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Systems Theory in Design

Variety and Requisite Variety

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Agenda

- Post holiday recap of ‘fundamentals’
- Diving into measurement
- Range, Resolution, and Frequency
- Variety

Systems Fundamentals

Why do systems matter?

"Managers are not confronted with problems that are independent of each other, but with dynamic situations that consist of complex systems of changing problems that interact with each other. I call such situations messes."

Horst Rittel called them "wicked problems."

—Russell Ackoff, 1979

What is a system?

*"A system is a set of things—
people, cells, molecules, or whatever—
interconnected in such a way
that they produce their own pattern of
behavior over time."*

— Donella H. Meadows

Levels of Systems

the level of **Frameworks**	Only the geography and anatomy of the subject is described and analyzed; a kind of system of static relations. [Most architecture and graphic design systems are of this type.]	**Mechanical**
the level of **Clockworks**	Machines that are determined.	
the level of **Thermostats**	The level of control in mechanical and cybernetical [sic] systems.	
the level of the **Cell**	As an open and self-maintaining system, having a throughput that transforms unpredicted inputs into outputs [what Maturana, Varela, and Uribe later called an “autopoetic” system].	**Biological**
the **Genetic** and **Societal** level	Of plants and accumulated cells.	
the level of the **Animal**	Specialized receptors, a nervous system, and an “image”.	
the **Human** level	All of the previous six—plus self-consciousness. The system knows that it knows, and knows that it dies.	**Social**
the level of the **Social Organism**	The unit at this level is a role, rather than a state; messages with content and meaning exist, and value systems are developed.	
the level of **Transcendental** systems	The “ultimates” and “absolutes” and the “inescapables” with systematic structure.	

— Kenneth Boulding, 1956

Three Models of Strategy

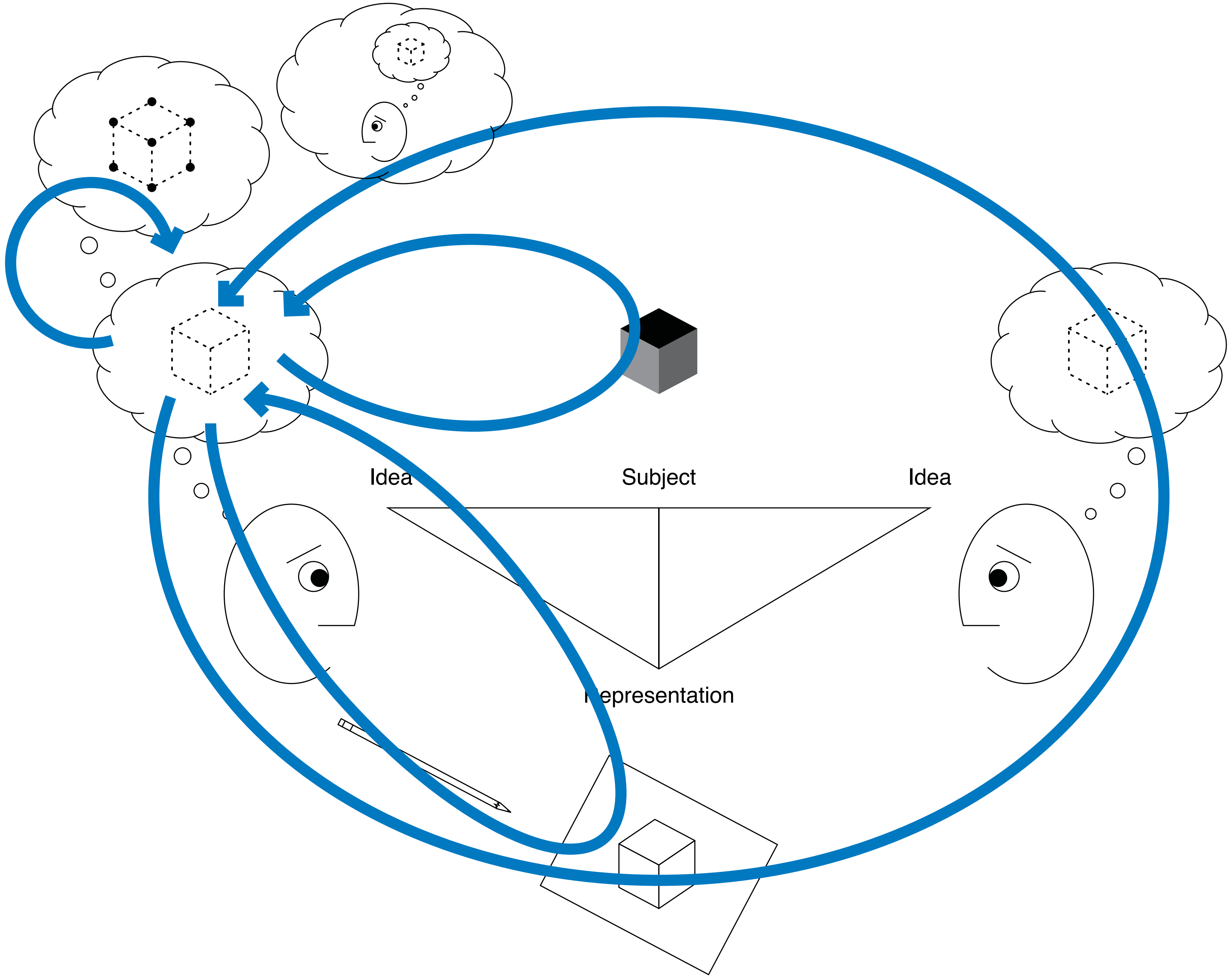
1. **Linear** — finding the best solution to a given problem or achieve a goal
focus is internal, oriented around process (mechanical)

2. **Adaptive** — finding fit with the environment
focus is on competitors + customers, a sense-respond feedback orientation, finding the right variety (biological)

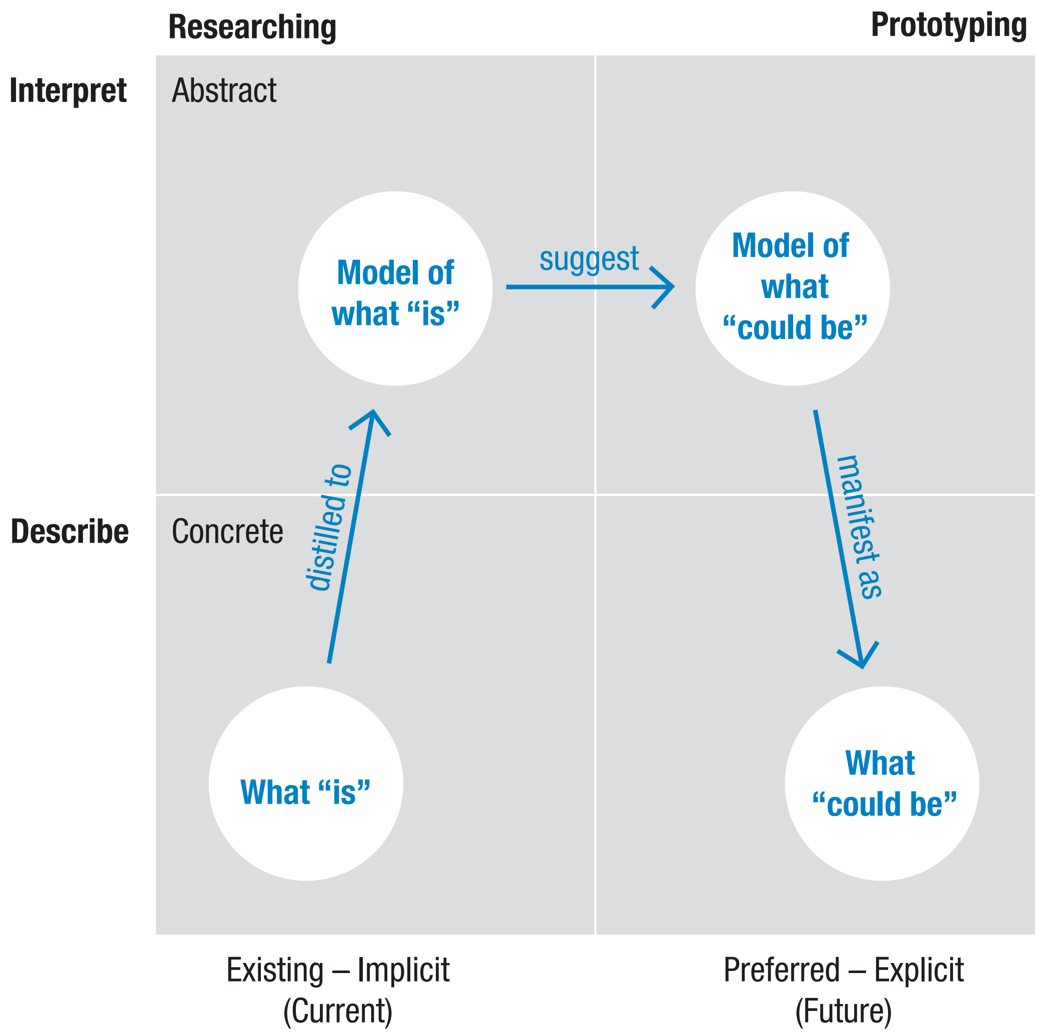
3. **Interpretive** — finding language enabling the necessary conversations
focus broadens to multiple stakeholders, oriented on organizing metaphors + culture (social)

