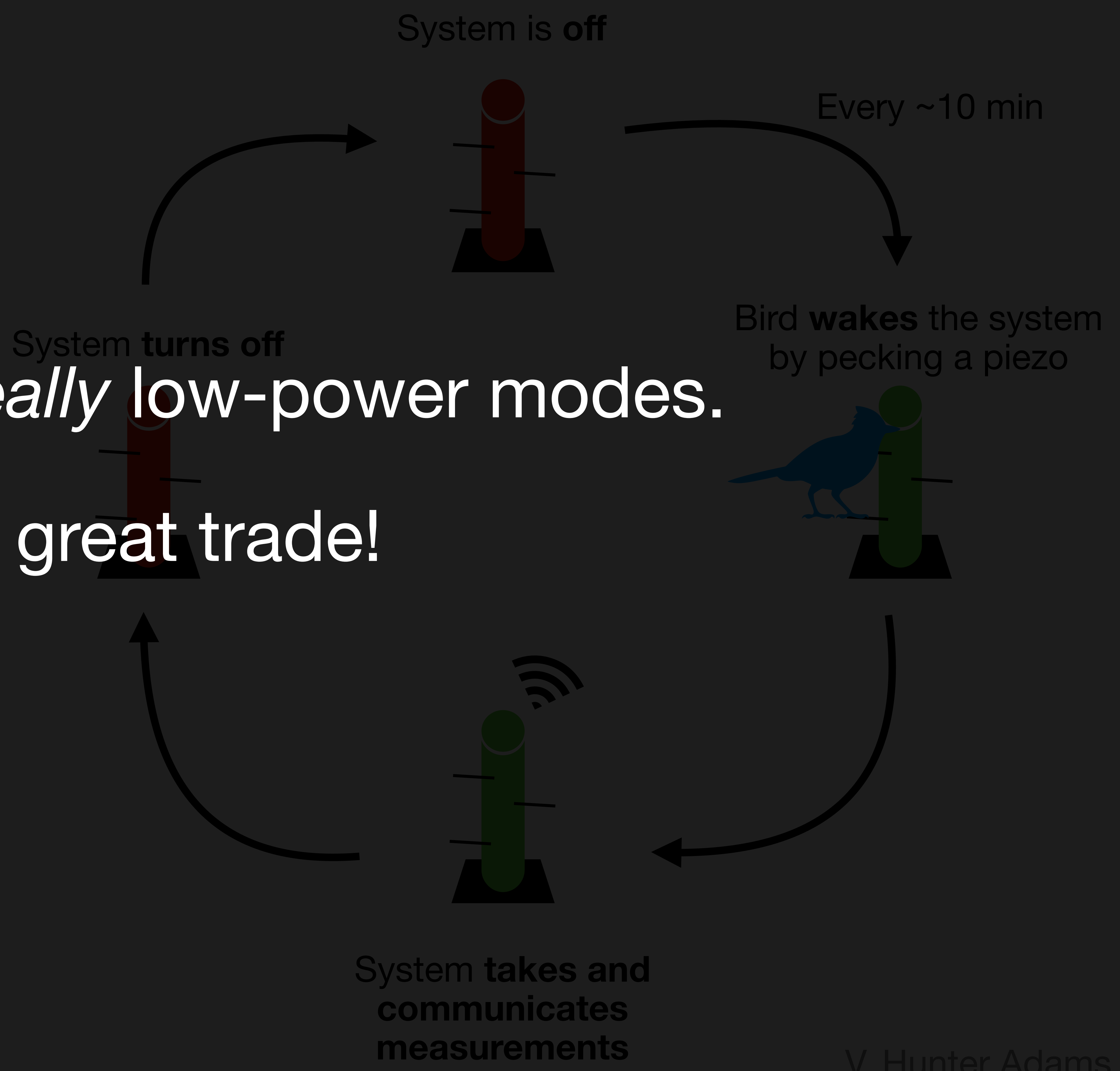

We **lose** timing guarantees but we **gain** *really* low-power modes.

For some applications, that's a great trade!

Nature and computing

Natural computation | Natural memory | Natural data transfer

Birds as timers in IoT systems

1. In digital agriculture applications, we generally don't require high-speed or high-precision timing in our ...

2. Allow for *some natural periodic process* to wake our system. Like, for instance, birds visiting a bird feeder!

System is **off**

Every ~10 min

System **takes and communicates measurements**

A student and I built a circuit to demonstrate this:

Figure 12: Sleep Mode Experimental Data

Figure 13: Dead to Alive Mode Experimental Data

Michael Awad (ECE MEng, 2024) final project report

Nature and computing

Long-term possibilities . . .

<u>Look how much compute this takes</u>. ***Nature just does it.***

1. Nature excels at **parallel computation**:
   - Though it take tremendous computational effort to do things like integrate the Navier-Stokes equations on an FPGA, nature **just does it**. For some computational physics experiments, we may be able to substitute sensors/actuators for parallelized computers. This resurrects a version of analog computation in which the analog computer is **already built.**
   - We aren't building an engineered analog for a process of interest. We're instead identifying natural computational processes, and looking for analogous computational problems which it might be used to solve.

2. Nature excels at **optimization**.
   - Can we find any examples of natural systems which are solving the Knapsack, or Traveling Salesman, or other NP hard problems? Can those natural systems be influenced to solve a **version** of that problem which is of interest to us?
   - A cliché example is that of a slime mold re-creating the Japanese rail system.

3. We've yet to fully realize the potential of the **brain as natural accelerator**.
   - With better input/output between brain and digital electronic computer, or better understanding of the brain's API, we may better realize the computational potential of the brain.

Nature and computing

Natural computation | Natural memory | Natural data transfer

Long-term possibilities

A slime-mould enthusiast told me about a test he had performed. He frequently got lost in IKEA stores and would spend many minutes trying to find the exit. He decided to challenge his slime moulds with the same problem and built a maze based on the floor plan of his local IKEA. Sure enough, without any signs or staff to direct them, the slime moulds soon found the shortest path to the exit.

- Merlin Sheldrake, *Entangled Life: How Fungi Make Our Worlds, Change Our Minds, and Shape Our Futures*

Look how much compute this takes. *Nature just does it.*

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   - A cliche example is that of a slime mold re-creating the Japanese rail system.
3. We've yet to fully realize the potential of the **brain as natural accelerator**.
   - With better input/output between brain and digital electronic computer, or better understanding of the brain's API, we may better realize the computational potential of the brain.

Nature and computing

Natural computation | Natural memory | Natural data transfer

Long-term possibilities . . .

This takes advantage of the fact that nature reuses her mathematical models. One natural system can be used to model another, or to model a non-natural system of human interest.

1. Nature excels at **parallel computation**.
   - Though it take tremendous computational effort to do things like integrate the Navier-Stokes equations on an FPGA, [illegible] for parallelized computers. This resurrects a version of analog computation in which the analog computer is **already built.**
   - We aren't building an engineered analog for a process of interest. We're instead identifying natural computational processes, and looking for analogous computational problems which it might be used to solve.

2. Nature excels at **optimization**.
   - Can we find any examples of natural systems which are solving the Knapsack, or Traveling Salesman, or other NP hard problems? Can those natural systems be influenced to solve a **version** of that problem which is of interest to us?
   - A cliché example is that of a slime mold re-creating the Japanese rail system.

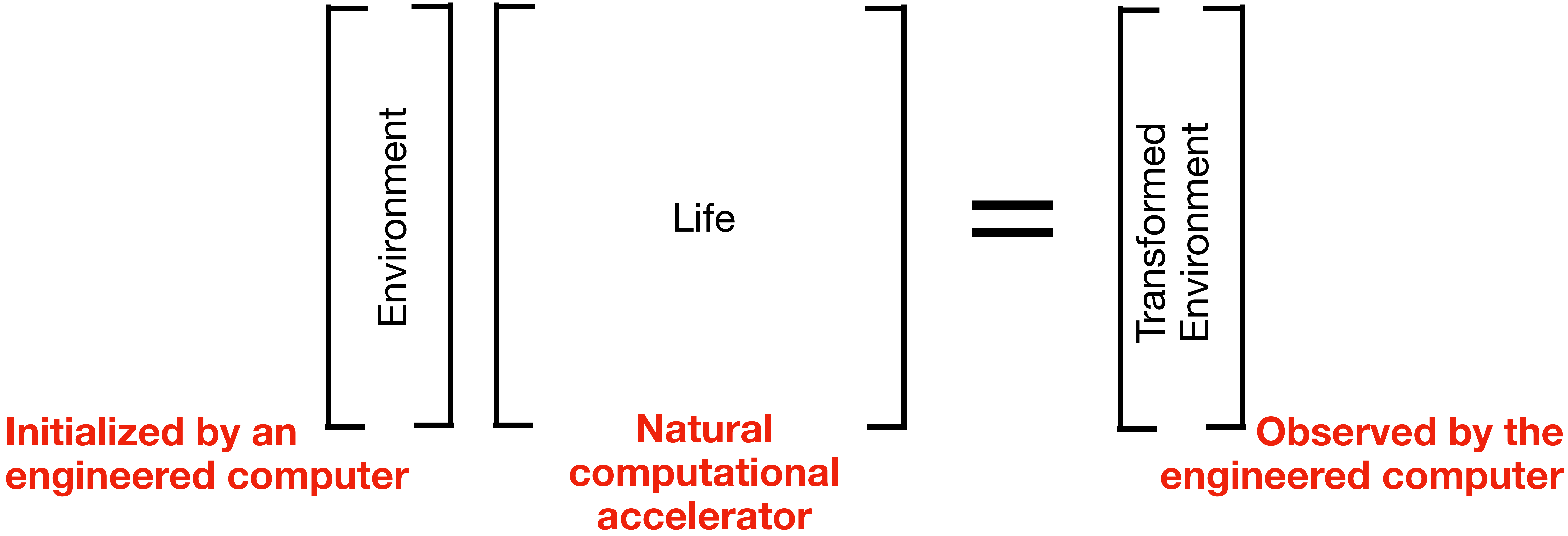
3. We've yet to fully realize the potential of the **brain as natural accelerator**.
   - With better input/output between brain and digital electronic computer, or better understanding of the brain's API, we may better realize the computational potential of the brain.

Nature and computing

More long-term possibilities . . .

The environment is a quantifiable system, which **life** transforms.

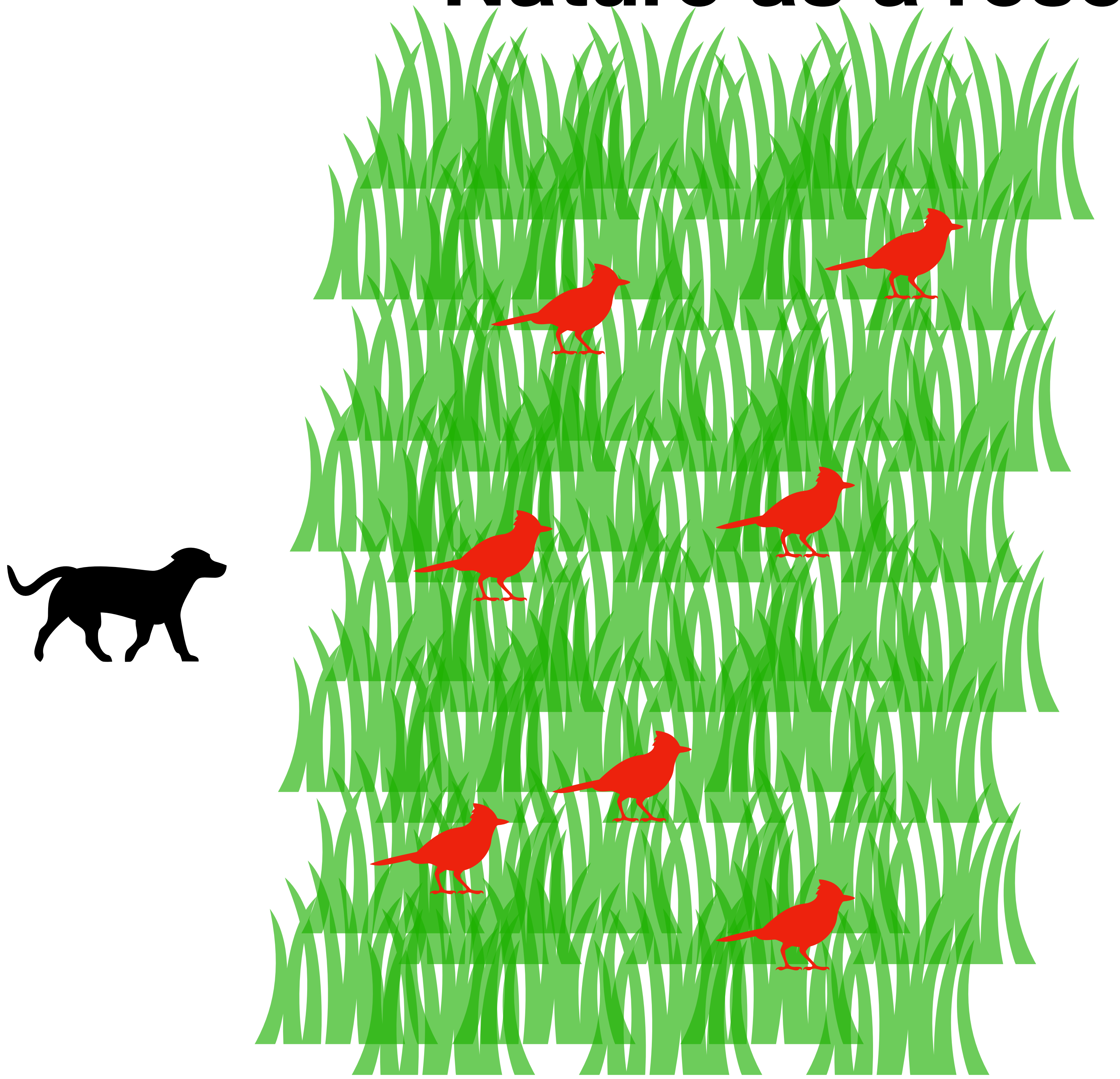
Linearize life about a moment in time, and it is a matrix which acts upon a long vector containing all of its environment's degrees of freedom. If those transformation are useful, then that life is a natural computational accelerator.



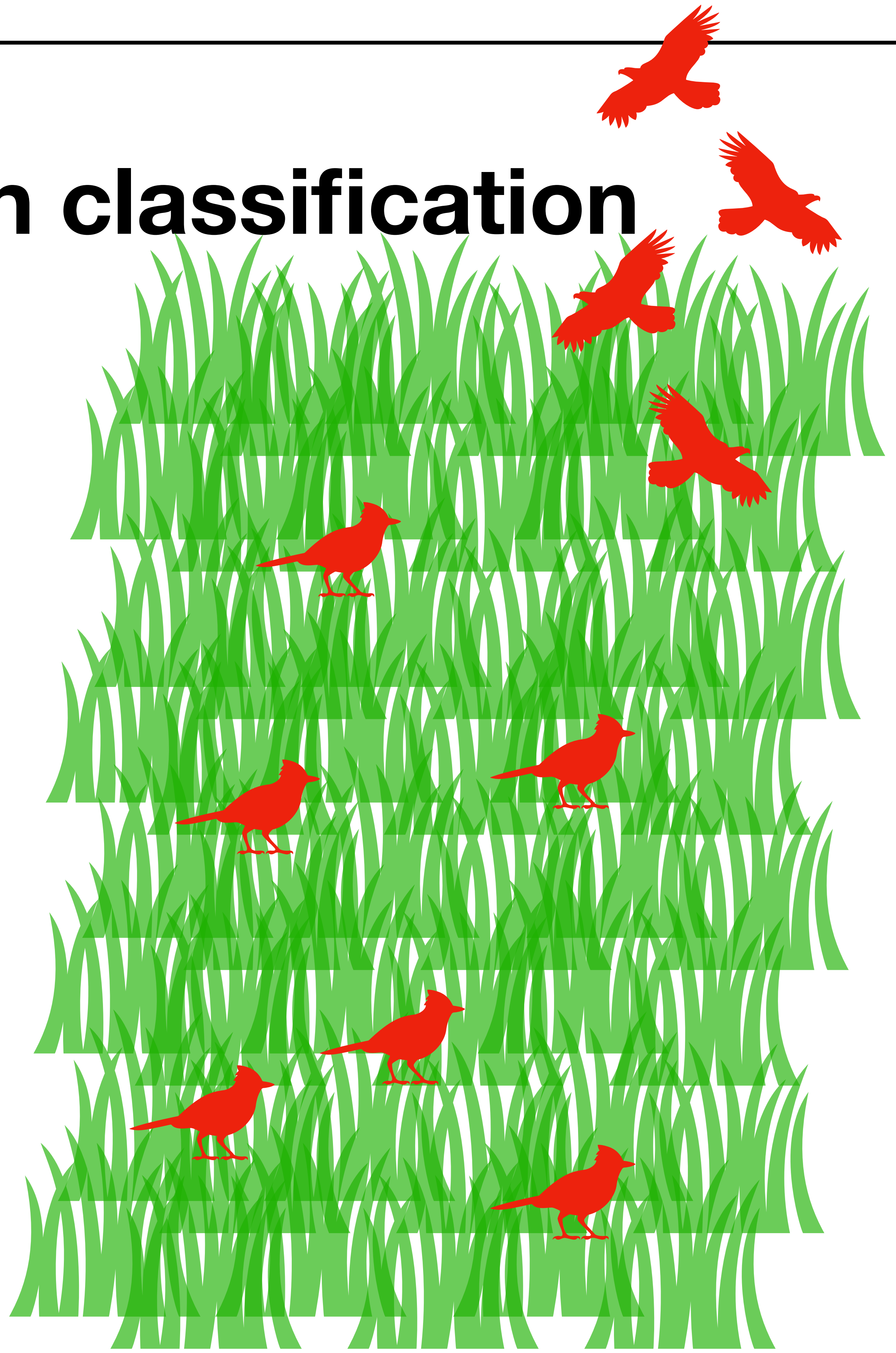
Nature and computing

Natural computation | Natural memory | Natural data transfer

Ecological Shadows:
Nature as a reservoir computer for intrusion classification



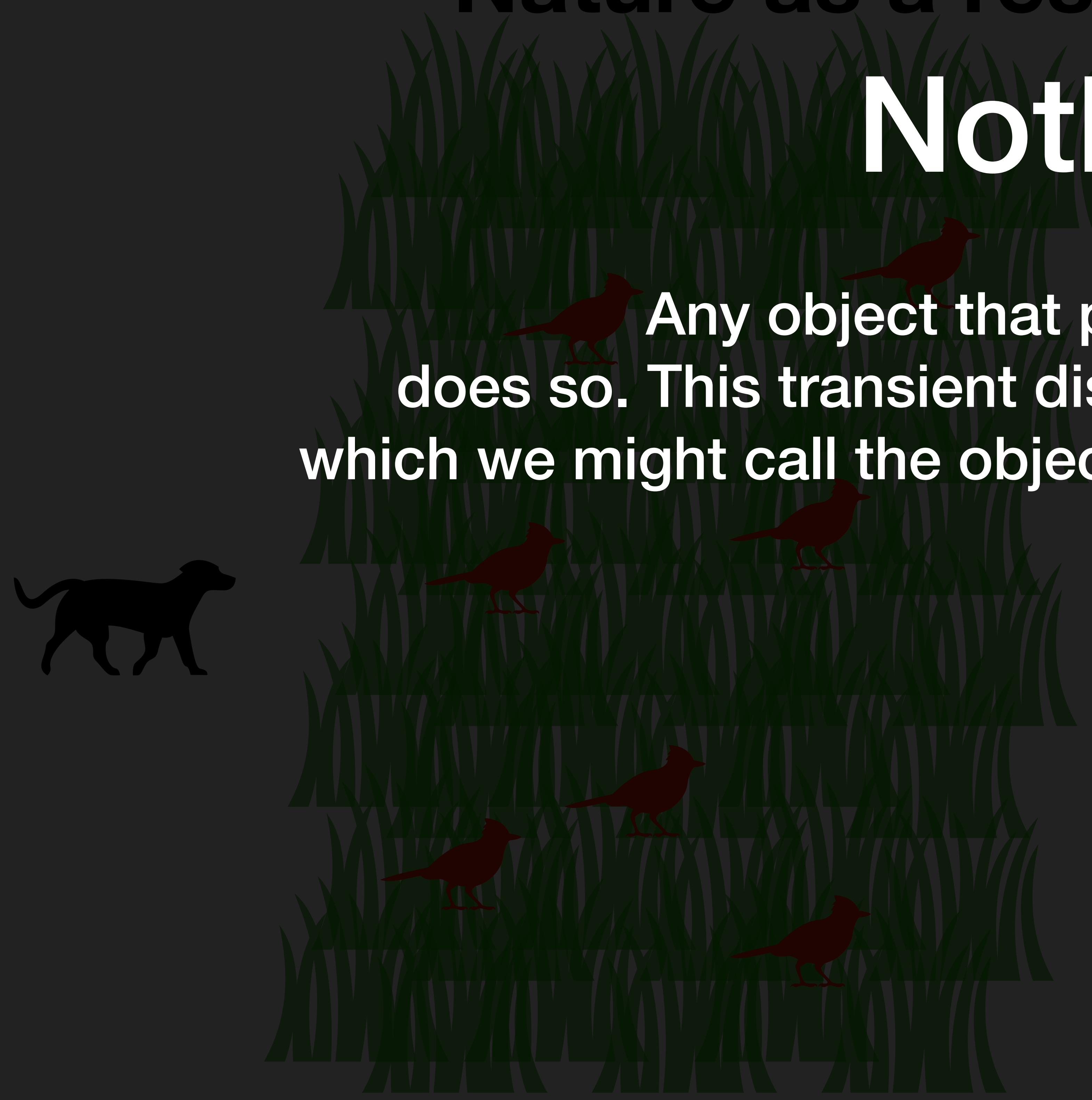
Though you can’t see him in the tall grass, can you locate the dog based on nature’s reaction to his presence?



Nature and computing

Natural computation | Natural memory | Natural data transfer

Ecological Shadows:
Nature as a reservoir computer for intrusion classification

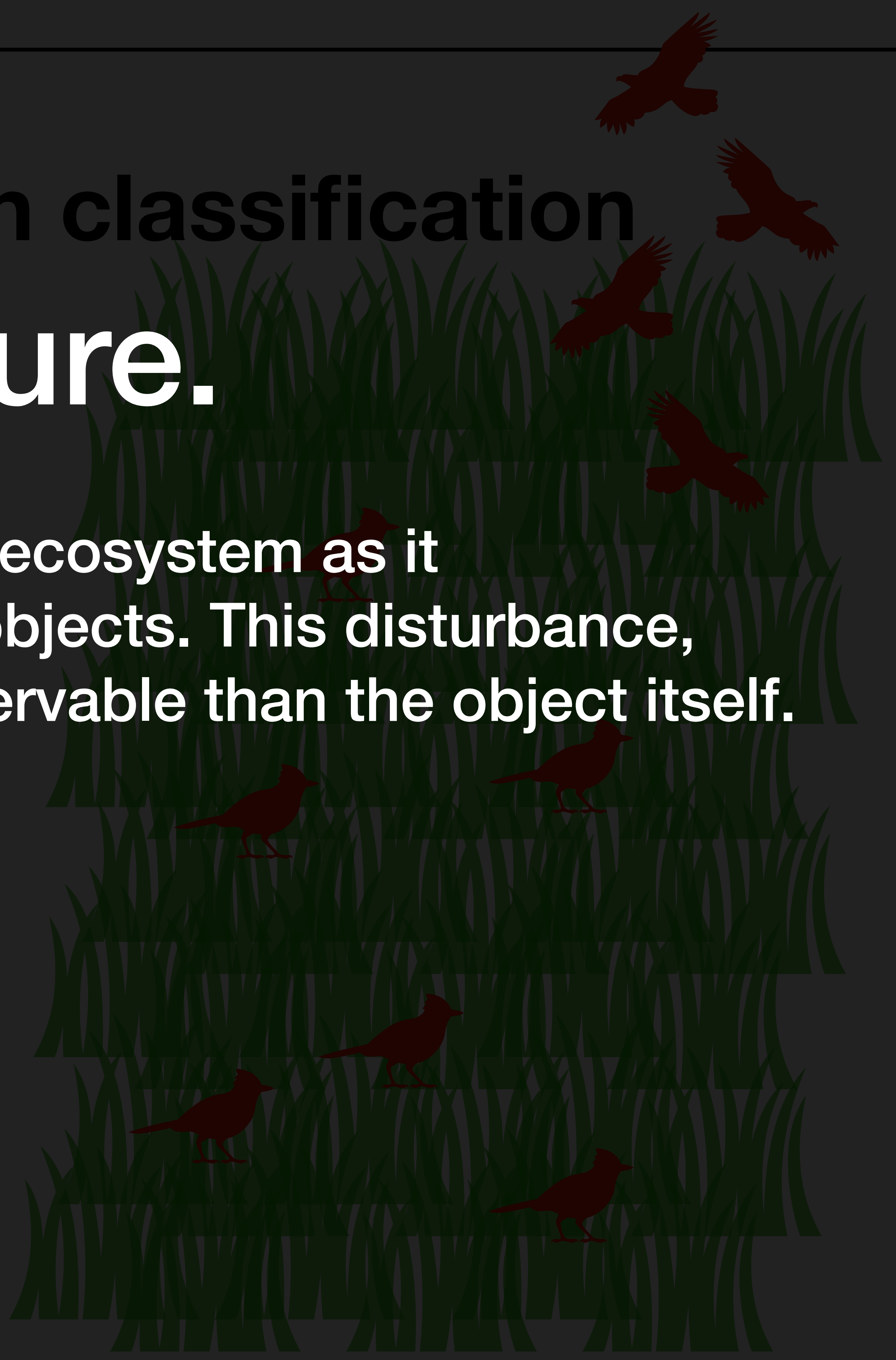


Nothing hides from nature.

Any object that passes through an ecosystem disturbs that ecosystem as it does so. This transient disturbance looks very different for different objects. This disturbance, which we might call the object's "ecological shadow," is often more observable than the object itself.

For instance . . .

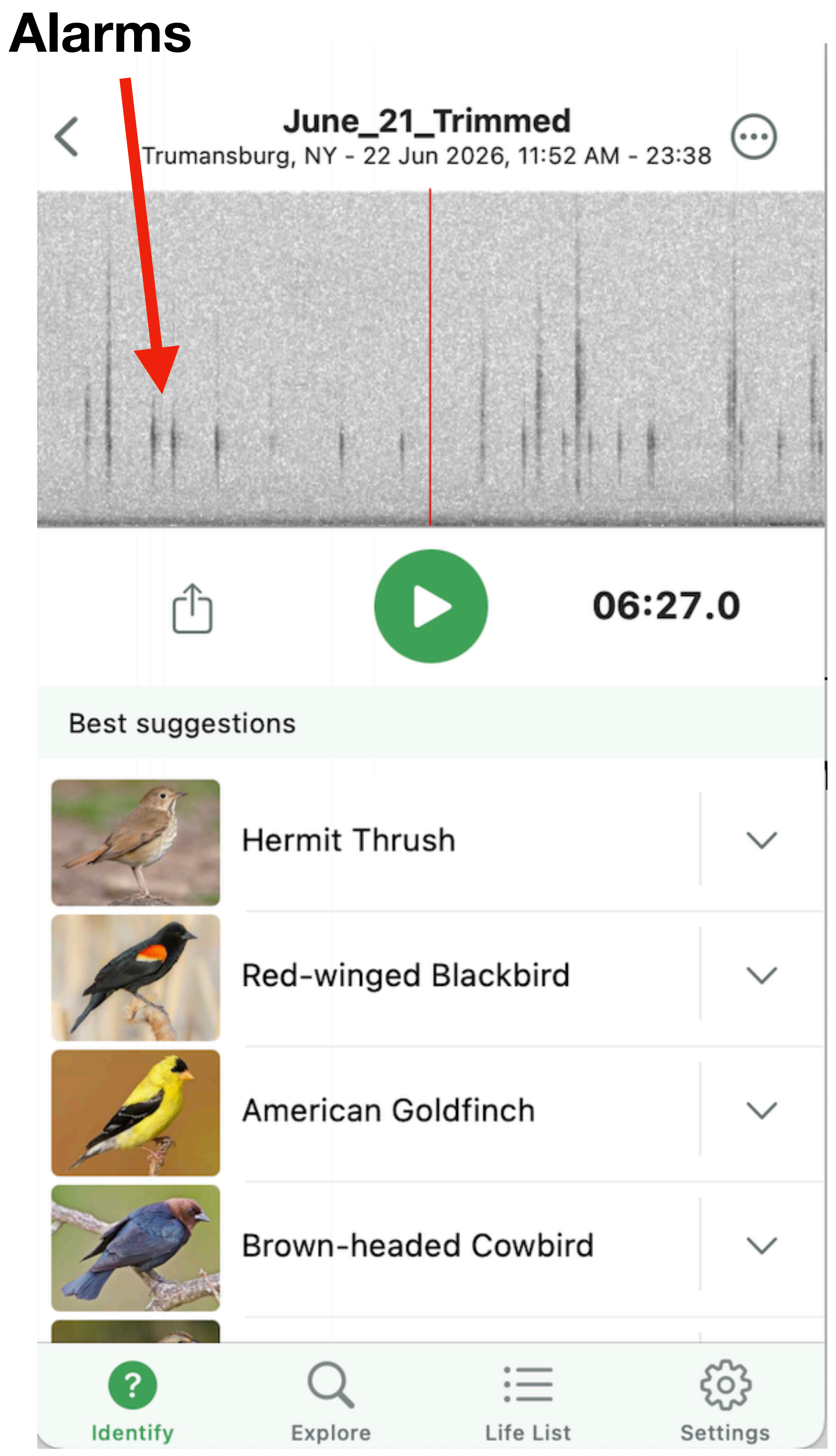
Though you can't see him in the tall grass, can you locate the dog based on nature's reaction to his presence?



Nature and computing

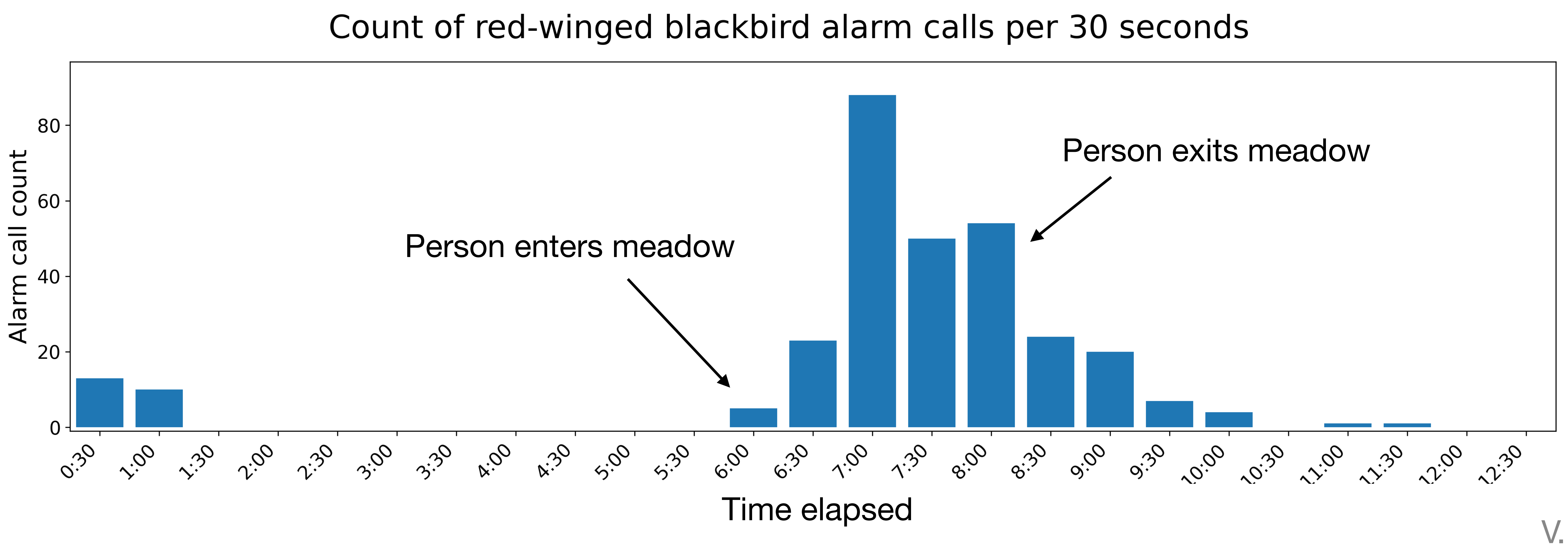
Natural computation | Natural memory | Natural data transfer

Ecological Shadows:
Nature as a reservoir computer for intrusion classification



Red-winged blackbirds generate an alarm to indicate an intrusion. Can you tell, based on the measured count of alarm calls, when a person entered the meadow?

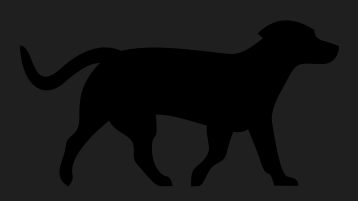
Watch the experiment at this link.

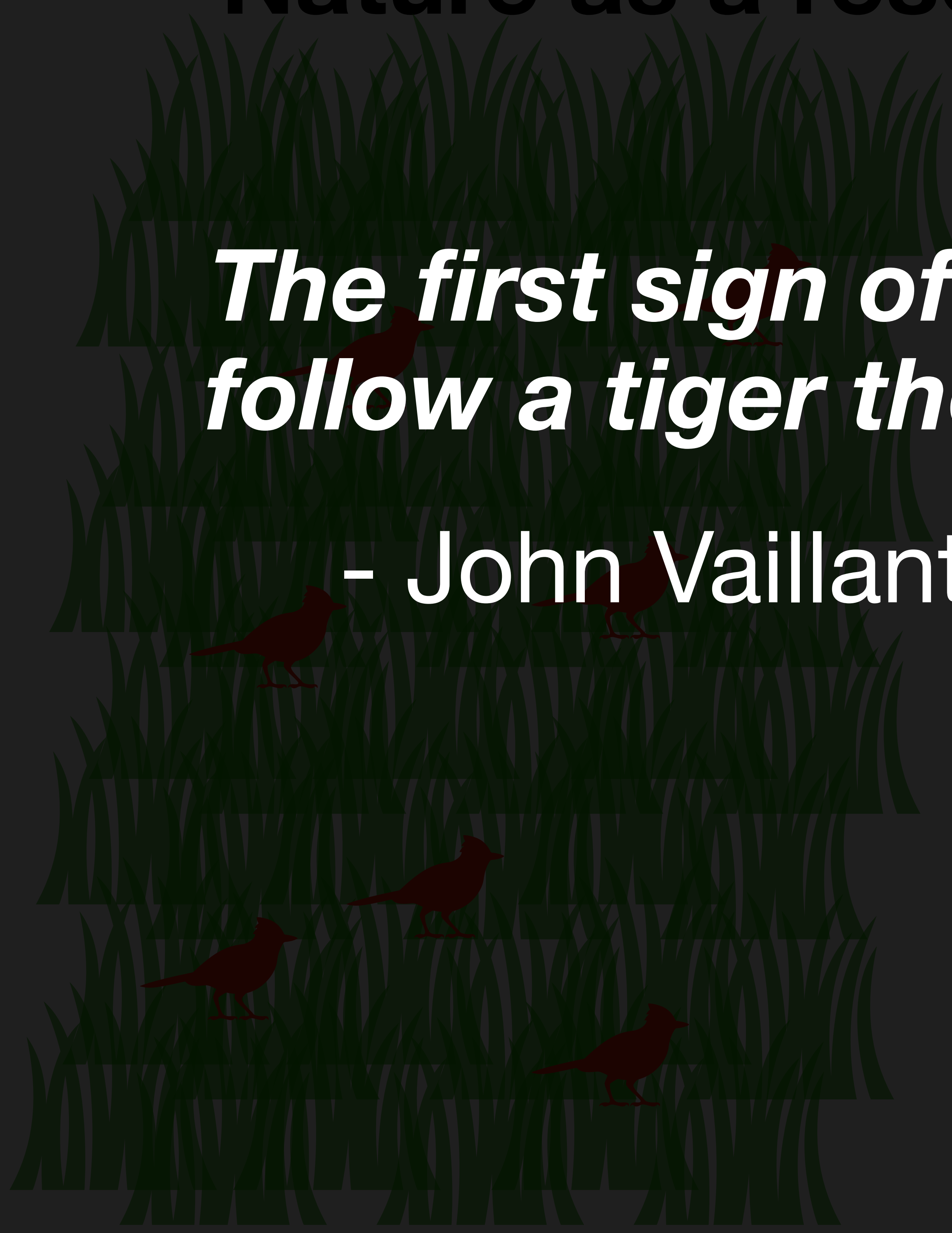


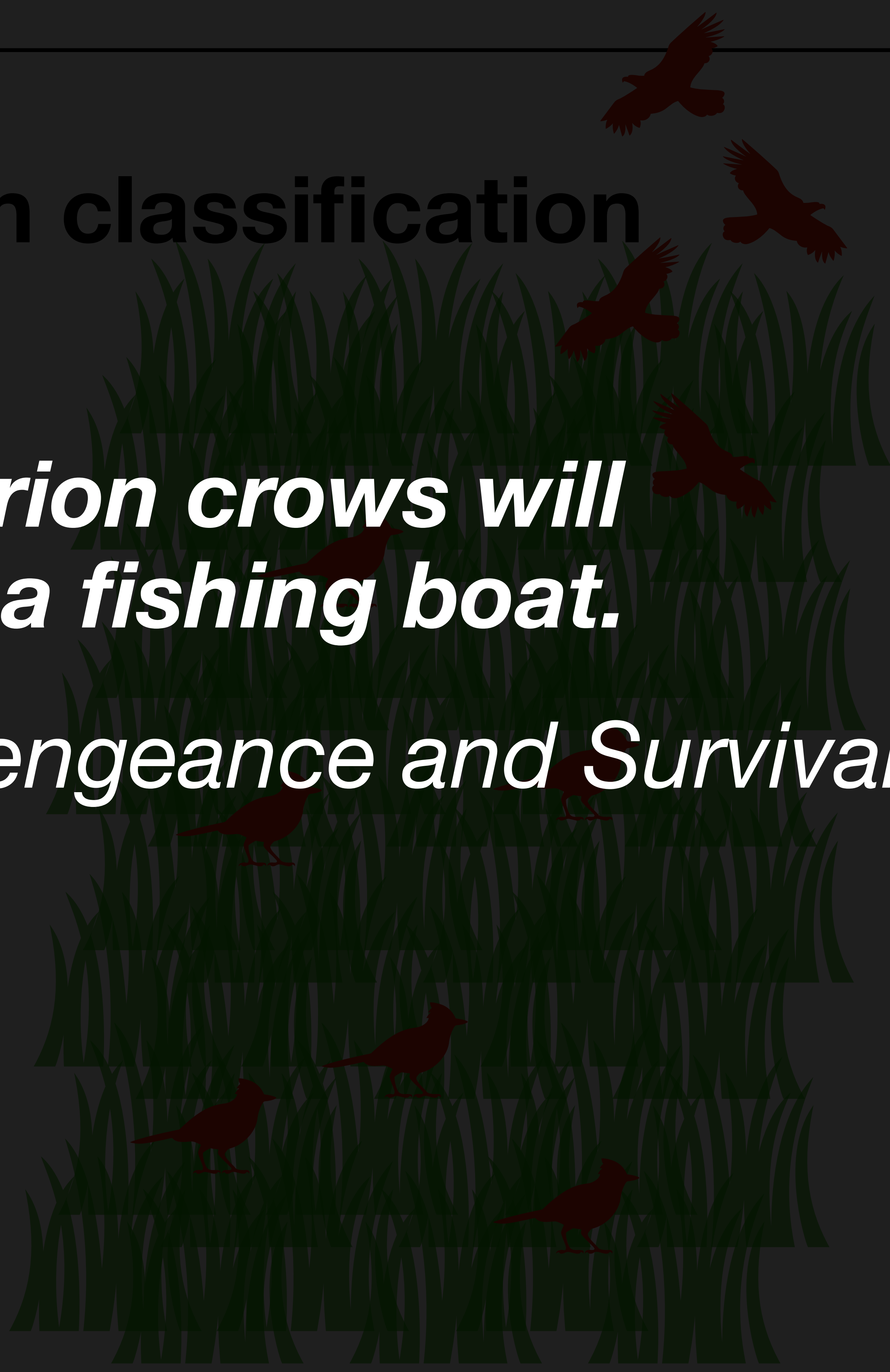
Nature and computing

Natural computation | Natural memory | Natural data transfer

Ecological Shadows:
Nature as a reservoir computer for intrusion classification







The first sign of trouble was the crows. Carrion crows will follow a tiger the same way seagulls follow a fishing boat.

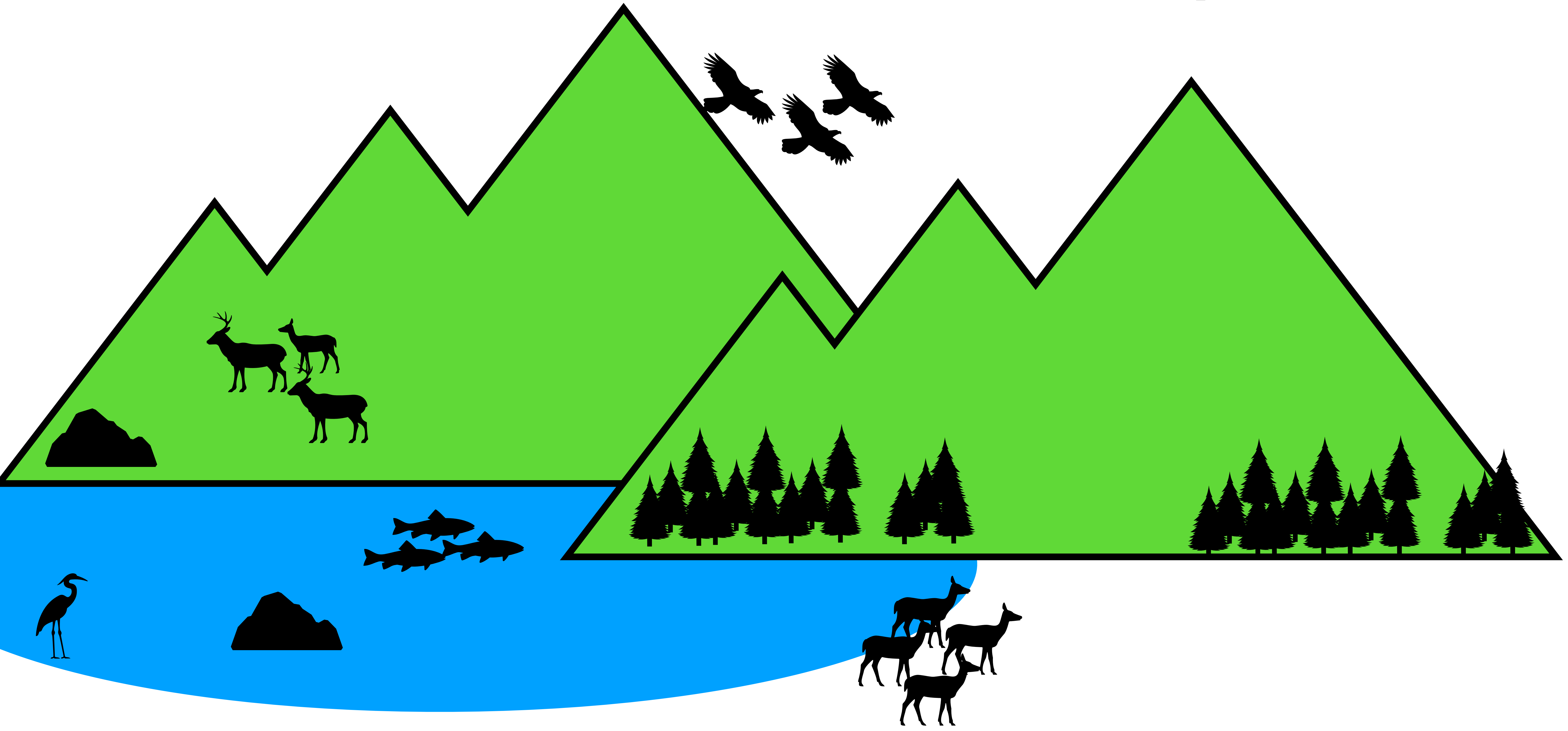
- John Vaillant, *The Tiger: A True Story of Vengeance and Survival*

Though you can't see him in
the dog based on nature's
reaction to his presence?

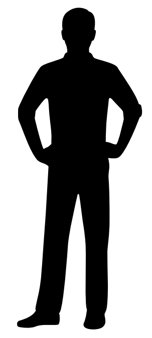
Nature and computing

Natural computation | Natural memory | Natural data transfer

Ecological Shadows: Nature as a reservoir computer for intrusion classification



"The behavior of the deer and birds on the western mountain suggest the presence of a drone, and the behavior of the fish suggest the presence of an AUV."



How do we increase the signal to noise ratio?

1. Track apex predators

   An intrusion by car, human, drone, etc. *probably* induces a threat response among creatures. Signal to noise ratio is maximized by paying particular attention to creatures for whom potential threats are **rare**.

2. Utilize AI tools

   This is a *big* machine learning problem. The hardware and algorithms generated for AI may be of tremendous use.

Nature and computing

Natural computation | Natural memory | Natural data transfer

Ecological Shadows:
Nature as a reservoir computer for intrusion classification

Even so, this is hard.

"The behavior of the deer and birds on the western mountain suggest the presence of a drone, and the behavior of the fish suggest the presence of an AUV."

Nature and computing

Natural computation | Natural memory | Natural data transfer

Problems to solve

1. Input/output between natural and engineered computers:
   - For a natural accelerator to be useful, the total time required to communicate inputs to the accelerator, compute outputs, and communicate those outputs back to the engineered computer with which it interfaces must be **less** than the time to compute the same algorithm on the engineered computer. We need high-speed I/O between nature and machine.
   - We must be able to affect the inputs to the natural system in a controlled fashion. This is easy for some systems, and very hard for others.

2. Generating models for natural computers:
   - In order for a natural computer to be of use, we must understand the relationship between its inputs and outputs. For some systems, this is easy. For others, it's extremely difficult.

Nature and computing

Natural computation | Natural memory | Natural data transfer

Nature doesn't *just* compute upon data, it also offers repositories for data.

Problems to solve

1. Input/output between natural and engineered computers:
   - For a natural accelerator … the accelerator, compute outputs, and communicate those outputs back to the engineered computer with which it interfaces must be **less** than the time to compute the same algorithm on the engineered computer. We need high-speed I/O between nature and machine.
   - We must be able to affect the inputs to the natural system in a controlled fashion. This is easy for some systems, and very hard for others.
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Nature and computing

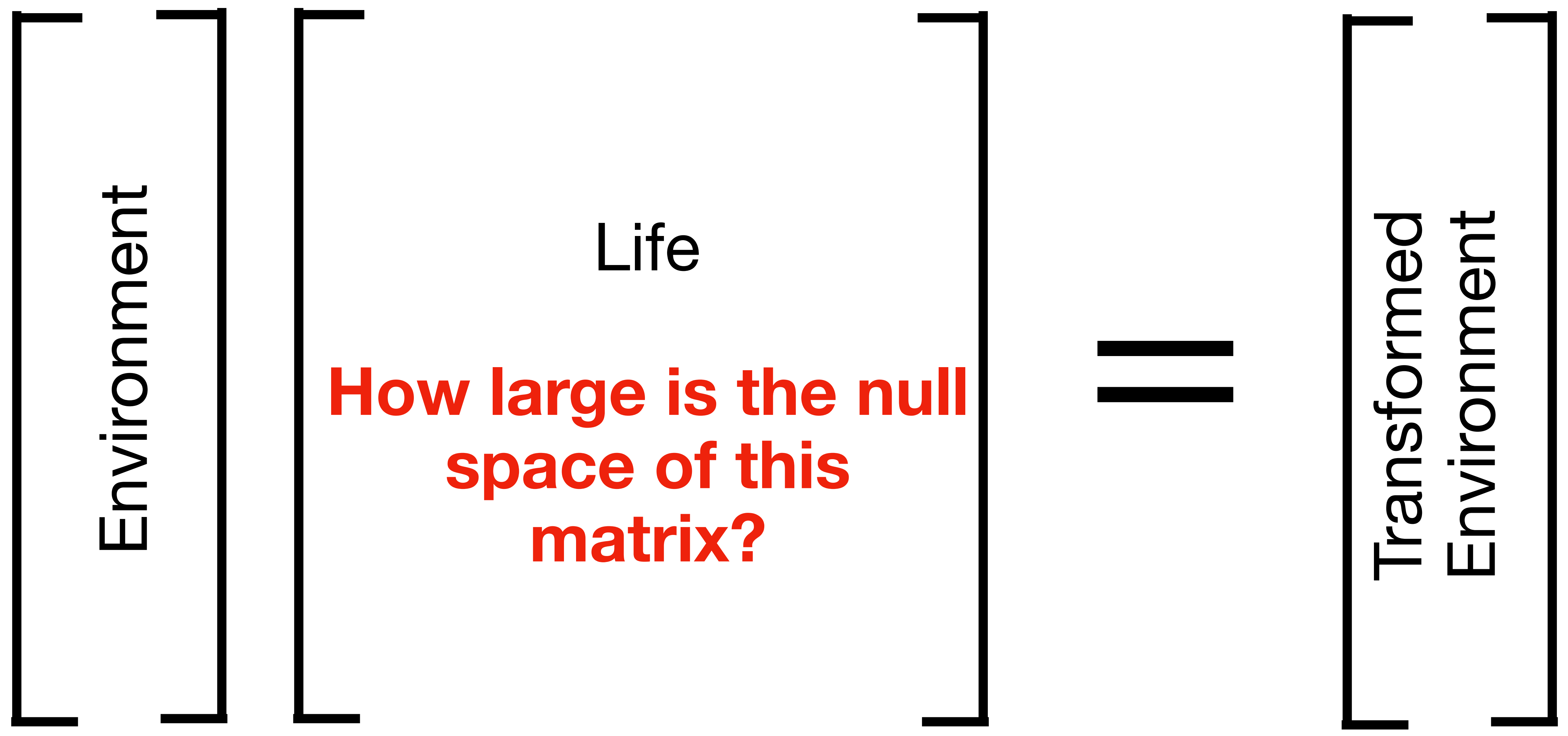
Natural computation | **Natural memory** | Natural data transfer

Nature offers repositories for data in *natural null spaces.*

These are environments with degrees of freedom which are effectively invisible to the organisms which inhabit those places. These invisible degrees of freedom can be used for information storage without adversely affecting any local life.

If interfaced with an engineered computer, these repositories for data can be used as **memory**. Some of these natural repositories have attractive features, including extreme non-volatility or extreme capacity.

Let us consider some specific examples of three varieties: **proof of concept**, **of niche application**, and **far-out**.



Nature and computing

Natural computation | **Natural memory** | Natural data transfer

Proof-of-concept examples of natural memory

Tree rings store information about past environmental conditions that the tree experienced. If that tree existed in a greenhouse, and if the environmental conditions of that greenhouse were modulated by some other data source (e.g. temperature/humidity controlled by GDP of the USA), then those tree rings instead encode that other data source (low-passed to ~1 datapoint/year).

Or if all environmental conditions are held constant *except* for water, then the tree rings encode the level of responsibility of the person responsible for watering the tree.

Ice cores encode information about past atmospheric conditions and composition. If the atmospheric condition/composition above a section of ice were modulated by some other data source, then an ice core at that place would similarly encode that other data source.

Very non-volatile! But not much data.

We might store data in these tree rings . . .

Forms and Patterns in Nature - Wolf Strache

We might store data in these tree rings . . .
Or *hide* data!! In these and other natural patterns.

Forms and Patterns in Nature - Wolf Strache

Thinking about patterns in nature

There is an **order** to patterns in nature. Wood grain looks like wood grain. Snowflakes look like snowflakes. Etc.

There is also a **randomness** to patterns in nature. You can have variations on a theme that allow for different patterns which are all unmistakably of the same kind. This giraffe has a completely different organization of spots than that giraffe, but both are unmistakably giraffe coat patterns.

So long as we maintain the order, we can generate synthetic patterns that hide data in the randomness.

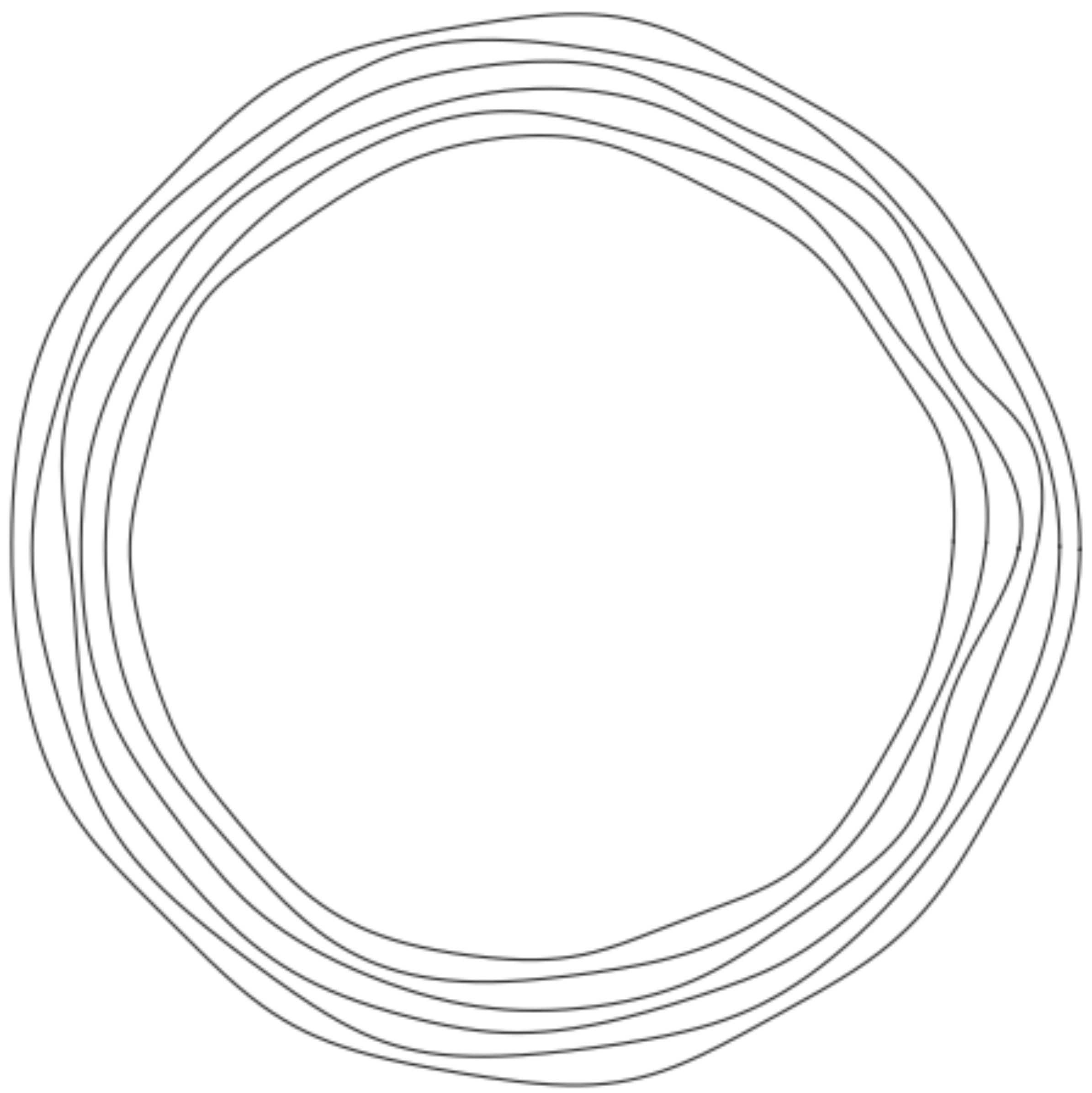
Let's look at some examples.

Forms and Patterns in Nature - Wolf Strache

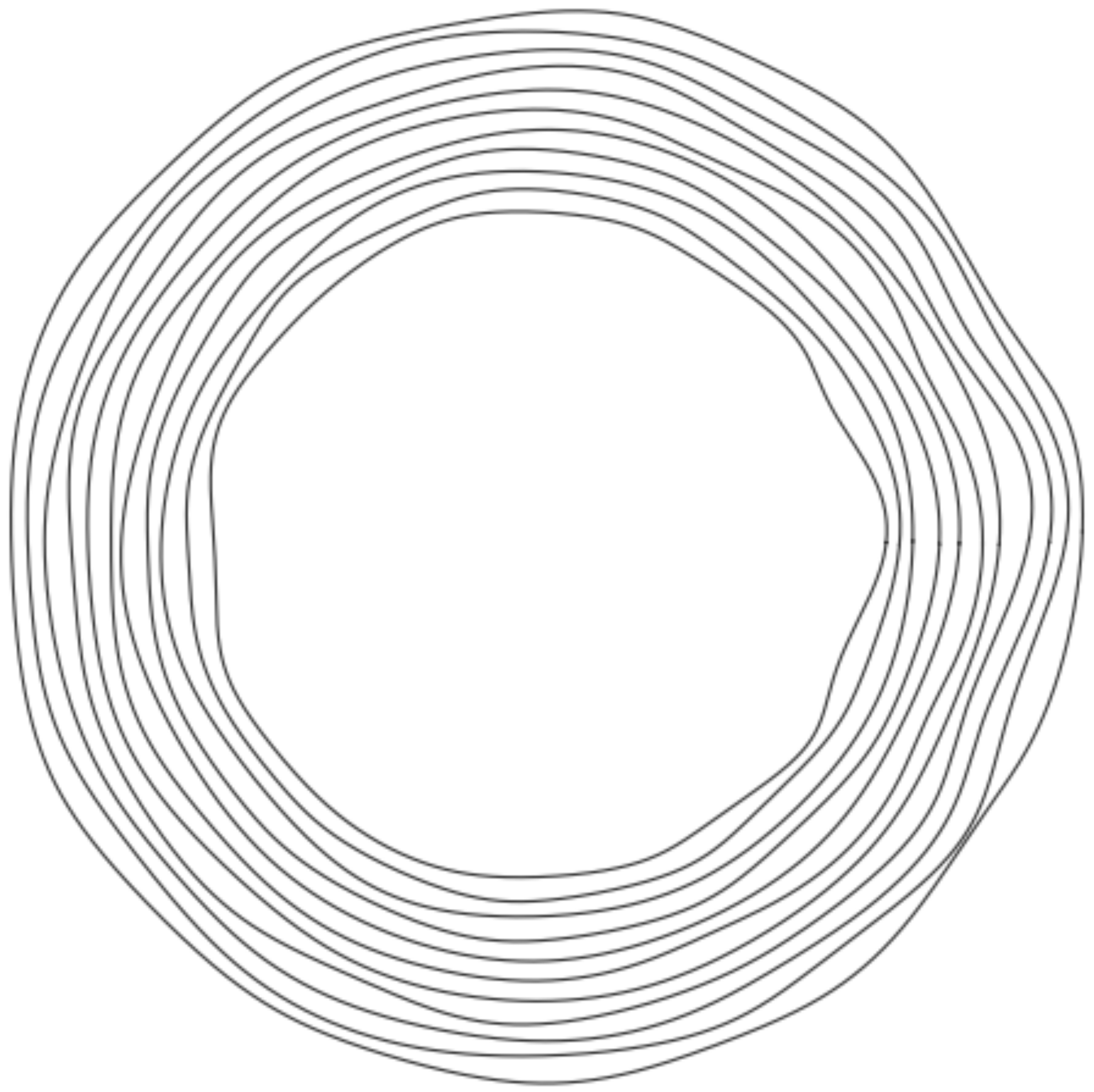
Nature and computing

Natural computation | **Natural memory** | Natural data transfer

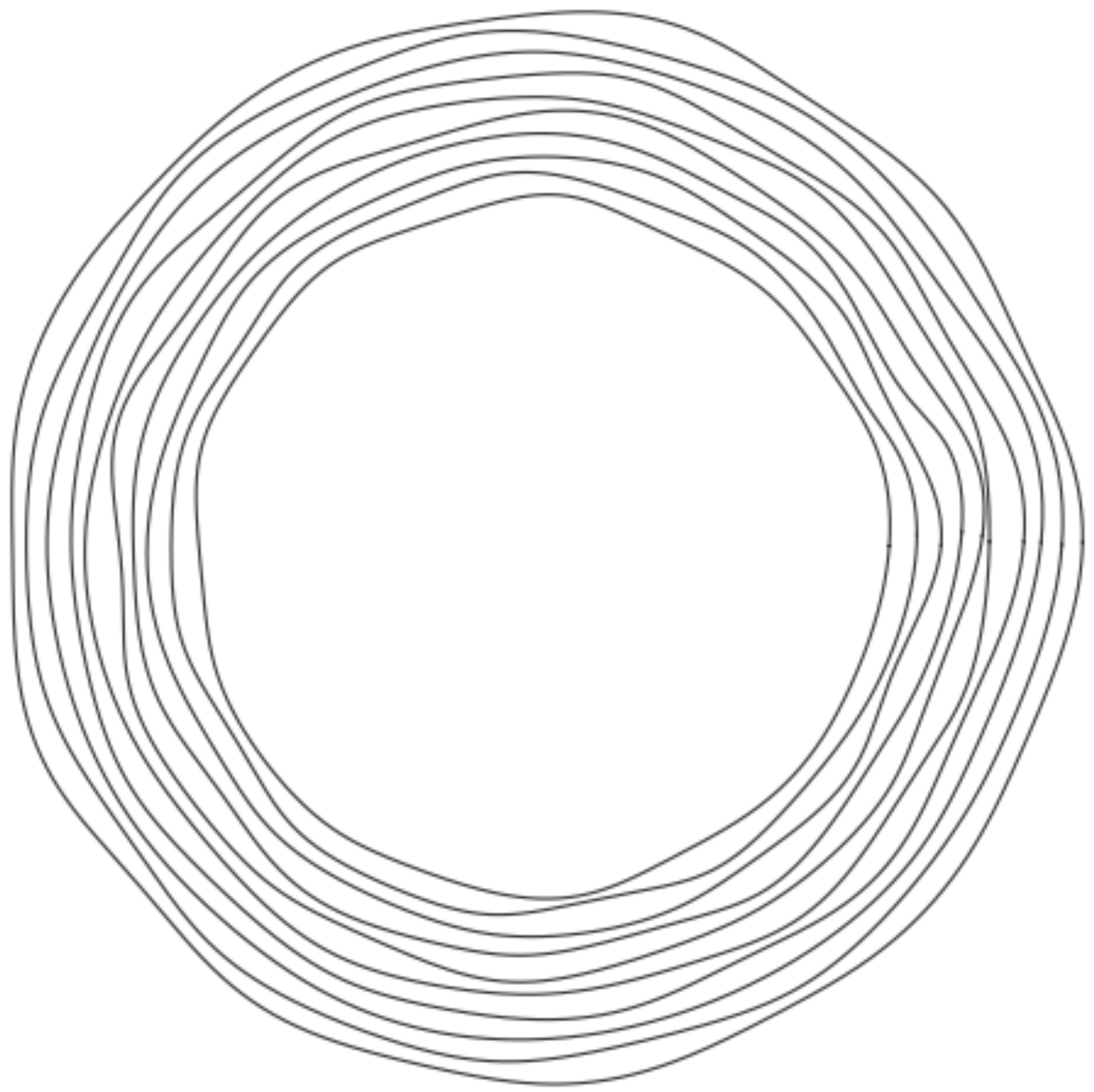
Natural steganography



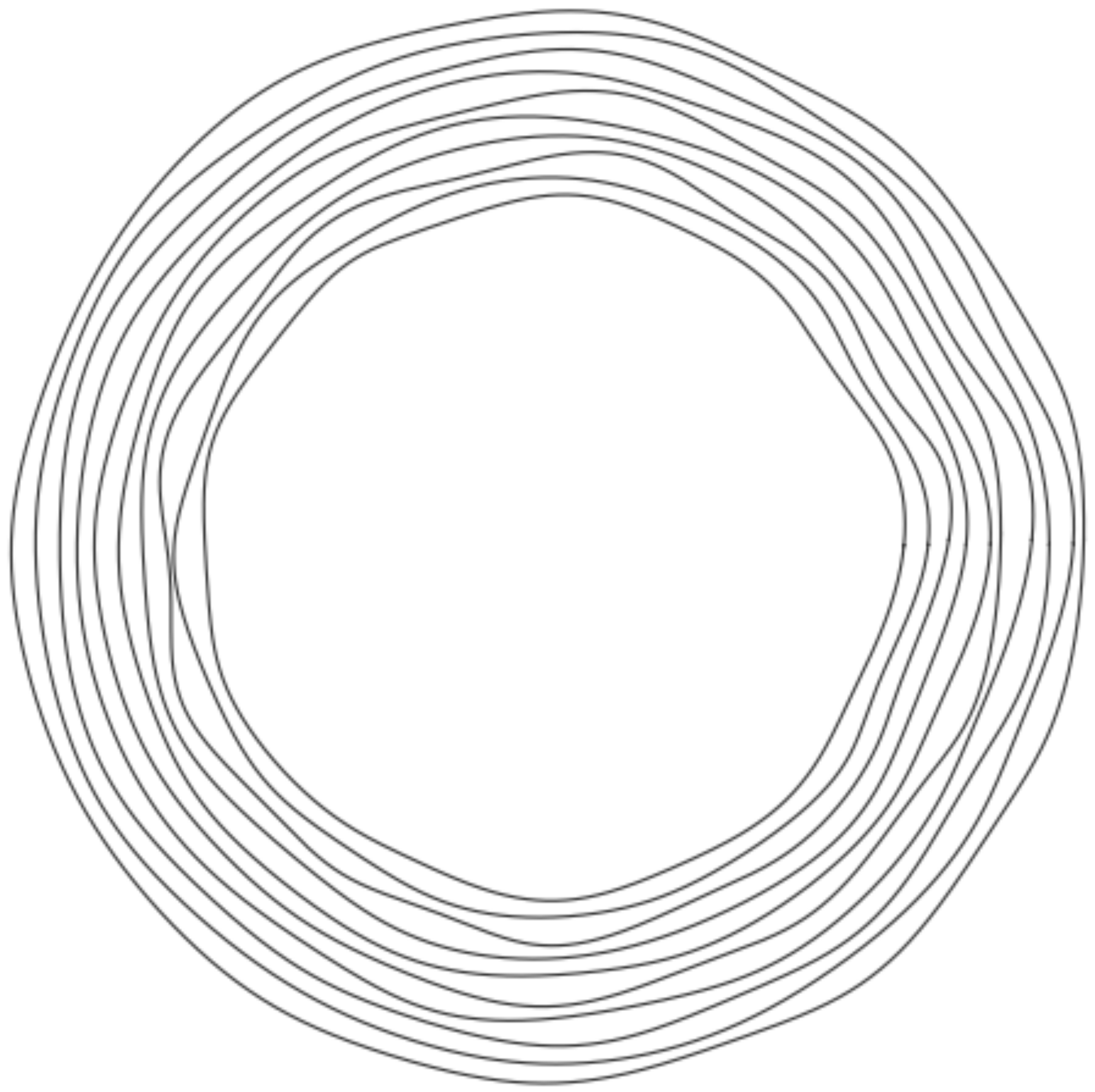
Hello World!



What hath God wrought?



Drink your Ovaltine!

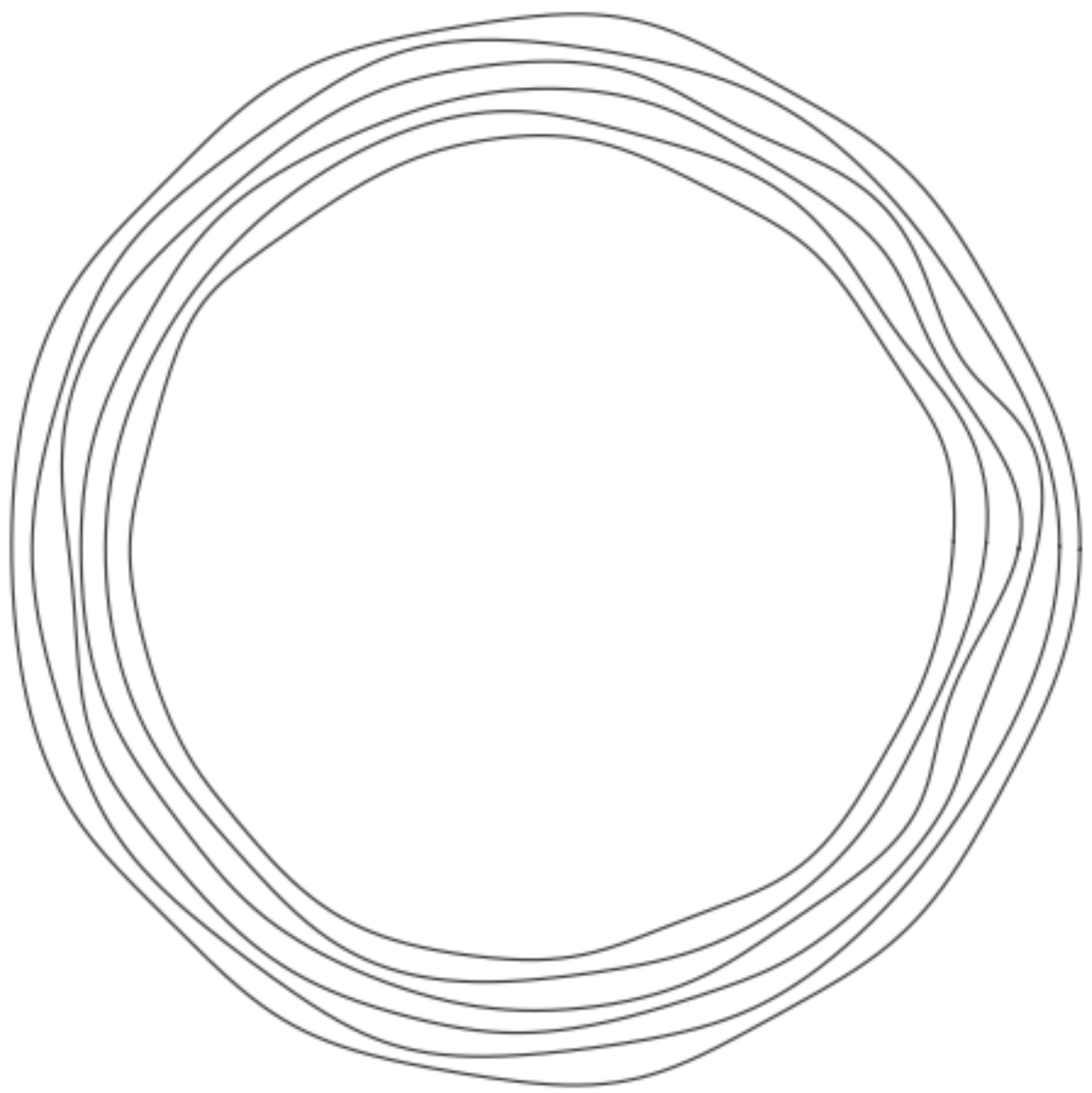


42.4534 N, 76.4735 W

Nature and computing

Natural computation | **Natural memory** | Natural data transfer

Natural steganography



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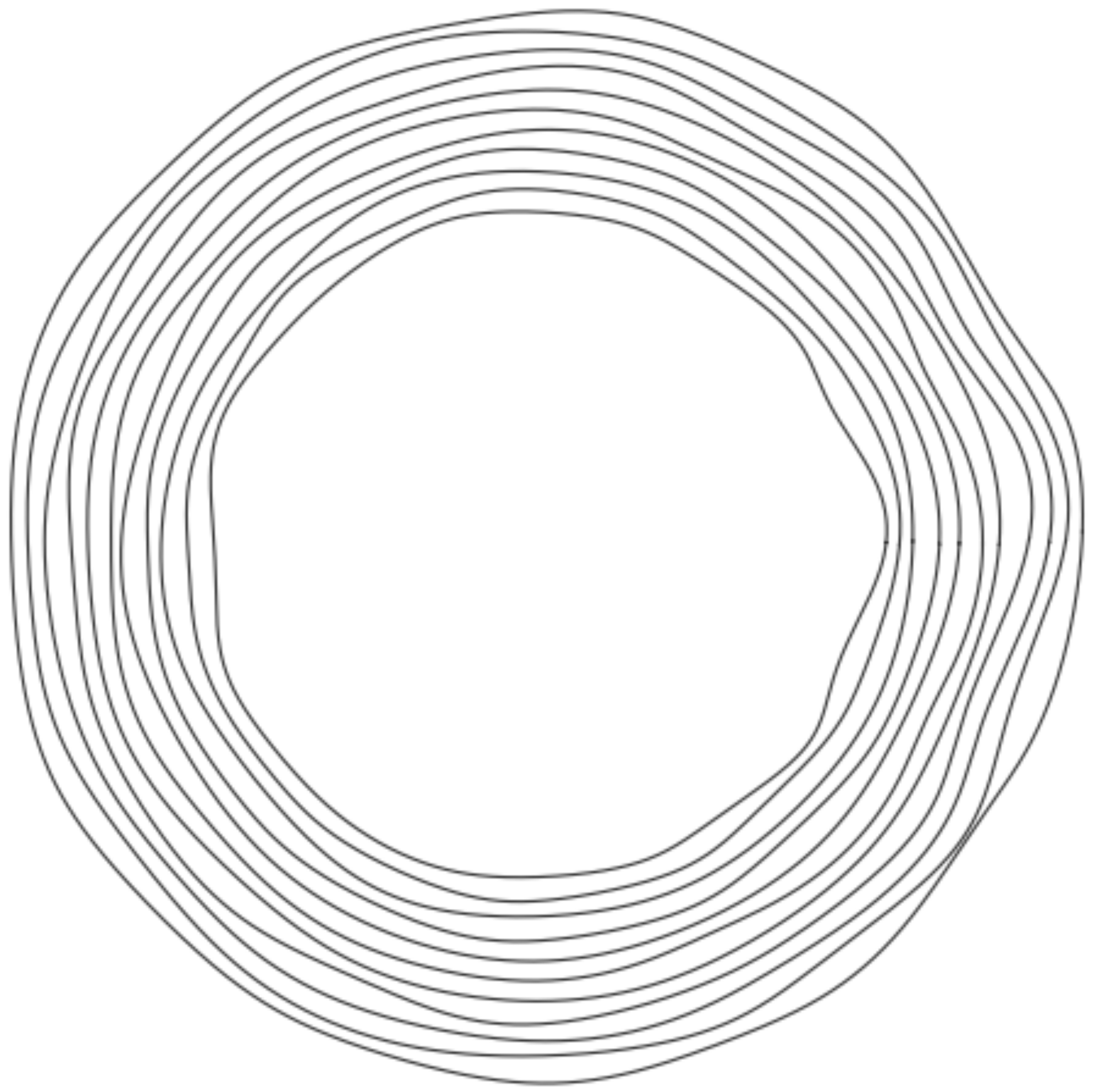

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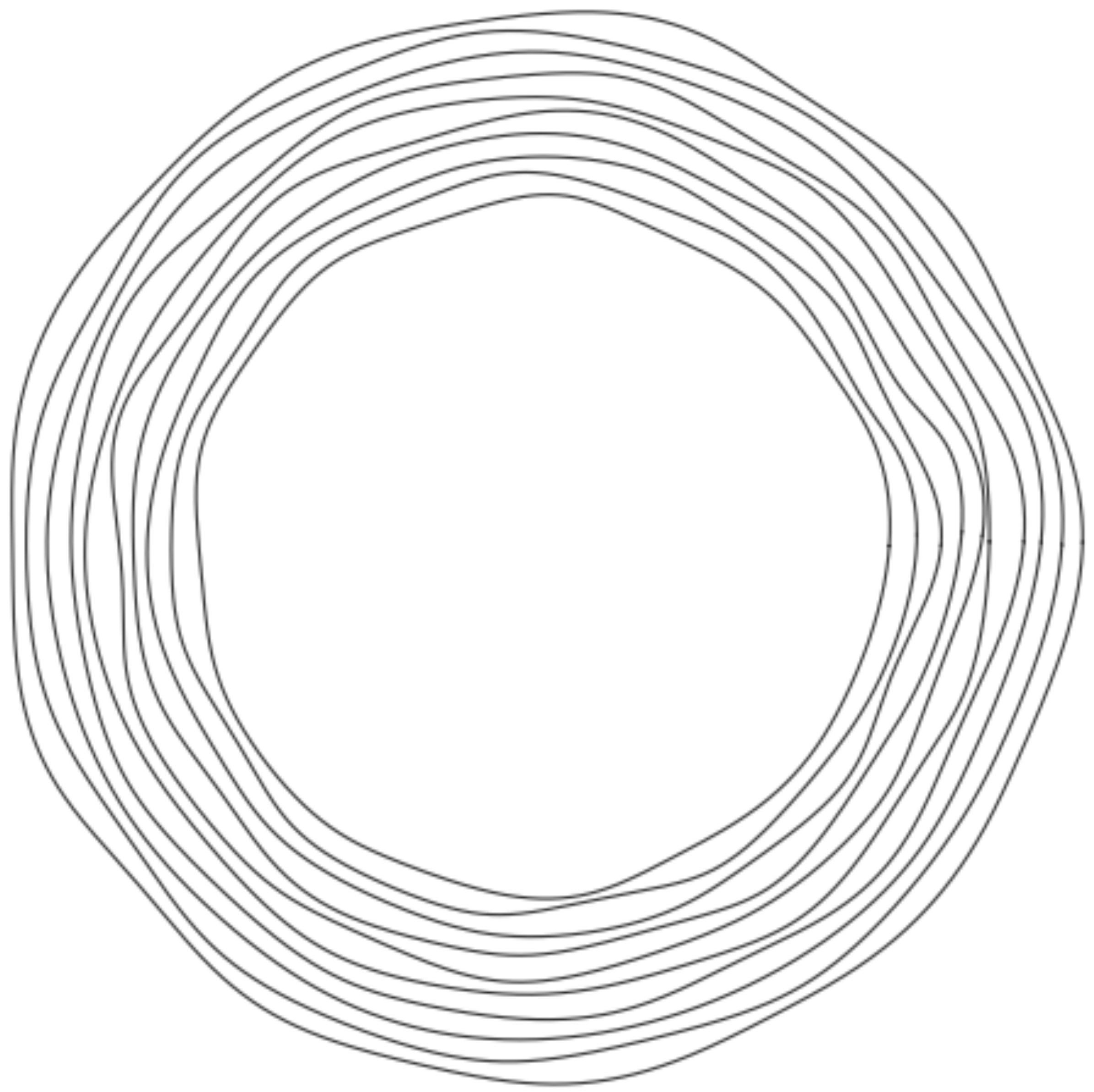

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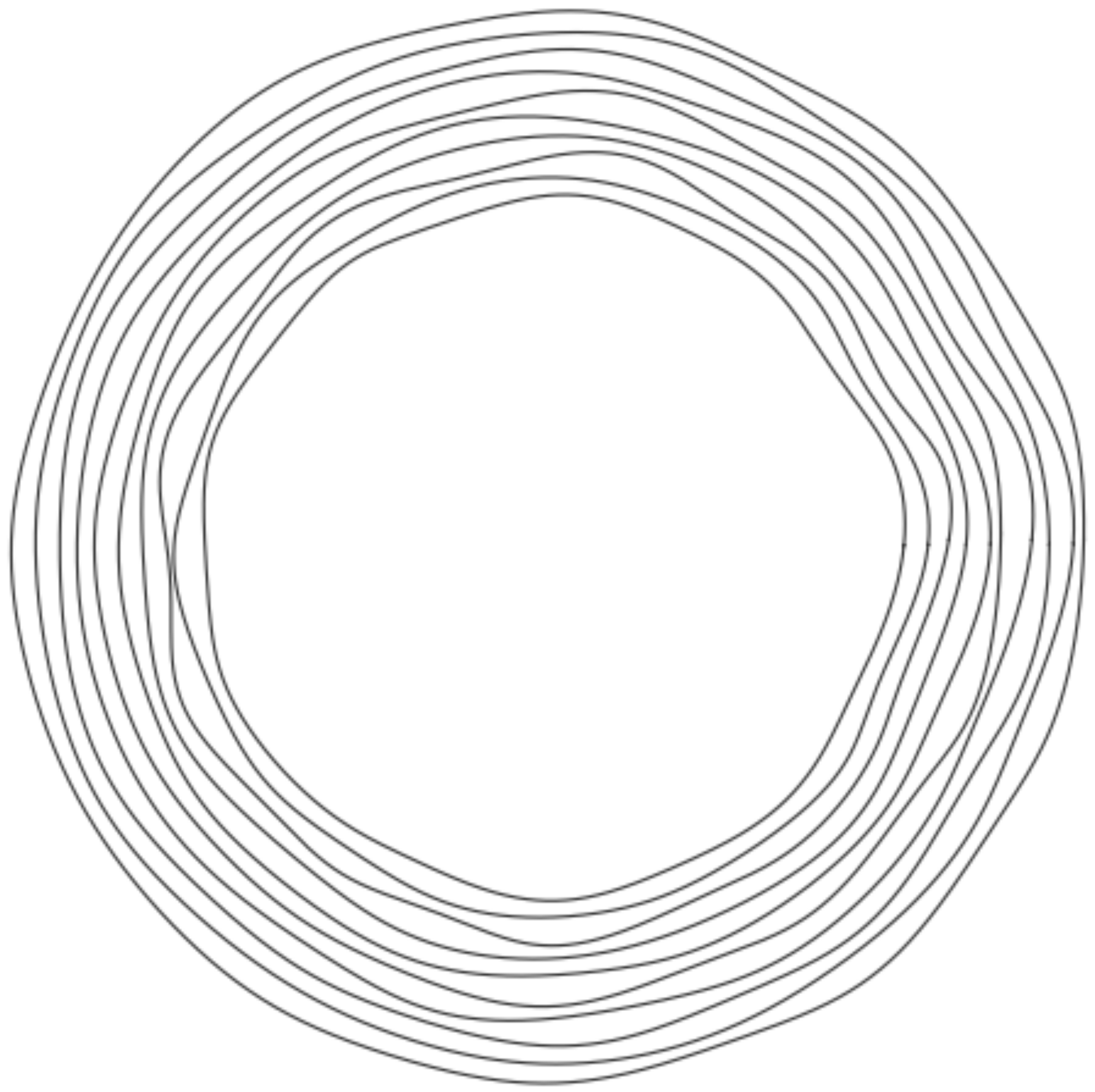

42.4534 N, 76.4735 W

How are these encoded?

Nature and computing

Natural computation | **Natural memory** | Natural data transfer

Natural steganography

Suppose we'd like to encode the text "Hi" into a tree ring.

"H" ⟶ 0 1 0 0 1 0 0 0 in ASCII

"i" ⟶ 0 1 1 0 1 0 0 1 in ASCII

Nature and computing

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"H" $\longrightarrow$ 0 1 0 0 1 0 0 0 in ASCII

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DC offset (0)

Sets size of ring

$$X(\theta) = A + B\cos\theta + C\cos 2\theta + D\cos 3\theta + E\cos 4\theta + F\cos 5\theta + G\cos 6\theta + H\cos 7\theta + I\cos 8\theta + J\cos 9\theta + K\cos 10\theta$$

Encodes the 8-bit ASCII representation for "H"

Set to 0 (just looks more organic)

DC offset (0)

Sets size of ring

$$Y(\theta) = A + B\sin\theta + L\sin 2\theta + M\sin 3\theta + N\sin 4\theta + O\sin 5\theta + P\sin 6\theta + Q\sin 7\theta + R\sin 8\theta + S\sin 9\theta + T\sin 10\theta$$

Encodes the 8-bit ASCII representation for "i"

Set to 0 (just looks more organic)

Nature and computing

Natural computation | **Natural memory** | Natural data transfer

Natural steganography

Suppose we'd like to encode the text "Hi" into a tree ring.

"H" $\longrightarrow$ 0 1 0 0 1 0 0 0 in ASCII

"i" $\longrightarrow$ 0 1 1 0 1 0 0 1 in ASCII

Plus a little random dithering for some nice organic wiggles

$$X(\theta) = 10\cos\theta + 0\cos 2\theta + 0\cos 3\theta + 1\cos 4\theta + 0\cos 5\theta + 0\cos 6\theta + 1\cos 7\theta + 0\cos 8\theta + 0\cos 9\theta + 0\cos 10\theta$$

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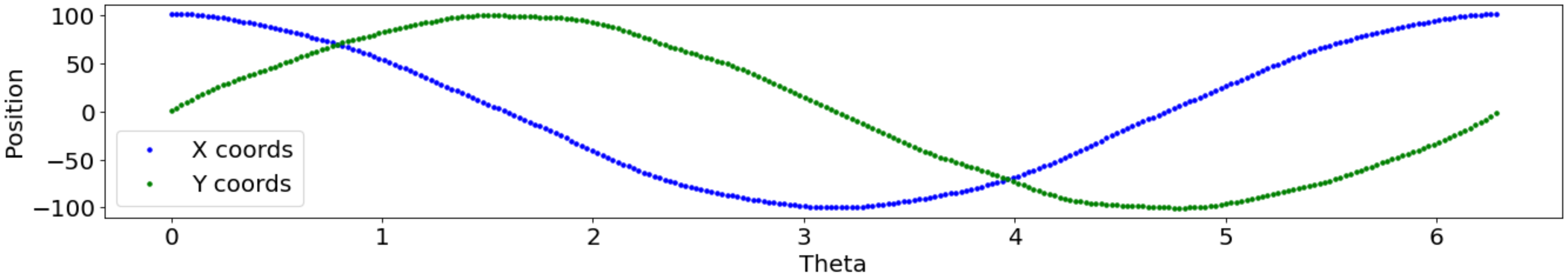

Nature and computing

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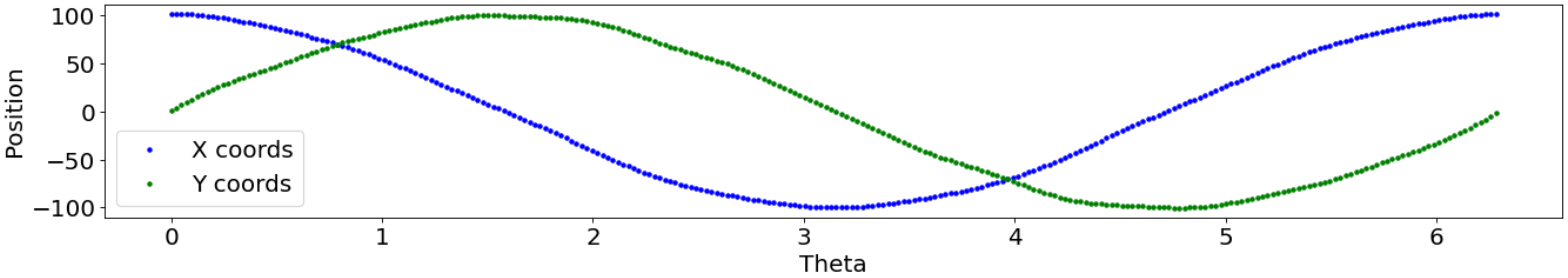
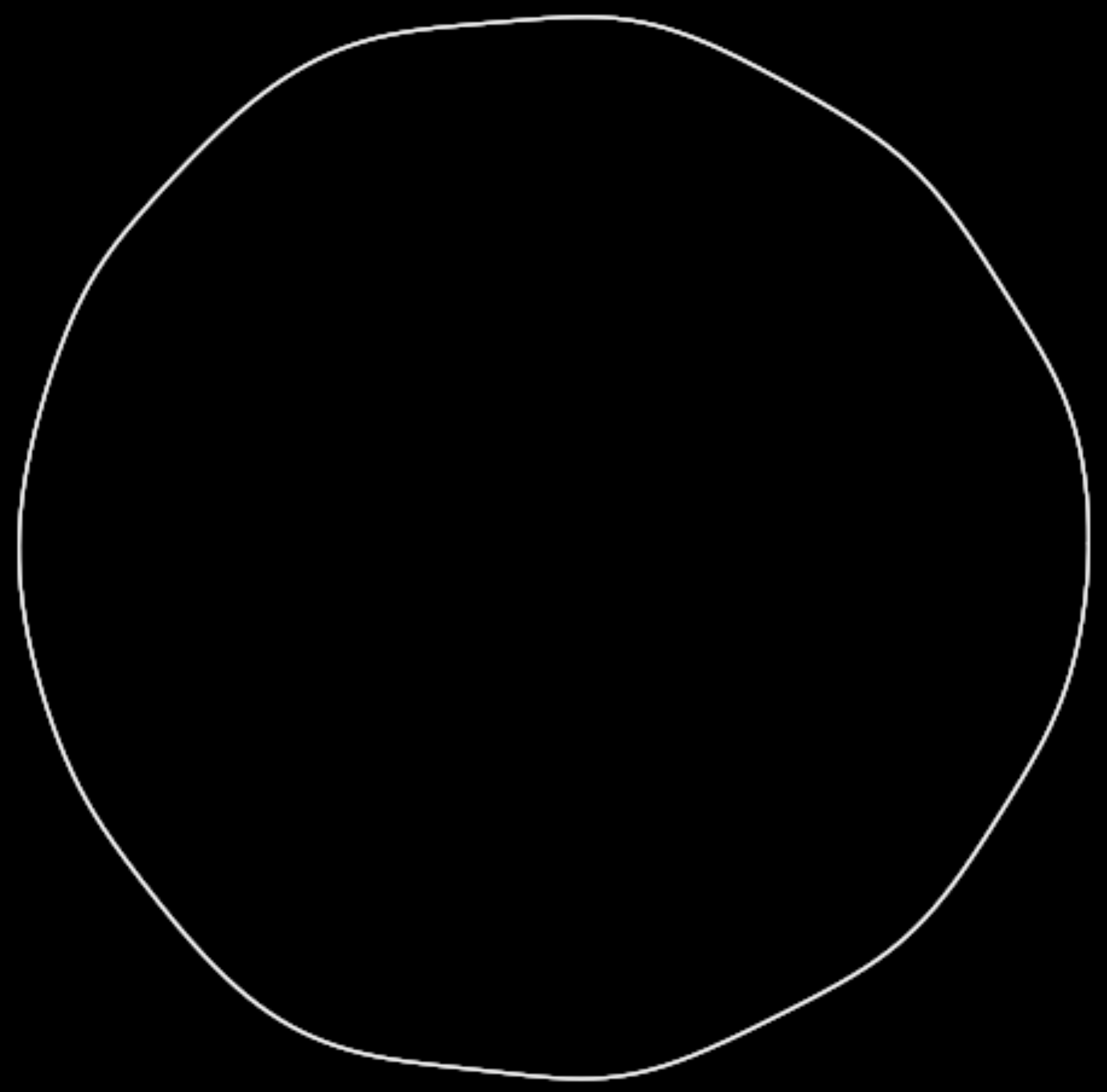
Pair X and Y coords by θ value