— Ellen Earle Chaffee, 1956

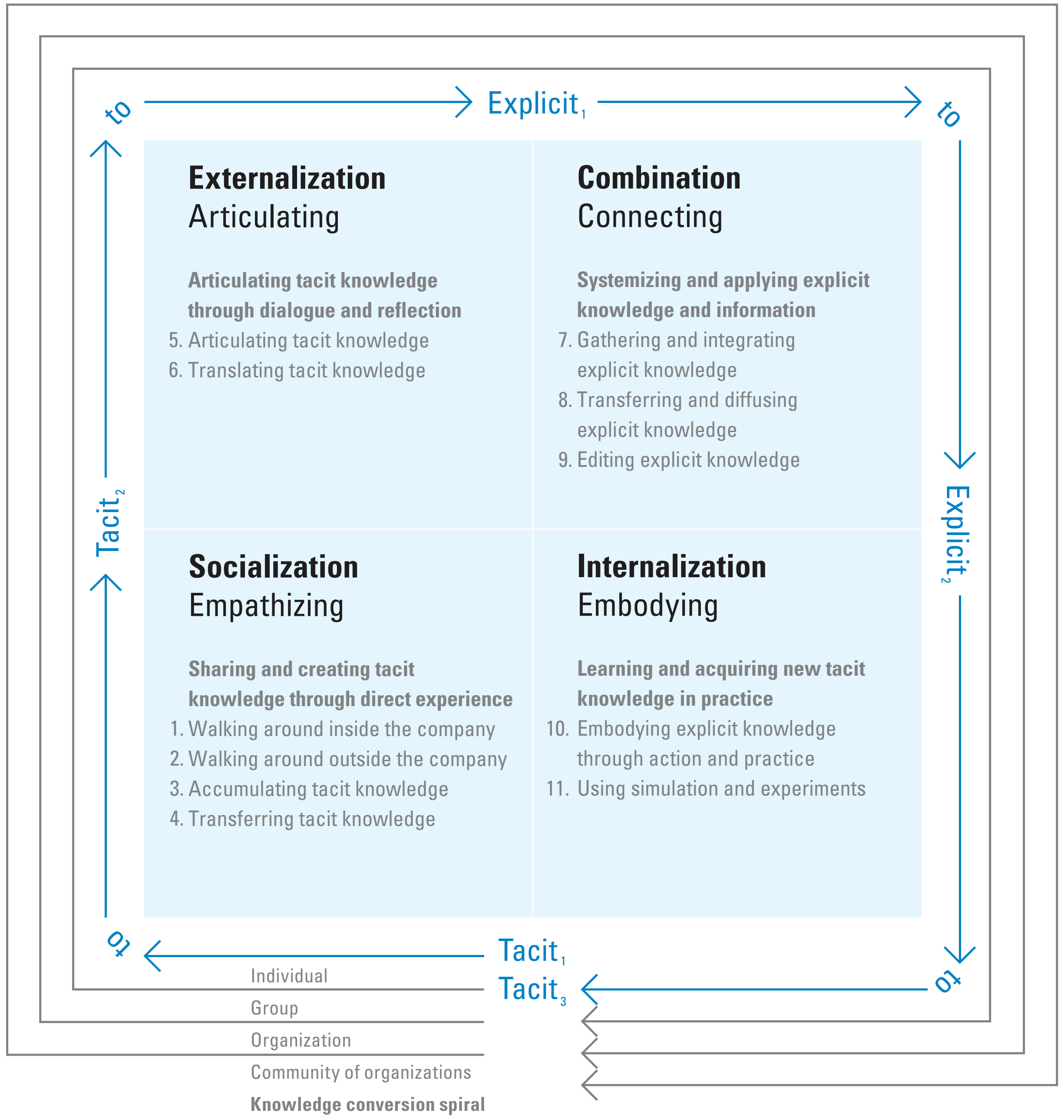
Understanding systems requires mental models — i.e., understanding a vocabulary + structural relationships.



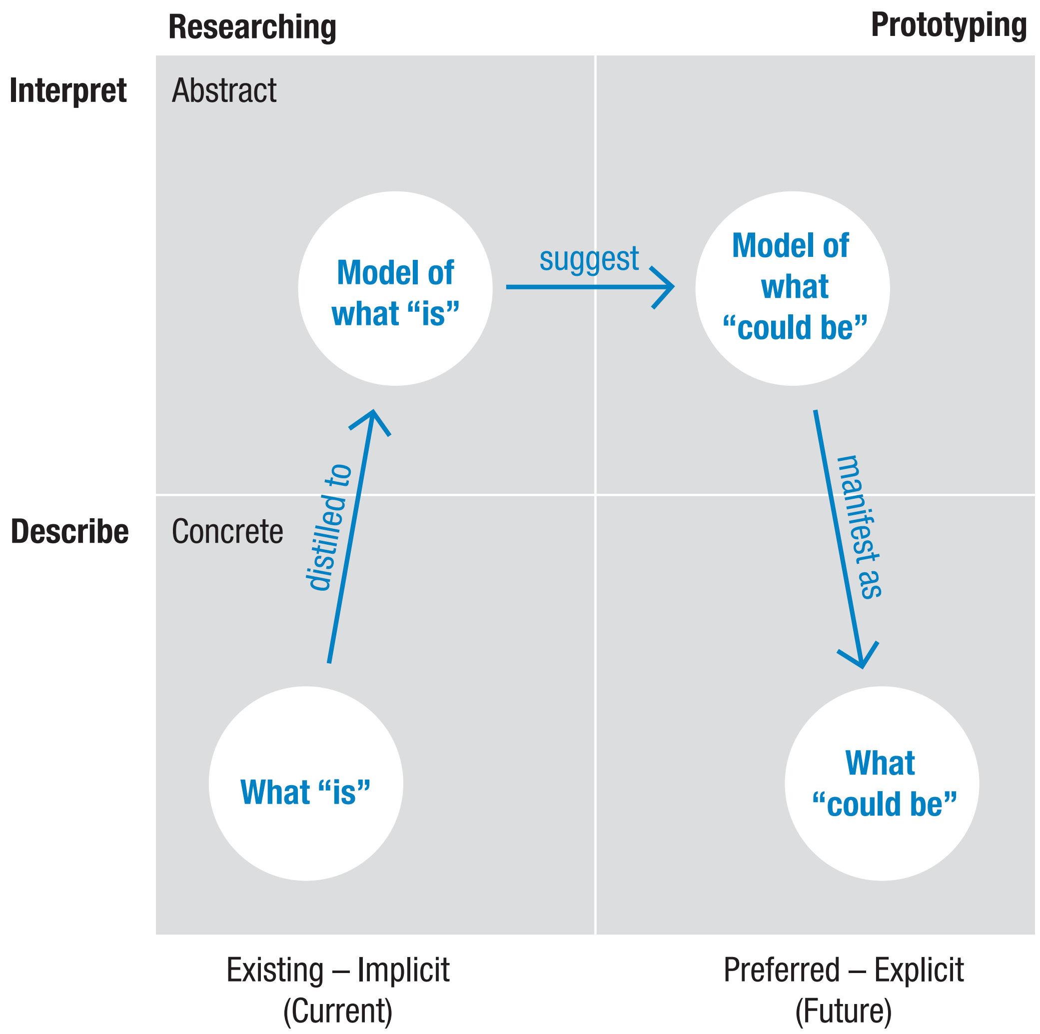
The Analysis-Synthesis Bridge Model shows how design crosses the gap between *what is* and *what should be*.



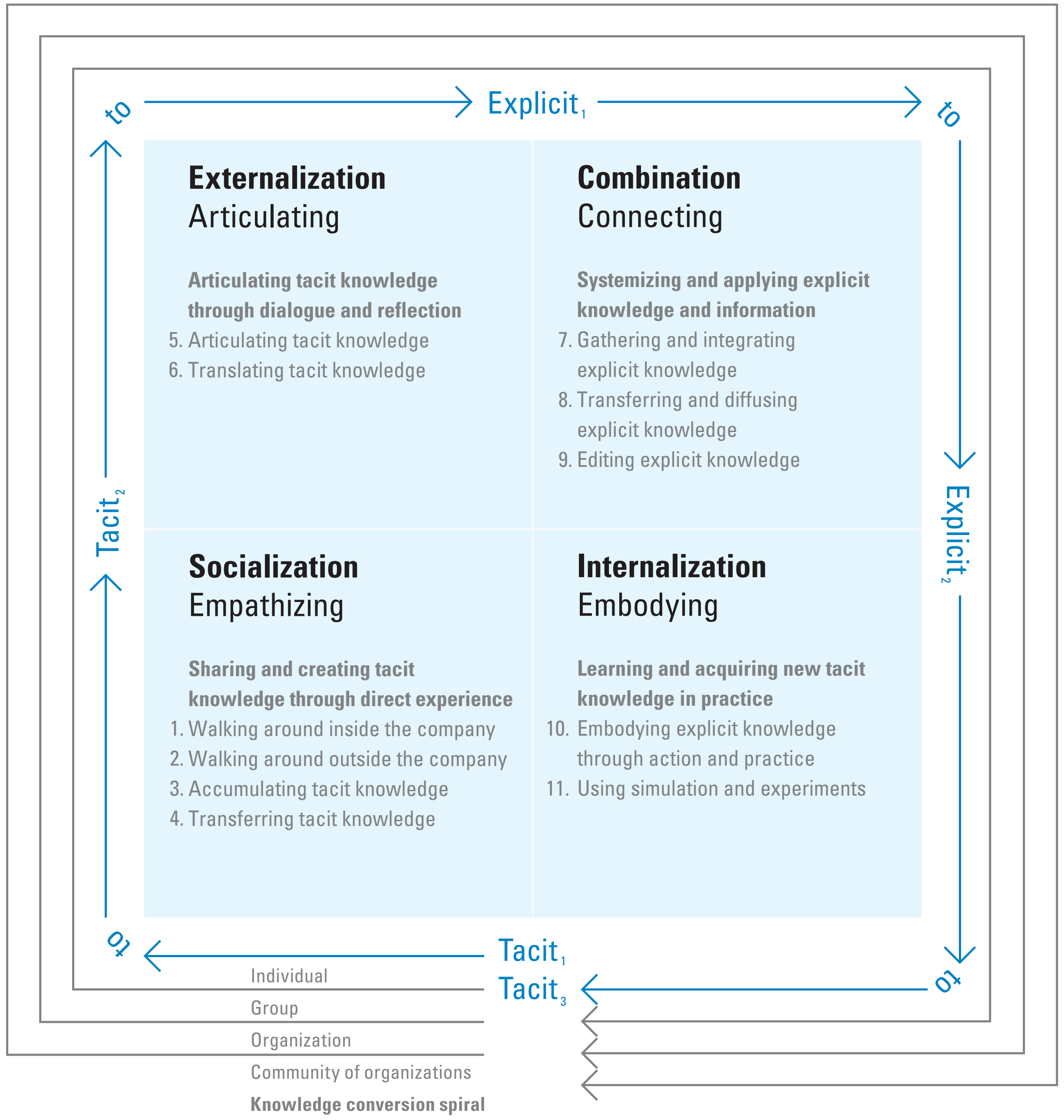
The SECI Model shows how organizations turn tacit knowledge into explicit knowledge, create new knowledge, and deploy it in operations.



Both models have the same basic structure—iterative loops—suggesting that designing *is* learning.



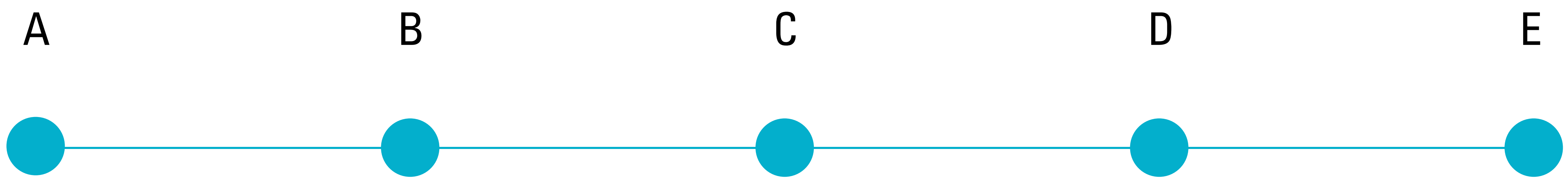
Analysis-Synthesis Bridge Model
Dubberly, Evenson & Robison (2008)



SECI model of knowledge create
Ikujiro Nonaka (1995)