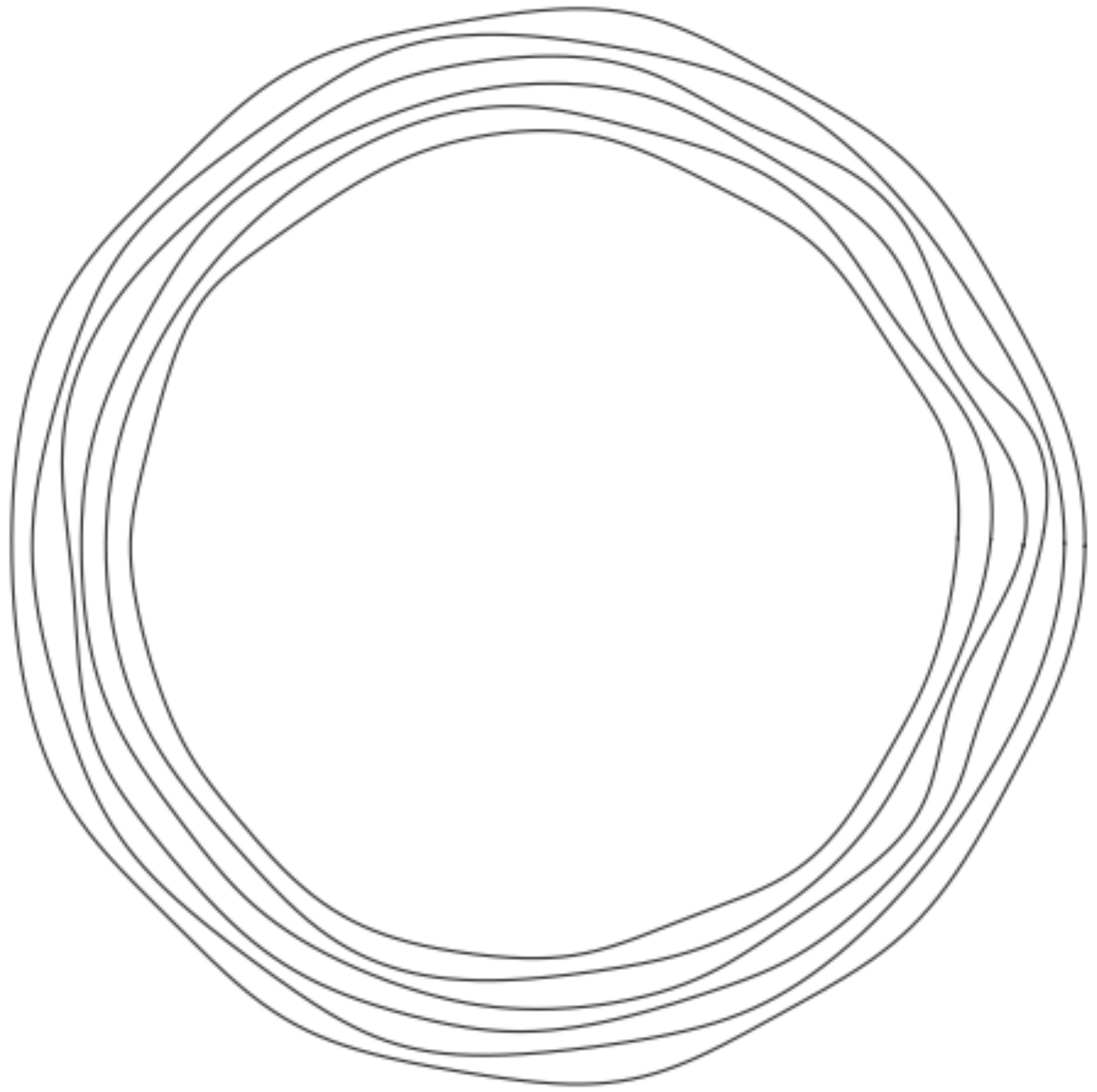
“Hi”



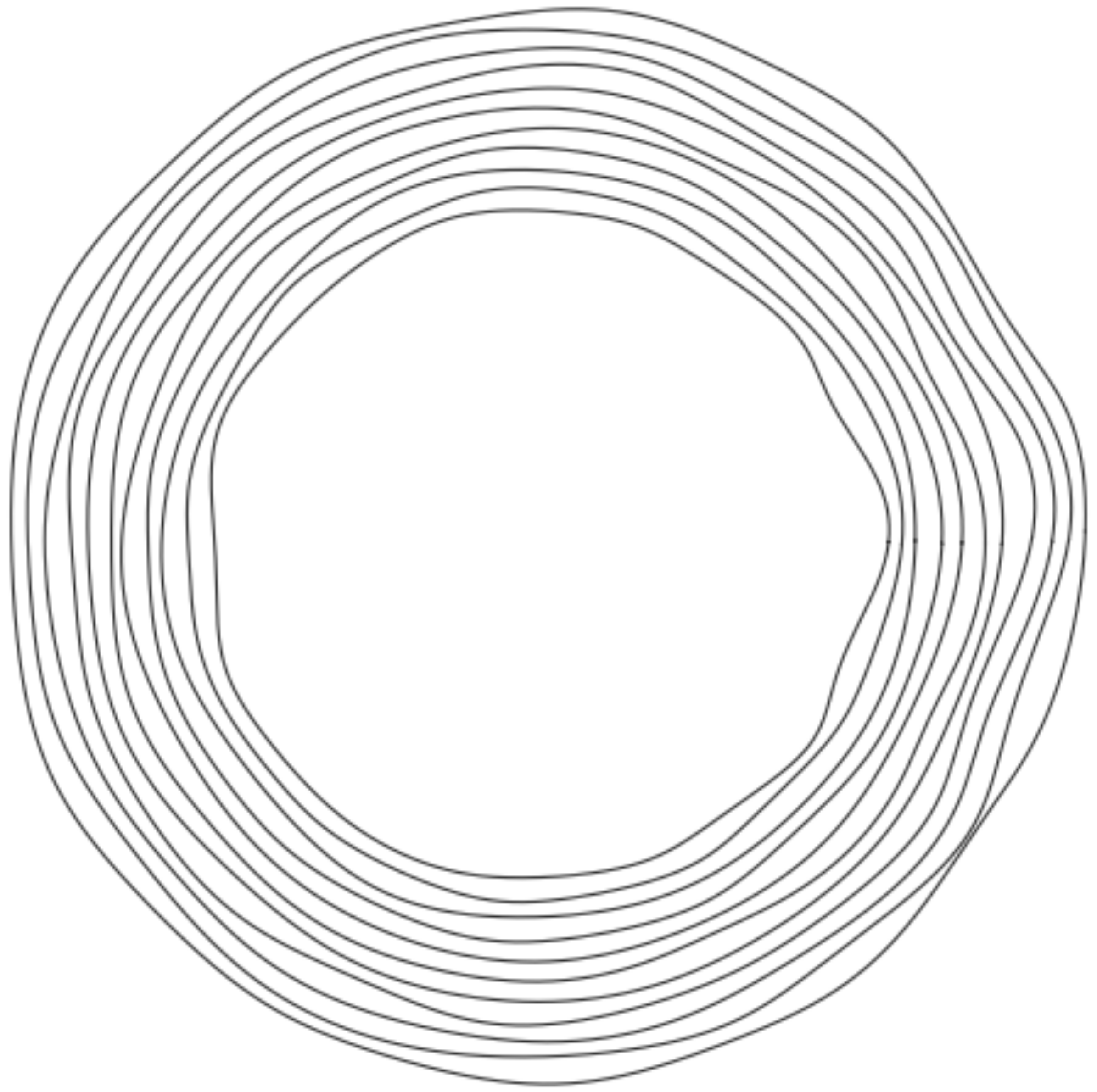
Nature and computing

Natural computation | **Natural memory** | Natural data transfer

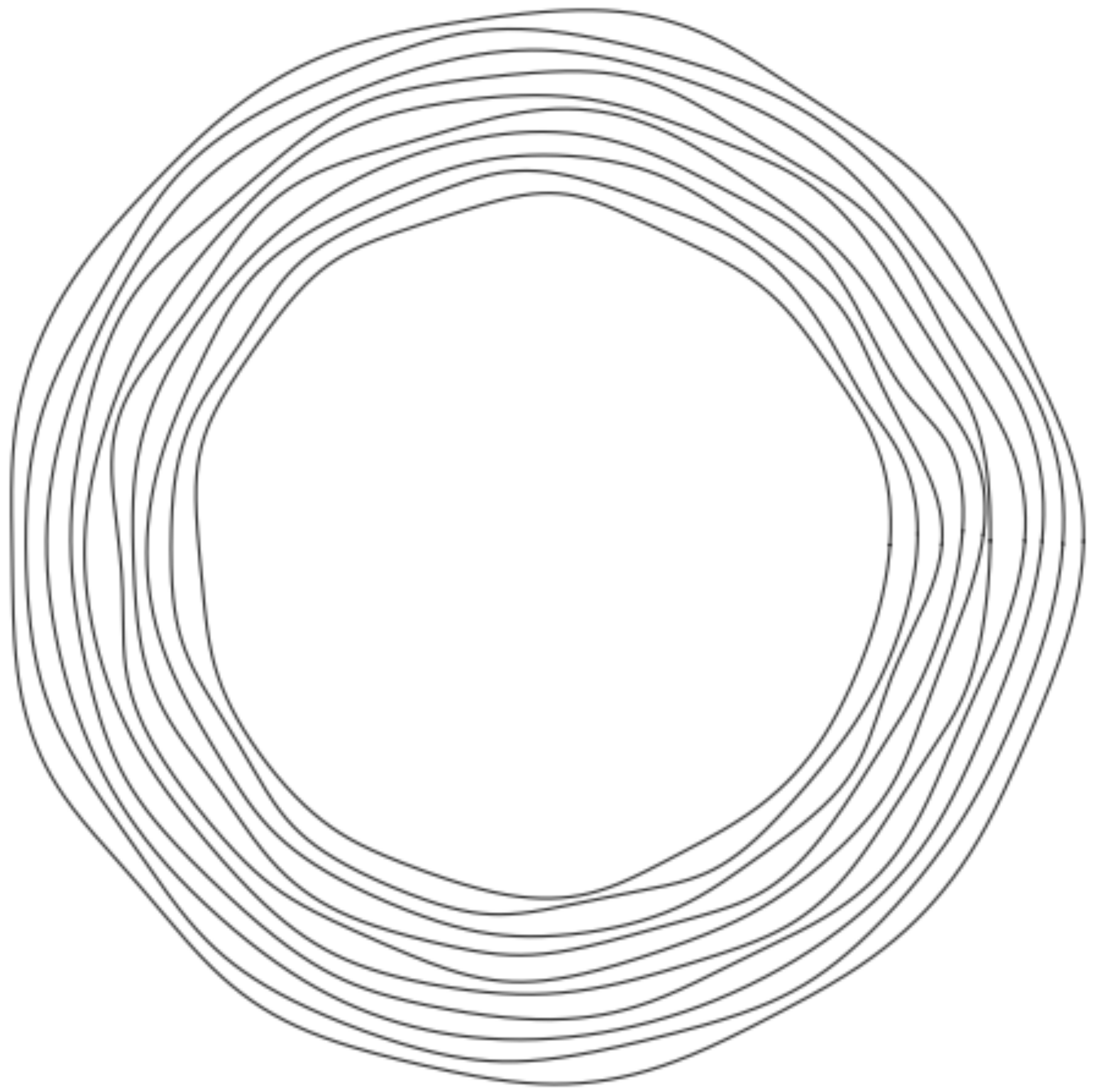
Natural steganography



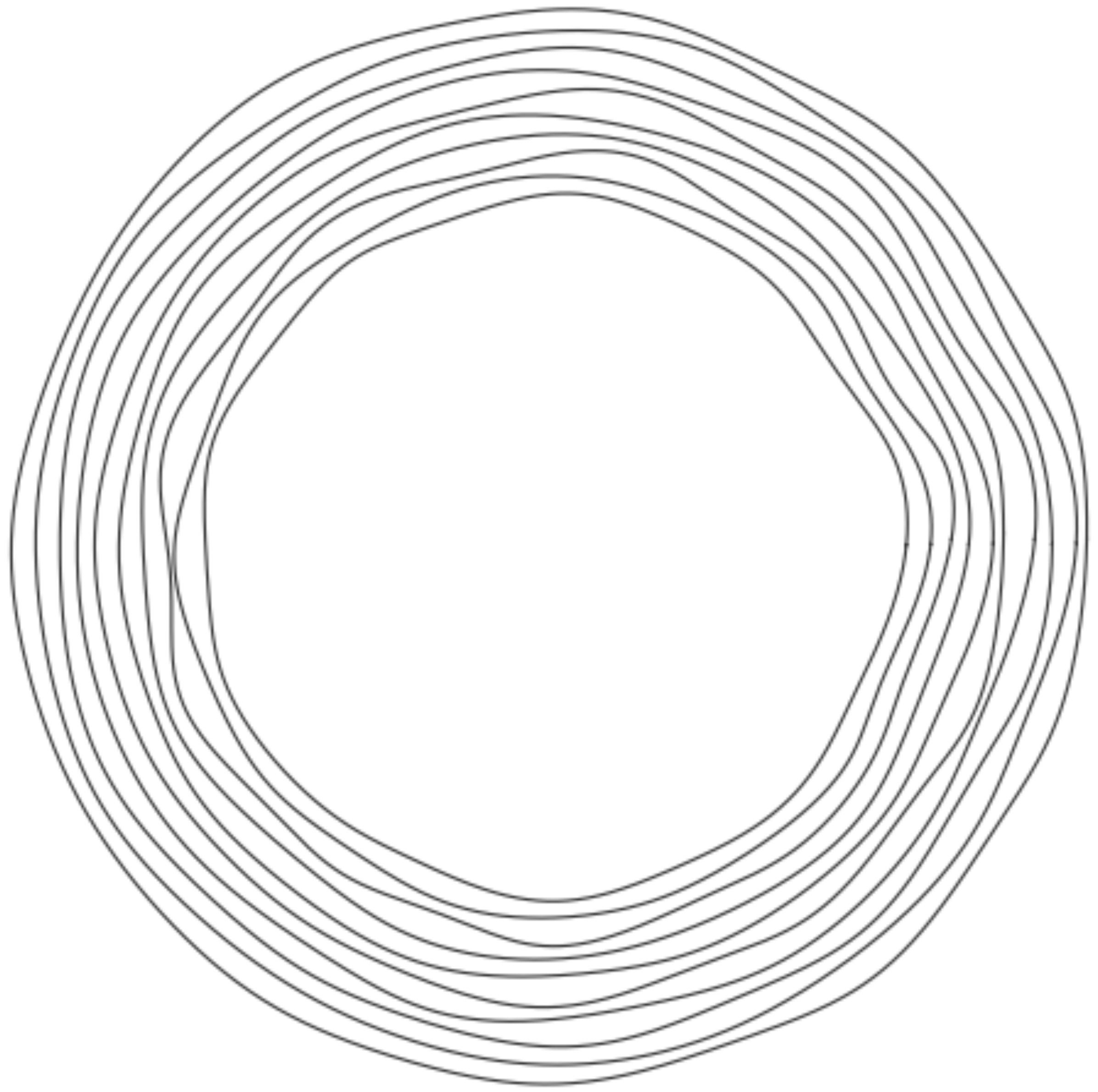
Hello World!



What hath God wrought?



Drink your Ovaltine!



42.4534 N, 76.4735 W

Nest rings to build up larger messages

Nature and computing

Natural computation | **Natural memory** | Natural data transfer

Natural steganography

Hello World!   What hath God wrought?   Drink your Ovaltine!   42.4534 N, 76.4735 W

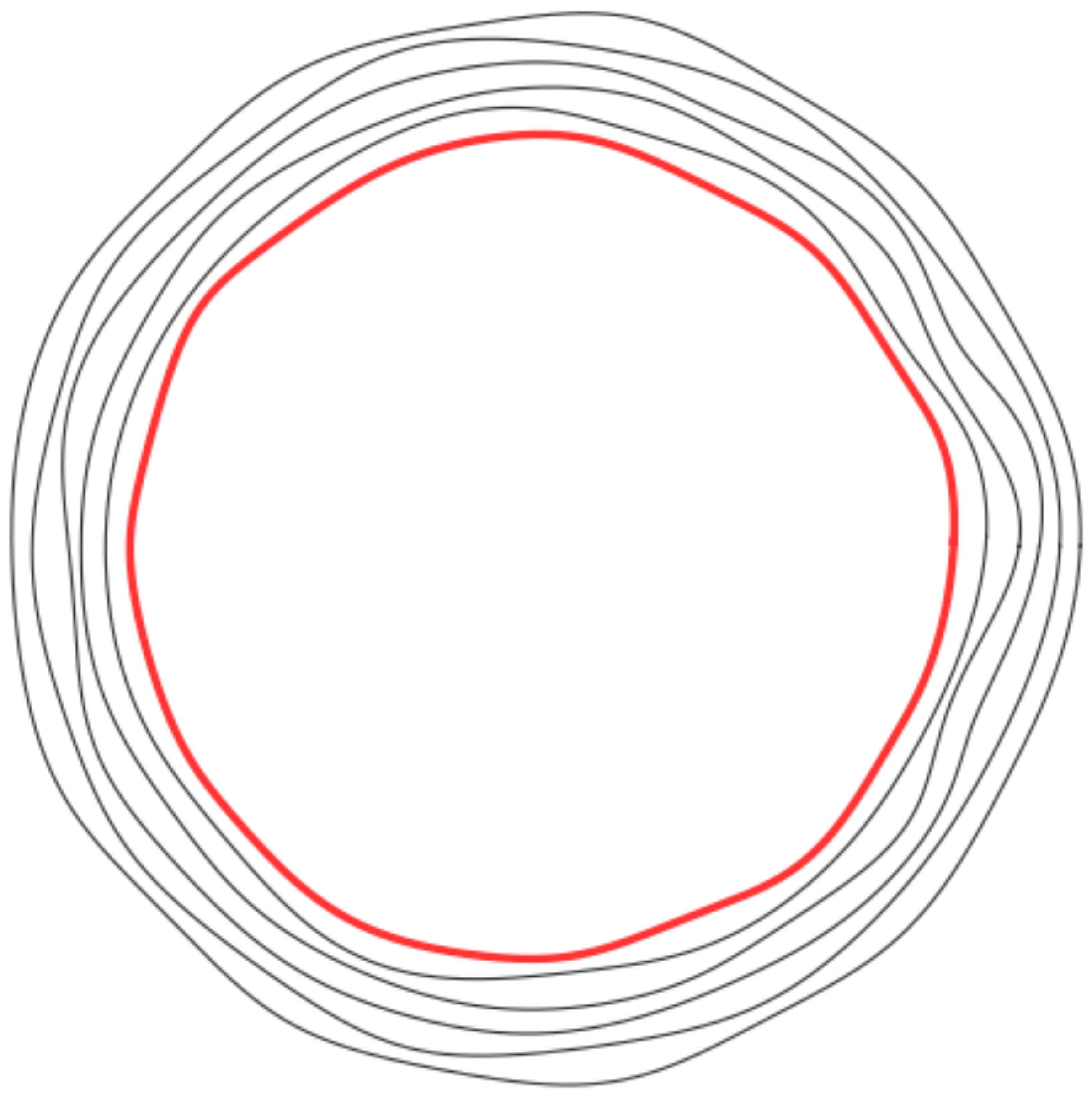
Nest rings to build up larger messages

Nature and computing

Natural computation | **Natural memory** | Natural data transfer

Natural steganography

Consider the inner-most ring:

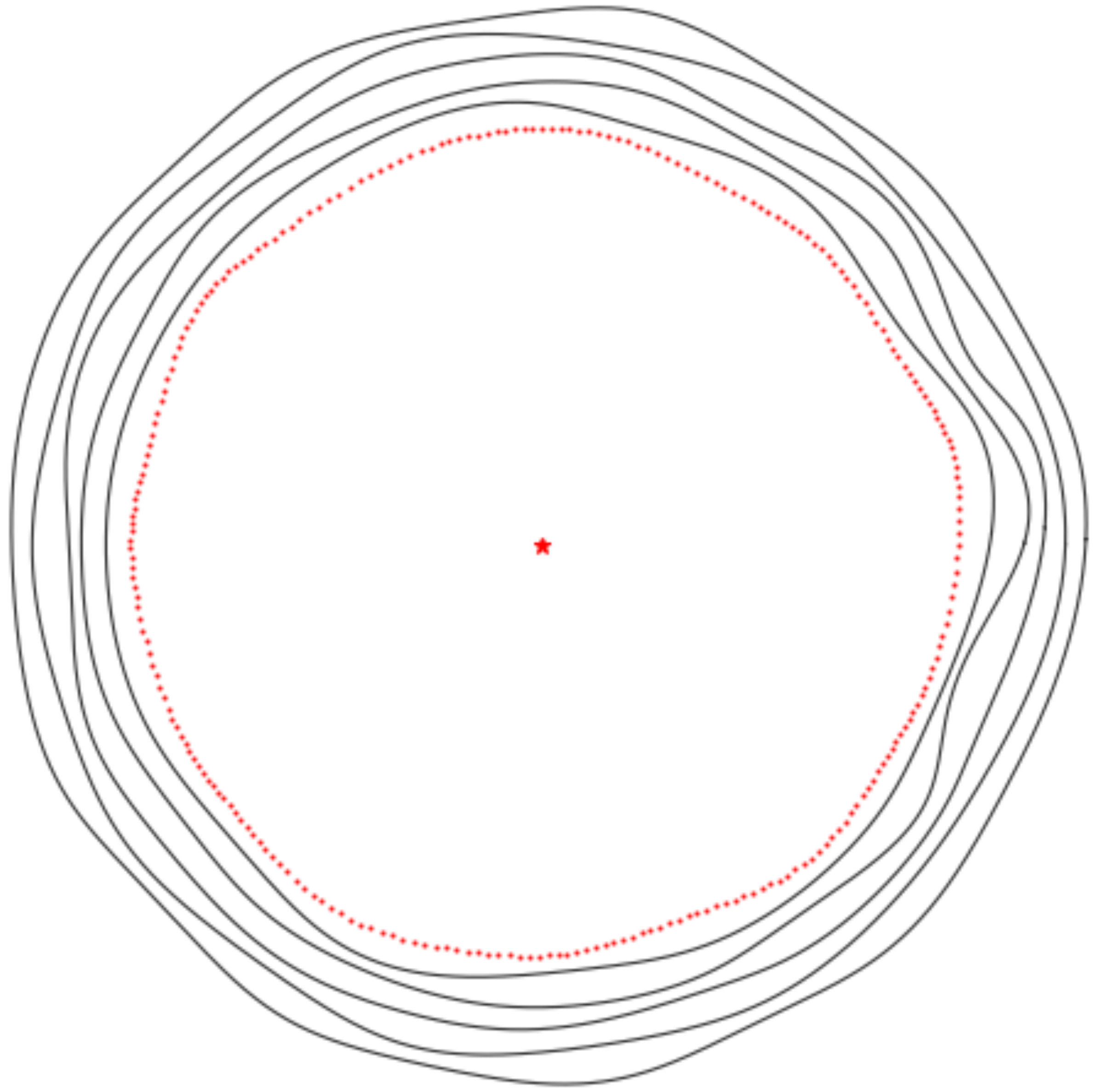


Nature and computing

Natural computation | **Natural memory** | Natural data transfer

Natural steganography

1. Discretely sample, and choose an origin

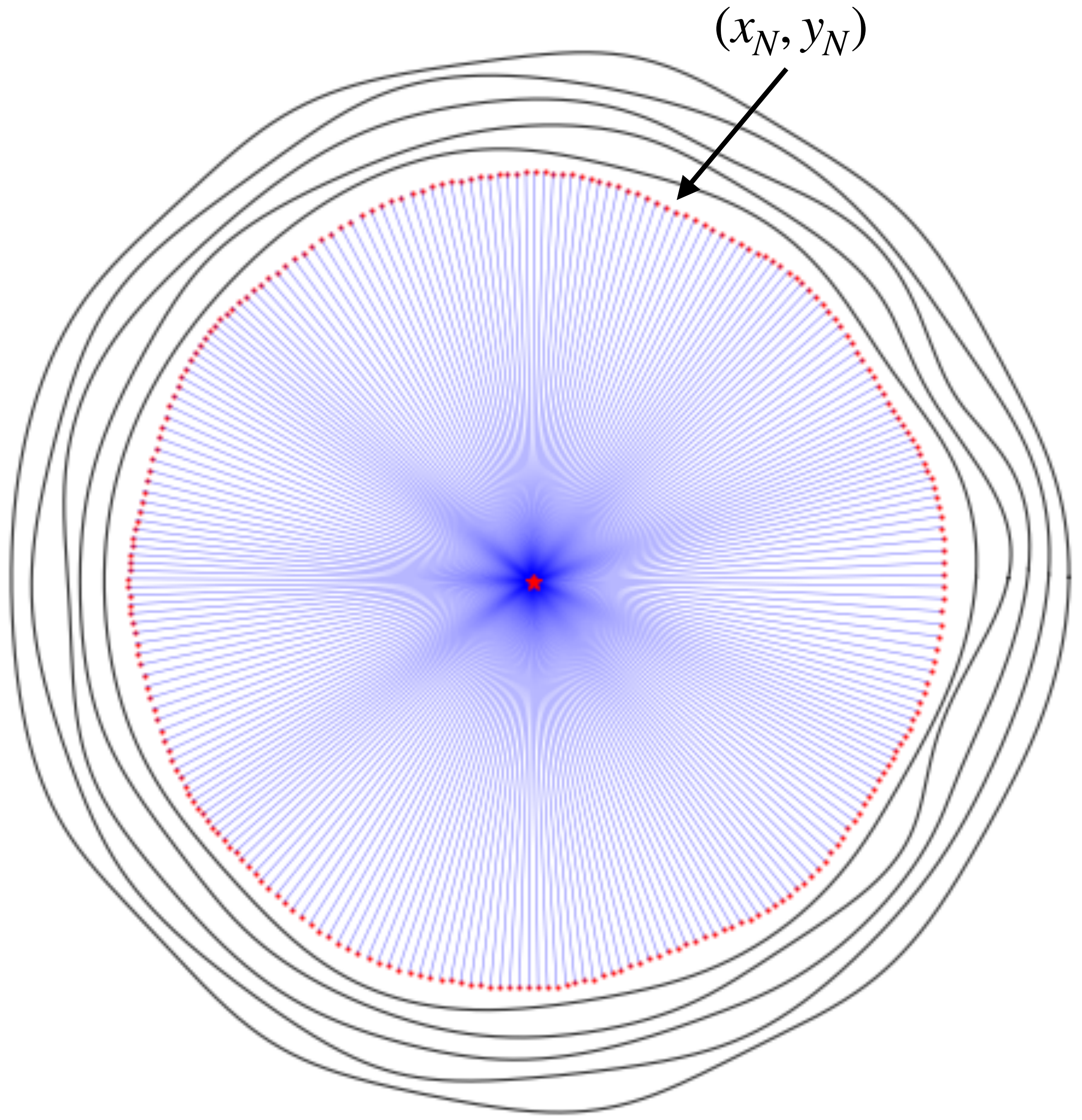


Nature and computing

Natural computation | **Natural memory** | Natural data transfer

Natural steganography

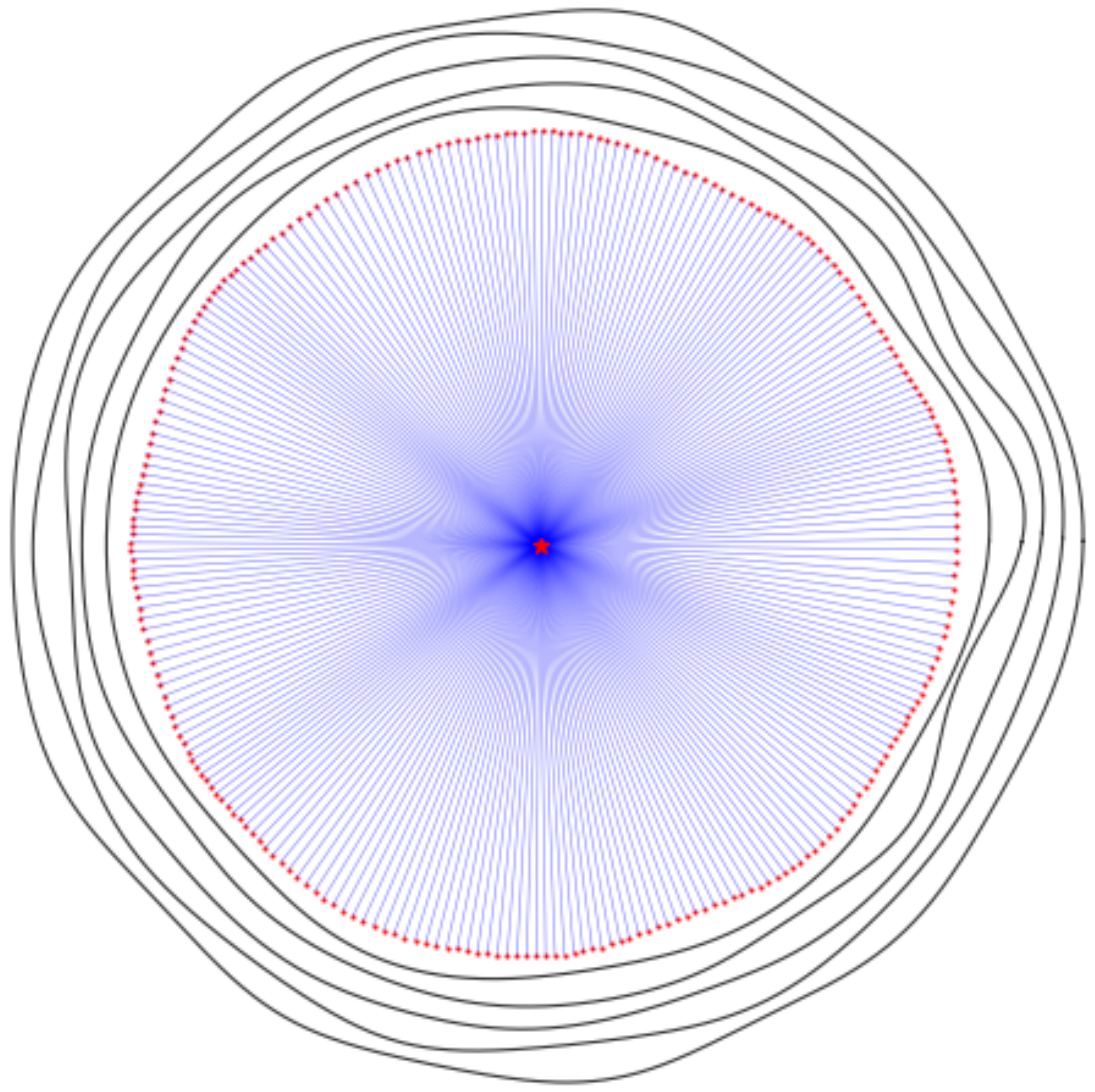
2. Generate (x, y) positions for each sample relative to origin

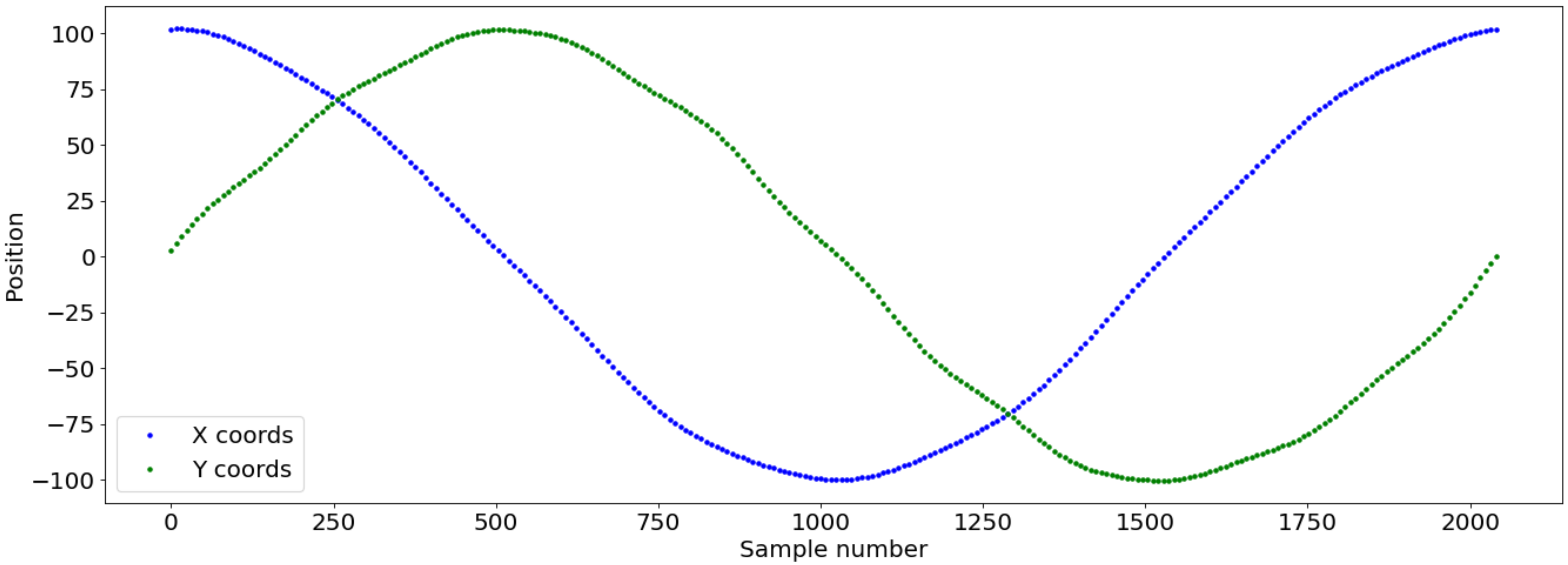


Nature and computing

Natural steganography

3. Consider the waveforms associated with the x and y coordinates of each sample in sequence



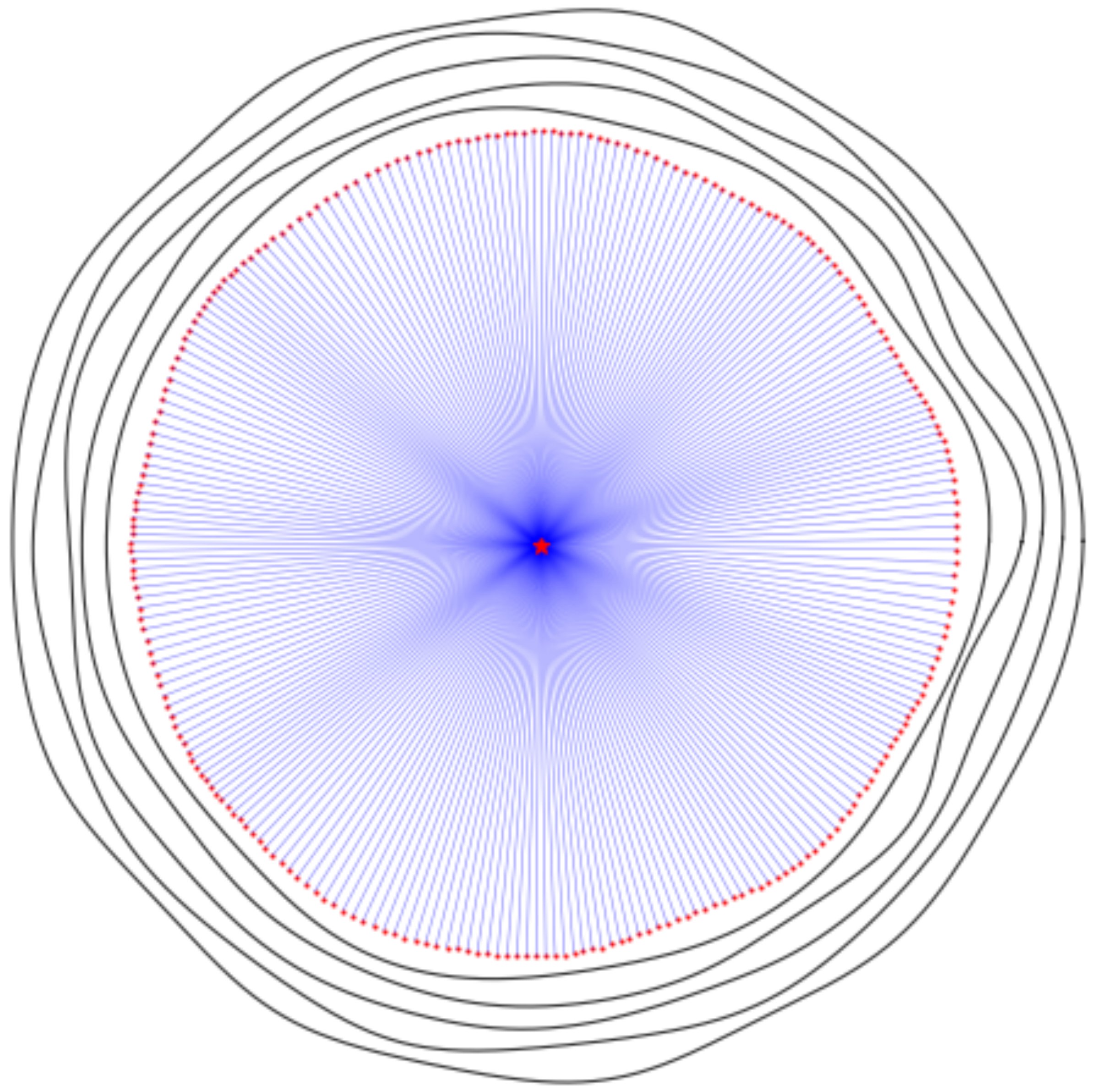


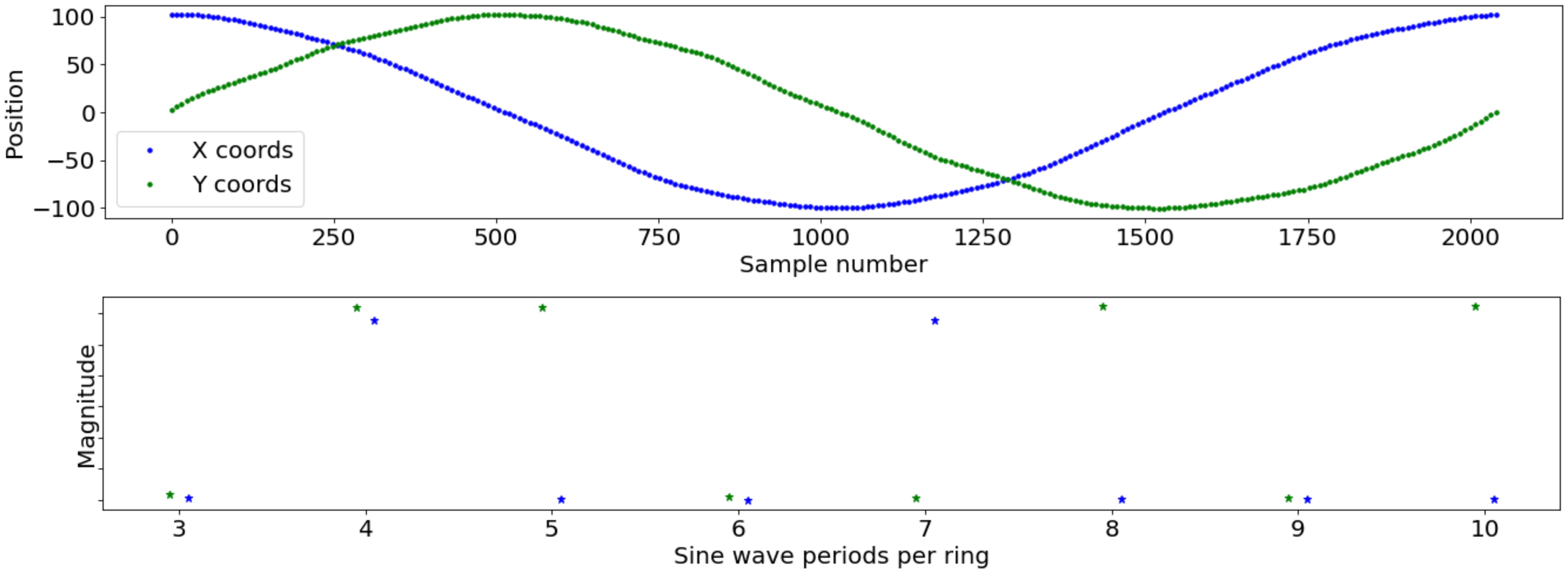
Nature and computing

Natural computation | **Natural memory** | Natural data transfer

Natural steganography

4. Compute the FFT of each waveform, consider frequencies of relevance



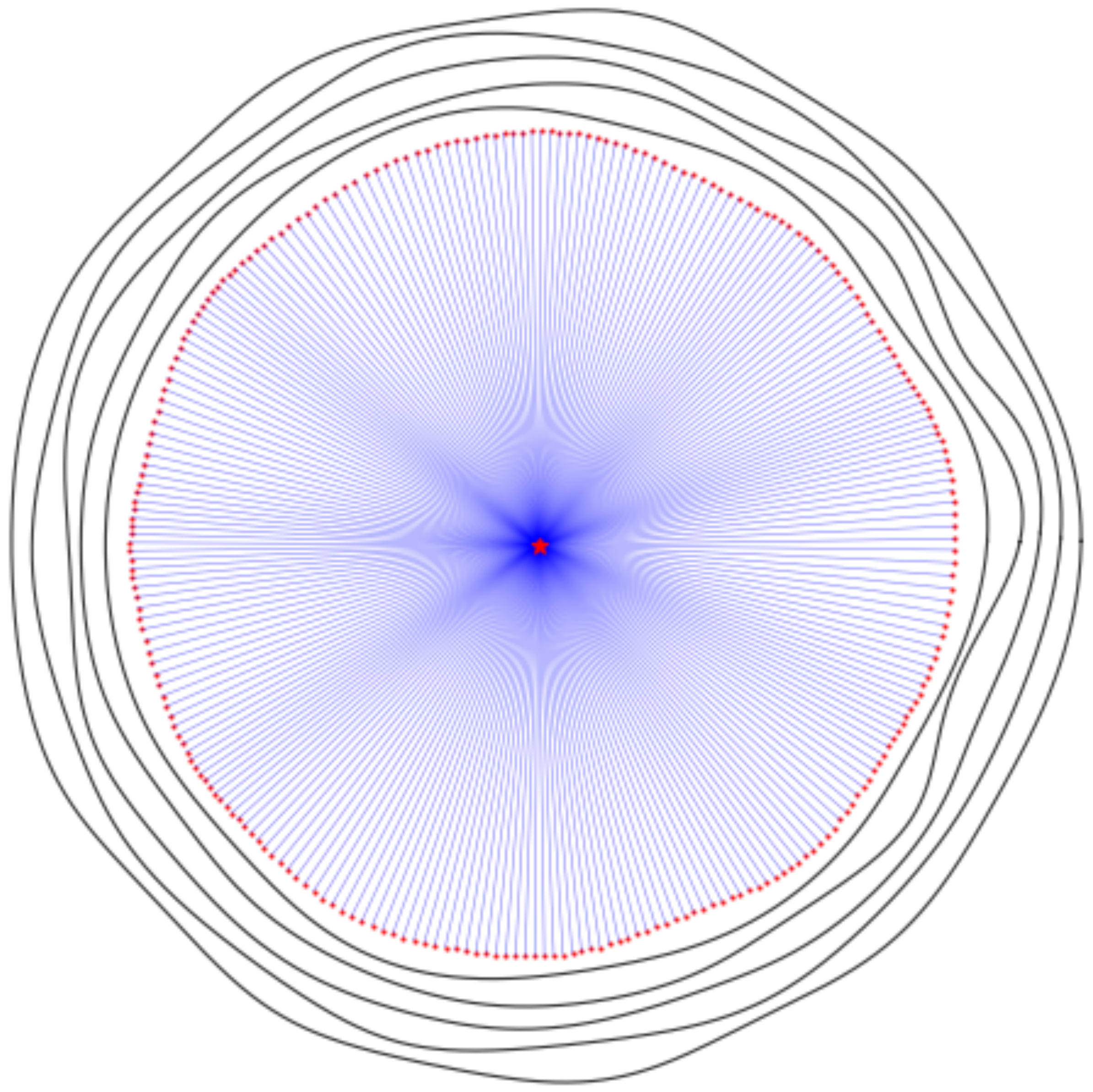


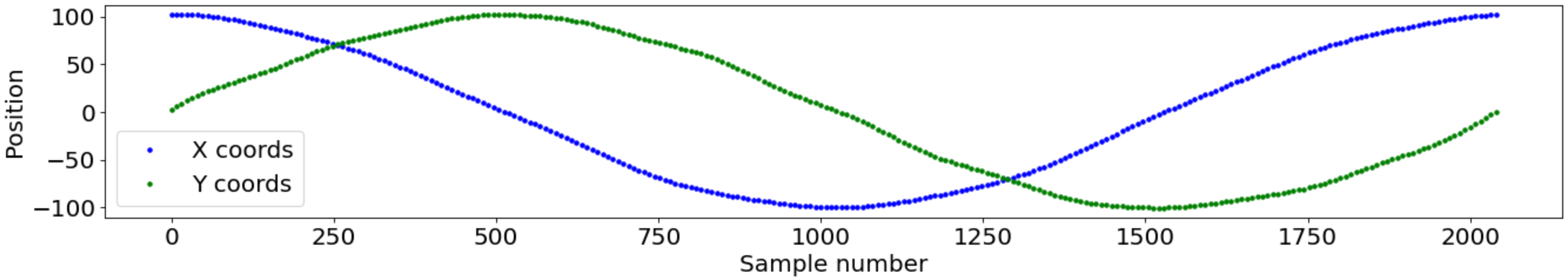
Nature and computing

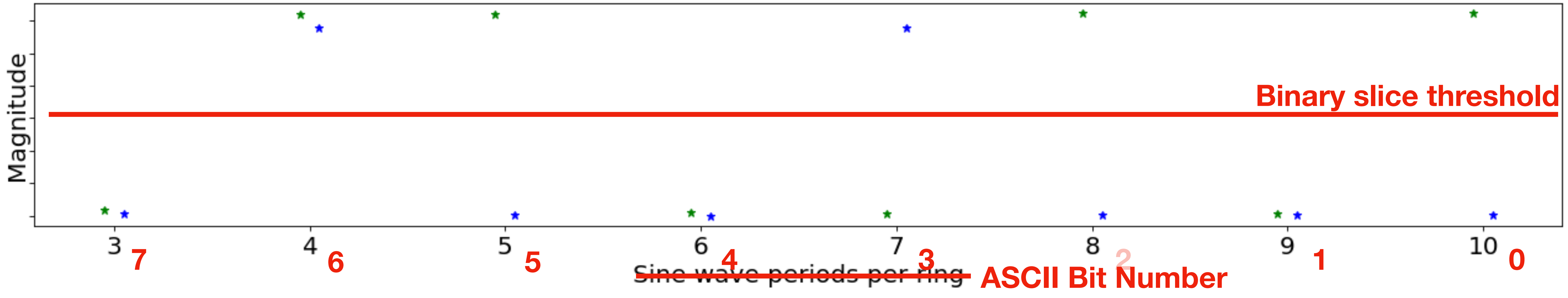
Natural computation | **Natural memory** | Natural data transfer