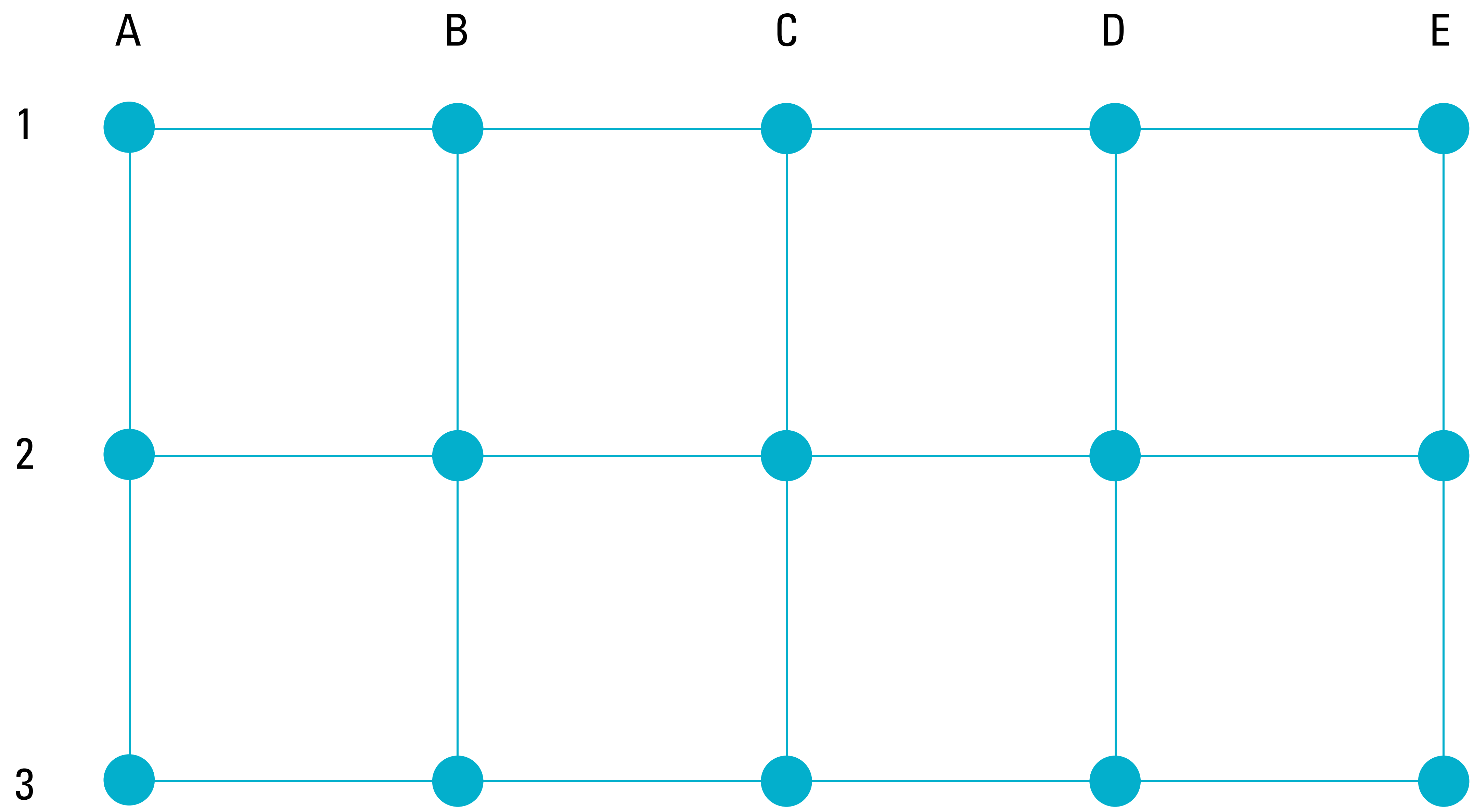
Information Structures

Array — a “string” or list — may be a process, journey, or path

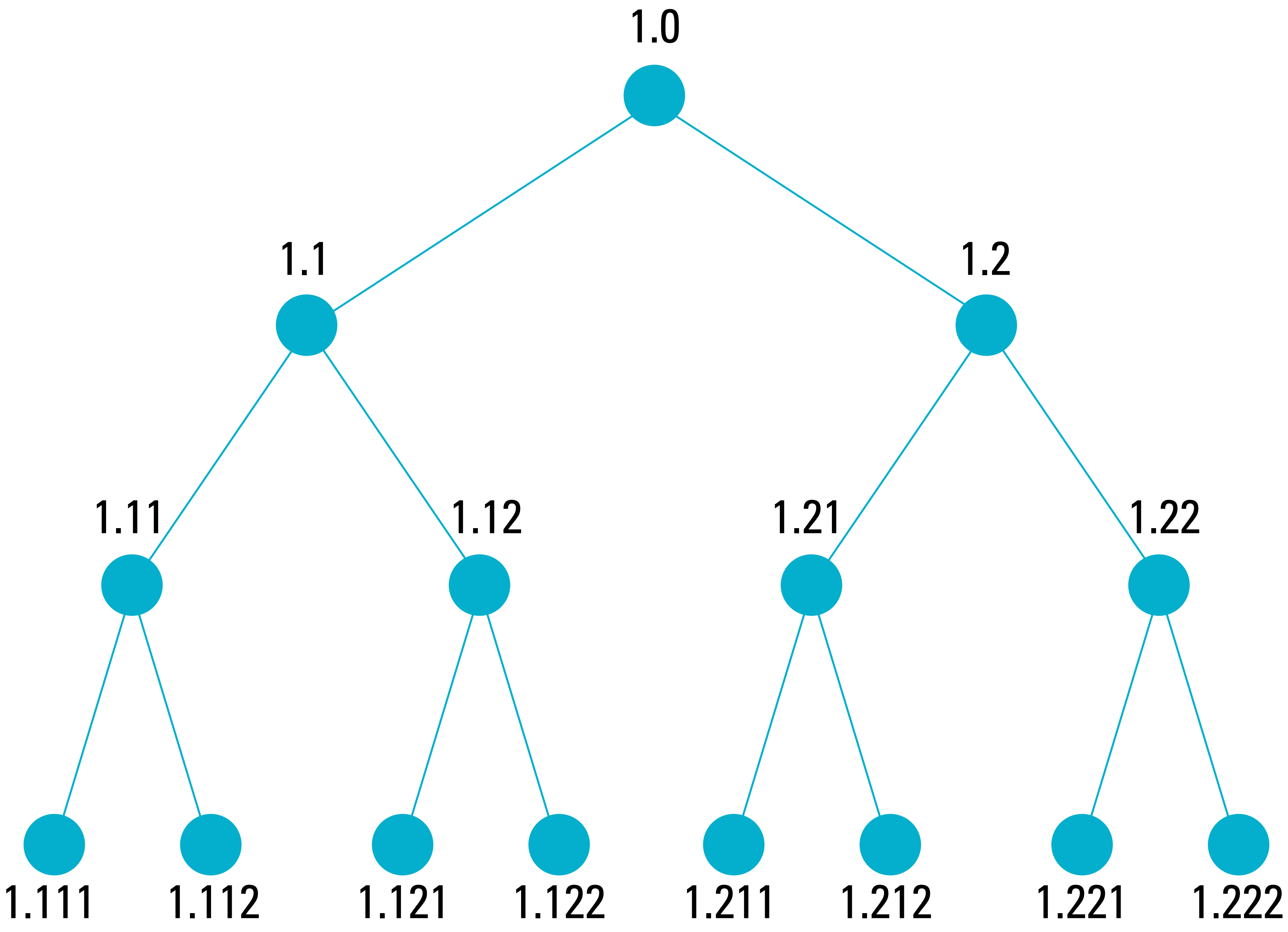


A process may also be represented as a loop, spiral, or helix.

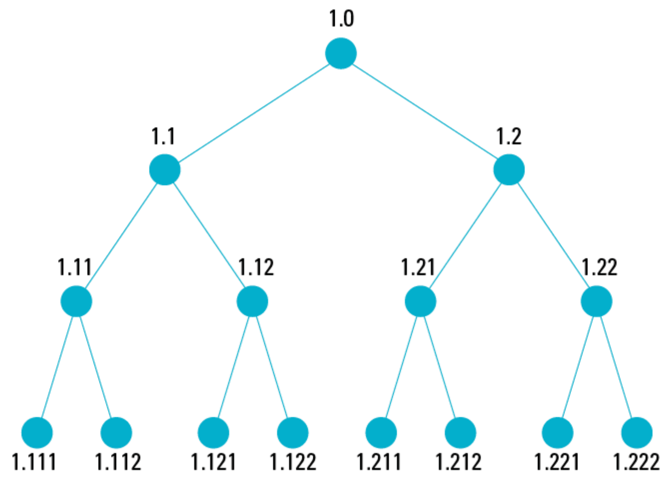
Matrix — also table or “flat file”