Natural steganography

5. Interpret relative magnitudes of relevant frequencies as bits in 8-bit ASCII





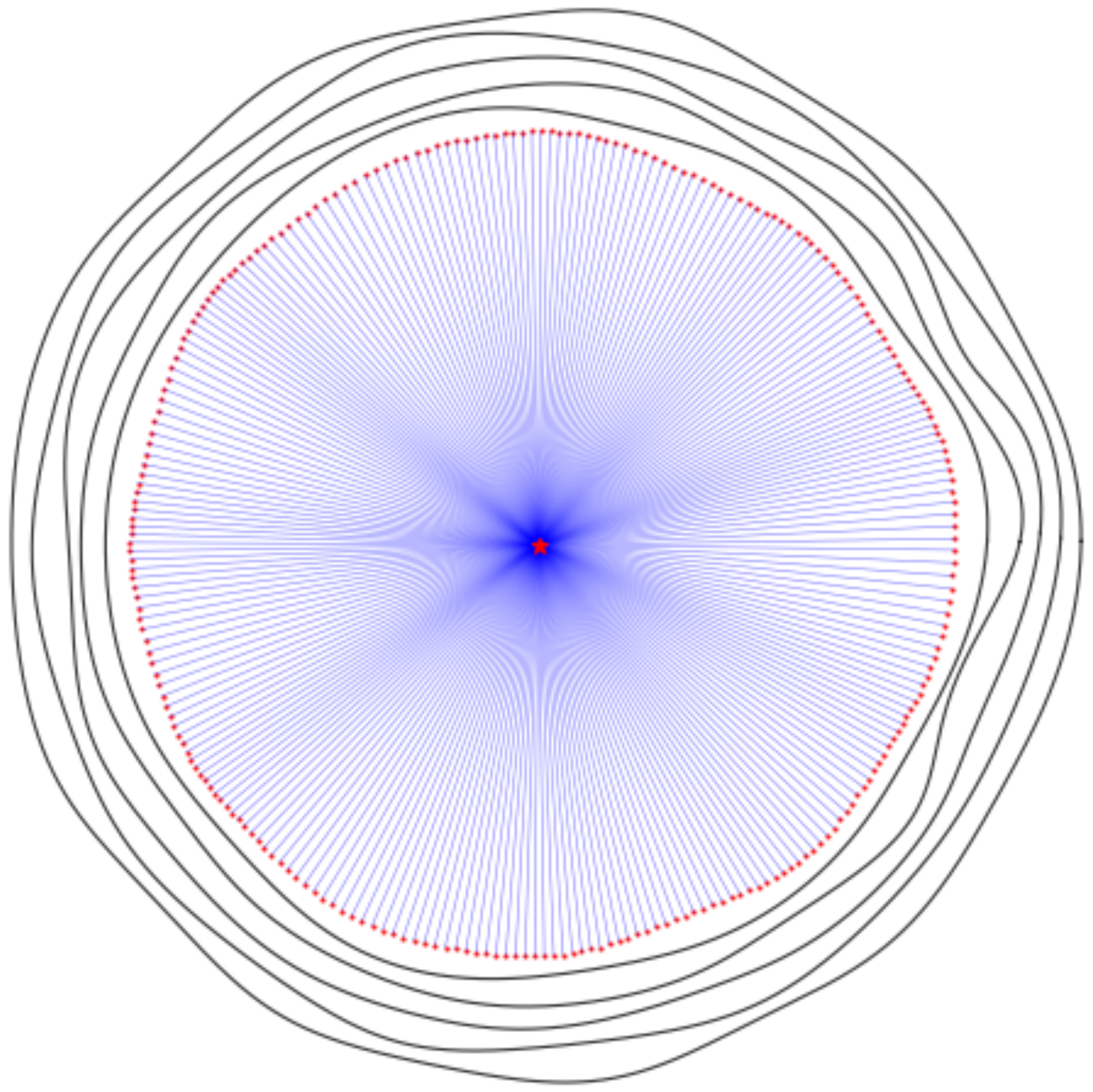


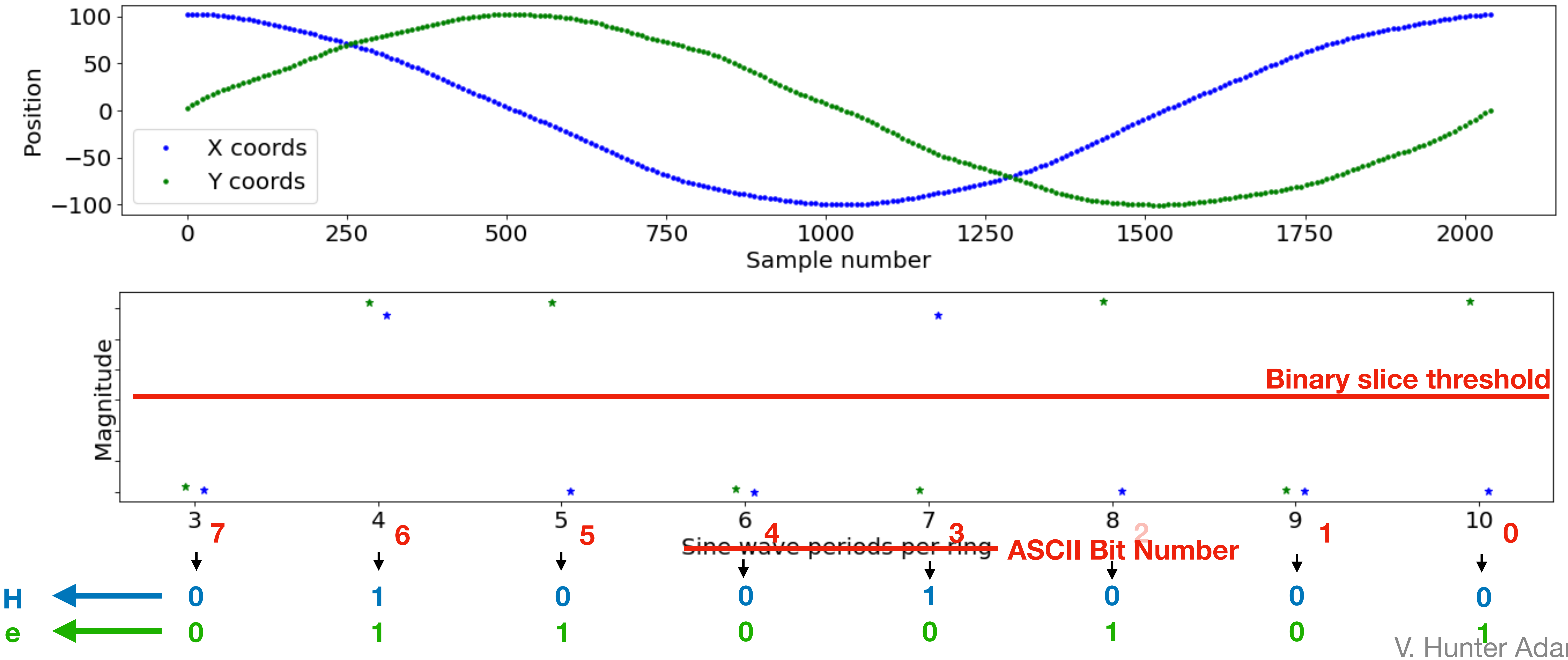
Nature and computing

Natural computation | **Natural memory** | Natural data transfer

Natural steganography

6. Assemble 8-bit ASCII values from relative magnitudes at frequencies of relevance



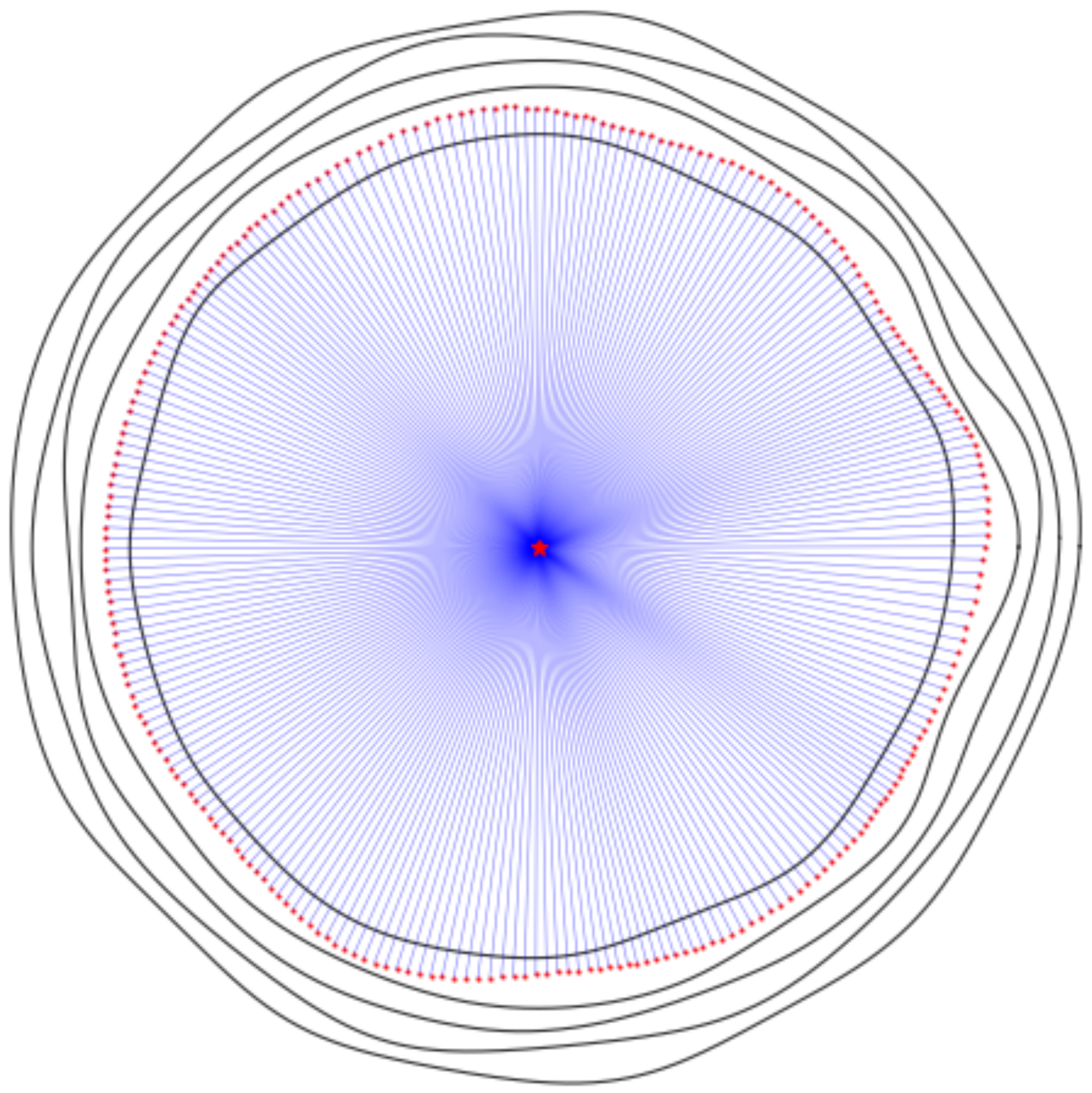


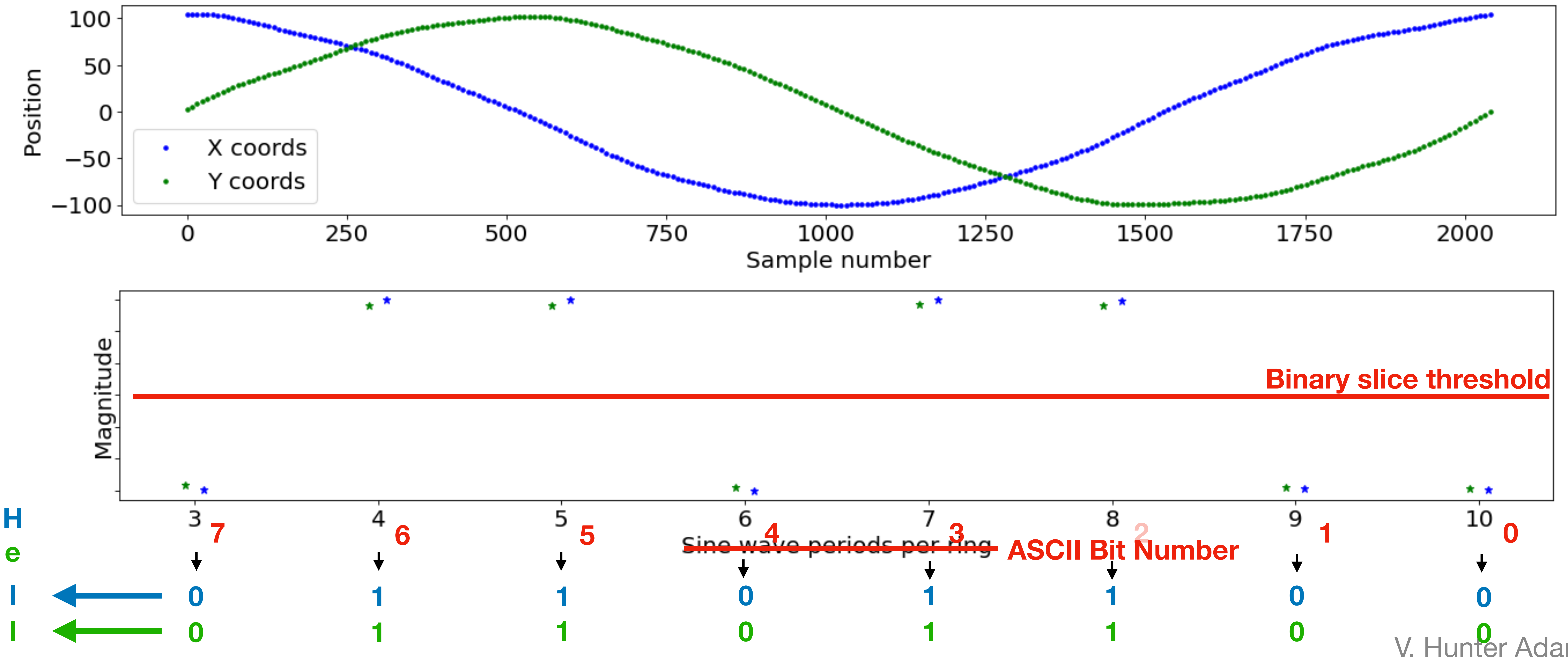
Nature and computing

Natural computation | **Natural memory** | Natural data transfer

Natural steganography

7. Move from center ring out





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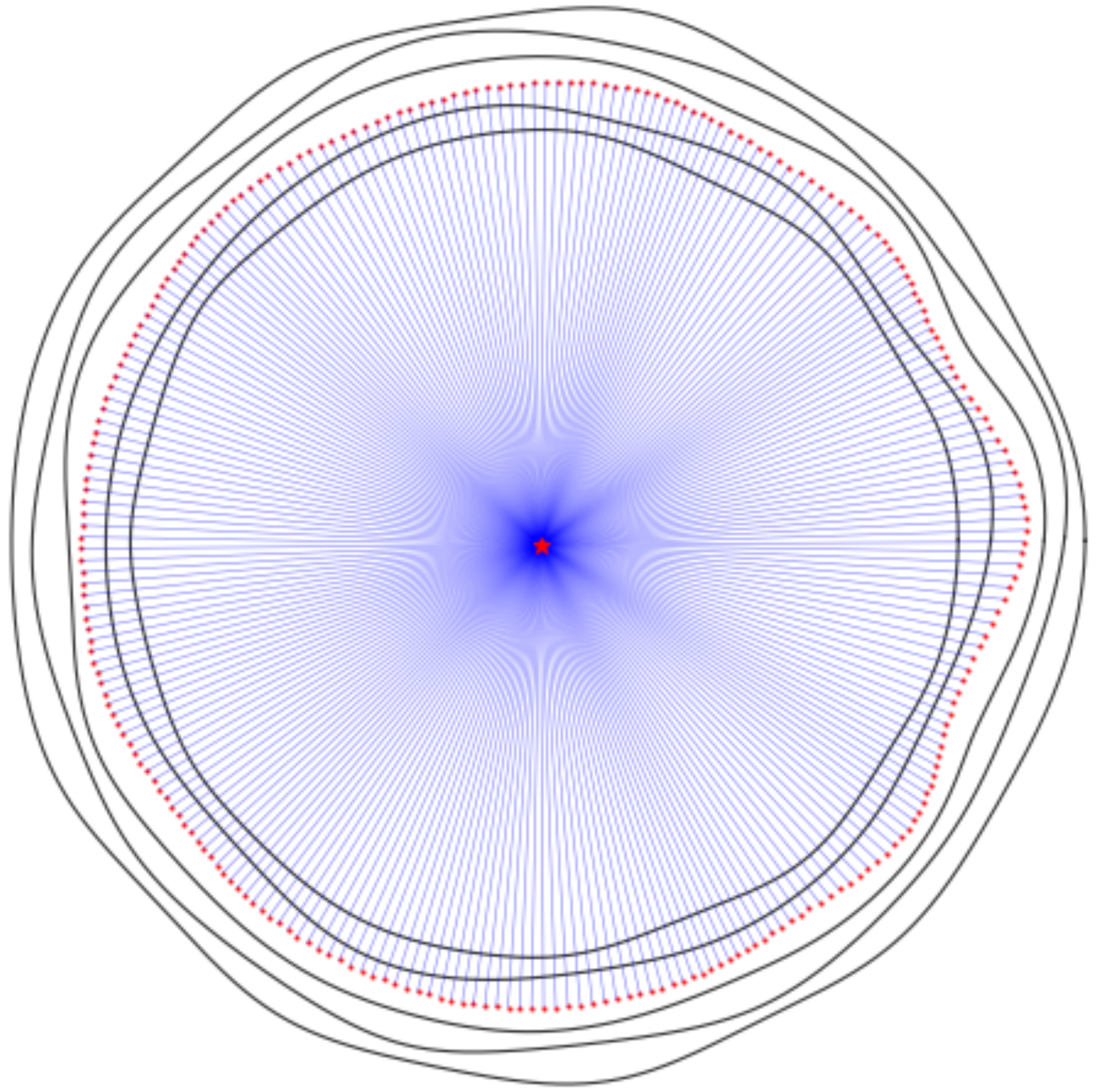
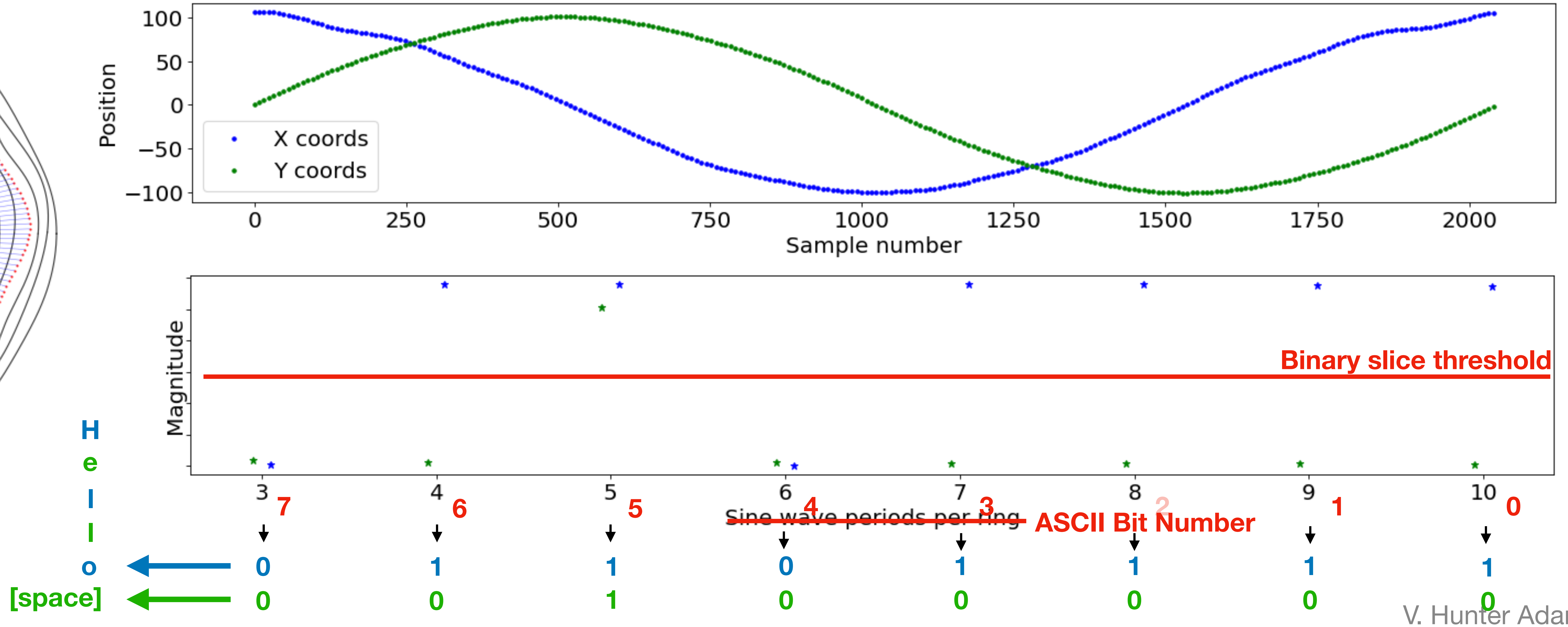
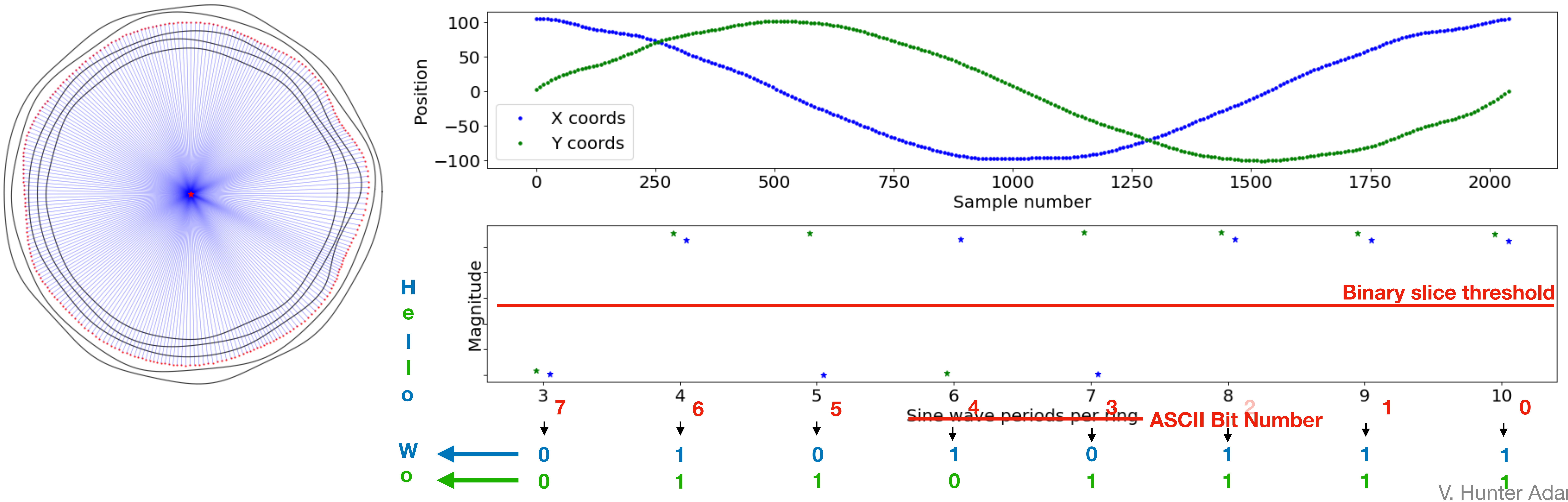




Nature and computing

Natural steganography

7. Move from center ring out

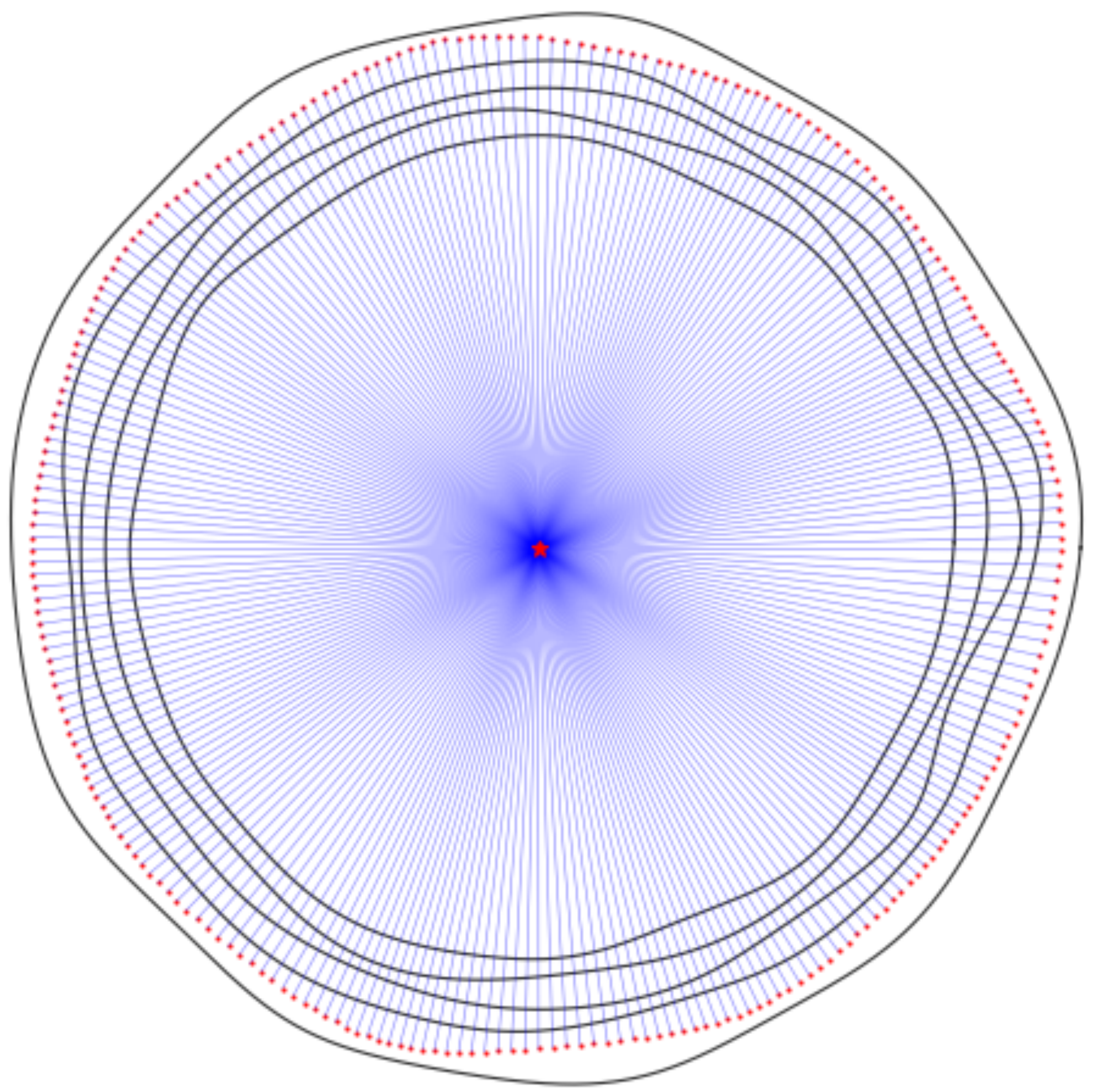


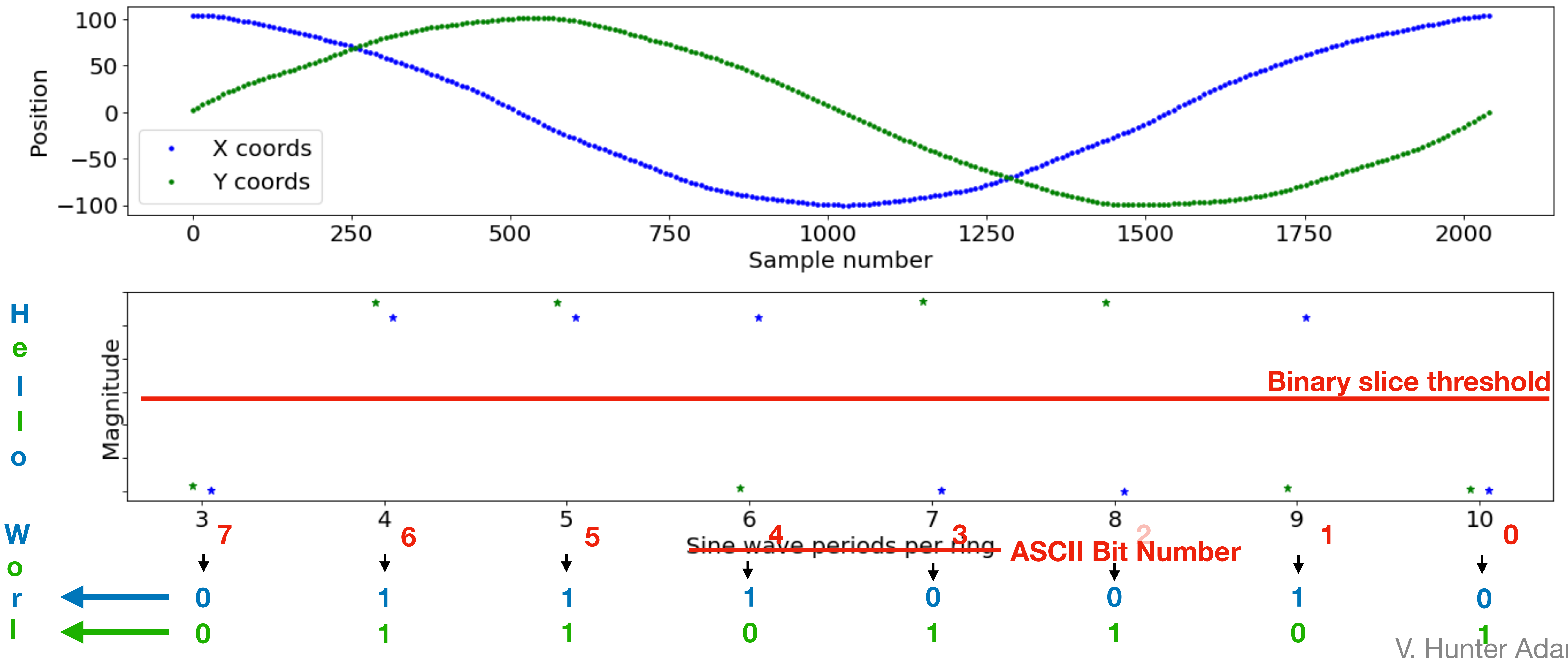
Nature and computing

Natural computation | **Natural memory** | Natural data transfer

Natural steganography

7. Move from center ring out





Nature and computing

Natural computation | **Natural memory** | Natural data transfer

Natural steganography

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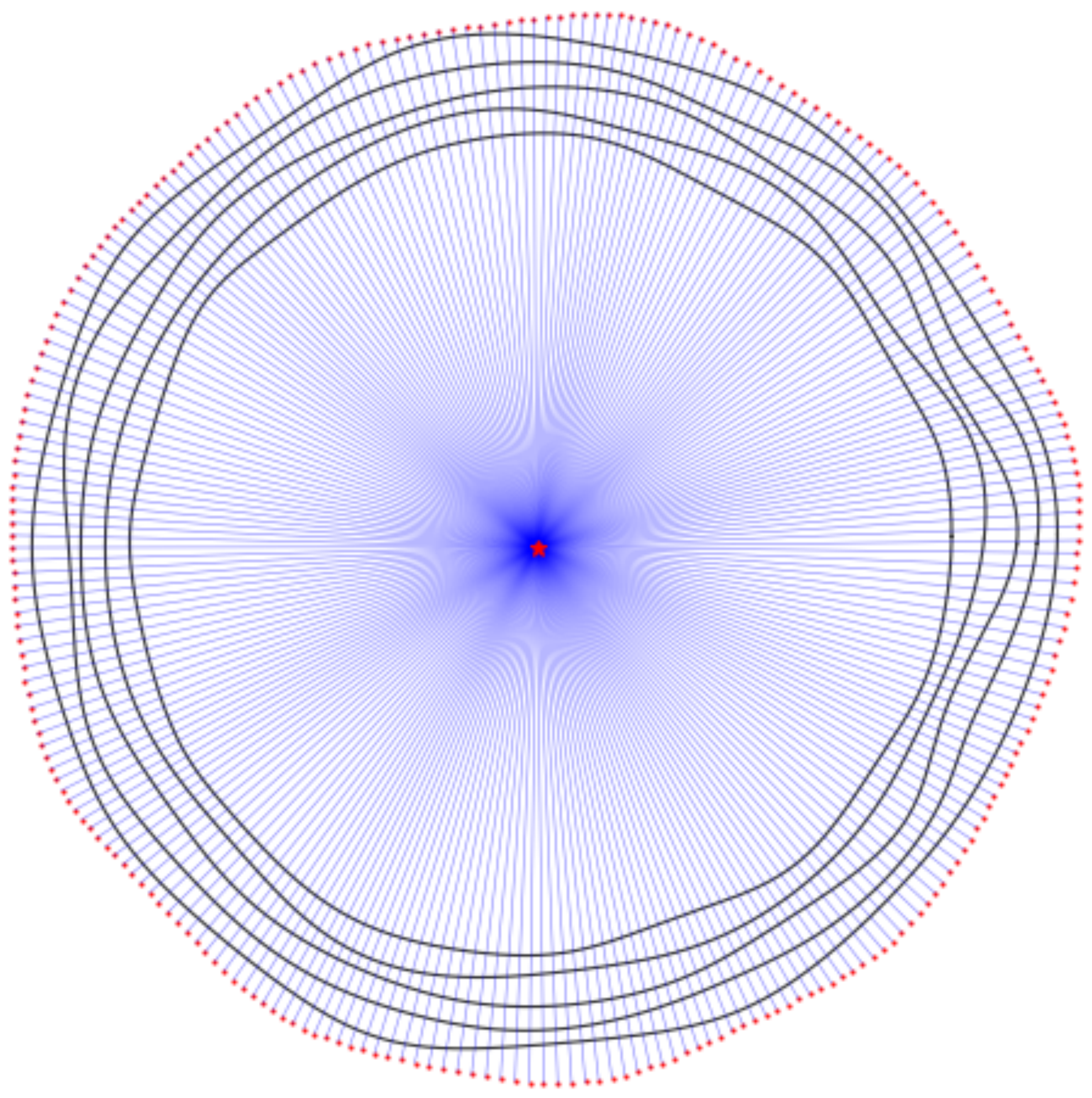

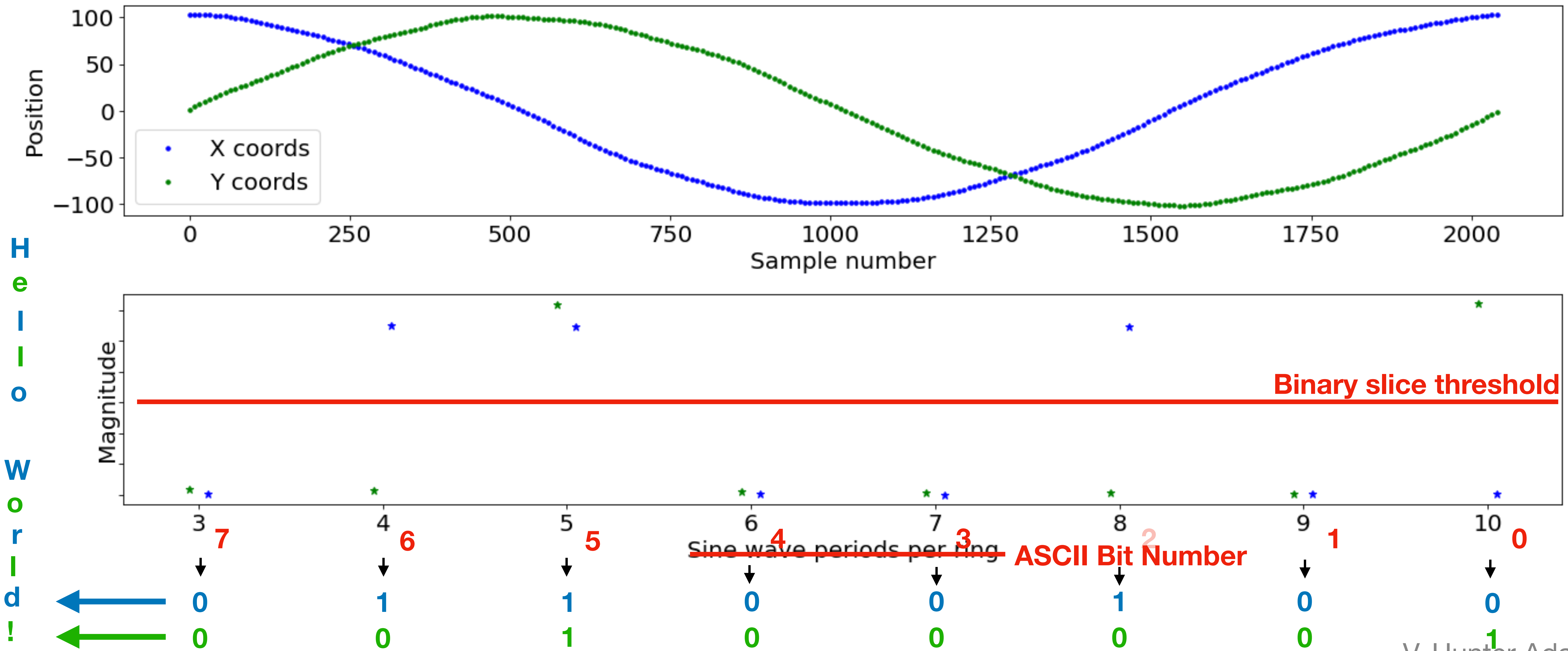

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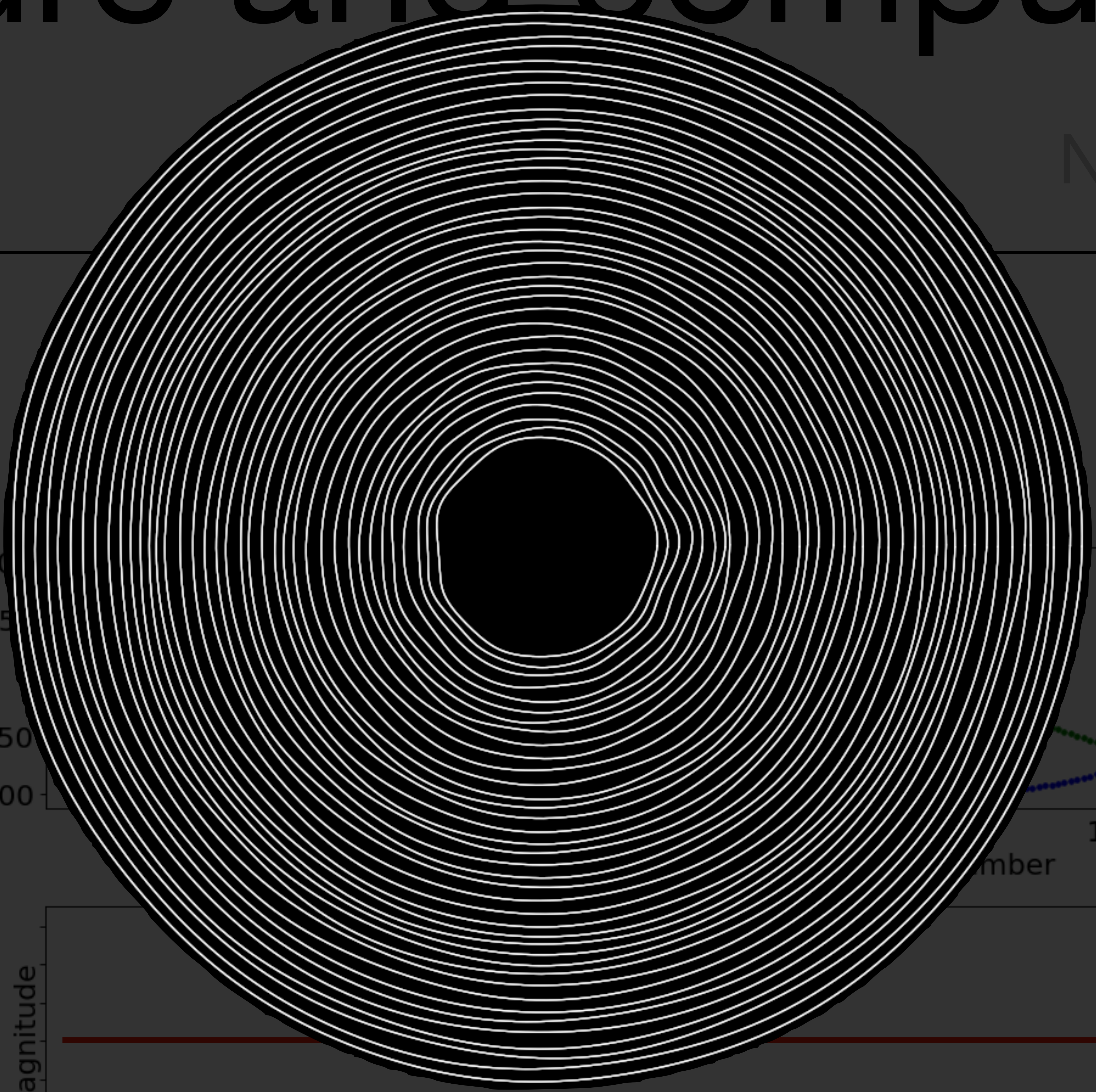
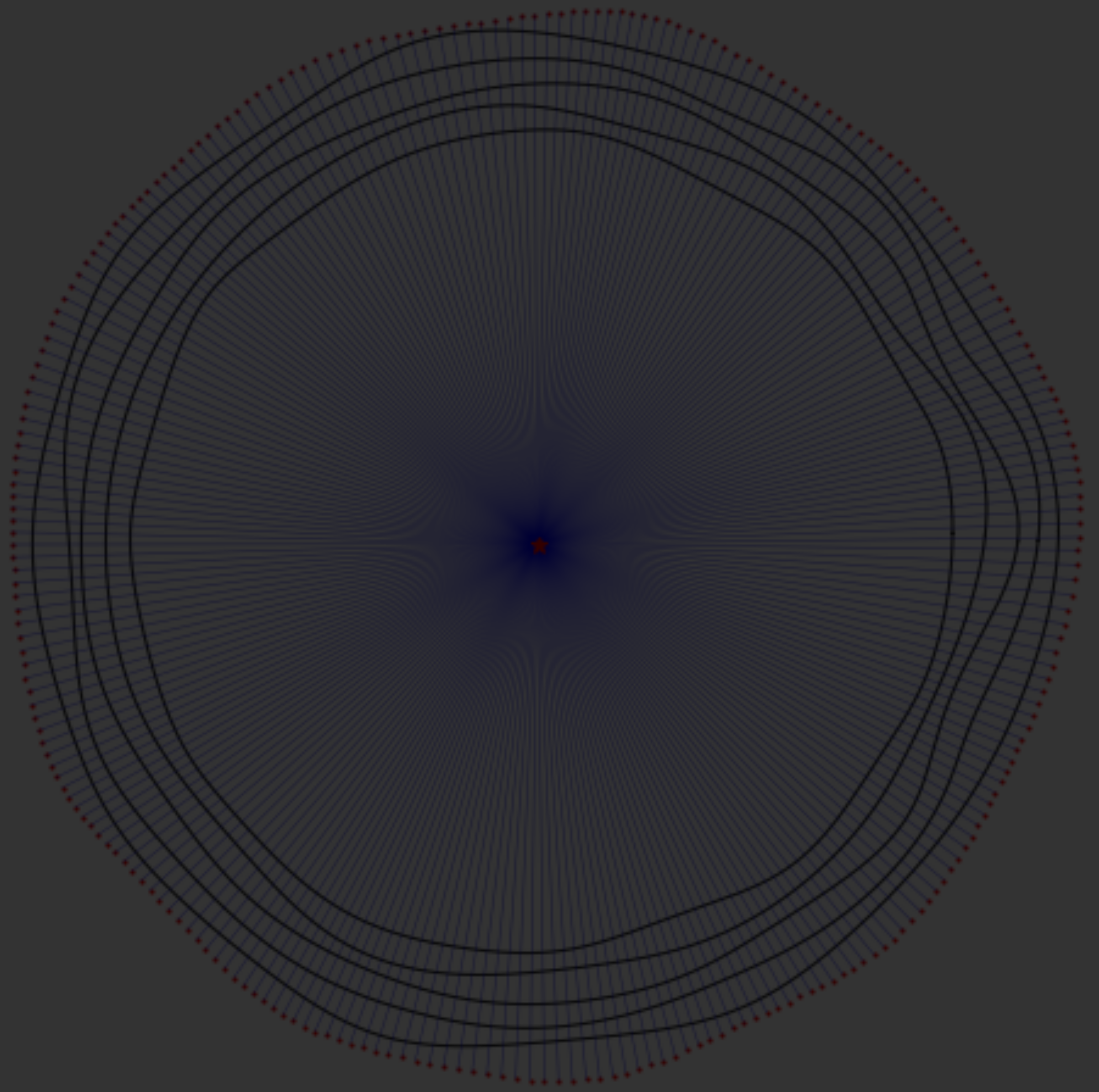
Nature and computing

Natural computation

Natural data transfer





"The whole wood is full of her spies. Even some of the trees are on her side."