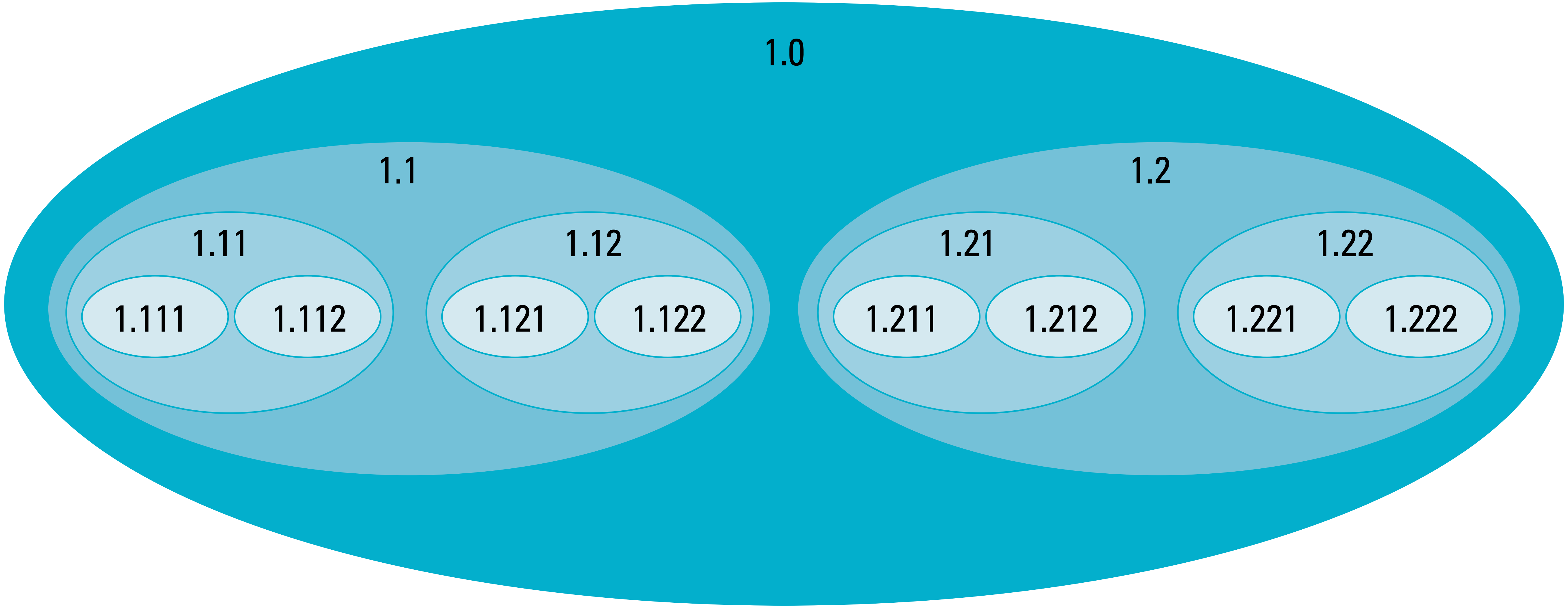


Tree — also hierarchy, taxonomy

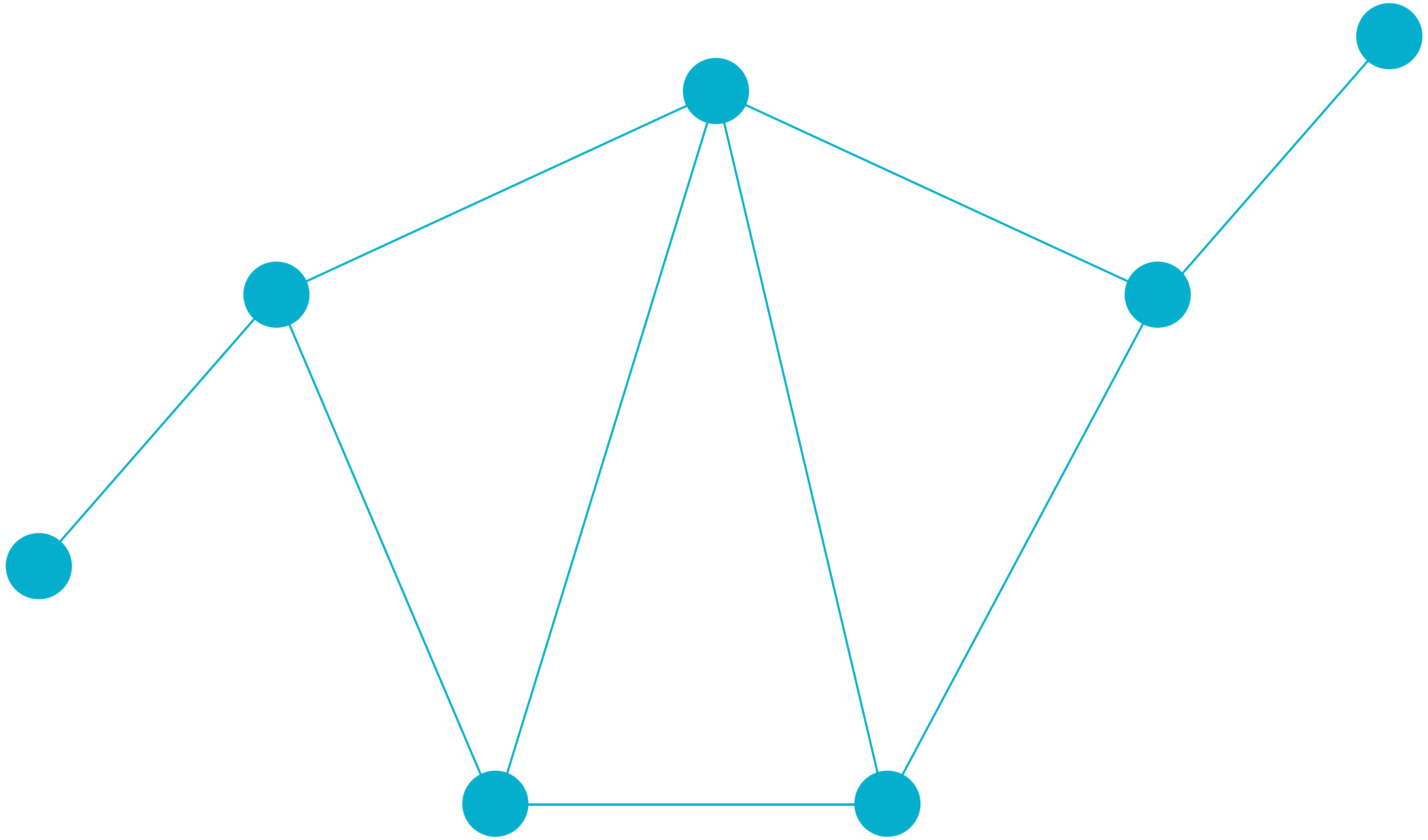


Trees can also be represented as Venn diagrams.