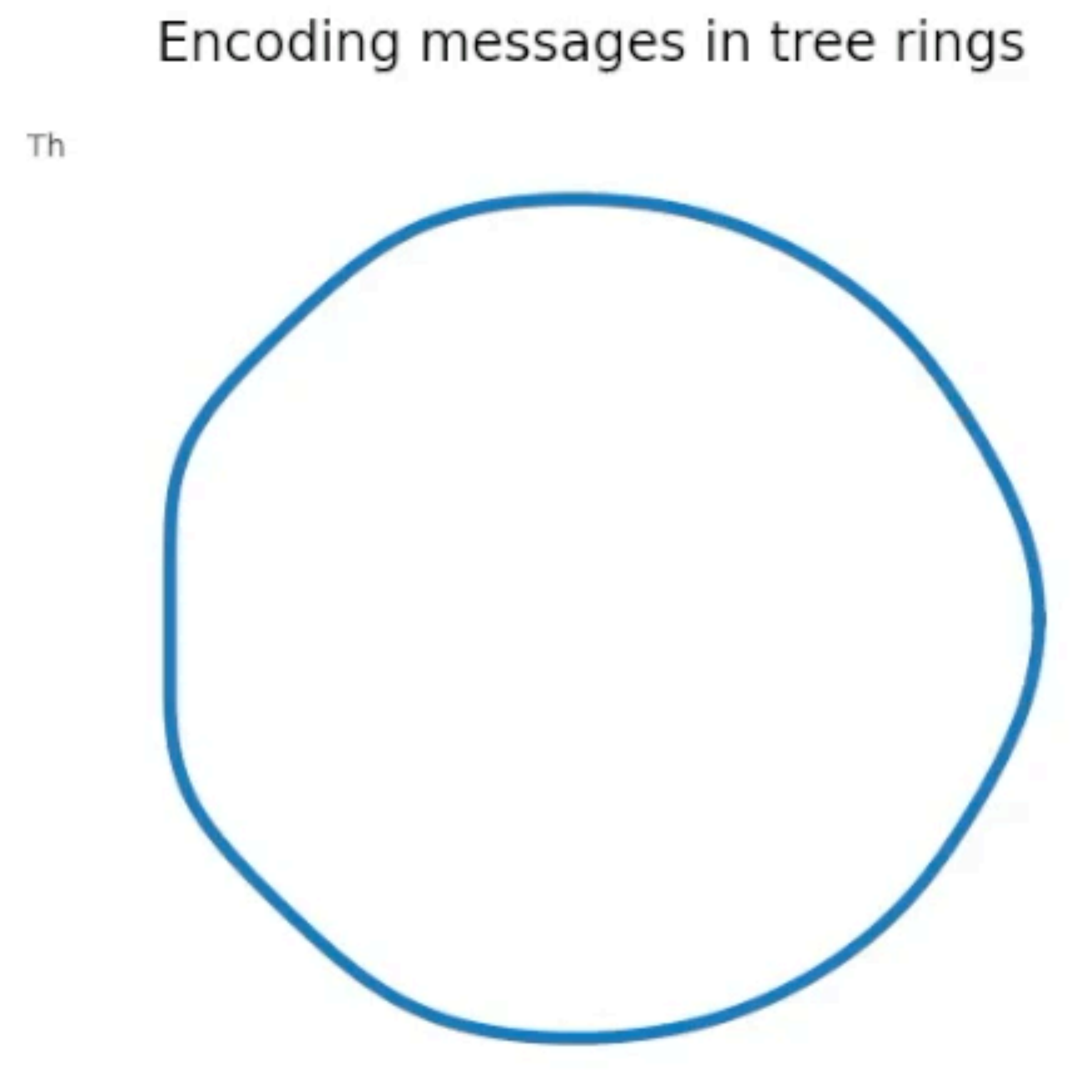
-CS Lewis, *The Lion, The Witch, and the Wardrobe*

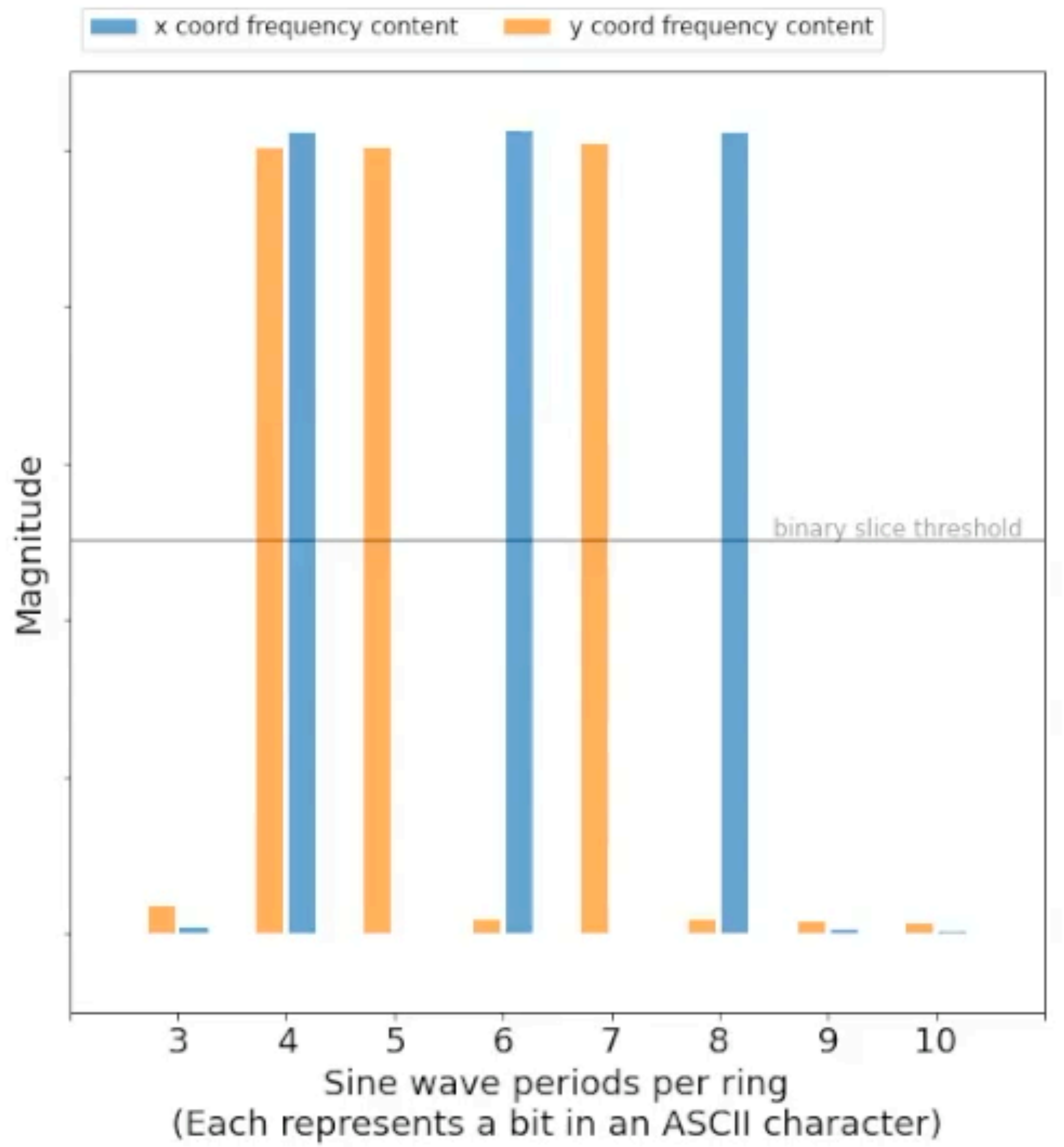
Nature and computing

Natural computation | **Natural memory** | Natural data transfer

Natural steganography

Or we can morph one ring into the next, generating wiggly animations and haunting sounds.





Link here

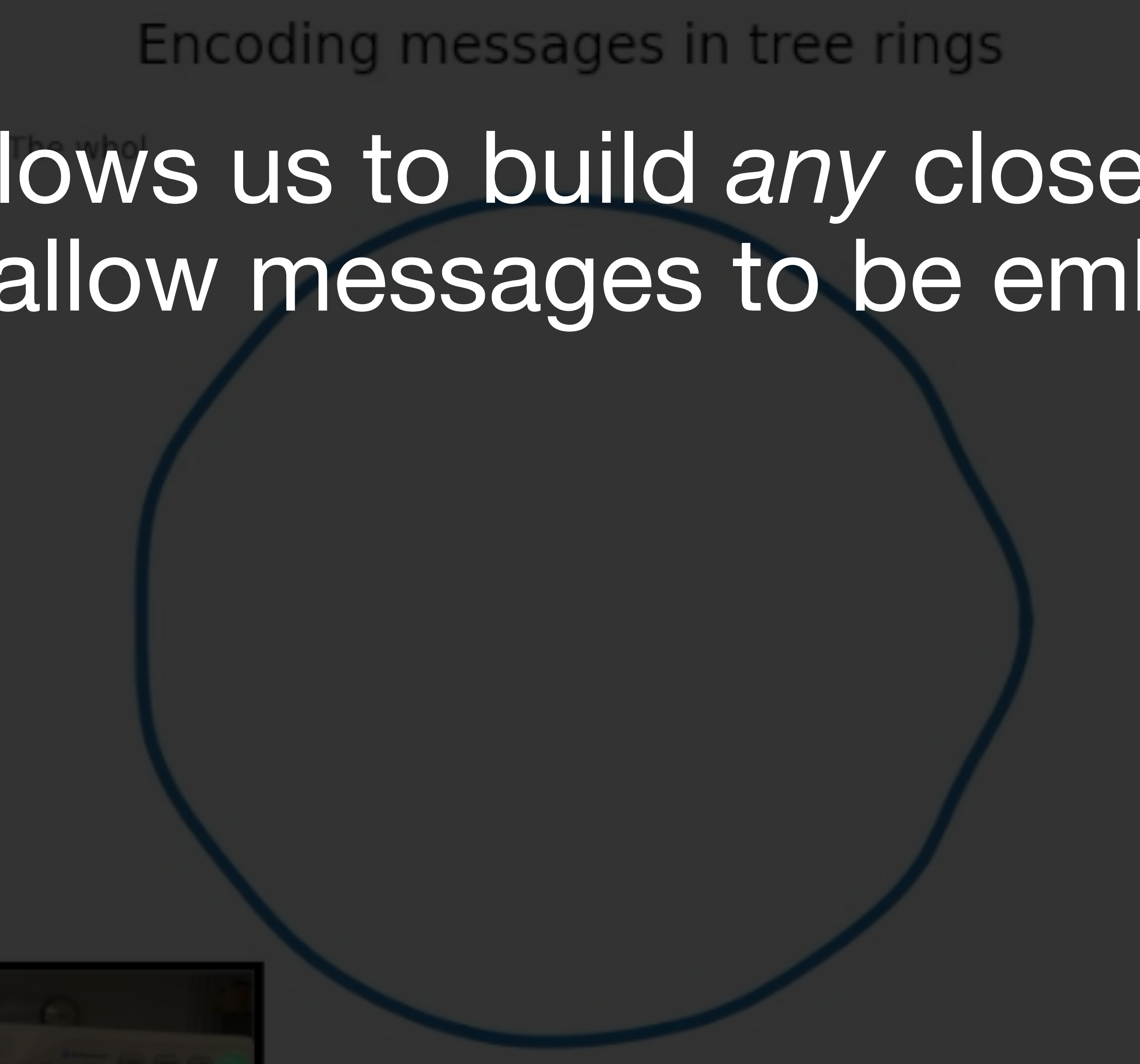
Nature and computing

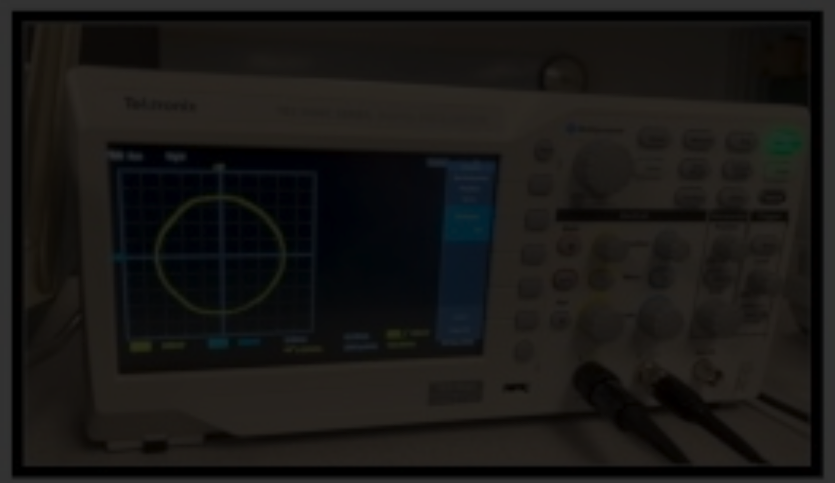
Natural computation | **Natural memory** | Natural data transfer

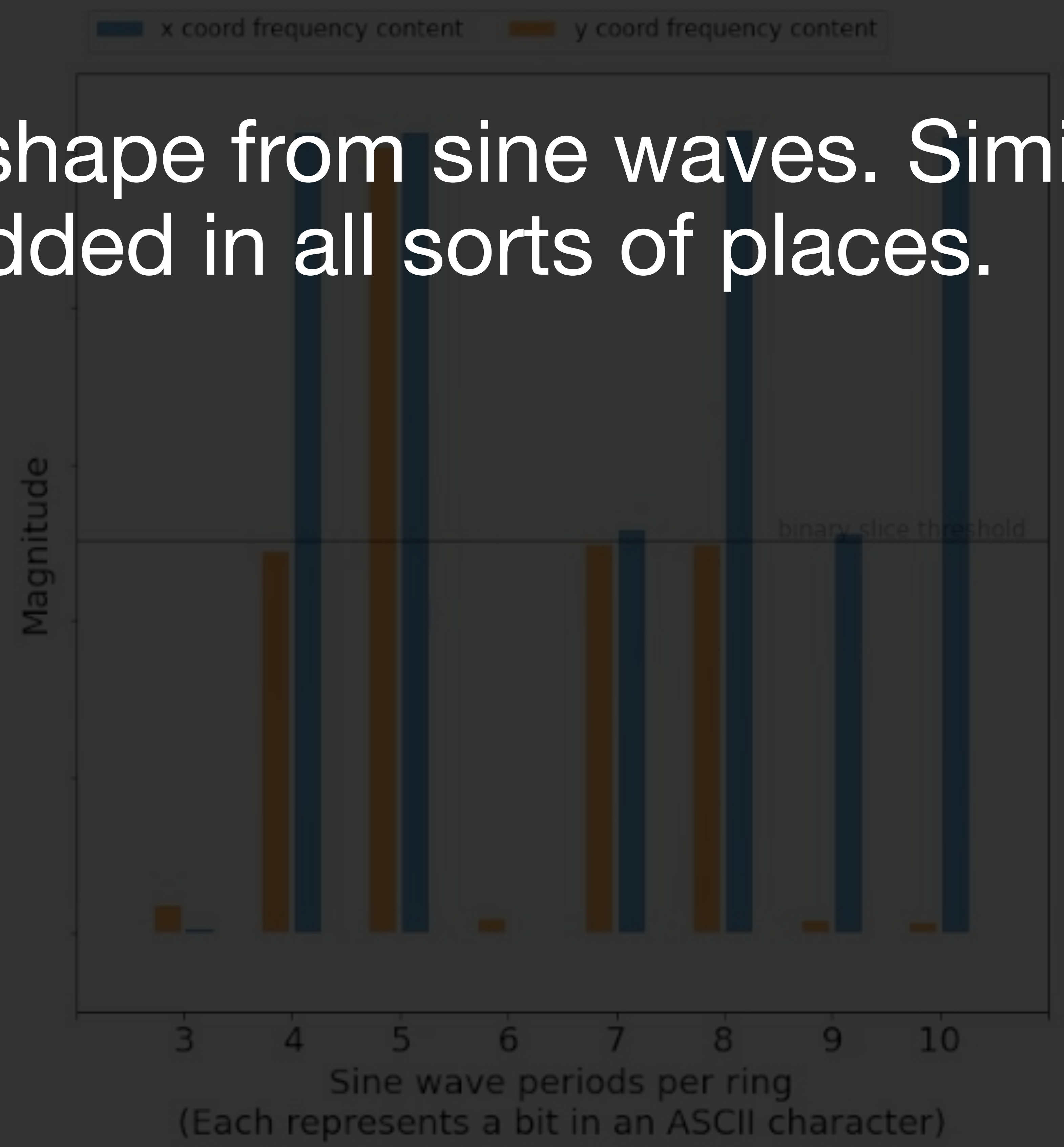
Natural steganography

Or we can morph one ring into the next, generating wiggly animations and haunting sounds.

Superposition allows us to build *any* closed shape from sine waves. Similar techniques allow messages to be embedded in all sorts of places.







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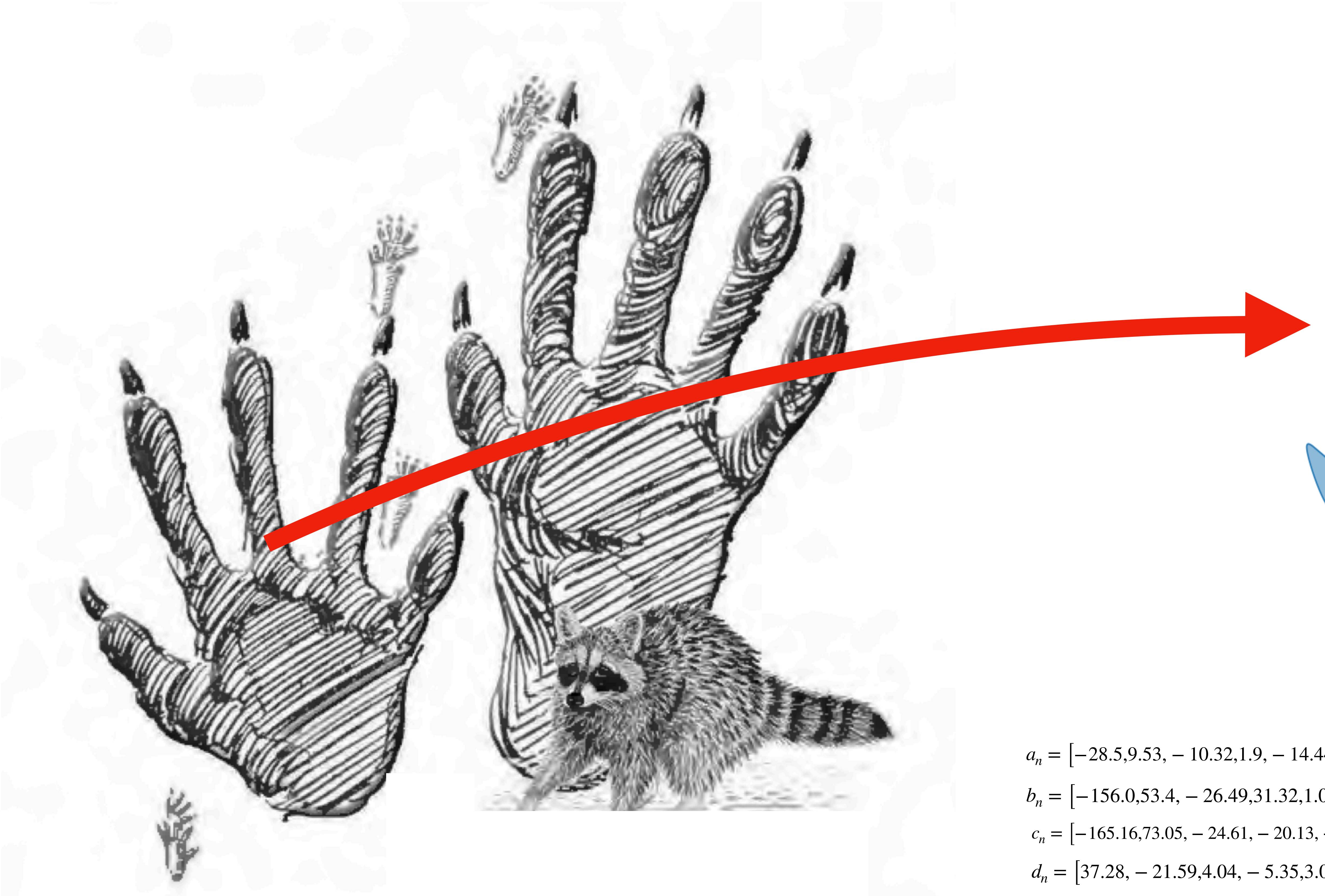
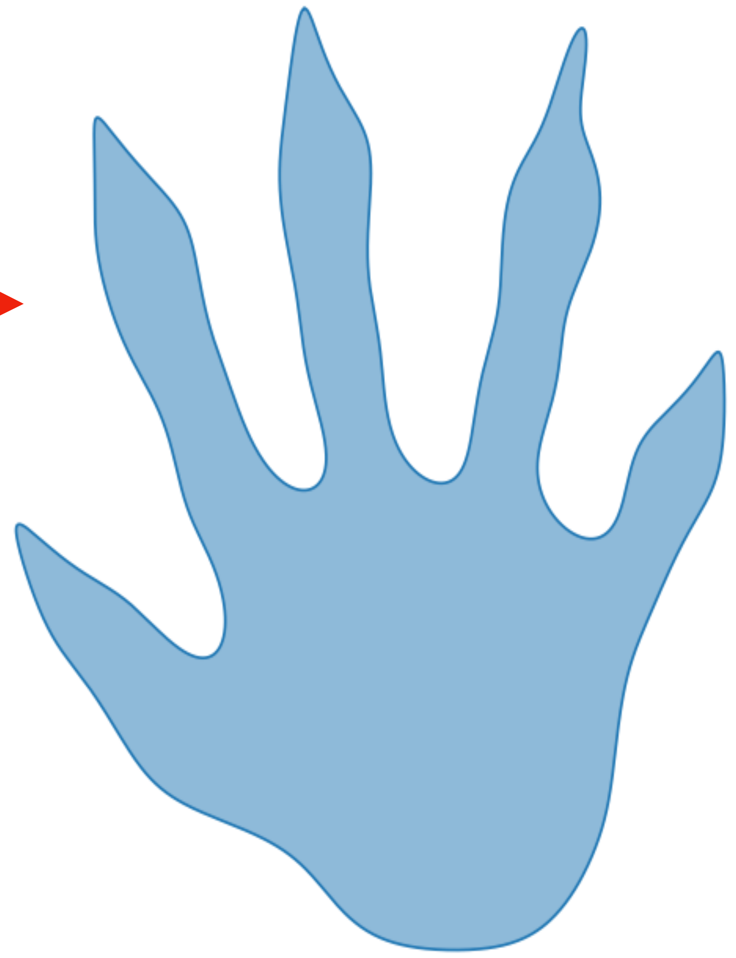
Nature and computing

Natural computation | **Natural memory** | Natural data transfer

Natural steganography

Embed information in the frequency content of footprints





$$x(l) = \sum_{n=1}^{30} \left(a_n \cos \frac{2\pi n l}{3544} + b_n \sin \frac{2\pi n l}{3544} \right)$$

$$y(l) = \sum_{n=1}^{30} \left(c_n \cos \frac{2\pi n l}{3544} + d_n \sin \frac{2\pi n l}{3544} \right)$$

(More about how this is done here)

$a_n = [-28.5, 9.53, -10.32, 1.9, -14.44, 1.35, -0.23, 0.76, 0.48, 1.38, -0.87, 0.44, 0.78, -3.49, -0.11, -0.34, -0.96, 0.01, 0.75, 0.8, -0.72, 0.09, -0.28, -0.11, -0.01, -0.22, -0.57, 0.74, 0.81, -0.06]$

$b_n = [-156.0, 53.4, -26.49, 31.32, 1.04, -19.97, 3.76, 3.49, -10.24, 0.62, -2.87, -0.43, 0.9, 3.2, 0.83, 0.13, -1.73, 0.63, -0.46, 0.66, 0.71, -0.69, 0.15, 1.82, 0.34, -0.56, 0.88, -0.24, -0.74, -0.19]$

$c_n = [-165.16, 73.05, -24.61, -20.13, -97.14, -15.83, 10.47, -5.03, 3.84, 6.66, -10.79, 4.98, 0.68, -7.67, -3.78, -1.25, -0.71, 1.46, 0.33, -0.51, -1.08, -0.33, 1.01, -2.98, -1.84, 0.18, -1.05, 1.19, 0.31, -1.89]$

$d_n = [37.28, -21.59, 4.04, -5.35, 3.01, 4.13, -2.68, 0.0, 1.66, 2.43, -0.03, 0.15, -1.02, -0.17, 0.59, -0.27, 0.11, -0.98, 0.5, 0.01, 0.22, -0.01, -0.89, -0.12, -0.07, 0.57, -0.15, -0.37, -0.21, 0.8]$

Image from NY State DEC (https://extapps.dec.ny.gov/docs/administration_pdf/tracks1.pdf)

Nature and computing

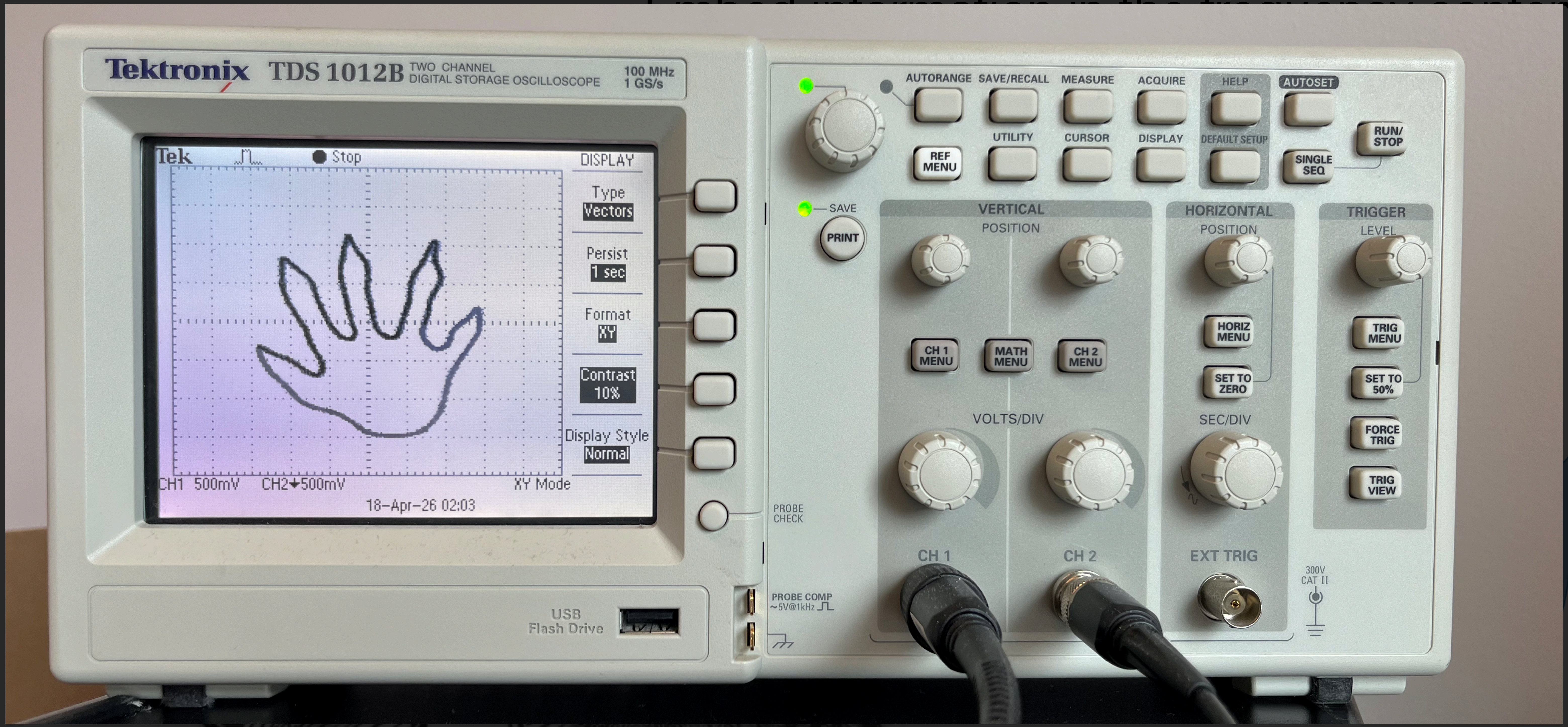
Since these are just sine waves, we can also *listen* to these images!

Natural computation | **Natural memory** | Natural data transfer

Send the x coordinates to the left-channel, and y-coordinates to the right.

Natural steganography

Embed information in the frequency content of footprints



What does the shape of a raccoon footprint sound like?

Listen here.

$$x(l) = \sum_{n=1}^{30} \left(a_n \cos \frac{2\pi nl}{3544} + b_n \sin \frac{2\pi nl}{3544} \right)$$

$$y(l) = \sum_{n=1}^{30} \left(c_n \cos \frac{2\pi nl}{3544} + d_n \sin \frac{2\pi nl}{3544} \right)$$

What do Picasso's line drawings sound like?

(More about this here)

Listen here.

$a_n = [-28.5, 9.53, -10.32, 1.9, -14.44, 1.35, -0.23, 0.76, 0.48, 1.38, -0.87, 0.44, 0.78, -3.49, -0.11, -0.34, -0.96, 0.01, 0.75, 0.8, -0.72, 0.09, -0.28, -0.11, -0.01, -0.22, -0.57, 0.74, 0.81, -0.06]$

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Image from NY State DEC (https://extapps.dec.ny.gov/docs/administration_pdf/tracks1.pdf)

There’s nothing special about tree rings or footprints.

Nature abounds in patterns, all of which might be used to hide information.

Forms and Patterns in Nature - Wolf Strache

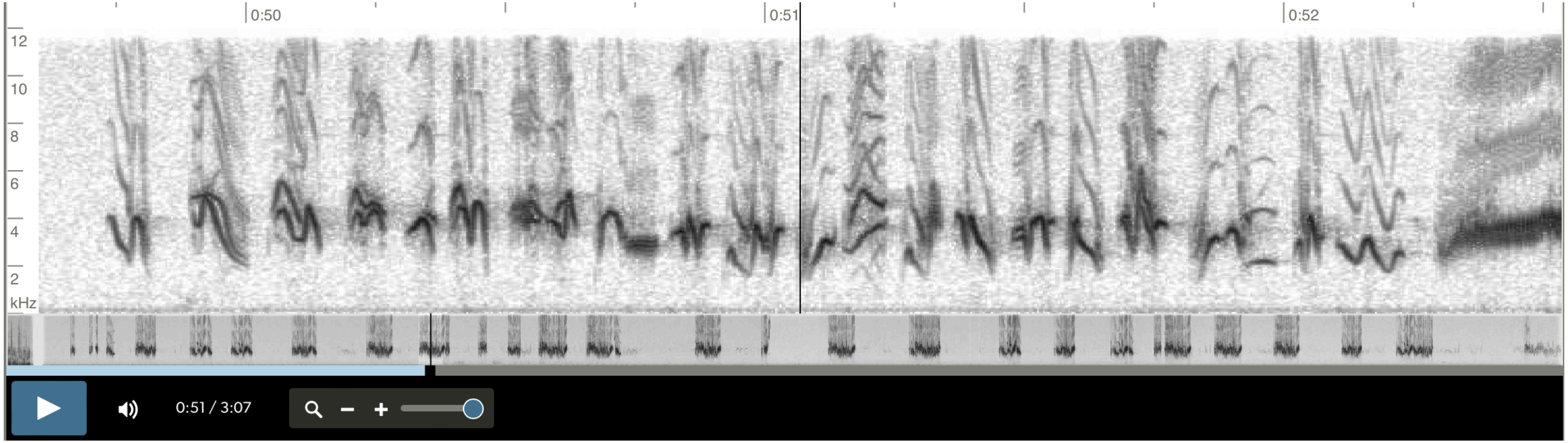
Forms and Patterns in Nature - Wolf Strache

Nature and computing

Natural computation | **Natural memory** | Natural data transfer

Birdsong steganography

There are lots of ways that one might hide messages in birdsongs. Let me offer a simple proof of concept.



The house finch sings in syllables. They have a large library of syllables, and each song composes them in an apparently random order.

https://macaulaylibrary.org/asset/22938

Nature and computing

Natural computation | **Natural memory** | Natural data transfer

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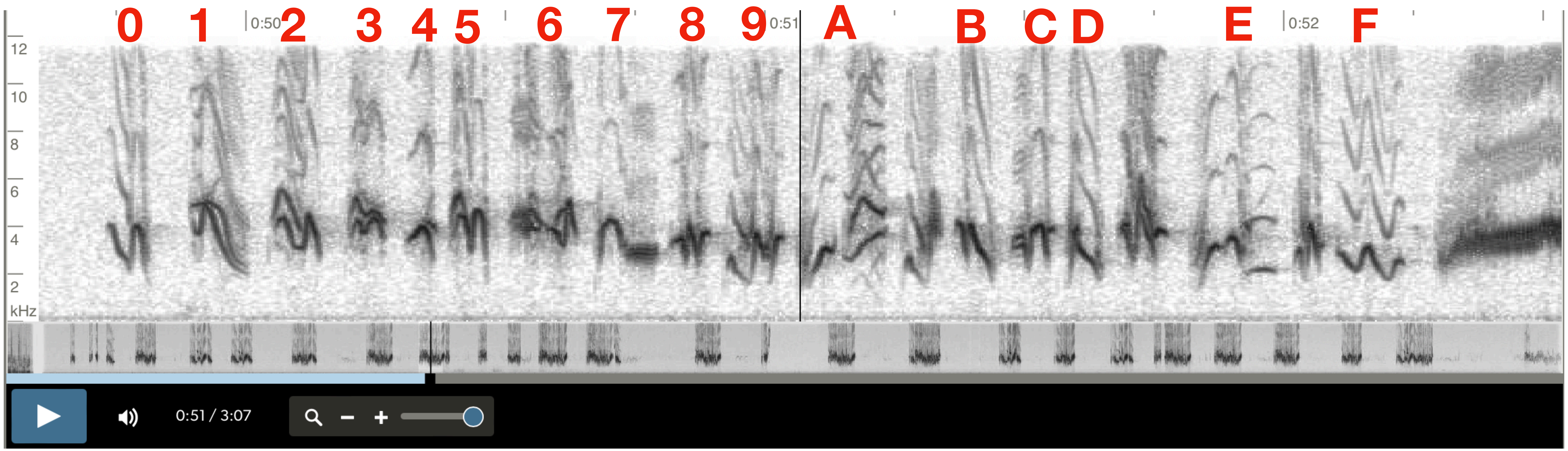

Associate each syllable with a symbol, and compose symbols into a song.

e.g. syllables to hexadecimal

https://macaulaylibrary.org/asset/22938 V. Hunter Adams

Nature and computing

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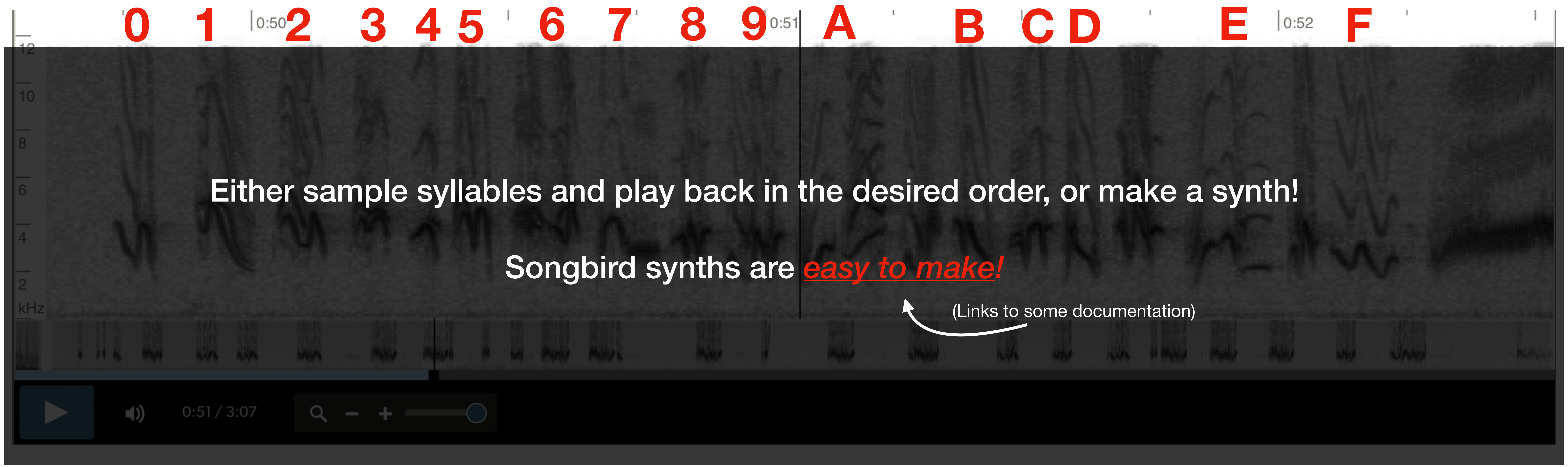

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Nature and computing

Natural computation | **Natural memory** | Natural data transfer

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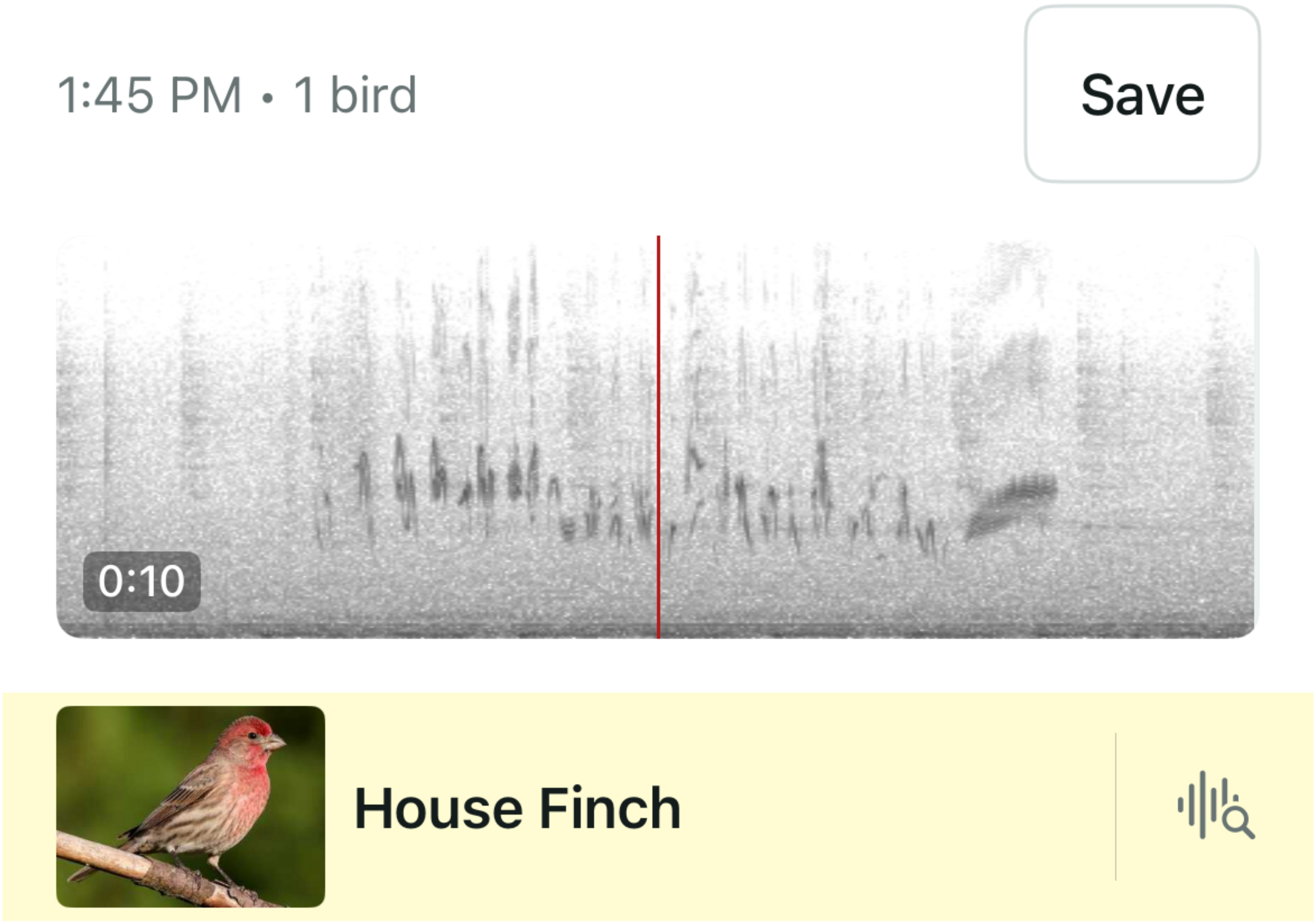
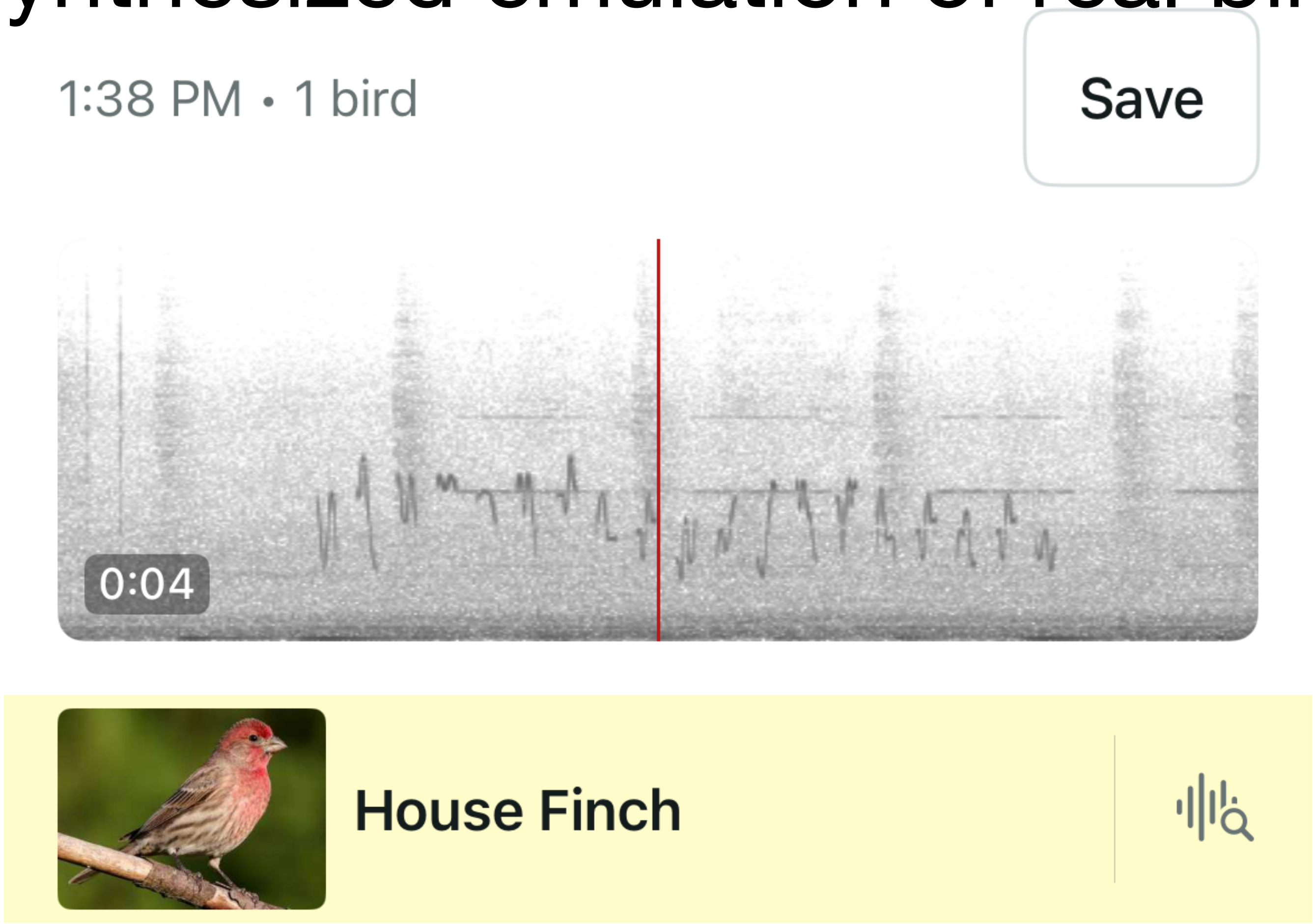
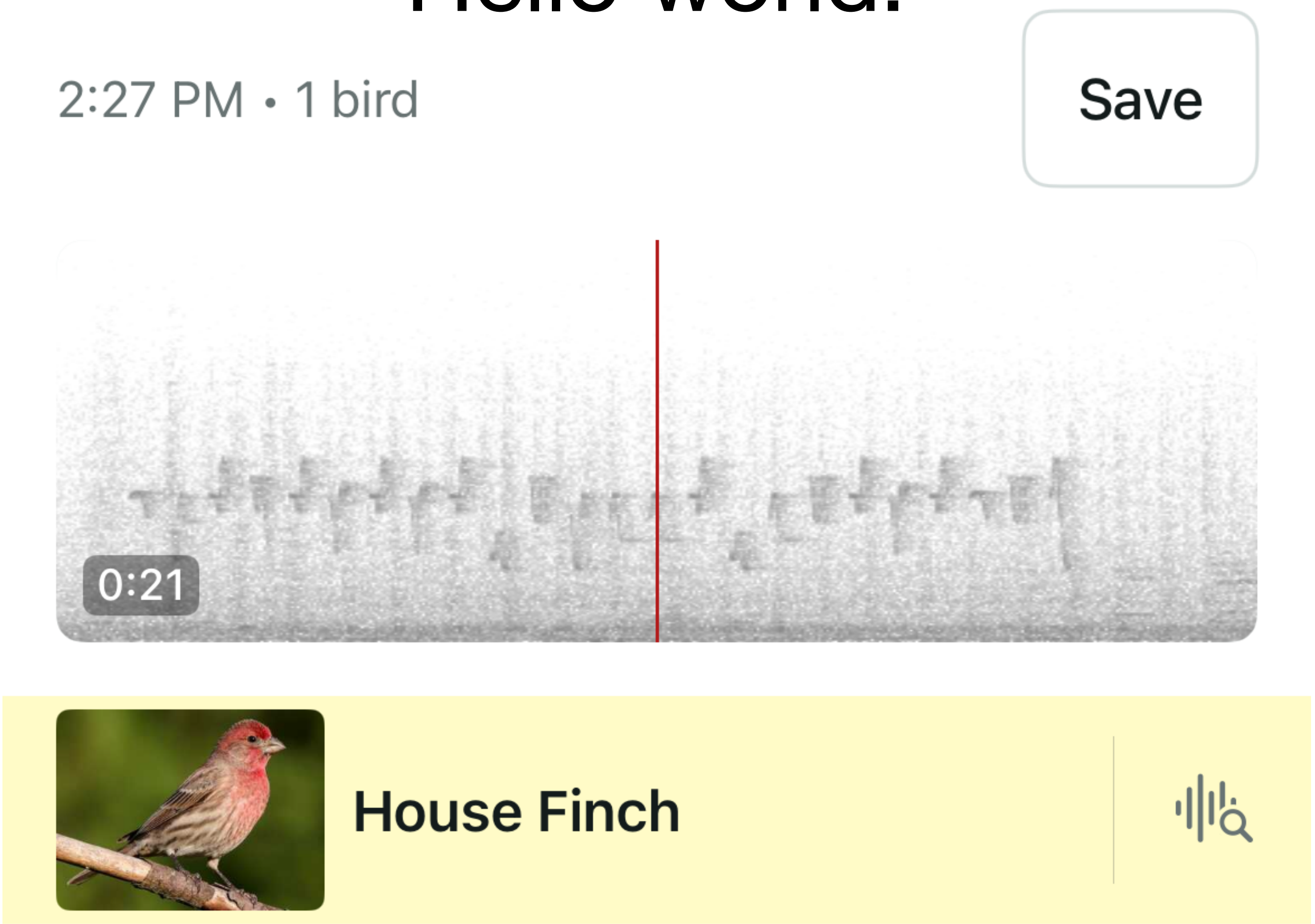
Real bird



Synthesized emulation of real bird



“Hello world!”