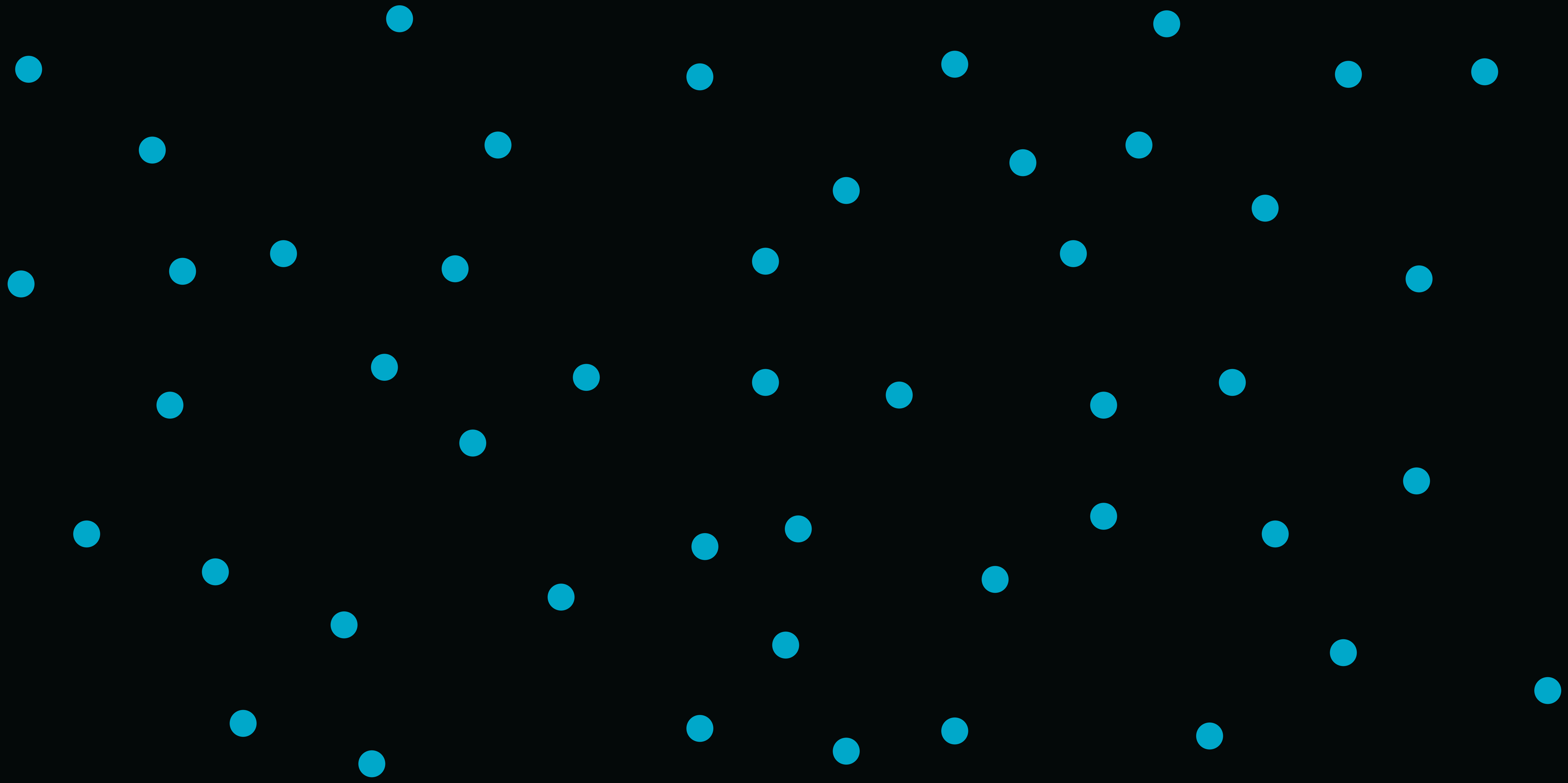


Web — also graph, network, ontology

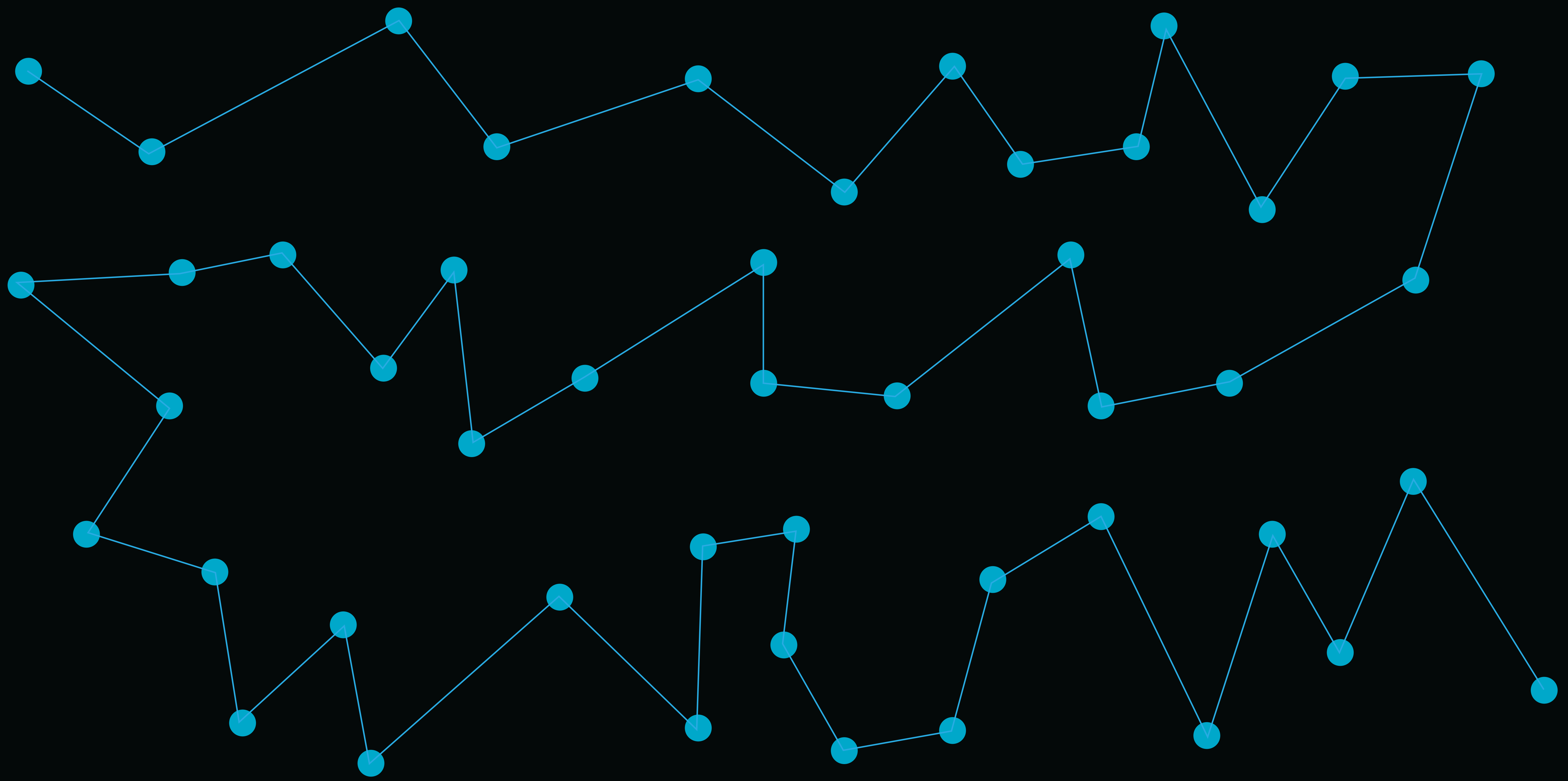


The same set of nodes may be connected to form many different structures.