The synthetic bird sounds real enough to trick Merlin. **Listen here, would it trick you?**

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Nature and computing

"Birds aren't real"

https://macaulaylibrary.org/asset/22938

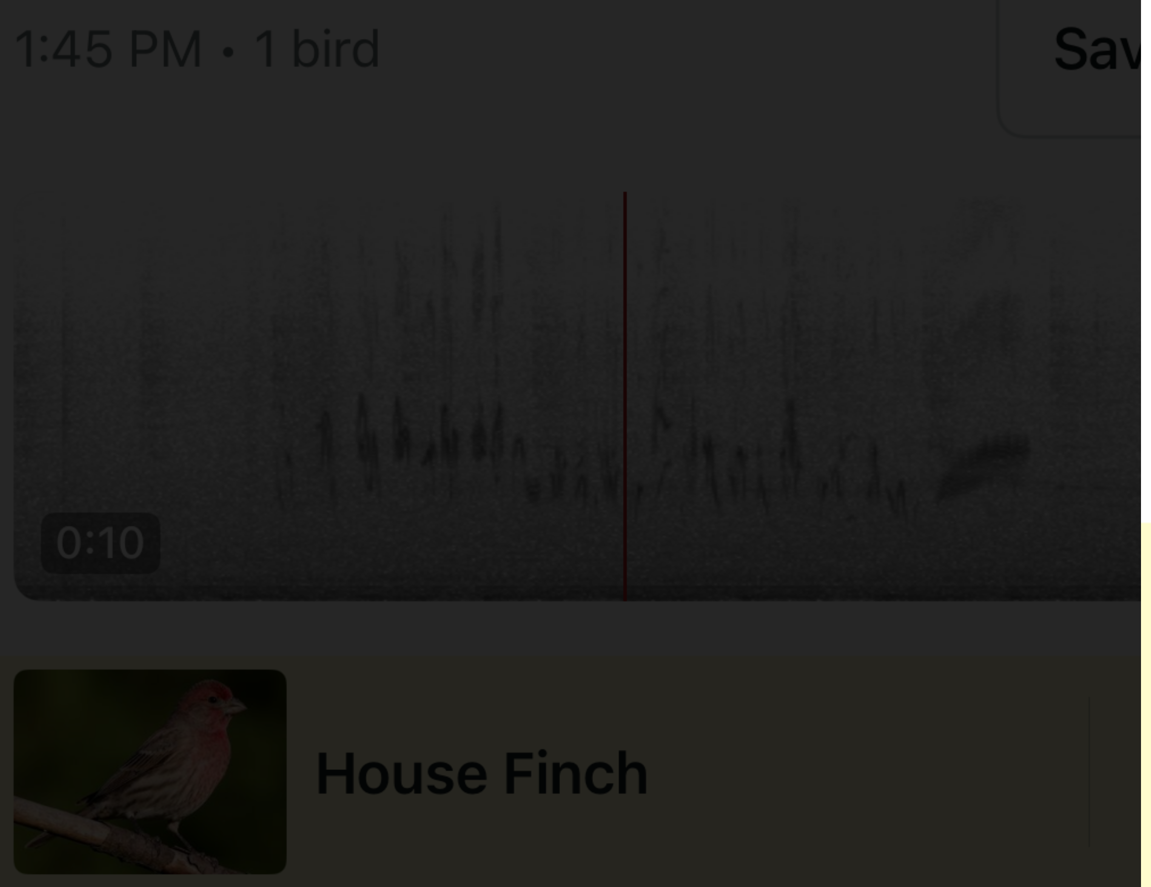
Nature and computing

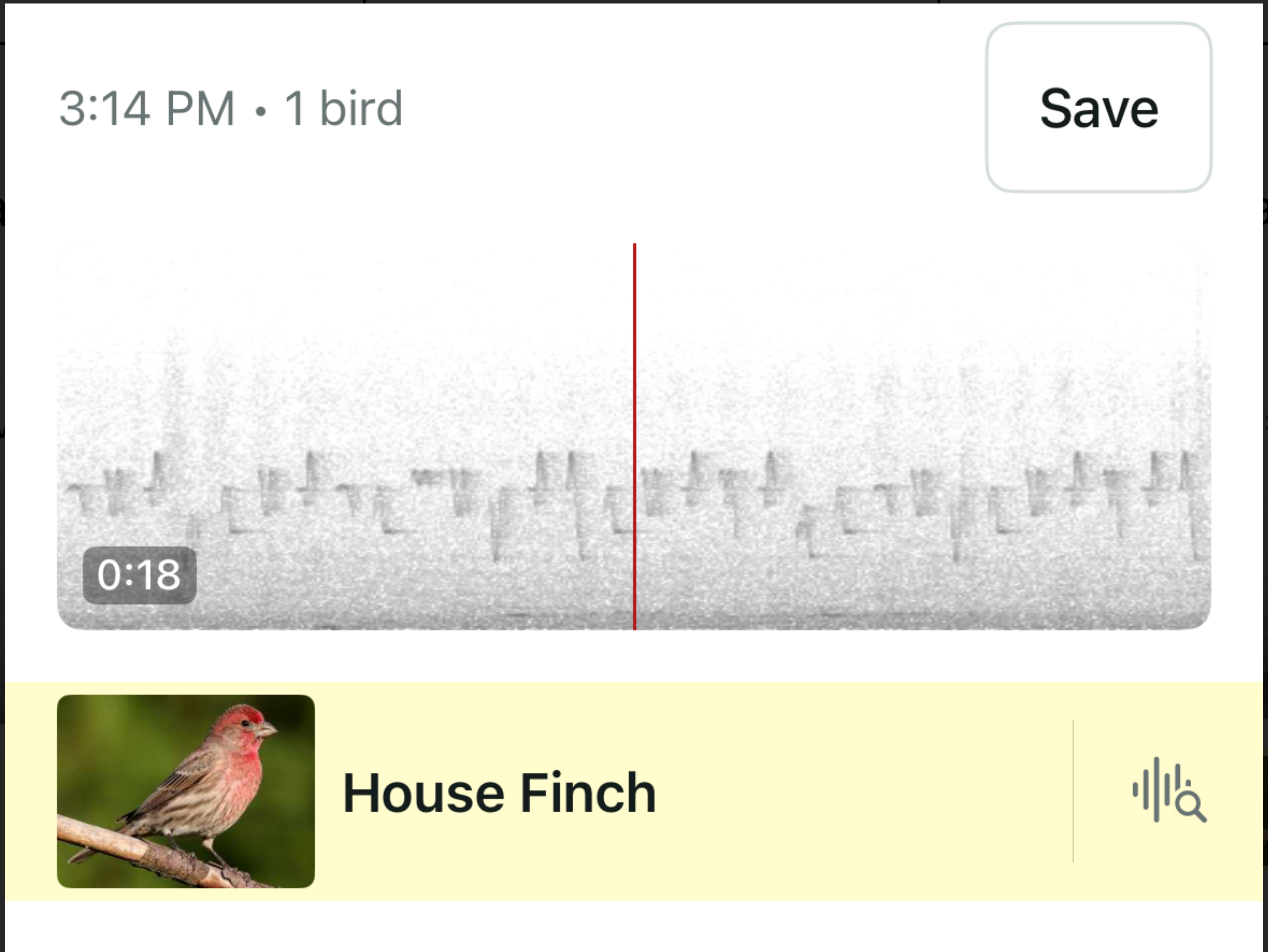
“Birds aren’t real”

Natural computation | **Natural memory** | Natural data transfer

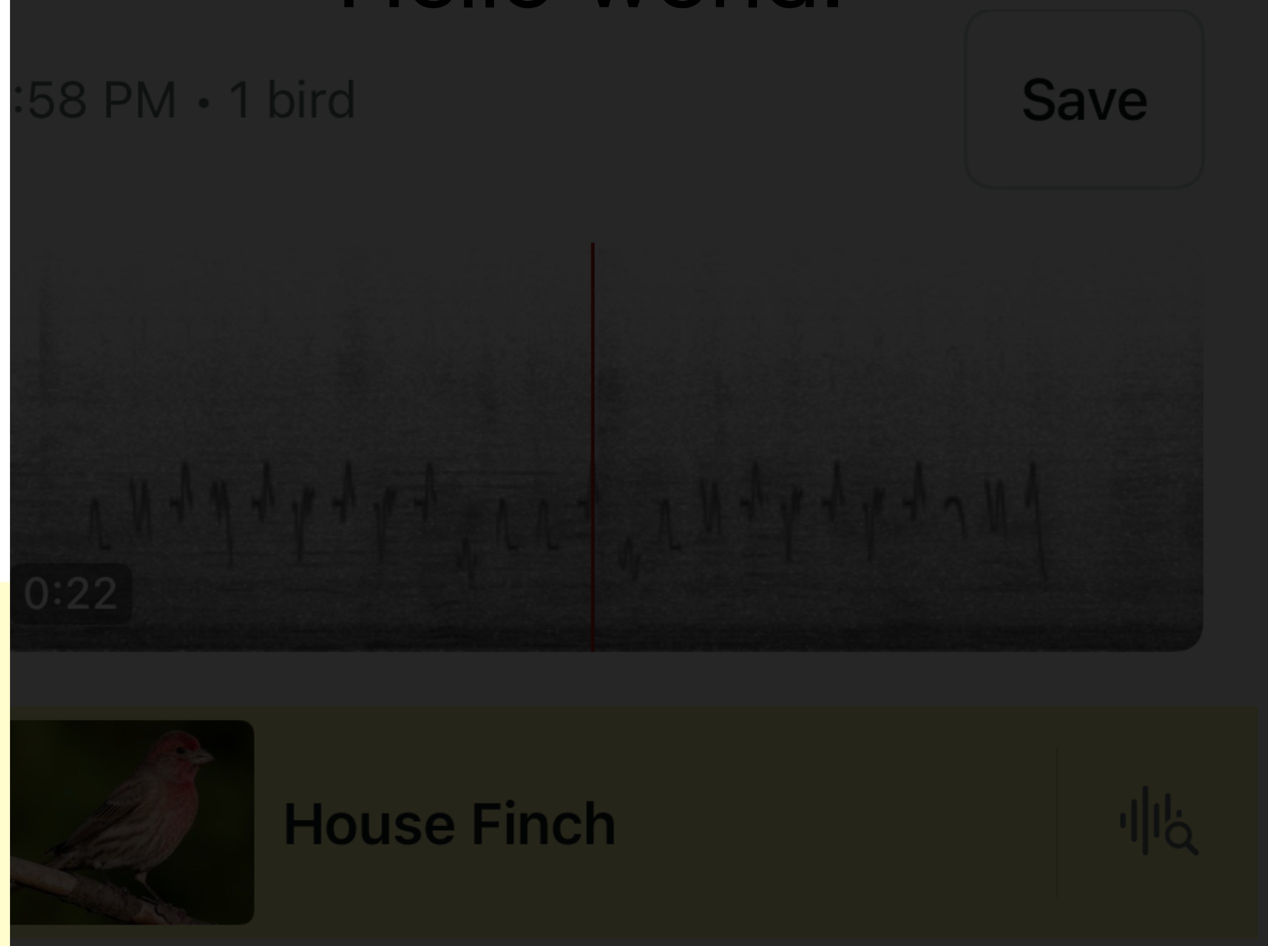
There are lots of ways tha … a simple proof of concept.

Real bird





“Hello world!”



The fake bird sounds real enough to trick *Merlin*. Would it trick you?

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Nature and computing

Natural computation | **Natural memory** | Natural data transfer

Cricket steganography

We can apply similar techniques to crickets.

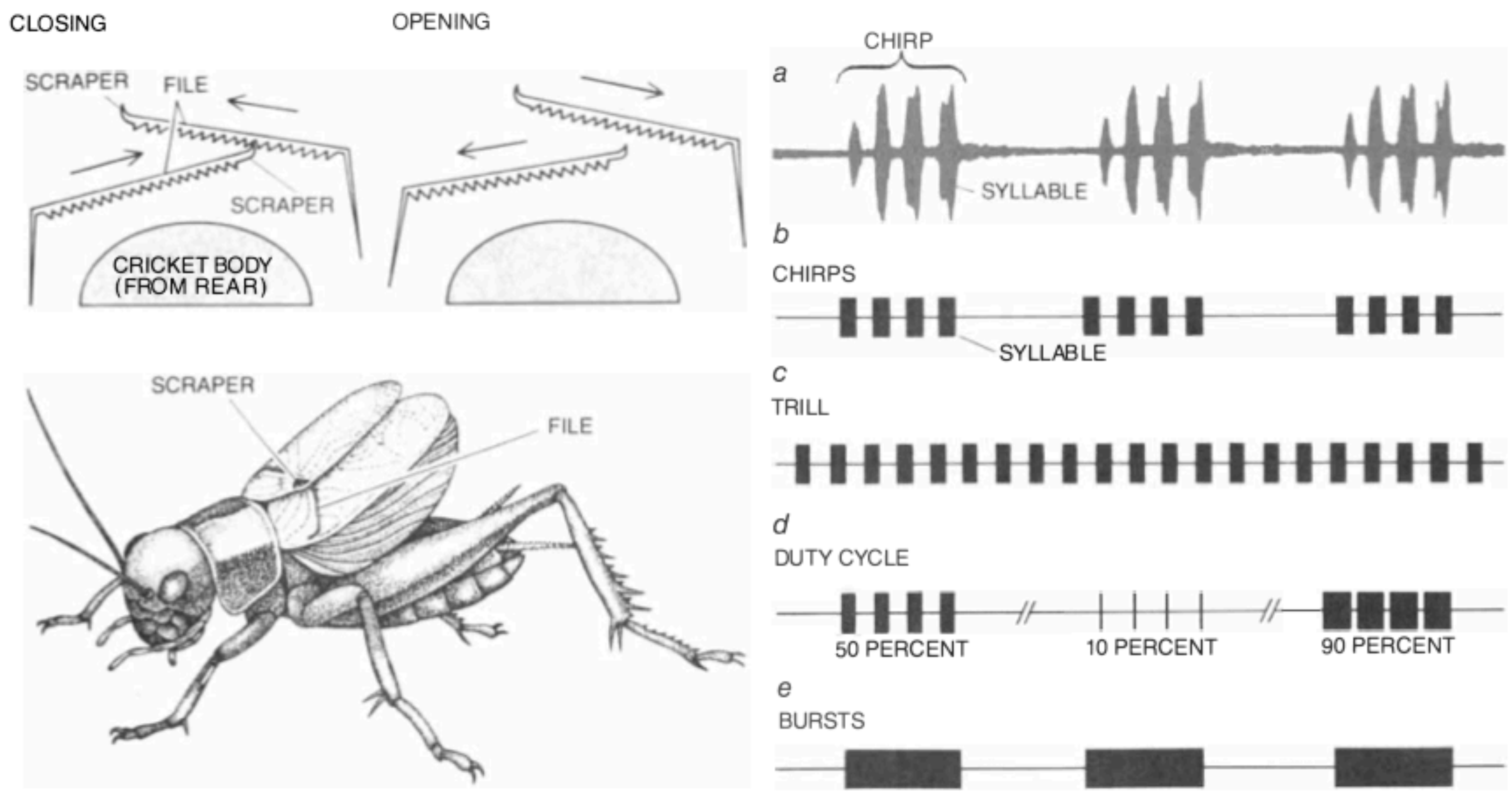


Figure from Huber, Franz, and John Thorson. "Cricket auditory communication." Scientific American 253.6 (1985): 60-73.

A cricket song is composed of chirps, and each chirp is composed of syllables.

As a proof of concept, compose a song of 8-syllable chirps, and adjust syllable-length for 1's and 0's

Here's "Hello world!" in cricket.

(And **here's more** on how this is done)

Nature and computing

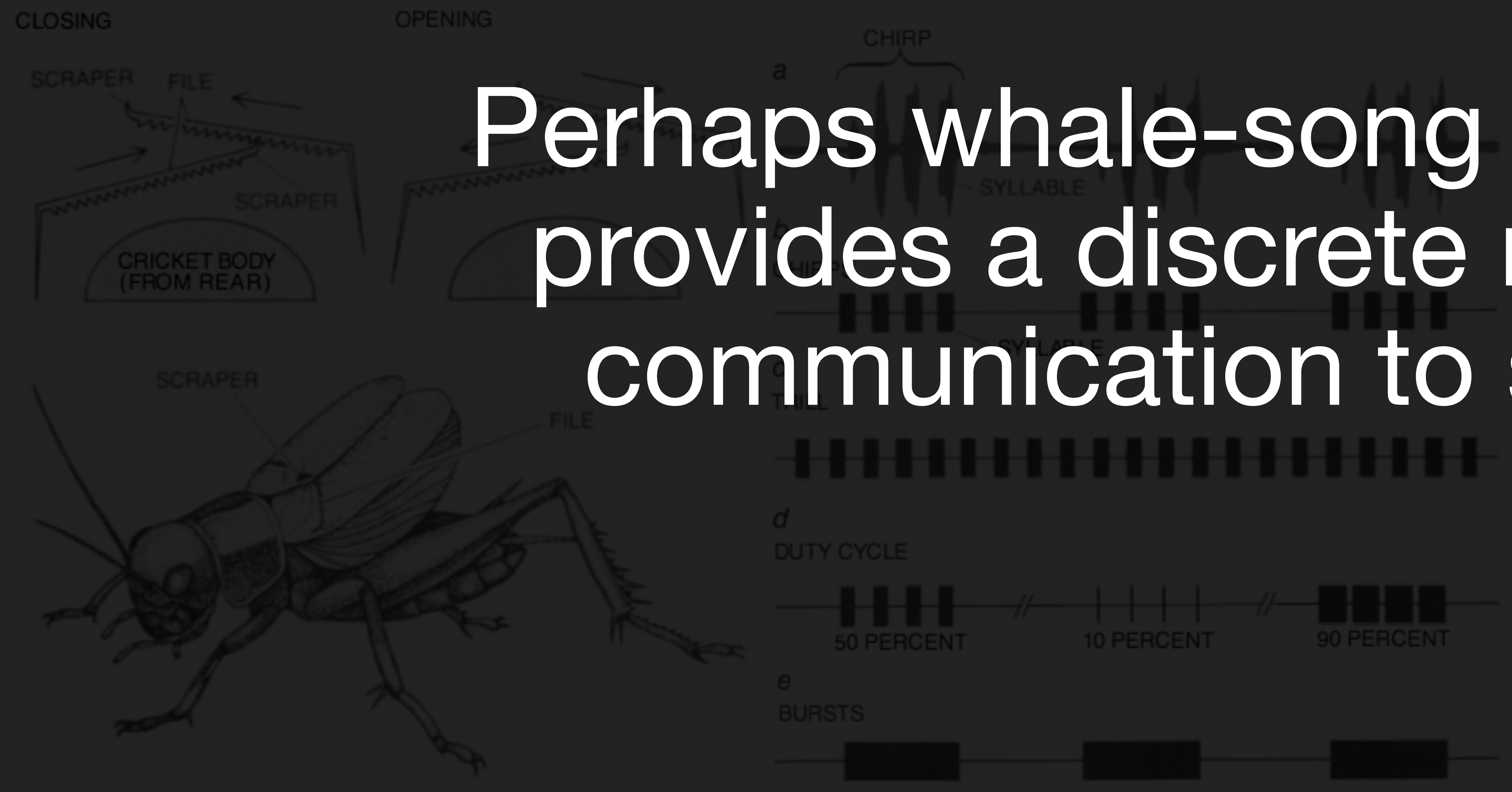
Natural computation | **Natural memory** | Natural data transfer

Cricket steganography

We can apply similar techniques to crickets.

We can keep playing these games.

Perhaps whale-song steganography provides a discrete mechanism of communication to submarines?



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Here's "Hello world!" in cricket.

(Audio player at bottom of page)

Nature and computing

Natural computation | **Natural memory** | Natural data transfer

Cricket steganography

We can apply similar techniques to crickets.

Did you notice . . .

“Hello world!” takes more symbols in cricket than it does in finch, because finches have larger alphabets than crickets.

Figure from Huber, Franz, and John Thorson. "Cricket auditory communication." Scientific American 253.6 (1985): 60-73.

…of chirps, and each chirp is composed of syllables.

As a proof of concept, compose a song of 8-… length for 1’s and 0’s

[Here’s “Hello world!” in cricket.]

(Audio player at bottom of page)

Nature and computing

Natural computation | **Natural memory** | Natural data transfer

Natural alphabets

An *alphabet* is the set of basic elements in a system which combine to form complex entities.

The bigger your alphabet, the more information is carried by each letter.

- **Binary**: Each symbol carries $log_2(2) = 1$ bits of information.
- **Hexadecimal**: Each symbol carries $log_2(16) = 4$ bits of information
- **English language**: Each symbol carries $log_2(26) \approx 4.7$ bits of information (actually less due to redundancies and non-uniform usage of the letters, but that's not relevant for this conversation).
- **Traditional Chinese**: Each symbol carries $log_2(50{,}000) \approx 15.6$ bits.

Nature and computing

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- **Binary**: Each symbol carries $log_2(2) = 1$ bits of information. → **Our cricket (with demo'd encoding)**
- **Hexadecimal**: Each symbol carries $log_2(16) = 4$ bits of information → **Our finch**
- **English language**: Each symbol carries $log_2(26) \approx 4.7$ bits of information (actually less due to redundancies and non-uniform usage of the letters, but that's not relevant for this conversation).
- **Traditional Chinese**: Each symbol carries $log_2(50{,}000) \approx 15.6$ bits.

Larger alphabets offer more bits per symbol, at the cost of symbol complexity.

𰻞

15.6 bits

A

4.7 bits

If you want to send a message with lots of information, you need *either*:

A long letter written in an alphabet that does not contain many symbols

or

A short letter written in an alphabet that contains *lots* of symbols.

Nature offer alphabets of both varieties.

Nature and computing

Natural computation | **Natural memory** | Natural data transfer

Natural alphabets

DNA provides a mechanism for *long* letters composed in an alphabet of *few symbols*.

Length of the alphabet: 4 symbols (A, T, C, and G nucleotide bases)

How to write a message: CRISPR or similar technology

How to read a message: Sequencing is now possible with **handheld devices**.

- Goldman, N., Bertone, P., Chen, S., Dessimoz, C., LeProust, E. M., Sipos, B., ... & Birney, E. (2013). Towards practical, high-capacity, low-maintenance information storage in synthesized DNA. Nature, 494(7435), 77-80.
- Church, George M., Yuan Gao, and Sriram Kosuri. "Next-generation digital information storage in DNA." Science 337.6102 (2012): 1628-1628.
- Shipman, Seth L., et al. "**CRISPR–Cas encoding of a digital movie into the genomes of a population of living bacteria.**" Nature 547.7663 (2017): 345-349.
- Erlich, Yaniv, and Dina Zielinski. "DNA Fountain enables a robust and efficient storage architecture." science 355.6328 (2017): 950-954.

Nature and computing

Natural computation | **Natural memory** | Natural data transfer

But what about **big** alphabets?

A useful alphabet has letters with the following properties:

1. Every symbol must be unique
2. Every symbol must be constructible by the sender
3. Every symbol must be distinguishable by the receiver
4. Those symbols must be *enumerable*, or able to be placed in an agreed-upon order

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Nature and computing

Natural computation | **Natural memory** | Natural data transfer

Natural alphabets

Organic chemistry provides a mechanism for *short* letters composed in an alphabet of *many symbols*.

Length of the alphabet: The GDB-17 database enumerates **166 billion** small organic compounds that contain <=17 atoms of C, N, O, S, and halogens. This is a small fraction of the total accessible space, but it is an *enumerated* fraction.

- Not all of these can be synthesized, and not all of them are highly stable!
- If we assume 40% of these compounds can be synthesized and are highly stable, that provides an alphabet of 66.4 billion letters.
- With an alphabet that long, each letter carries $log_2(66{,}400{,}000{,}000) \approx 36$ bits of information

Nature and computing

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How much information is this?

Nature and computing

Natural computation | **Natural memory** | Natural data transfer

Natural alphabets

Organic chemistry provides a mechanism for *short* letters composed in an alphabet of *many symbols*.

Let's think about a message written in an alphabet that contains 66.4 billion letters . . .

If that message only contained a *single symbol* (one organic compound), it would carry sufficient information to communicate any one of the following:

1. Any date (DDMMYY)
2. 5 standard ASCII characters (a name?)
3. A latitude/longitude with enough resolution to specify any location on the surface of the Earth to within ~150 meters (allowing 17 bits to 180 degrees of latitude and 18 bits to 360 degrees of longitude)

Nature and computing

Natural computation | **Natural memory** | Natural data transfer

Natural alphabets

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Let's think about a message written in an alphabet that contains 66.4 billion letters . . . Distinguishing this many compounds is hard, but plausible (?)

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Nature and computing

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Natural alphabets

Organic chemistry provides a mechanism for *short* letters composed in an alphabet of *many symbols*.

How do we distinguish 66.4B compounds?

Not easily. But!

1. There's a long history of applying AI to the problem of organic molecule identification. Indeed, *Dendral*, the first expert system in AI from the 1960's, was designed for this purpose

2. And since then, folks have continued to apply ML to the problem of compound identification. Specifically, trying to recover the chemical structure for a molecule based on its mass spectrum.

3. This is all to say that this is an area of active research, but it's being researched by a rather niche group of folks, most of whom are chemists/chembiologists. With help from folks that are absolute specialists in building AI/LLM systems, I wonder if step-change progress might be possible?

https://pmc.ncbi.nlm.nih.gov/articles/PMC6954430/

Nature and computing

Natural computation | **Natural memory** | Natural data transfer

This notion is reminiscent of the Kodak company's 1945 detection of the Trinity Test in New Mexico by way of Cesium 141 contamination in their strawboard packaging for X-Ray film.

The beta-emitter was lofted by the test to their facilities in Iowa and Indiana where they contaminated packaging. The beta emission generated dark spots on their X-Ray film. Kodak was able to deduce that the test had taken place by way of this inadvertent chemical message.

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Nature and computing

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Natural alphabets

Organic chemistry provides a mechanism for *short* letters composed in an alphabet of *many symbols*.

Having written a message, *how do we send it*?

How do we distinguish 66.4B compounds?

Not easily. But!

Nature offers solutions for this too.

1. There's a long history of applying AI to the problem of organic molecule identification. Indeed, *Dendral*, the first expert system in AI from the 1960's, was designed for this purpose

2. And since then, folks have continued to apply ML to the problem of compound identification. Specifically, trying to recover the chemical structure for a molecule based on its mass spectrum.

3. This is all to say that this is an area of active research, but it's being researched by a rather niche group of folks, most of whom are chemists/chembiologists. With help from folks that are absolute specialists in building AI/LLM systems, I wonder if step-change progress might be possible?

https://pmc.ncbi.nlm.nih.gov/articles/PMC6954430/

Nature and computing

Natural computation | **Natural memory** | Natural data transfer

Natural alphabets

Organic chemistry provides a mechanism for *short* letters composed in an alphabet of *many symbols*.

Nature **moves** and **consolidates** matter.

Wherever matter is moving, information is moving too. We can send messages by making use of **natural Schelling points**.

How do we distinguish [illegible] compounds?

Not eas[illegible]

1. There's a long history of applying AI to the problem of organic molecule identification. Indeed, *Dendral*, the first expert system in AI from the 1960's, was designed for this purpose

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Nature and computing

Natural computation | Natural memory | **Natural data transfer**

What is a Schelling point?

A concept best introduced via example . . .

Suppose you and another person must find one another in New York City tomorrow, but you and that person may not communicate or coordinate.

Where would you go? And when?

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Some common answers to this question include:

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Solutions that people tend to choose by default in the absence of communication to avoid coordination failure.

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Solutions that people tend to choose by default in the absence of communication to avoid coordination failure.

Nature offers these in droves. We can send our data by way of one of nature's matter migrations and find it at a Schelling point.

Nature and computing

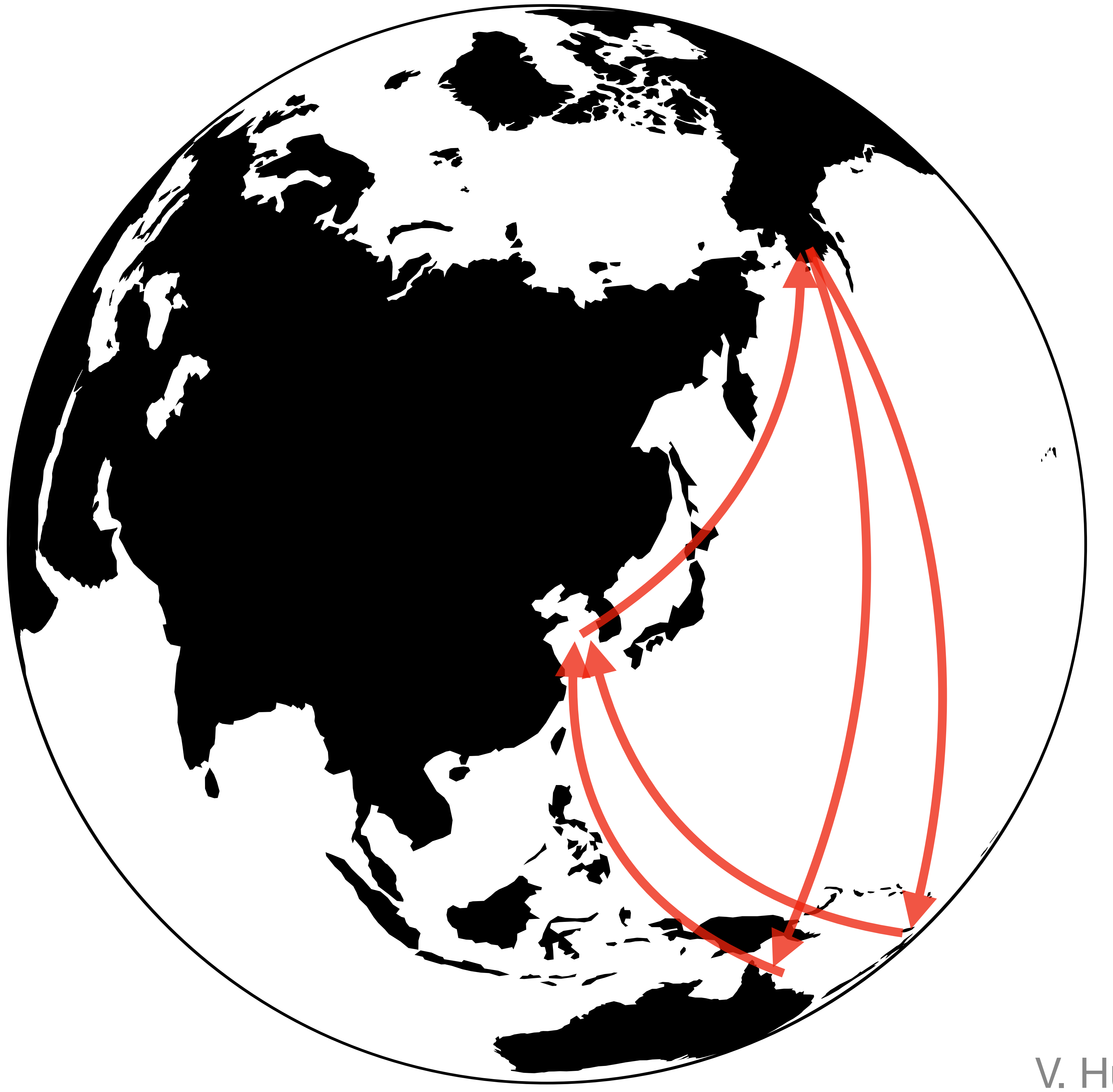
Natural Schelling points

Suppose you must find a particular **bar-tailed godwit** that you encountered in Alaska. Where would you go?

The Yellow Sea

Nearly every bar-tailed godwit in Australia and New Zealand stops in the Yellow Sea on its northward migration to breeding grounds in Alaska.

If you give a godwit a message in Alaska, New Zealand, or Australia, you have a high probability of receiving that message in the Yellow Sea.



Nature and computing

Natural computation | Natural memory | **Natural data transfer**

Natural Schelling points

Suppose you must find a particular **bar-tailed godwit** that you encountered in Alaska. Where would you go?

We can find more Schelling points at migratory choke points.

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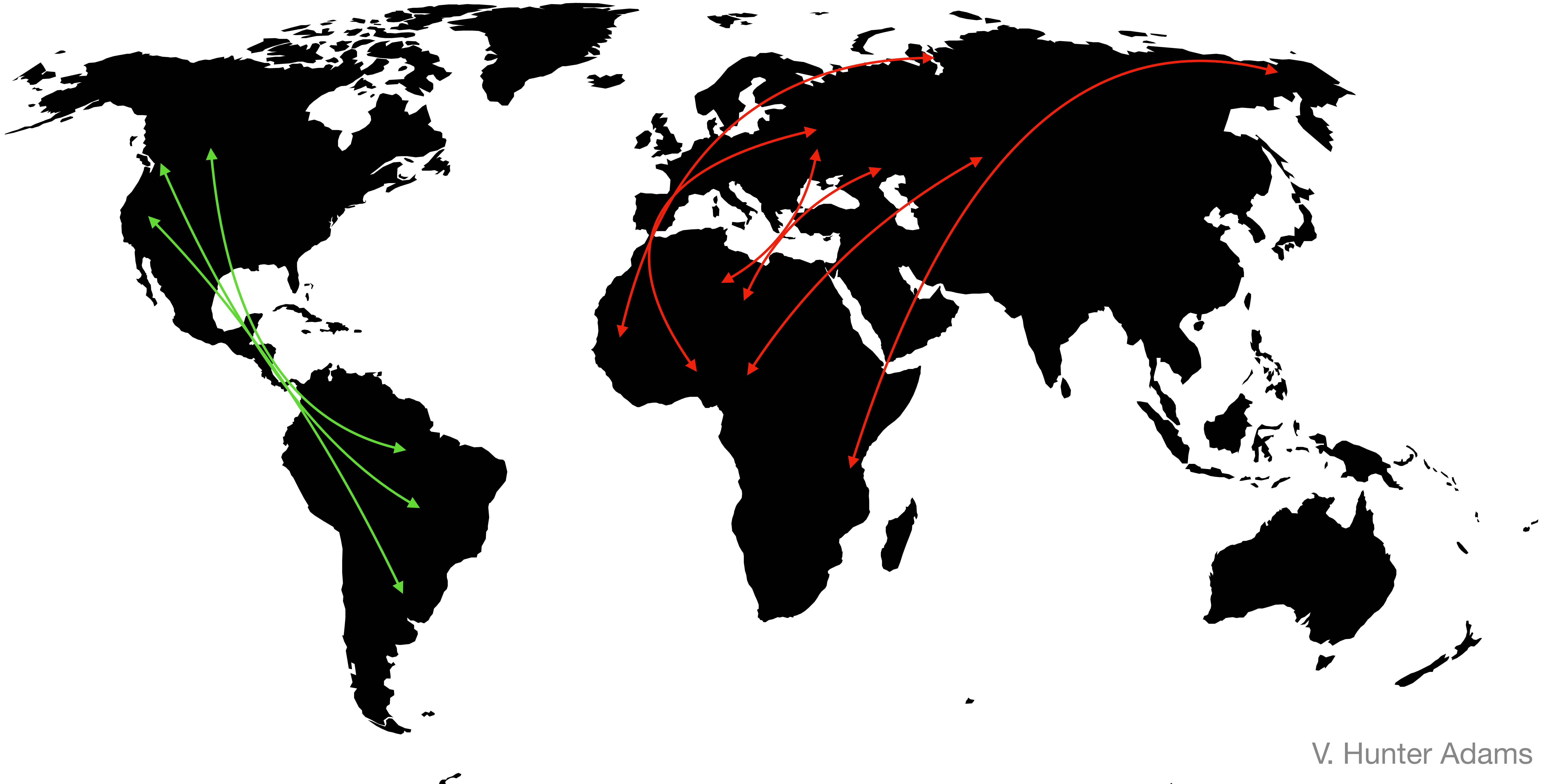
Nature and computing

Natural computation | Natural memory | **Natural data transfer**

Natural Schelling points

Choke-points on the great migratory flyways

Migratory soaring birds (e.g. honey buzzards, black kits, booted eagles, white storks) avoid long overwater flights due to lack of thermals. This creates migratory bottlenecks at straights and isthmuses.



Nature and computing

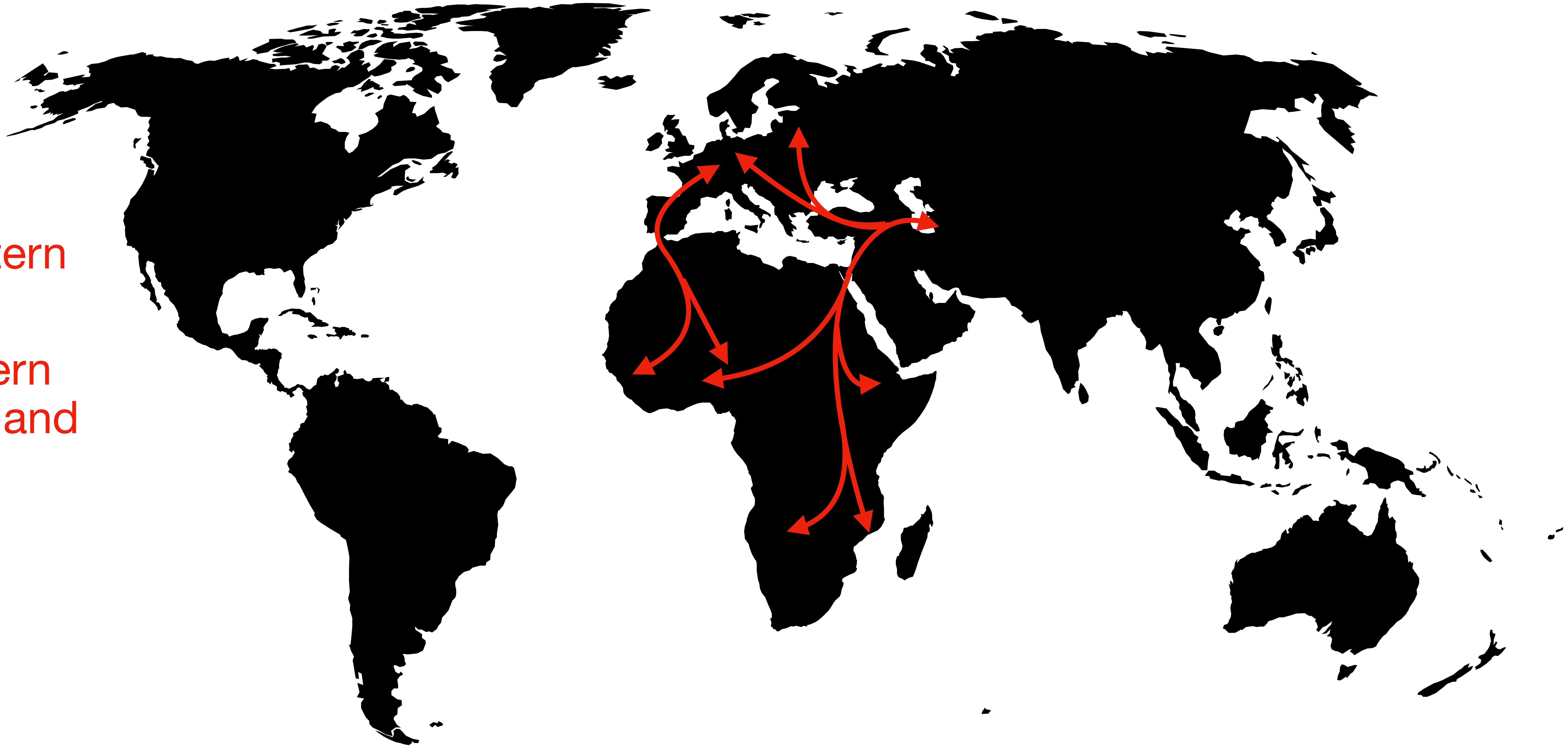
Natural computation | Natural memory | **Natural data transfer**

Natural Schelling points

Choke-points on the great migratory flyways

Give a **white stork** a message in Western Europe, you'll find it at Gibraltar.

Give a white stork a message in Eastern Europe, the Middle East, or the Levant and you'll find it at the Bosphorus.



Nature and computing

Natural computation | Natural memory | **Natural data transfer**

Natural Schelling points

Choke-points on the great migratory flyways

This is a single example. We can find **many more.**

Lots of animals exhibit strong site fidelity and **philopatry** (the tendency to habitually return to a particular area).

Salmon, monarch butterflies, sea turtles, bogong moths, Atlantic puffins, humpback whales, whooping cranes, bats, arctic terns, mule deer, pronghorn, shorebirds of many varieties, etc.

If you give any such animal a message, you can retrieve that message when it returns to its highly-predictable **home**, at a **choke-point** on its journey, or at an established **stopping-point** on that journey.

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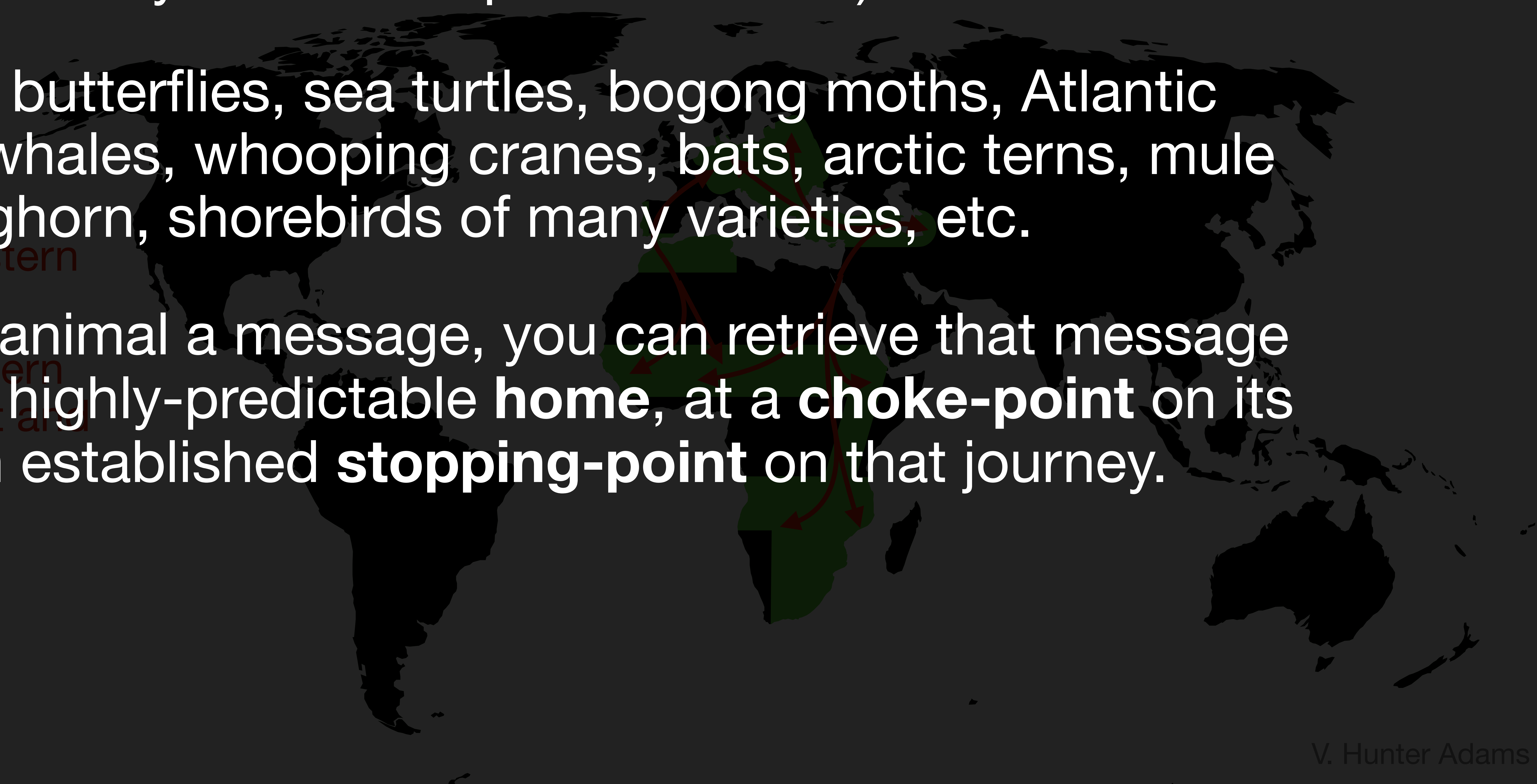
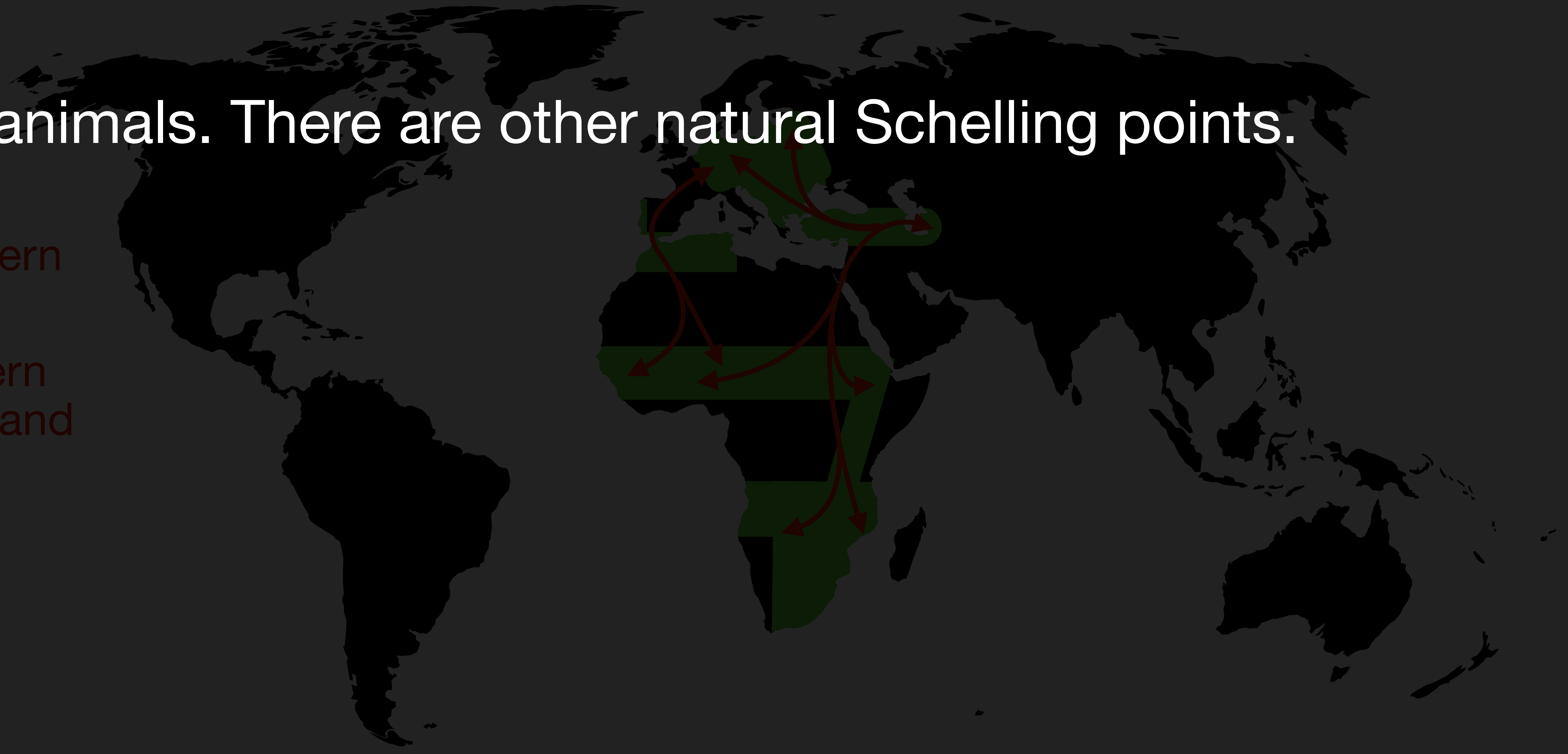


Nature and computing

Natural Schelling points

Choke-points on the great migratory flyways



This is not limited to animals. There are other natural Schelling points.