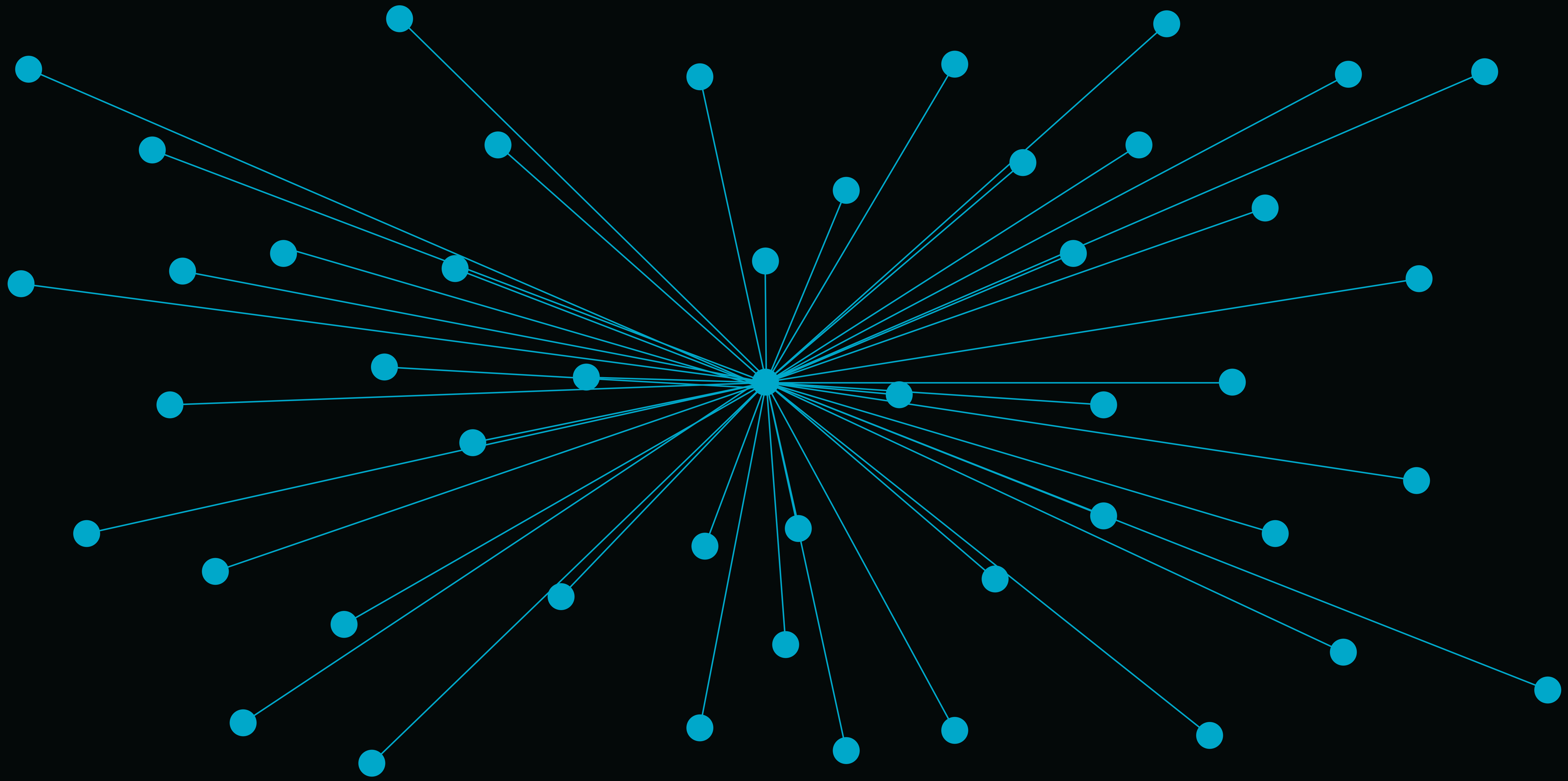
Nodes



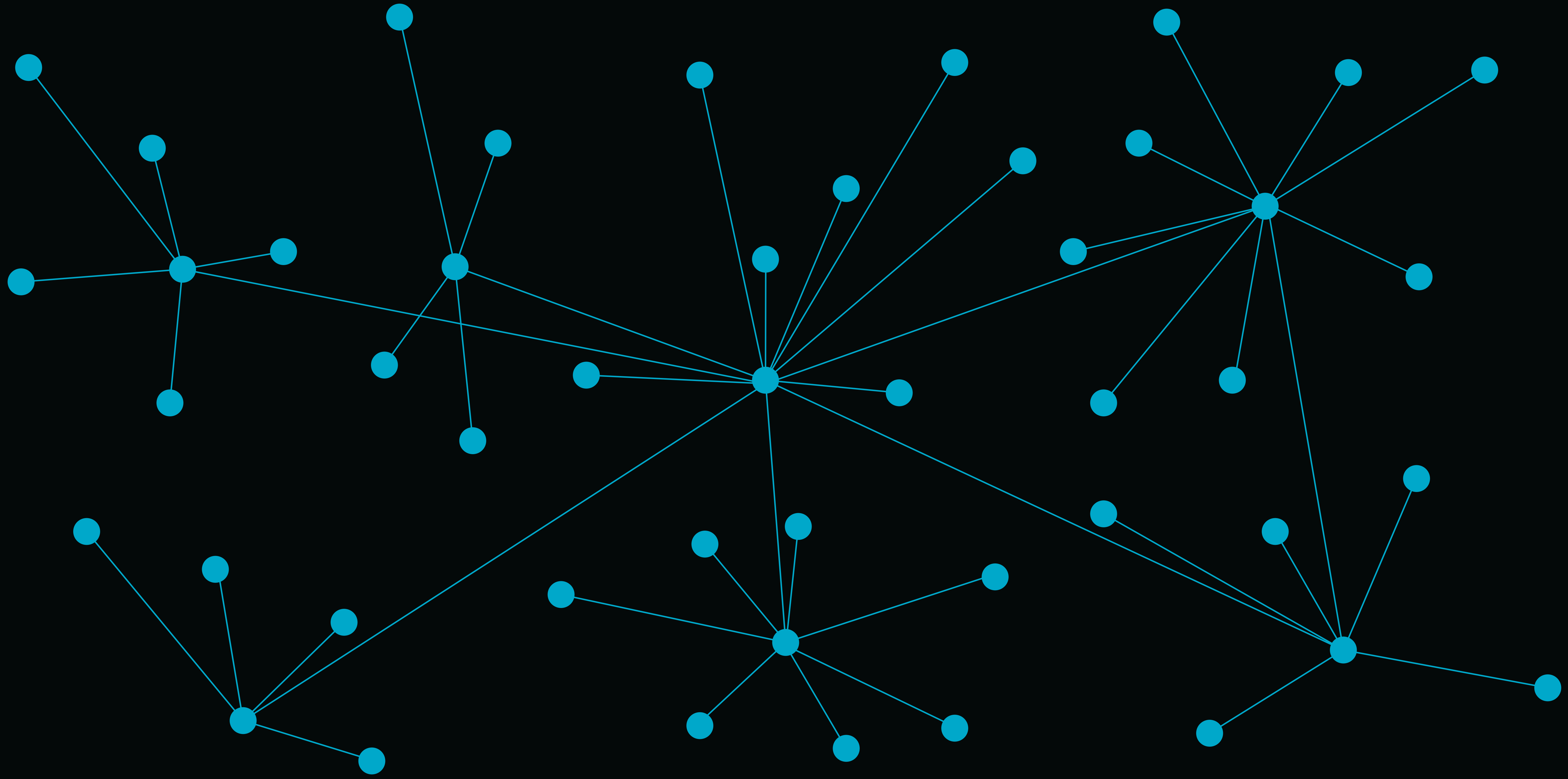
Sequences — “Daisy Chain”