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Nature and computing

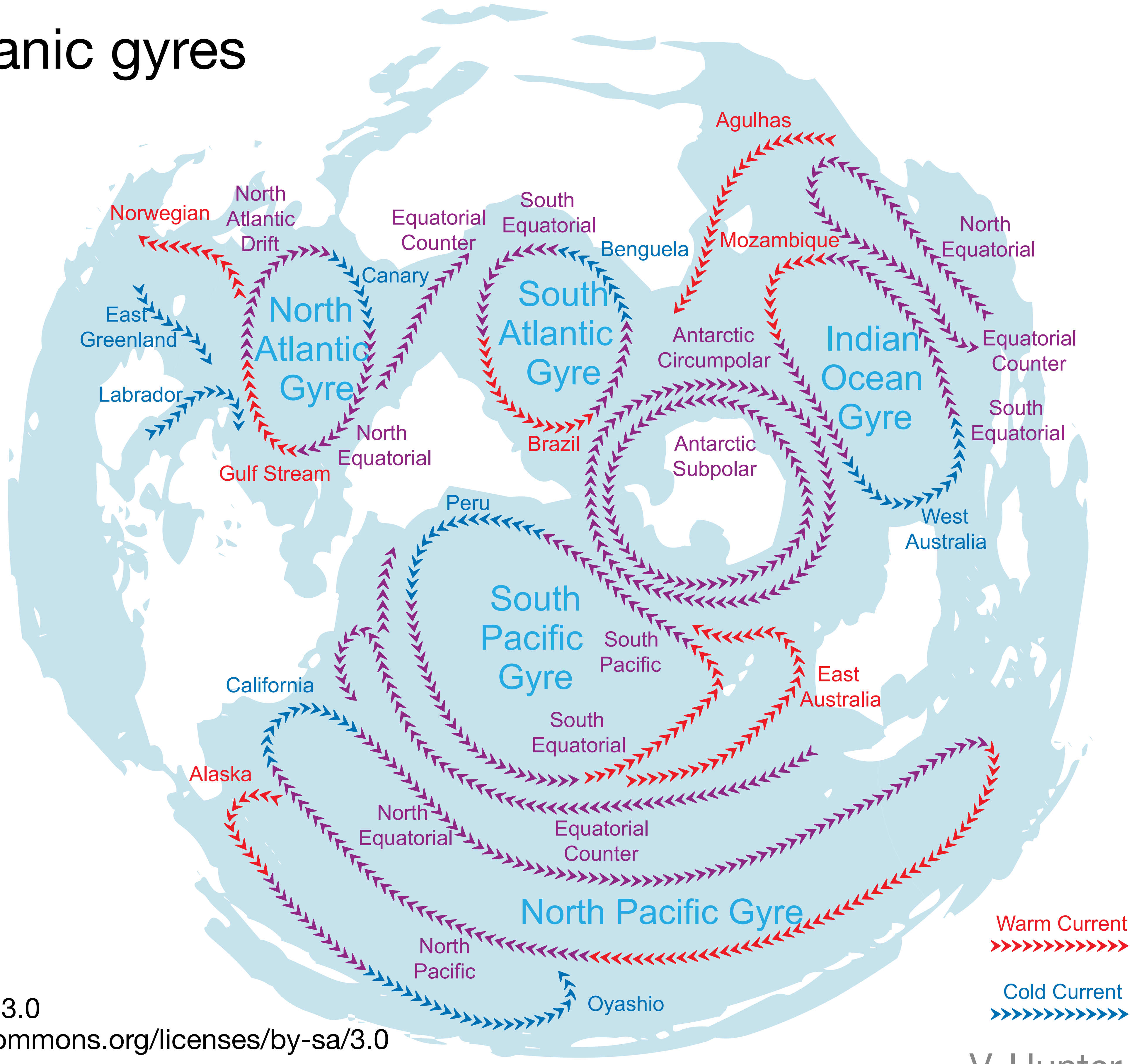
Natural computation | Natural memory | **Natural data transfer**

Natural Schelling points

Mass accumulation in oceanic gyres

Oceanic gyres are wind-driven systems of ocean currents moving in a circular fashion. These gyres tend to consolidate floating material in their centers (e.g. the Great Pacific Garbage Patch).

Messages thrown overboard in the North Pacific Gyre are likely to be found somewhere in the garbage patch.



Nature and computing

Natural computation | Natural memory | **Natural data transfer**

Natural Schelling points

River deltas and watersheds

Messages deployed in river tributaries are likely to be found at their deltas.

Messages deployed in watersheds are likely to be found in the body of water into which that region drains.

 Forms and Patterns in Nature - Wolf Strache

Nature and computing

Natural computation | Natural memory | **Natural data transfer**

Some general observations . . .

1. Nature is **really good** at moving huge amounts of matter over huge distances. Rivers, ocean currents, the jet stream, the water/carbon cycles, planets and moons, etc.
2. These are tremendously **energetic** processes, and humanity has a long history of extracting small amounts of energy from some of these processes for use on other work. Water wheels, hydroelectric generators, wind farms, etc.
3. Humanity has **underutilized** these processes for data transfer. By moving huge amounts of matter, **nature is also moving huge amounts of data.**

Nature and computing

Near-term opportunities

- We can add matter, in the form of conventional mass storage devices, to these systems such that they are “swept along” from origin to destination (likely a natural Schelling point)
- This makes the communication channel “bursty” in the sense that the information arrives all at once rather than bit-by-bit. But it enables very large **average data transfer rates**.
- As a silly example, the data rate of a single pigeon carrying 1TB SD cards from NYC to Boston is ~3GB/s. Other systems (ocean currents, trade winds, etc.) possess *way* more capacity for excess mass, and thus allow even larger average data transfer rates.

Long-term possibilities

- We encode the data *in the matter itself*. How do we read/write this matter efficiently? I’m not sure yet.

Nature and computing

Natural computation | Natural memory | **Natural data transfer**

Once at the Schelling point, how do you find the message?

This is a superb application for **optimal search**. This is the same technique that the United States used in 1966 to locate an H-bomb that it had lost in the Mediterranean Sea (oops). It is also the same technique that the US Navy used to locate the *USS Scorpion* in 1968.

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Nature and computing

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Optimal search is best explained via example. Let's consider one.

Long-term possibilities

- We encode the data *in the matter itself*. How do we read/write this matter efficiently? I'm not sure yet.

Nature and computing

Natural computation | Natural memory | **Natural data transfer**

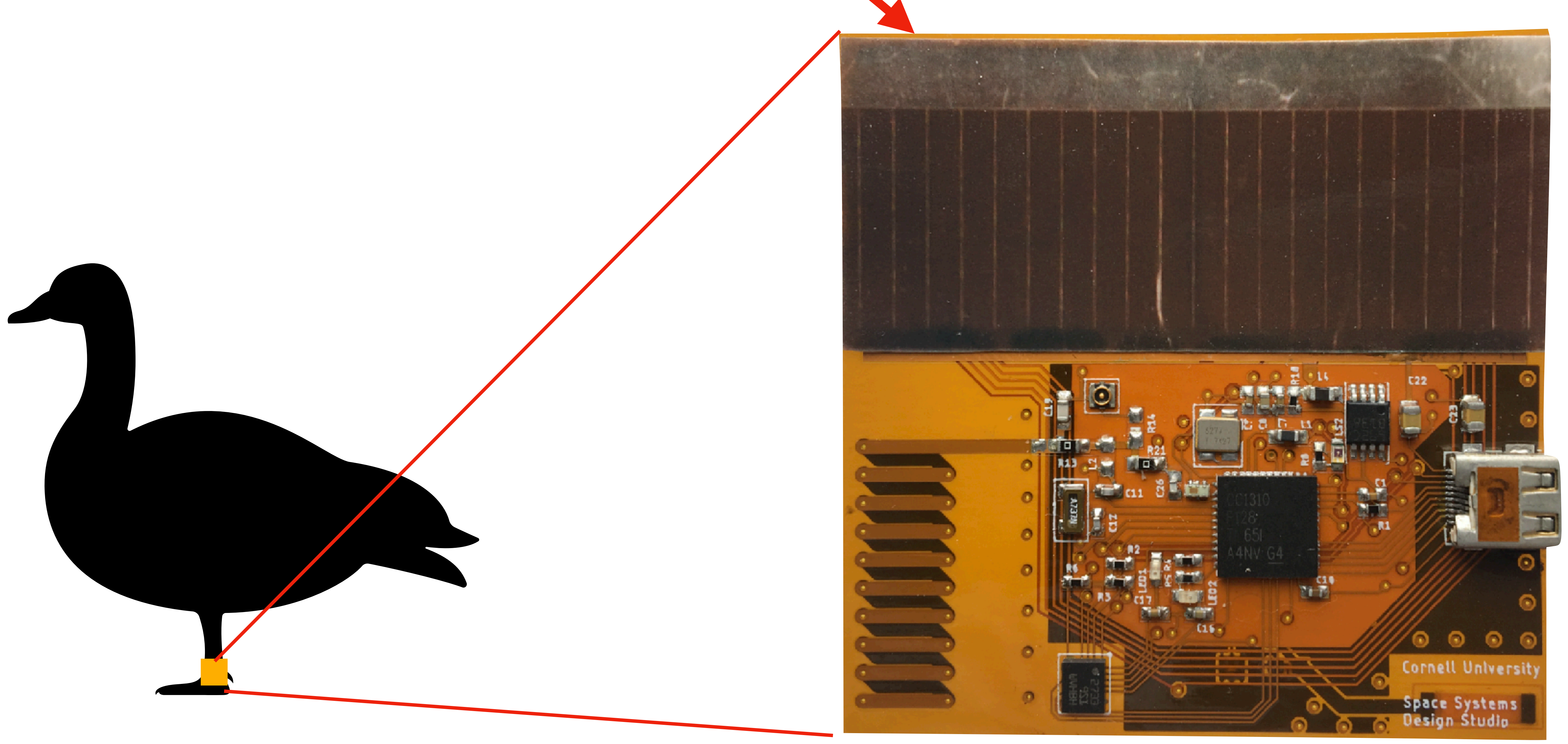
A toy example of natural data transfer to a Schelling point

Suppose that we have attached a message in the form of something like a *chipsat*, shown right, to a collection of **snow geese** in the DC area. We would like to recover this message as the geese pass through Ithaca on their way north.

Because this is a *super-secret spy mission*, the chipsat tags to not transmit. They carry a GPS and, when they detect that they are in the recovery zone, they let go of the goose.

We have to find them. But how?

More on these here.



Nature and computing

Natural computation | Natural memory | **Natural data transfer**

A toy example of natural data transfer to a Schelling point

In an alternative version of this story, perhaps the bird carries its message in its **biology**. We might adjust its dialect before its journey and detect the message in its vocalizations.

Storing an image in a birdsong.

S…

in…
messa… …aca
on their way north.

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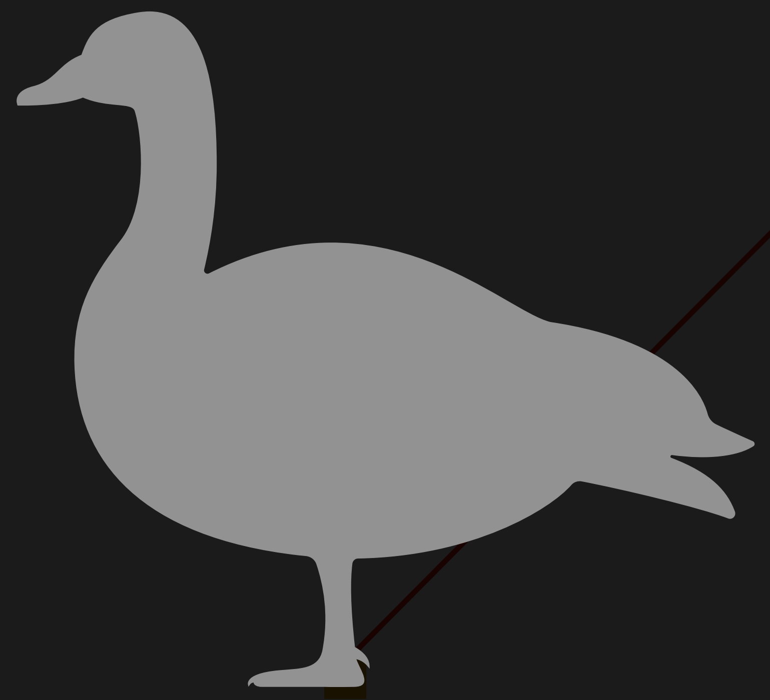
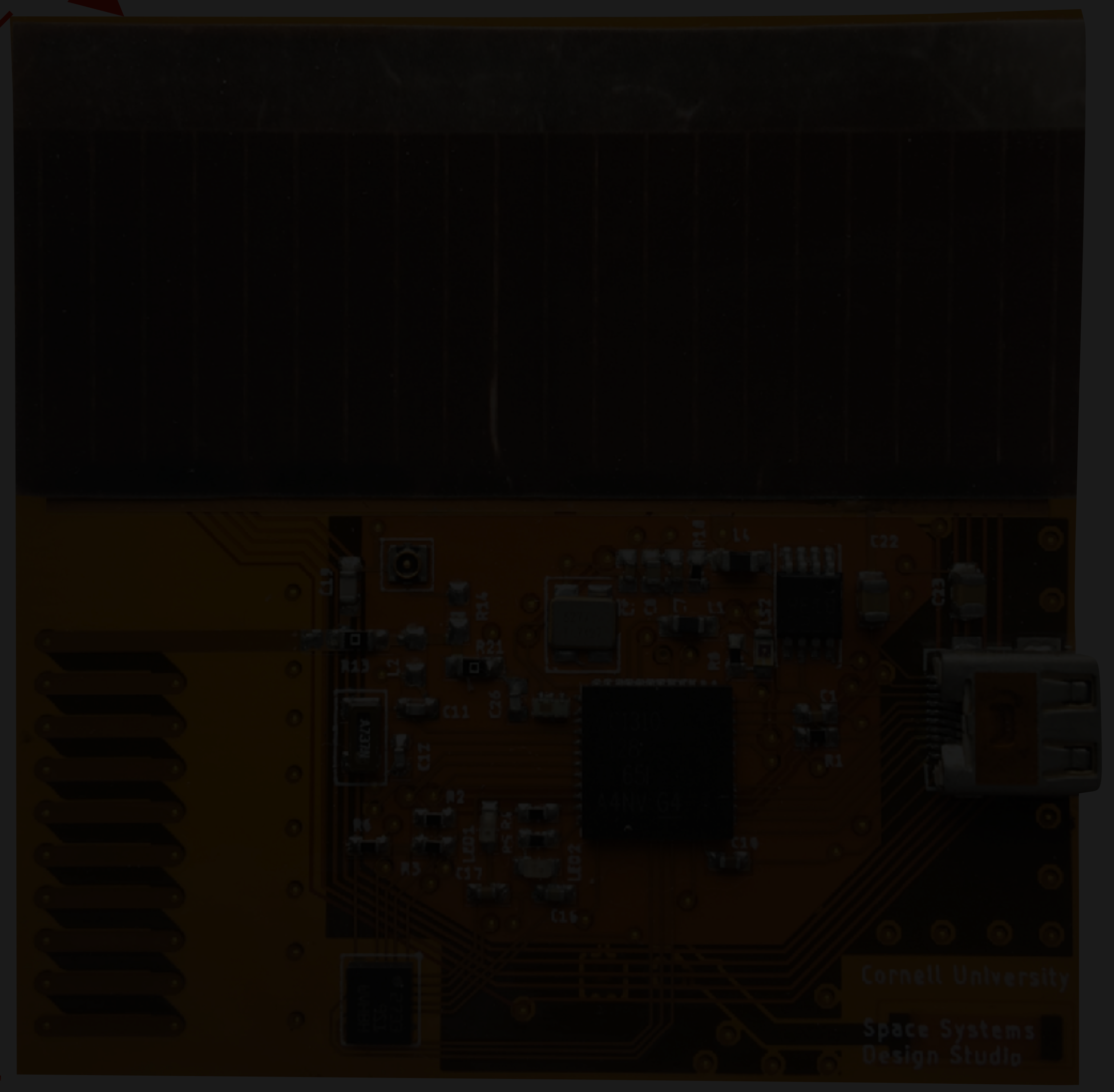
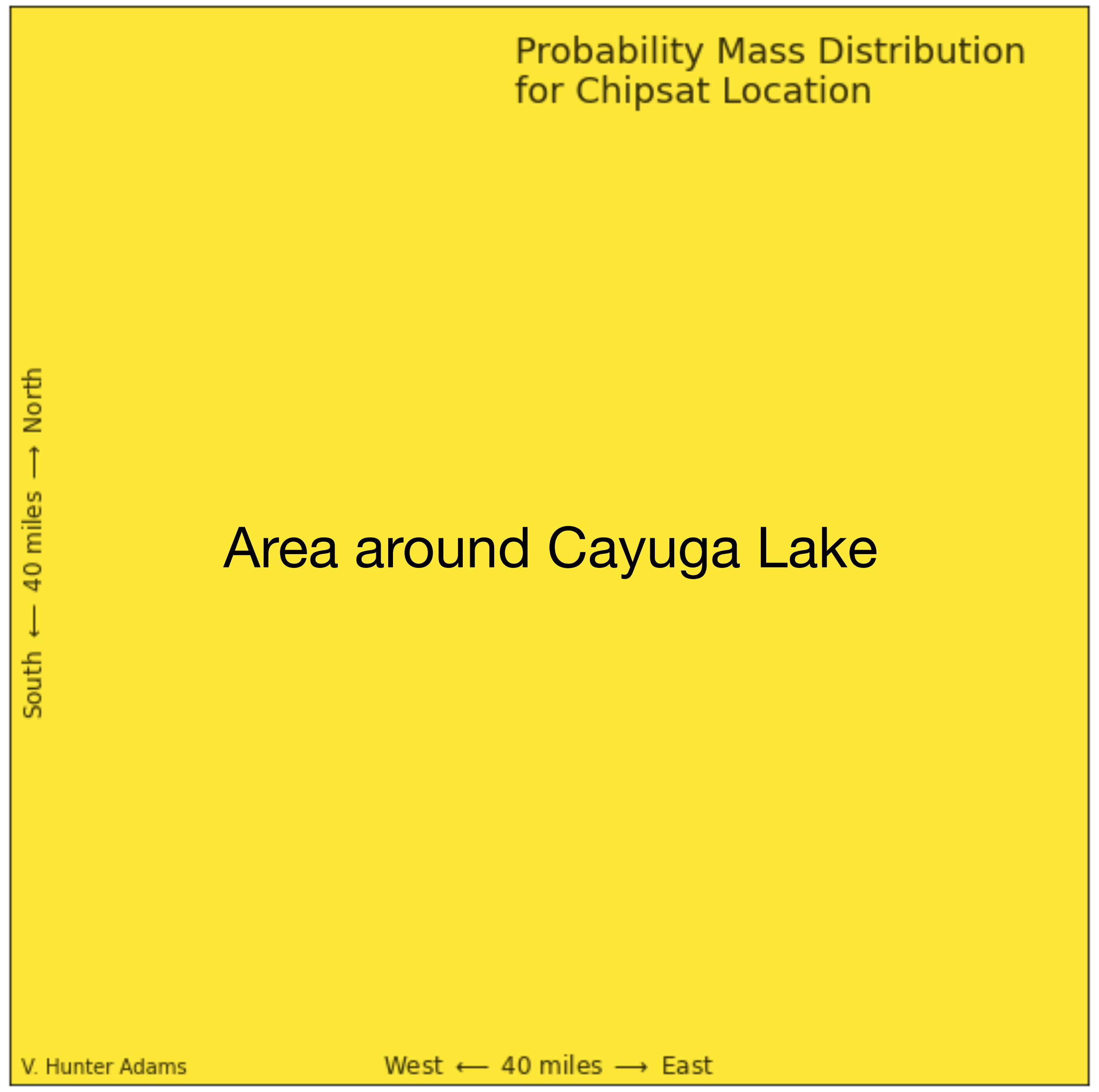




Nature and computing

Natural computation | Natural memory | **Natural data transfer**

Finding what we're looking for at a natural Schelling Point



With *only* this problem statement, we've no reason to prefer any location to another in our search.

Our initial probability mass distributions for the locations of the objects we seek are *uniform* within the recovery zone.

Start with ignorance → Generate priors → Estimate searchability → Prioritize search → Search! → Update priors → A north wind blows

Top

Nature and computing

Natural computation | Natural memory | **Natural data transfer**

Before we even start looking, we can apply some things that we know about our migratory messenger!

Start with ignorance → **Generate priors** → Estimate searchability → Prioritize search → (Search!) Update priors → A north wind blows

Nature and computing

Natural computation | Natural memory | **Natural data transfer**

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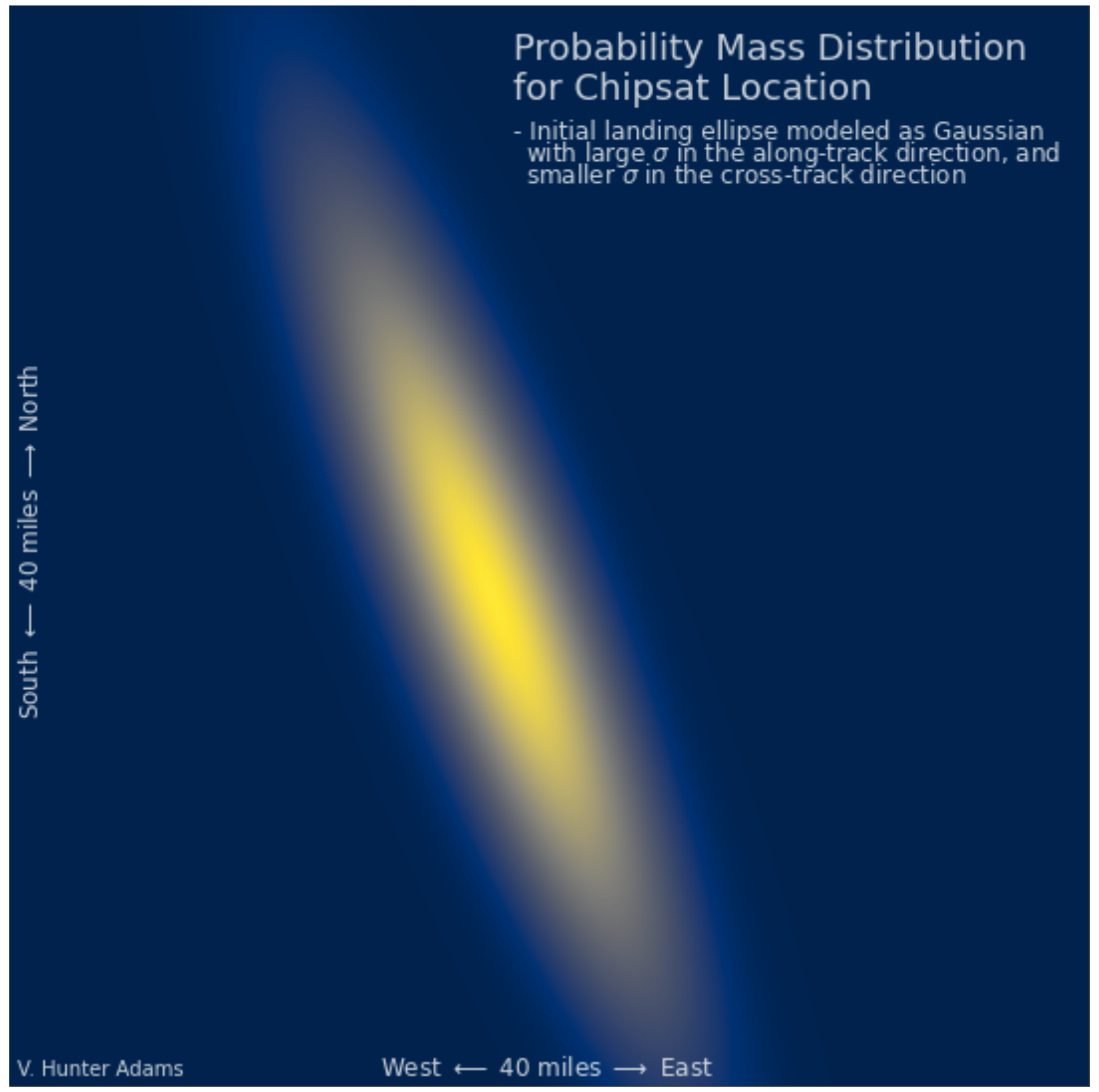

p(chipsat is in this cell)

(Total probability mass normalized to 1)

Let's suppose we know:

- The chipsat only releases itself from the bird when it is over Cayuga Lake.
- Birds tend to migrate North ↔ South

Start with ignorance → **Generate priors** → Estimate searchability → Prioritize search → (Search!) Update priors → A north wind blows

Nature and computing

Natural computation | Natural memory | **Natural data transfer**

But our search space is not uniformly searchable! The region contains deep gorges and treacherous terrain where it would be easy to miss a chipsat.

Start with ignorance → Generate priors → Estimate searchability → Prioritize search → (Search!) Update priors → A north wind blows

Nature and computing

Natural computation | Natural memory | **Natural data transfer**

Suppose that which we seek is in a particular cell, and suppose we look for it in that cell, what is the probability that we don't see it?

Start with ignorance → Generate priors → **Estimate searchability** → Prioritize search → (Search!) → Update priors → A north wind blows

Nature and computing

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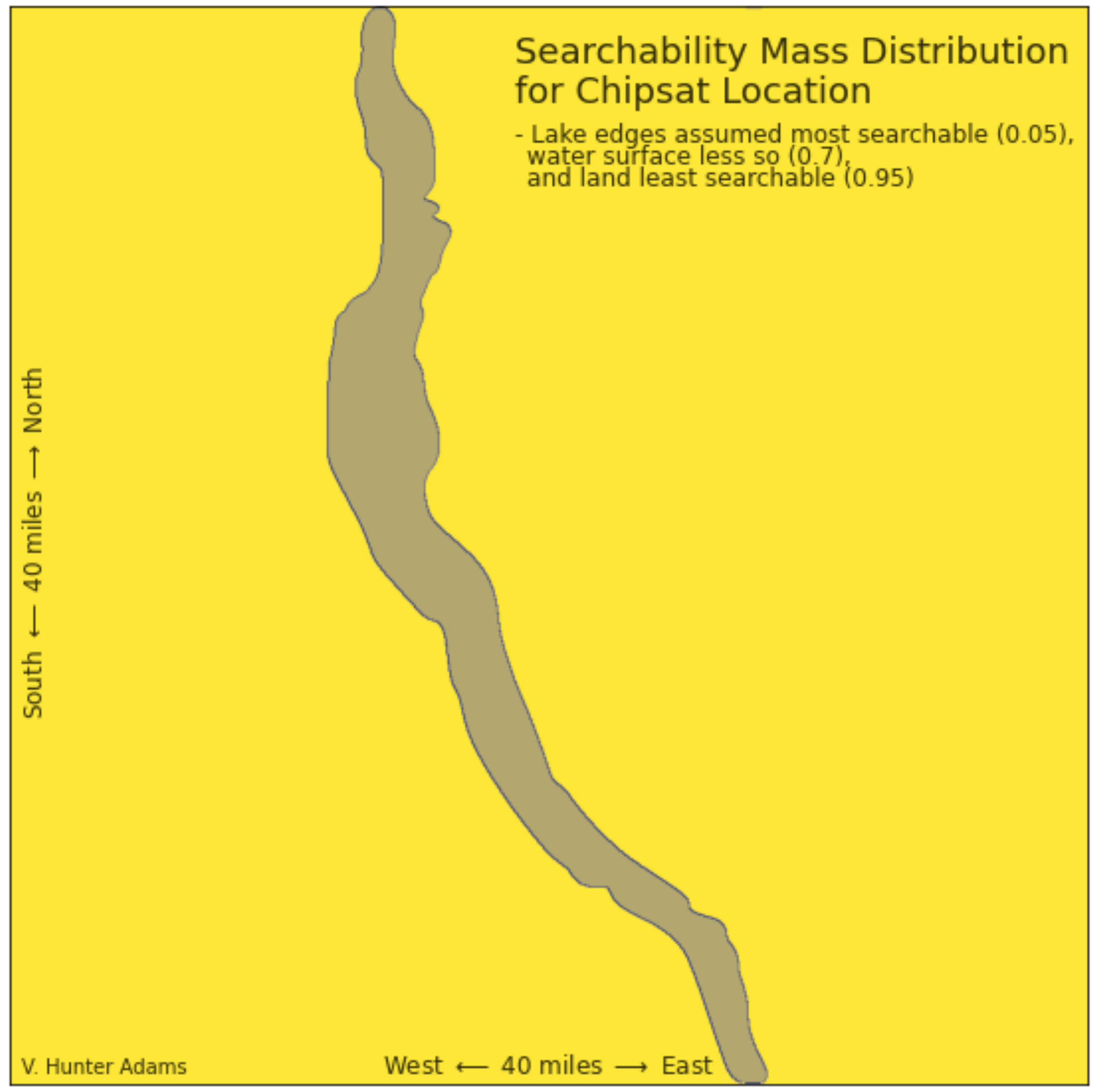


p(not finding chipsat in cell | chipsat is located in that cell)

For purposes of this discussion, let's suppose:

- The shores of the lake are very searchable (it's easy to find a chipsat on the beach)
- The water itself is moderately searchable
- Land has poor searchability (challenging terrain, hard to access, etc.).

Start with ignorance → Generate priors → **Estimate searchability** → Prioritize search → (Search!) → Update priors → A north wind blows

Nature and computing

Natural computation | Natural memory | **Natural data transfer**

We don't want to search in the places where what we're looking for is most likely to be located.

We want to search in the places that we're most likely to find what we're looking for.

Start with ignorance → Generate priors → Estimate searchability → **Prioritize search** → (Search!) Update priors → A north wind blows

Nature and computing

Natural computation | Natural memory | **Natural data transfer**

For each cell, we can compute how likely we are to find what we're looking for in that cell.

These are the places where we should begin our search.

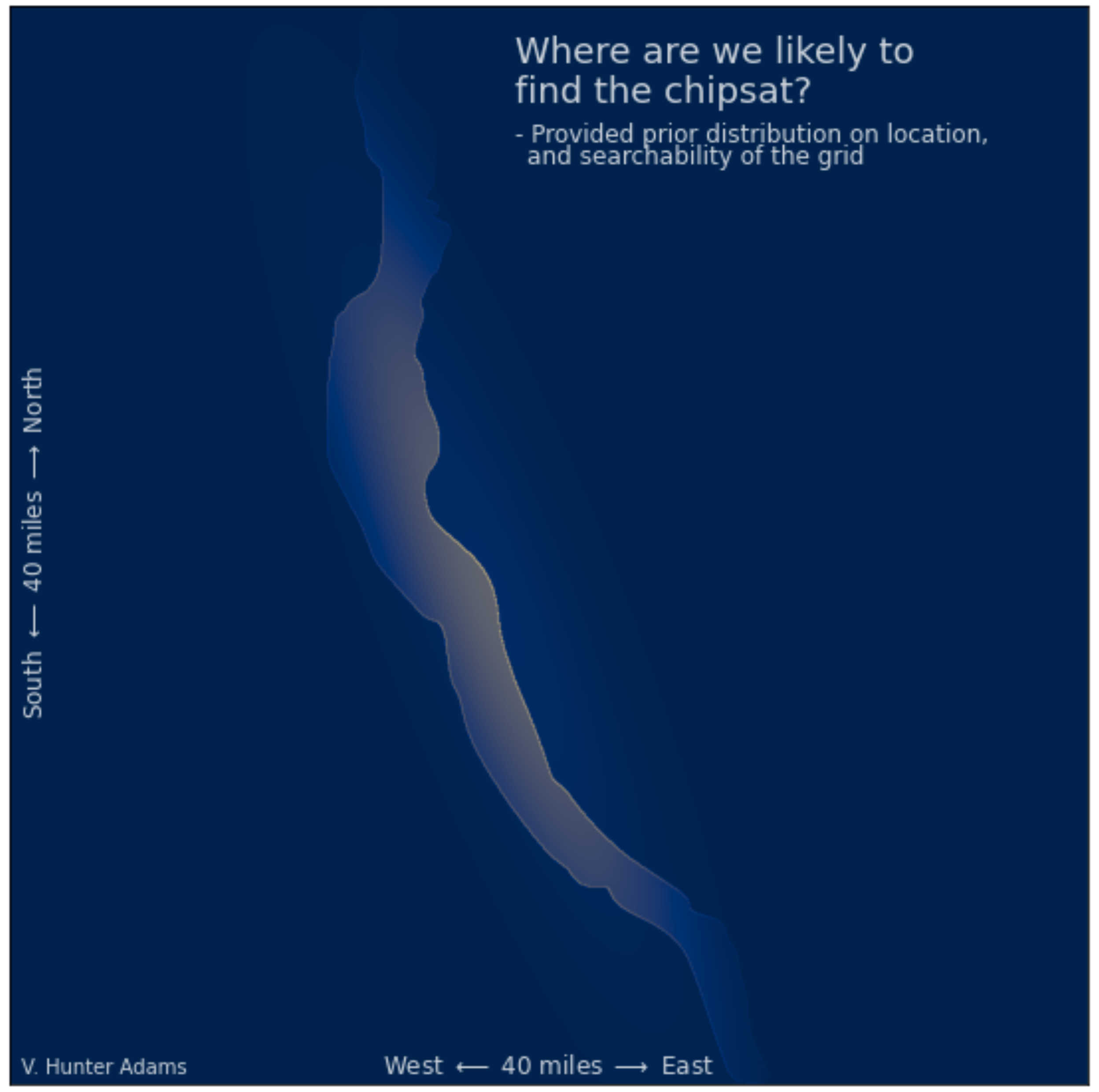
$$p(\text{we're looking in the right cell}) \cdot \left(1 - p(\text{not seeing what we're looking for | we're looking in the right cell})\right)$$

Start with ignorance → Generate priors → Estimate searchability → **Prioritize search** → (Search!) Update priors → A north wind blows

Nature and computing

Natural computation | Natural memory | **Natural data transfer**

Finding what we're looking for at a natural Schelling Point



Search the shores and water.

Start with ignorance → Generate priors → Estimate searchability → **Prioritize search** → (Search!) Update priors → A north wind blows

Nature and computing

Natural computation | Natural memory | **Natural data transfer**

Look for what you’re trying to find! Start in the cells you’ve identified as being most promising.

Nature and computing

Natural computation | Natural memory | **Natural data transfer**

Every time **you** ***don't*** **find what you're looking for in a single cell, you can update your entire map by way of the equation below (just Bayes' Rule).**

$$p(\text{What I'm seeking is in this cell} \,|\, \text{I did not find it in this cell}) = \frac{p(\text{it's in this cell}) \cdot p(\text{not seeing it in this cell} \,|\, \text{it's in this cell}))}{p(\text{not seeing what I'm looking for})}$$

Let's suppose we search the ***whole*** **map, and we don't find anything.**

Start with ignorance → Generate priors → Estimate searchability → Prioritize search → (Search!) → **Update priors** → A north wind blows → (back to Prioritize search)

Nature and computing

Natural computation | Natural memory | **Natural data transfer**

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Talked about this already

Talked about this already

$$p(\text{What I'm seeking is in this cell} \mid \text{I did not find it in this cell}) = \frac{p(\text{it's in this cell}) \cdot p(\text{not seeing it in this cell} \mid \text{it's in this cell}))}{p(\text{not seeing what I'm looking for})}$$

Just normalize over the search space

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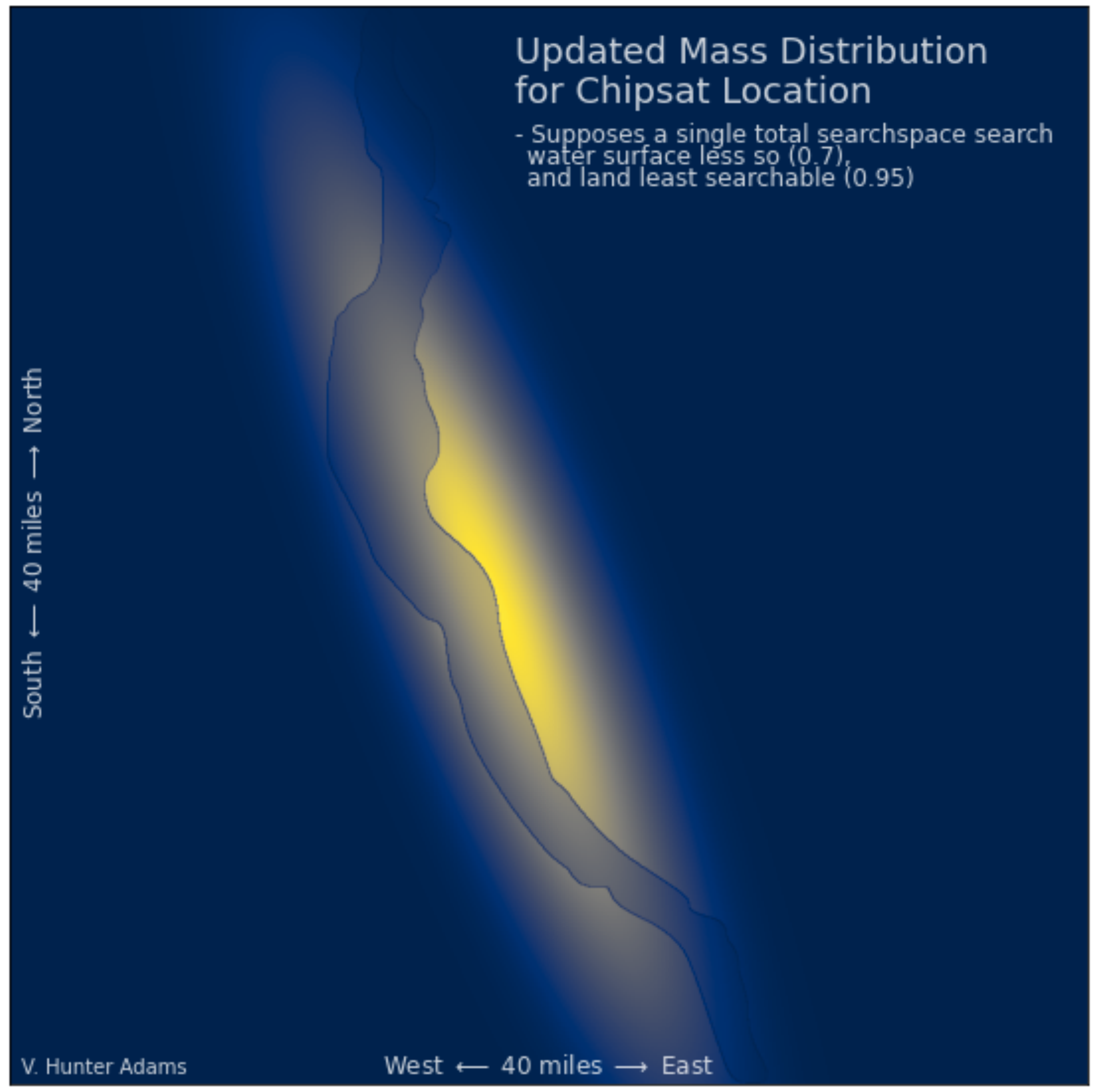


(Total probability mass automatically stays normalized to 1)

←

Decreased confidence that the object is in the lake or on a shore (we'd probably have seen it). Increased confidence it's on land.

Start with ignorance → Generate priors → Estimate searchability → Prioritize search → (Search!) → **Update priors** → A north wind blows

Nature and computing

Natural computation | Natural memory | **Natural data transfer**

Let us suppose something happens which changes our understanding of the search space.

Perhaps a north wind blows.

That's ok! We just update and carry on.

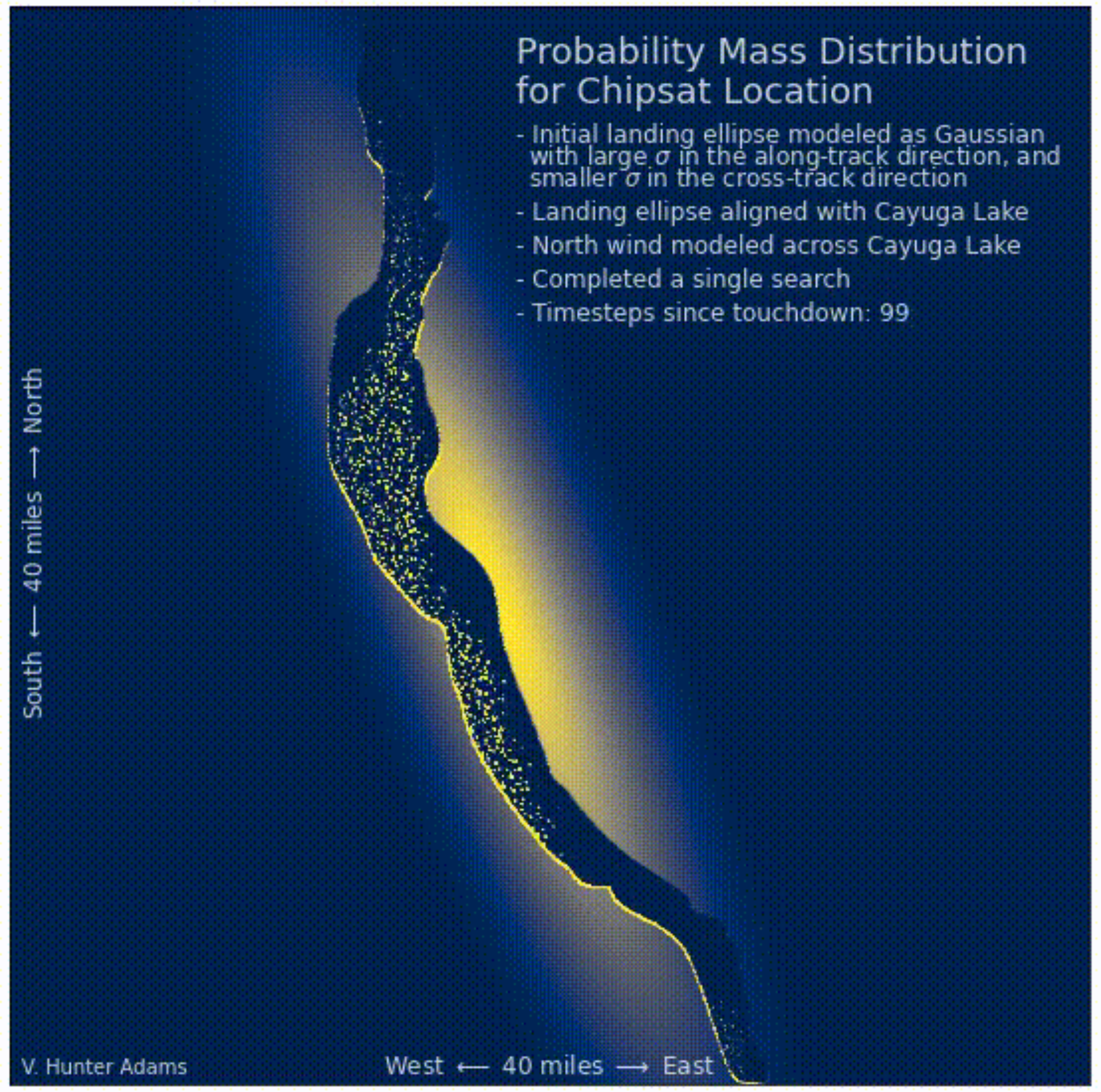
Start with ignorance → Generate priors → Estimate searchability → Prioritize search → (Search!) → Update priors → **A north wind blows** (→ back to Prioritize search)

Nature and computing

Natural computation | Natural memory | **Natural data transfer**

Finding what we're looking for at a natural Schelling Point

Click here for a gif!



A north wind moves probability mass on the *surface* of the lake south. It accumulates on north-facing shores.

Start with ignorance → Generate priors → Estimate searchability → Prioritize search → (Search!) Update priors → **A north wind blows**

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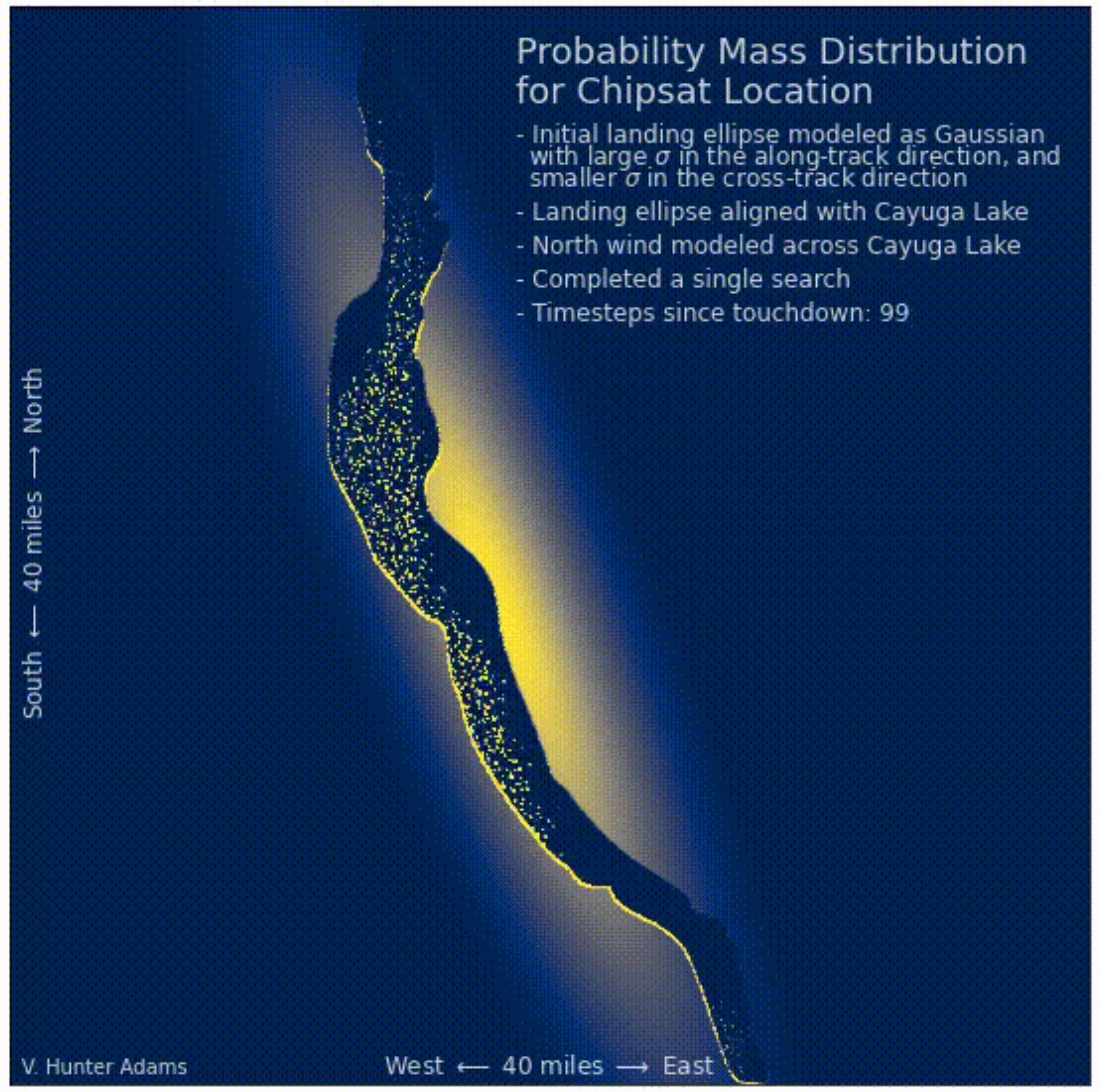
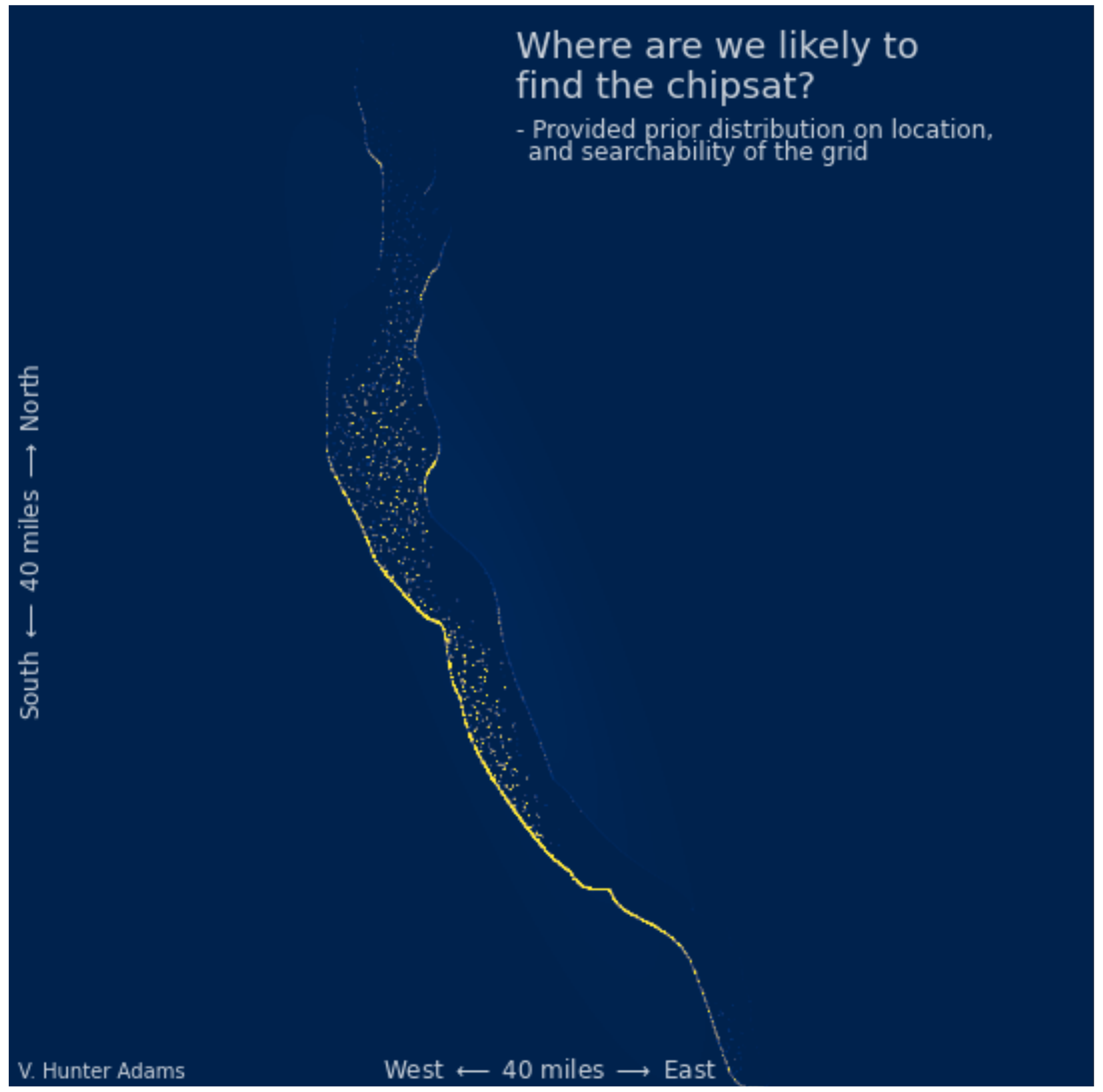


We should check the south shores again, even though we already looked there. →



Start with ignorance → Generate priors → Estimate searchability → **Prioritize search** → (Search!) Update priors → A north wind blows (↺ back to Prioritize search)

How does this start?

Where does it lead?

Nature and computing

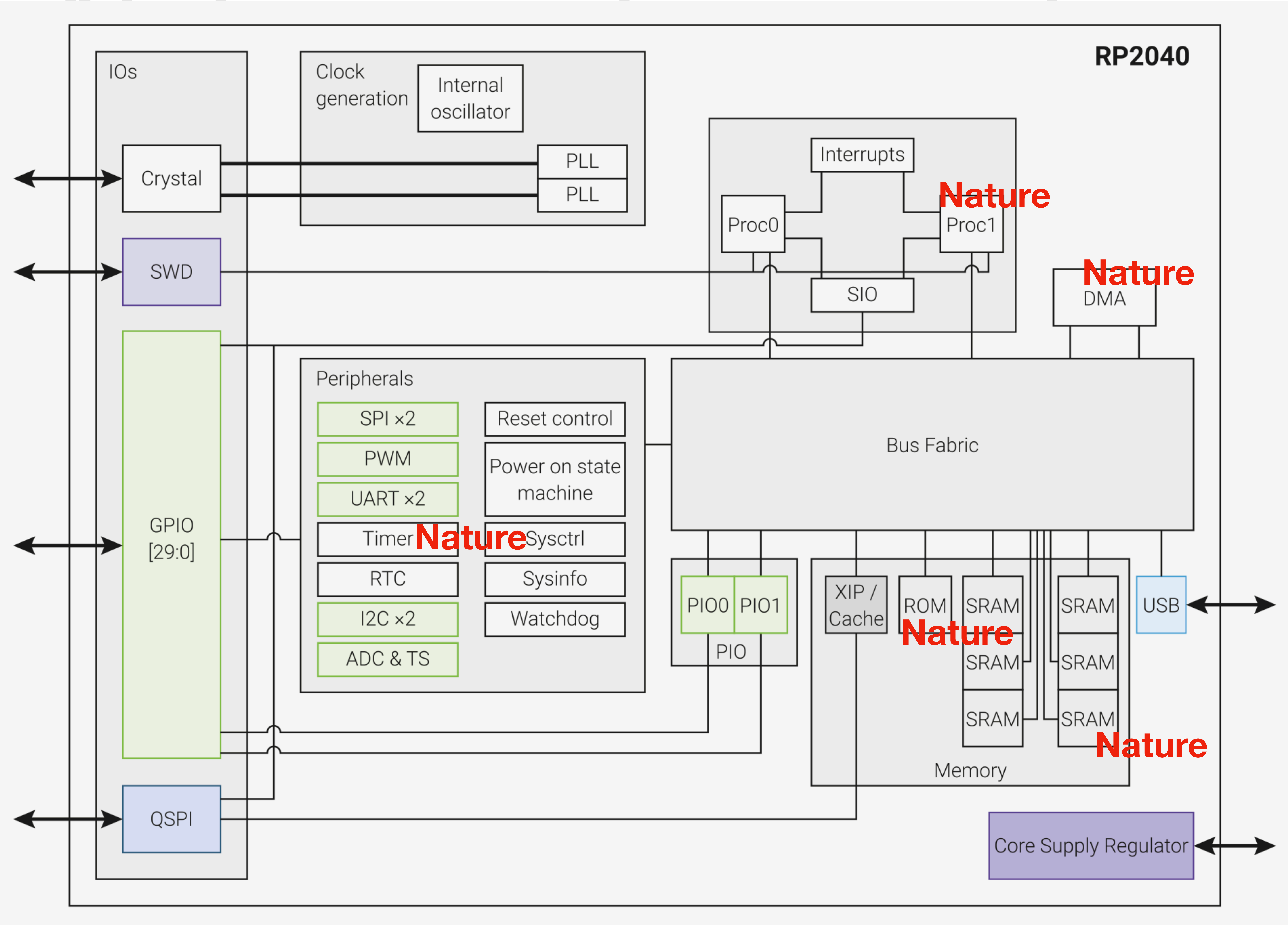
How this starts | Where it goes

Near-term opportunities

- Developing natural computers will occur in phases, the first of which resurrects the naturalist of previous centuries. Like those naturalists, the natural computing researcher will go into the wilderness to look for new things. Rather than searching for new plants and animals, this person seeks natural computational processes, natural repositories for data, and natural migrations of matter.

- These processes will be studied and modeled to gain an understanding of their algorithmic qualities, and then the researcher will design and build devices which make these evolved systems components of a larger machine.

- Development for natural computers will proceed similarly to the development of conventional computers. Like the original ENIAC and its predecessors, the first natural computers will be special-purpose.


RP2040
IOs
Crystal
SWD
GPIO
[29:0]
QSPI
Clock
generation
Internal
oscillator
PLL
PLL
Interrupts
Proc0
Proc1
SIO
DMA
Nature
Nature
Peripherals
SPI ×2
PWM
UART ×2
Timer
RTC
I2C ×2
ADC & TS
Reset control
Power on state
machine
Sysctrl
Sysinfo
Watchdog
Nature
Bus Fabric
PIO0
PIO1
PIO
XIP /
Cache
ROM
SRAM
SRAM
SRAM
SRAM
SRAM
SRAM
Nature
Memory
Nature
USB
Core Supply Regulator

Nature and computing

How this starts | **Where it goes**

Natural computing can push us past the Anthropocene

- The incorporation of these natural processes into computing machine will **incentivize their preservation**. Natural places will be preserved for their computational utility and potential.
- Unlocking the latent computational potential of nature will **change the world** in much the same way that unlocking nature's latent potential for power production changed the world. Total global compute will radically increase.
- **Here is a link to a short story which describes a vision of this future.**

Who should conduct this research?

Who might fund it?

Who is a natural computing researcher?

A natural computing researcher requires . . .

- A depth of knowledge in computing, and in hardware acceleration.
- A breadth of knowledge which includes mechanical engineering and the natural sciences.
- Practical experience designing, building, and debugging devices which interface with the natural world.
- An obsession with identifying patterns across fields and disciplines.

I believe that *my experience* makes me well qualified to engage in this work.

Calls to action

From an engineering perspective . . .

- Build proof-of-concept devices, which use a natural system to perform computation, data storage, or data transfer
- Build a device which achieves "natural supremacy." Like quantum supremacy, natural supremacy is the goal of solving a problem faster than is possible for a classically engineered computer.
- Scale these naturally-accelerated systems, and incorporate them into existing computational infrastructure.
- Incorporate natural computation, data transfer, and data storage into a single general-purpose natural computer.

From an analytical perspective . . .

- Develop a metric for **computational utility**. This should be a value, computable for any system (natural or engineered), that describes that system's utility as a computer. Such a metric *probably* incorporates that system's entropy, mutual information, transfer entropy, information storage capacity, information observability, etc. Such a metric allows for comparison of systems *as computers*.

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But who will fund such things?

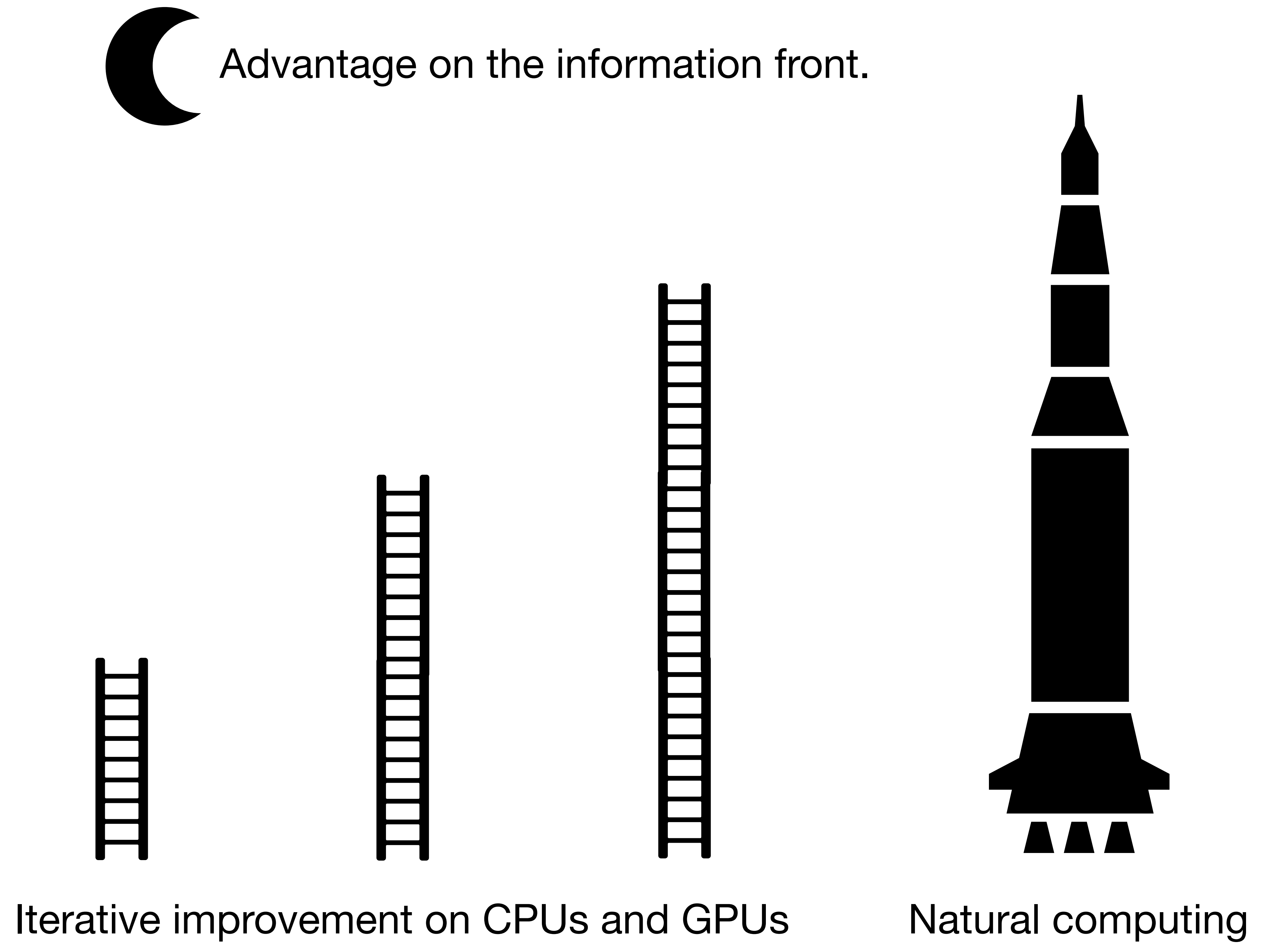
Funded by those who are motivated by . . .

Increasing compute availability | Preserving/understanding nature

The five domains of warfare include land, sea, air, space, and **information**.

The nation which most efficiently converts raw data into actionable knowledge has the advantage in the information domain. This conversion requires computation.

Natural computing could radically increase national compute availability.



Funded by those who are motivated by . . .

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Natural computation **complicates the battlefield** by forcing the opponent into a state of paranoid schizophrenia.

They are forced to regard every tree ring, bird song, cricket chirp, etc. with **conspiratorial suspicion.** They are forced to act as if the forest itself is *watching*.

Funded by those who are motivated by . . .

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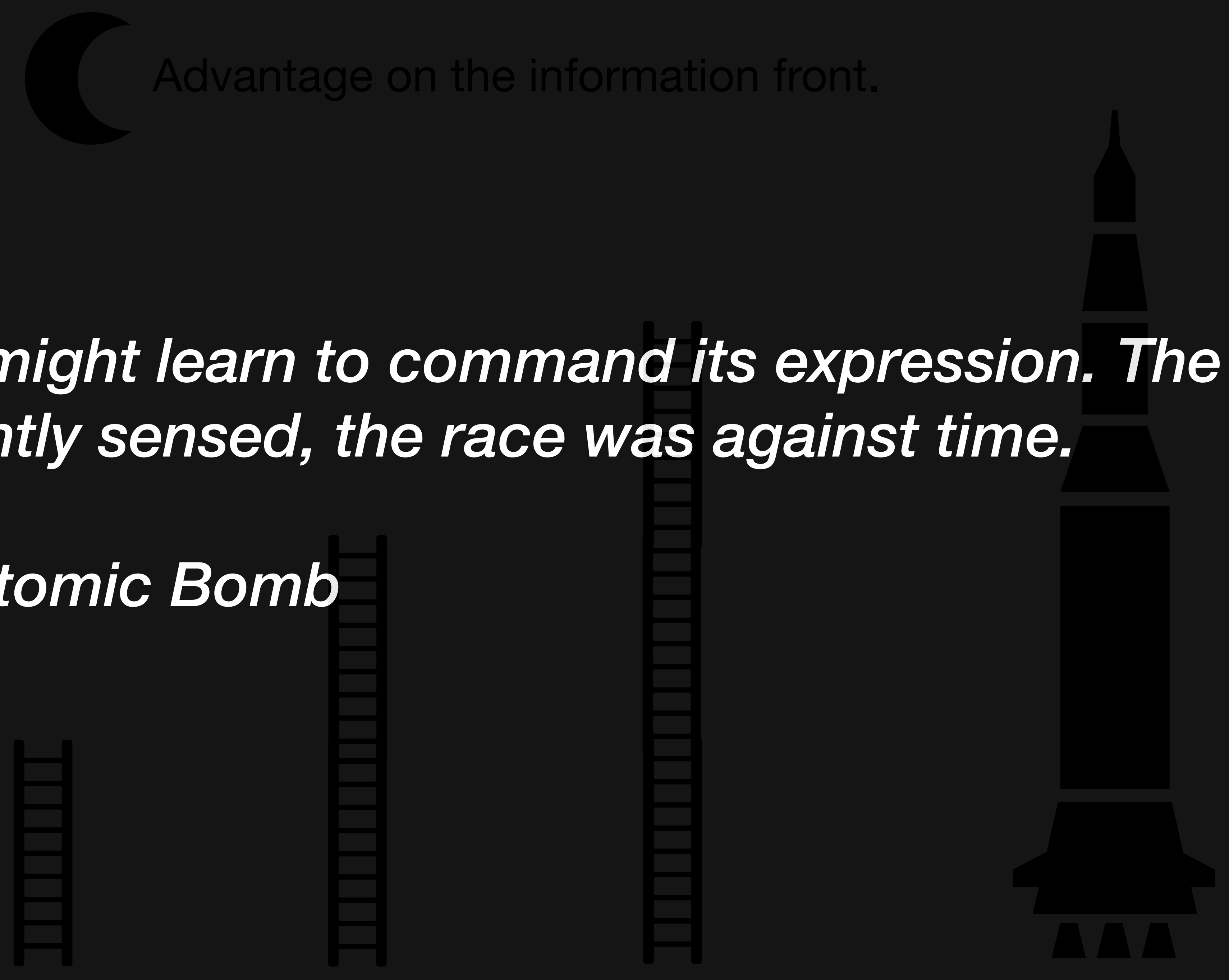
Natural computing could radically increase national compute availability.



The bomb was latent in nature as the genome is latent in flesh. Any nation might learn to command its expression. The race therefore was not merely against Germany. As Roosevelt apparently sensed, the race was against time.

- Richard Rhodes, *The Making of the Atomic Bomb*

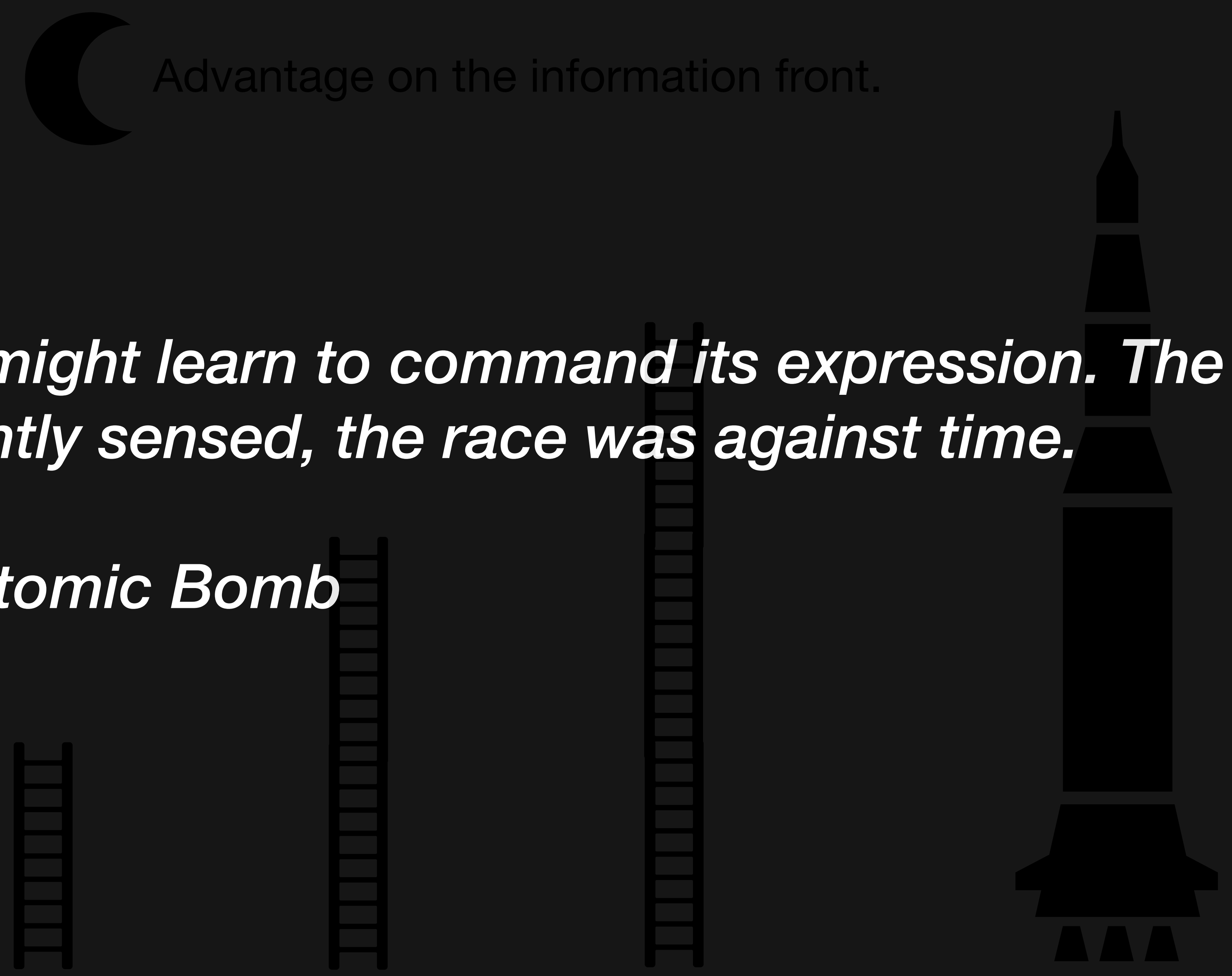
Funded by those who are motivated by . . .

Increasing compute availability | Preserving/understanding nature

The five domains of warfare include land, sea, air, space, and **information**.

The nation which most efficiently converts raw data into actionable knowledge has the advantage in the information domain. This conversion requires computation.

Natural computing could radically increase national compute availability.



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Funded by those who are motivated by . . .

Increasing compute availability	**Preserving/understanding nature**

We can save the planet by turning it into a computer

- Appeals to altruism are **not sufficient** for guaranteeing the preservation of natural places.
- Environmentalism by regulation lasts no longer than the nations which enforce those laws, and possibly for a much shorter time than that.
- We will save the planet by making natural places more economically valuable **intact** than they are **disassembled** into their raw materials.
- This value must be realizable in decades, not centuries, or else psychology will work against the effort.
- We can realize this value by tapping into the computational potential which exists in nearly all natural systems and processes. In the process, we will
    - Learn more about these natural systems, in a scientific sense.
    - Improve input/output between nature and machines.


Photo by Vlad Hilitanu on Unsplash
Preserved for natural computation

For seven and a half million years, Deep Thought computed and calculated, and in the end announced that the answer was in fact Forty-two — and so another, even bigger, computer had to be built to find out what the actual question was.

And this computer, which was called the Earth, was so large that it was frequently mistaken for a planet—especially by the strange apelike beings that roamed its surface, totally unaware that they were simply part of a gigantic computer program.

And this is very odd, because without that fairly simple and obvious piece of knowledge, nothing that ever happened on the Earth could possibly make the slightest bit of sense.

- Douglas Adams, *The Restaurant at the End of the Universe*

Appendix A: Nature/machine symbiosis

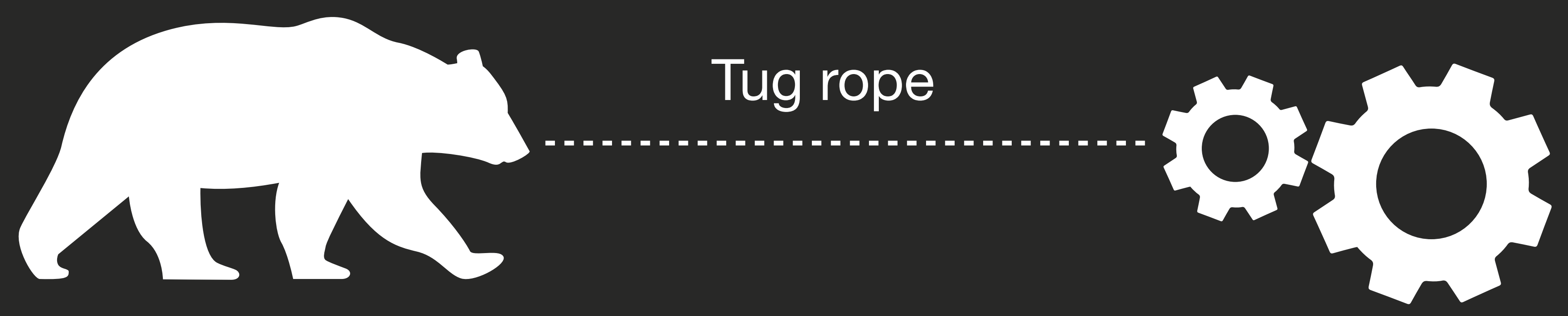
Natural computing is a (particularly interesting) subset of nature/machine symbiosis. There are other examples of nature/machine symbiotic systems which I would love to implement.

The Megafauna Playground

Powering and distributing sensors in Earth’s most desolate places with animal play

- There exist places on Earth where interesting environmental things are happening, but sources of energy are hard to come by (the deep ocean, winter in the polar regions, etc.)
- Some of these regions have tremendous *consolidations* of energy in the form of megafauna (whales, bears, seals)
- These megafauna are *playful*. If we engineer a system that these megafauna enjoy playing/interacting with, we might extract some energy from their play.
- Bears and whales tugging ropes for mechanical potential energy, birds lifting objects for gravitational potential energy, or whales diving with objects for traversal of a pressure gradient.

Lifts/drops toy, adding gravitational potential energy



Mechanical energy storage for environmental sensor

Diving thru pressure gradient, carrying a toy

The Megafauna Playground

Powering and distributing sensors in Earth's most desolate places with animal play

- These animals also traverse hard-to-reach places, often returning to predictable locations on predictable schedules

- If we recruit these creatures as collaborators, and ask that they bring a small sensor along with them for their trip, we can achieve *massive* distribution of sensors with guaranteed consolidation of those sensors at the end of the migration

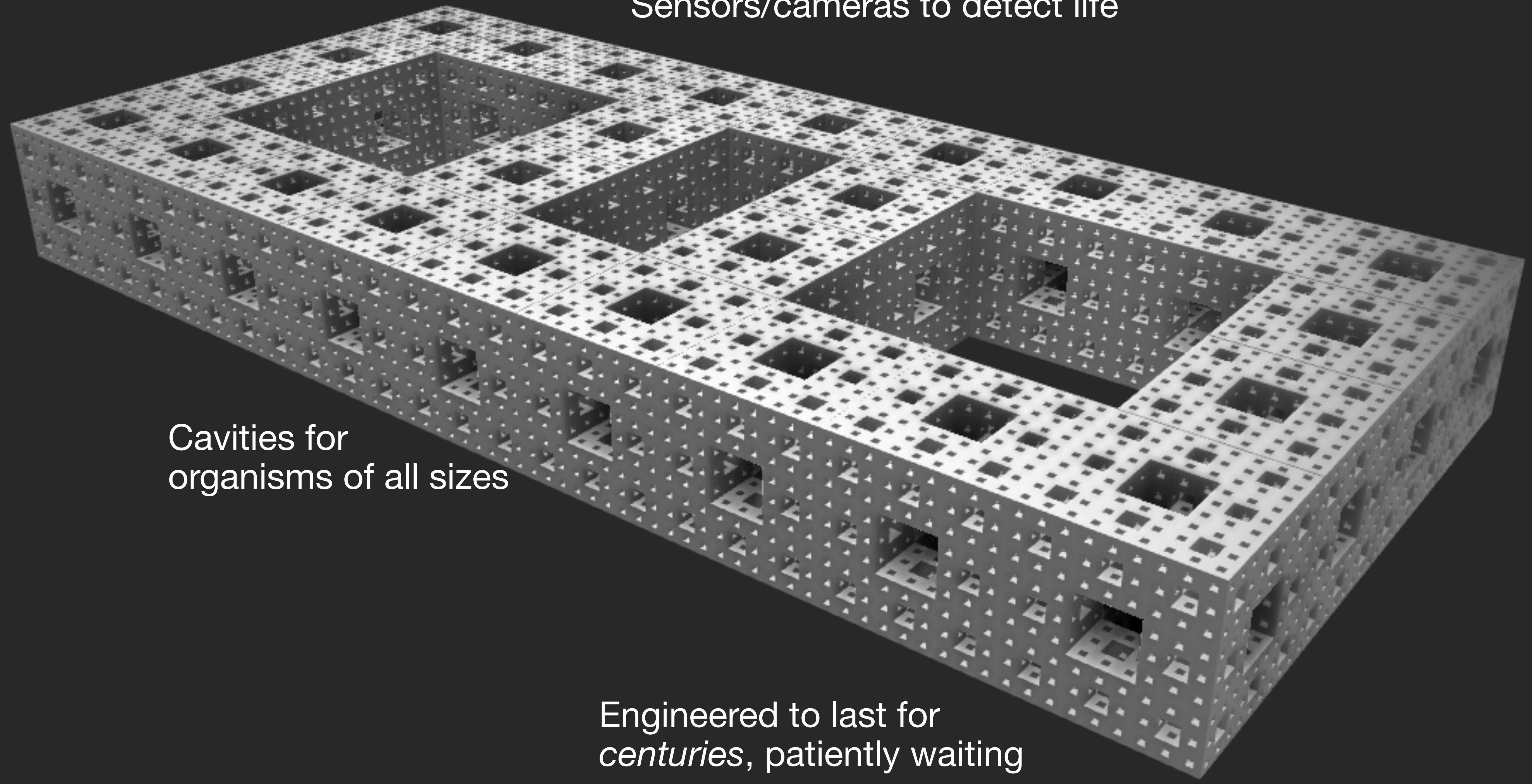
- Polar bears might help gather magnetic field measurements in the high arctic. Whales can gather sea water temperature and salinity measurements. Etc.

- We will save these animals by making them more valuable alive and behaving naturally than they are dead. This assigns them value by recruiting them for data acquisition and movement.

The Monolith

An artificial reef placed in Titan’s methane lakes to wait for life.

- Life on Earth tends to inhabit infrastructure placed in its environment.
- The same may be true anywhere that an evolutionary process is taking place.
- The Monolith offers a substrate and cavities for organisms to inhabit, and uses a suite of sensors and cameras to detect those organisms when they arrive. It alerts humanity to their presence.
- Its fractal design maximizes surface area, minimizes volume, offers cavities of a huge range of sizes, and appeals to fans of Arthur C. Clarke.



Appendix B: More examples of natural memory

Nature and computing

Natural computation | **Natural memory** | Natural data transfer

Far-out examples of natural memory

Natural systems contain an unbelievable amount of **state**. How long would the vector be which fully specifies the state of a cubic meter of beach? Or the molecular state of a mineral? Or which specifies all degrees of freedom in a coral reef?

Life is a matrix which acts on these vectors. We are free to store data (a lot of data) in the null space of this matrix without having any effect on local life. It is worth noting that every degree of freedom is available for information storage in environments that contain no life, like the Moon and asteroids. Tantalizingly, some of these repositories for data *move*.

For some of these, entropy may present a problem.

If only we can figure out how to read/write it, we can use nature's huge state space to store information.

Nature and computing

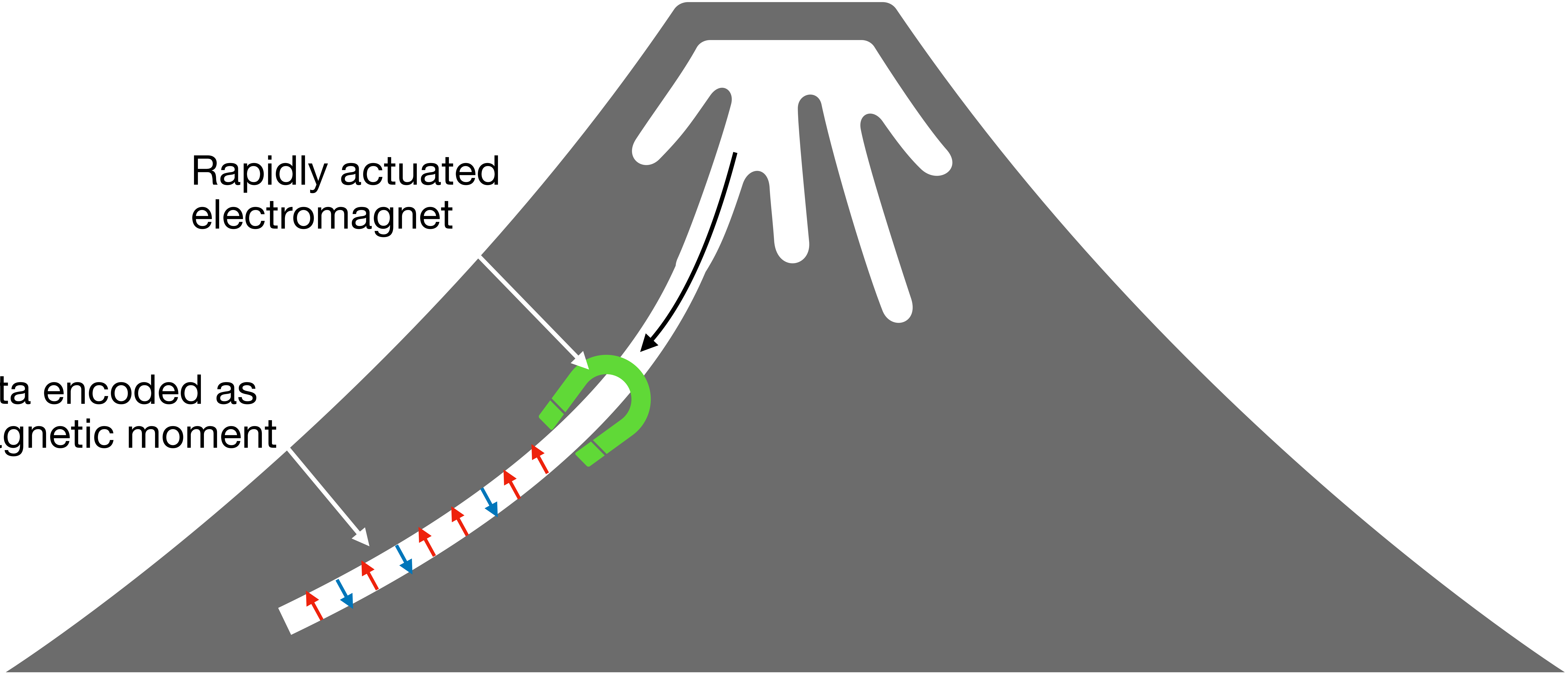
Natural computation | **Natural memory** | Natural data transfer

An example of natural memory with niche utility

Paleomagnetism is the study of the history of the Earth's magnetic field by means of the magnetic moments of volcanic rock. Lava contains ferromagnetic crystals that align themselves with the direction of the magnetic field as the lava cools. Once the lava gets below a certain temperature, the magnetic moments become locked into the rock, recording the direction and intensity of the local magnetic field at the time that the lava cooled.

If we built a device which quickly actuated the magnetic field of cooling lava as it moved under the device, we could record data in the magnetic moment of the rock. Potentially, a lot of data. These data could then be retrieved by means of a magnetometer which traversed that section of rock.

This is **super non-volatile**, and offers a bit more data storage!

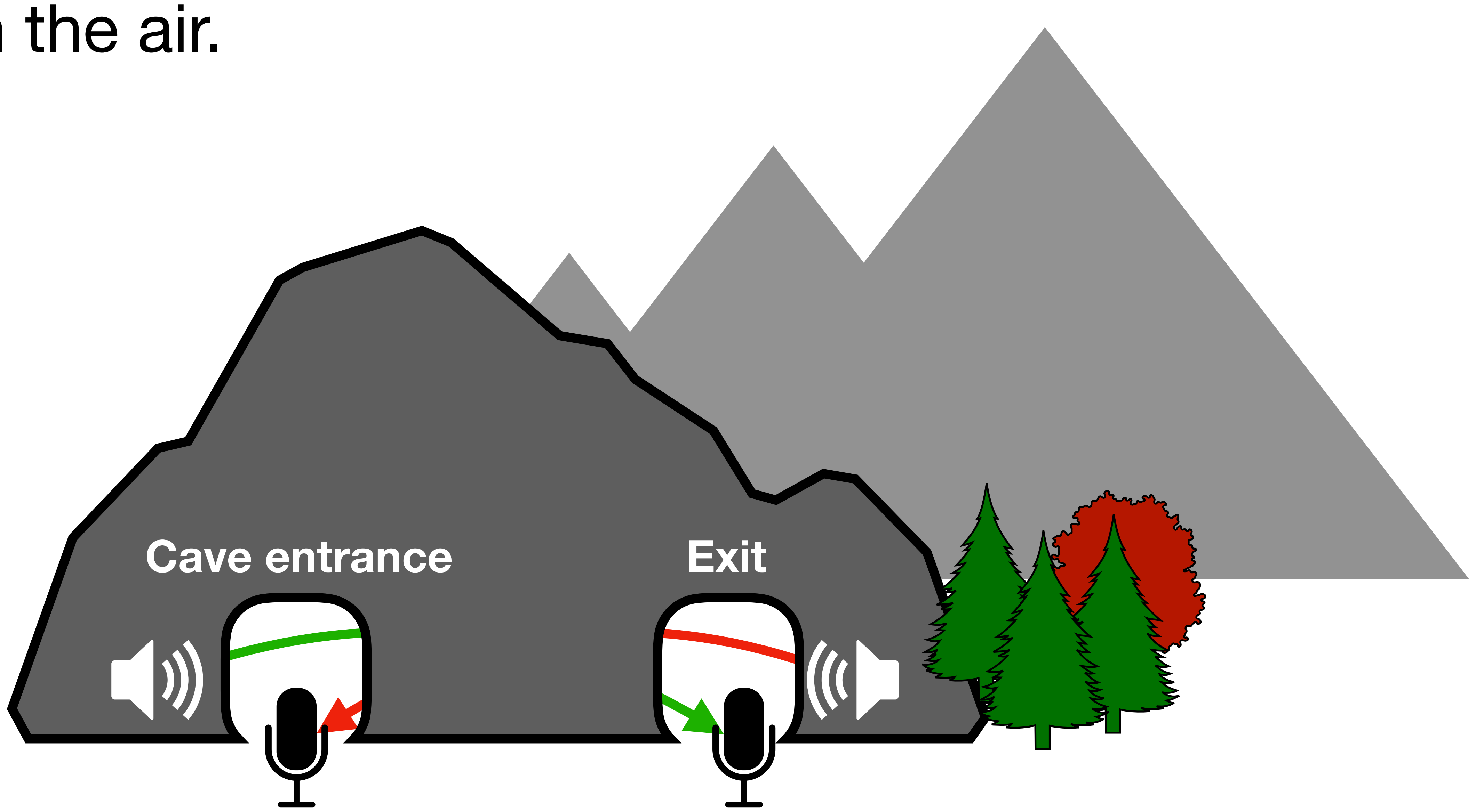

Rapidly actuated electromagnet
Data encoded as magnetic moment

Nature and computing

Natural computation | **Natural memory** | Natural data transfer

Refreshable sequential-access memory in natural delay lines

Because information moves at finite (and medium-dependent) speed, we can store data *in the channel*. We might store data in pressure waves in air, which propagate into and then echo out of a cave. With a repeater at the exit, the data persists in the air.



Acoustic repeaters at entrances of cave system store data in-flight as pressure waves.

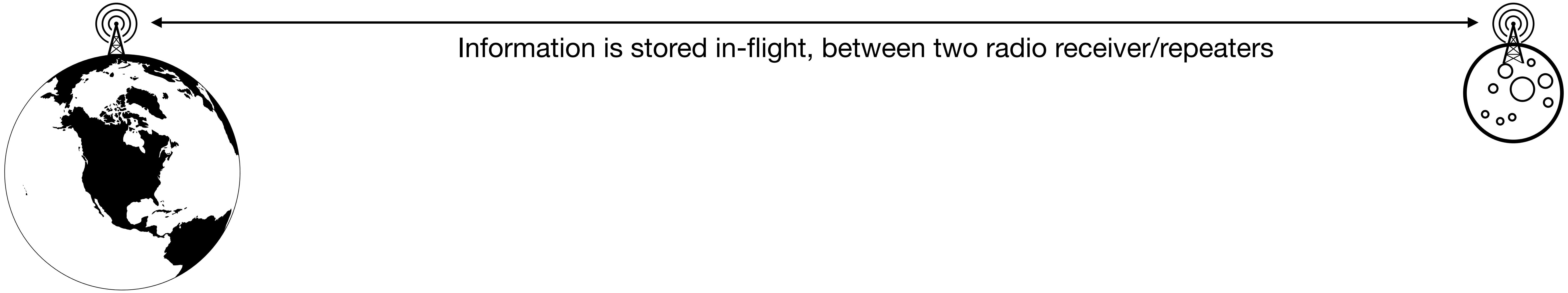
Nature and computing

Natural computation | **Natural memory** | Natural data transfer

Refreshable sequential-access memory in natural delay lines

Because information moves at finite (and medium-dependent) speed, we can store data *in the channel*. We might store data in pressure waves in air, which propagate into and then echo out of a cave. With a repeater at the entrance, the data persists in the air.

We might also store data in electromagnetic waves between Earth and other planets or celestial bodies, if we put a repeater on that planet or body.



Appendix C: More thoughts on natural data transfer

Nature and computing

Natural computation | Natural memory | **Natural data transfer**

Thinking about moving **matter** as moving **information** . . .

There are 1.26×10^{26} molecules of water in one gallon. Each of these molecules has a position and an orientation (6 degrees of freedom).

700,000 gallons of water flow over Niagara Falls every second. That's 5.3×10^{32} degrees of freedom. That's over one **zettabyte** (10^{23}) of information.

What is the information channel capacity of the Nile? Or the Jet Stream?