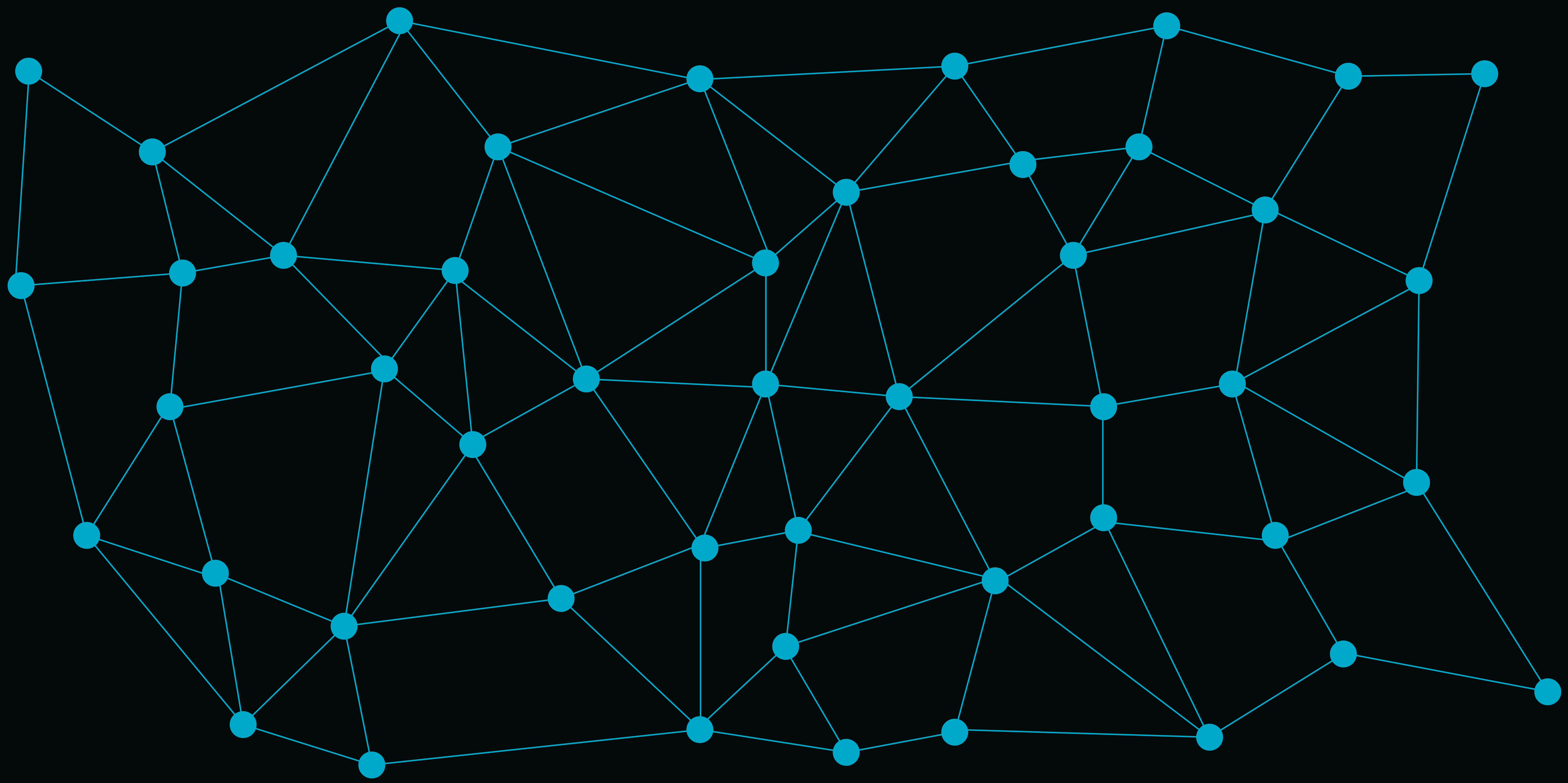
Centralized System



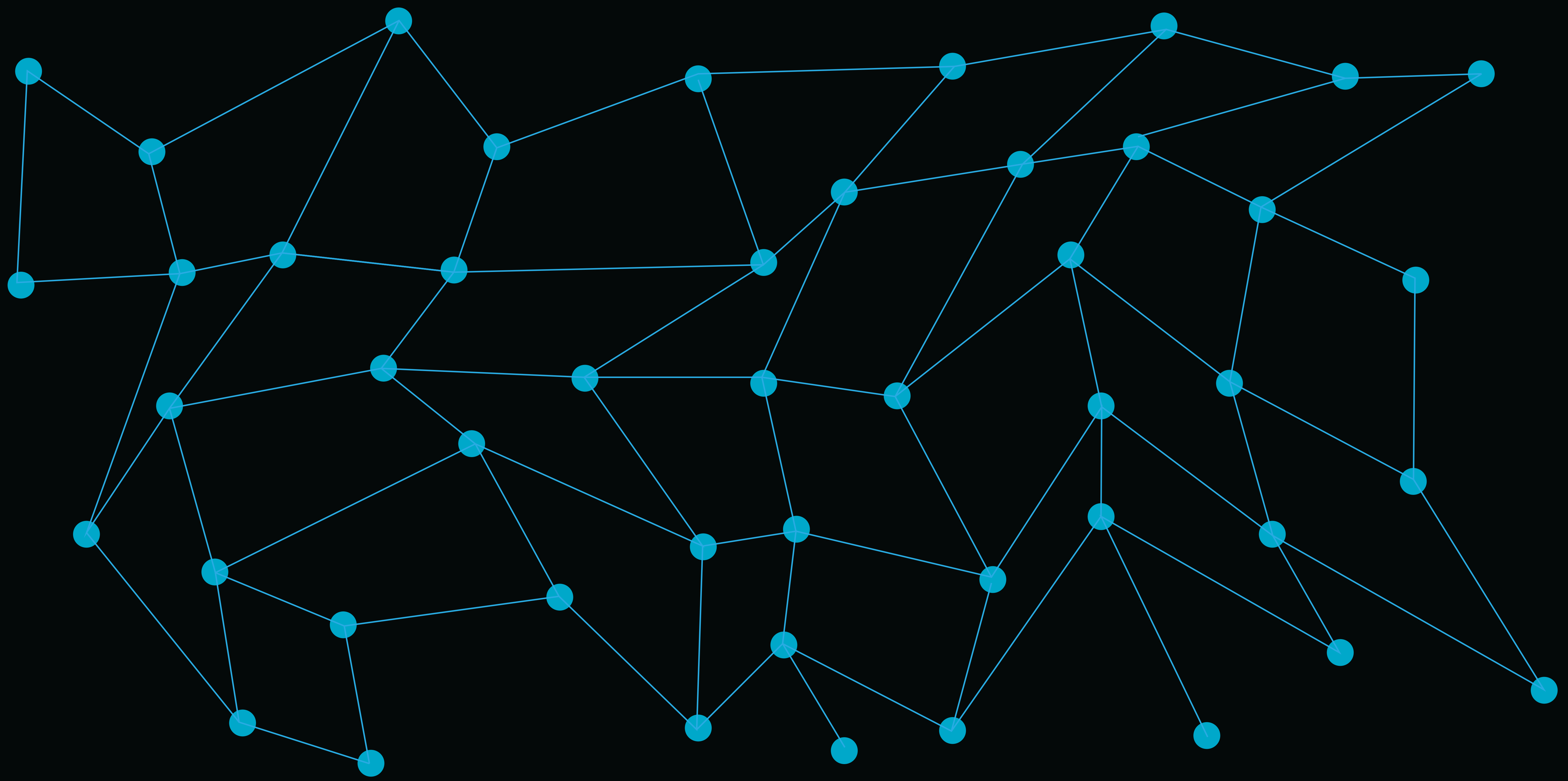
Decentralized System



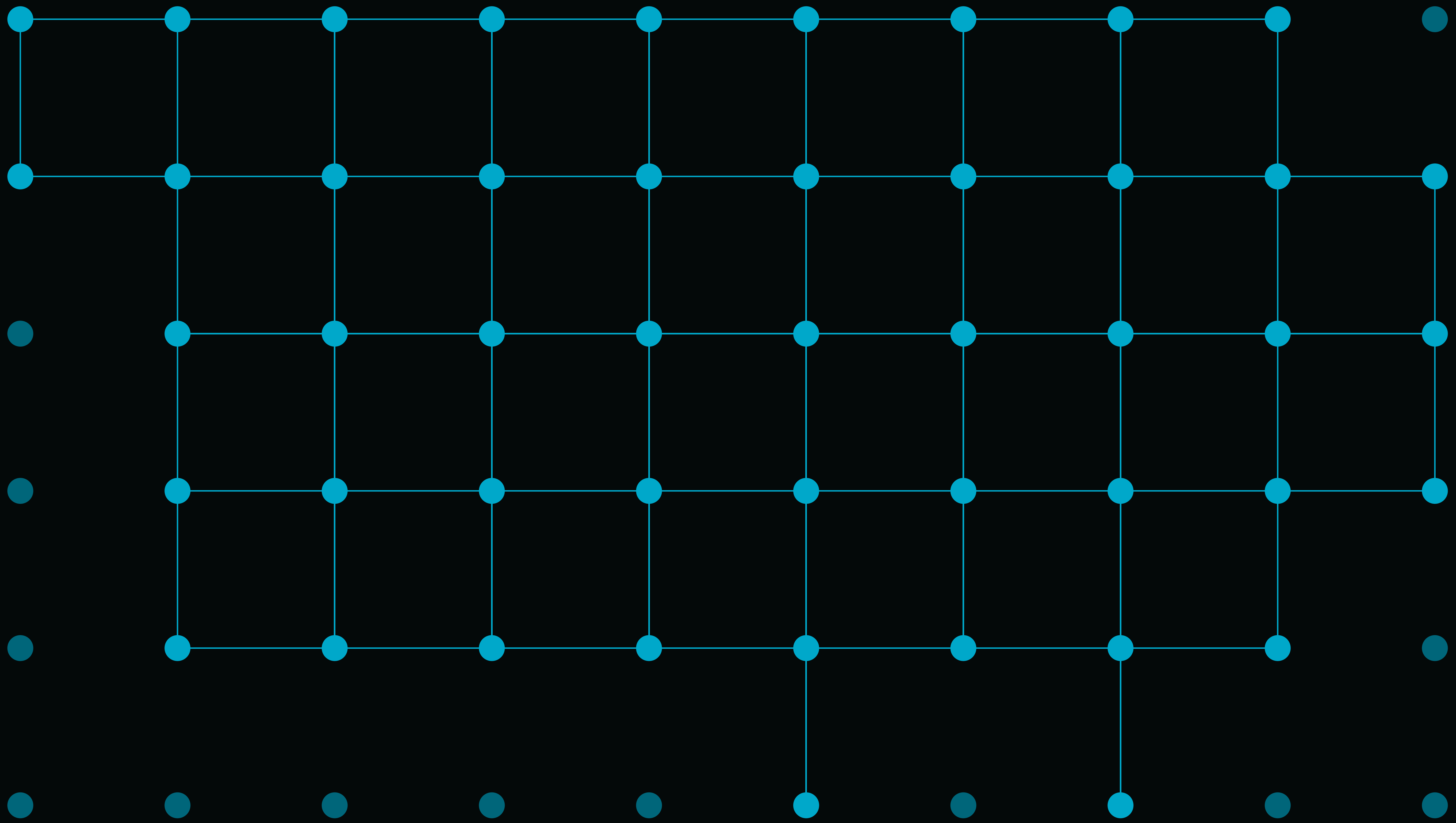
Distributed System



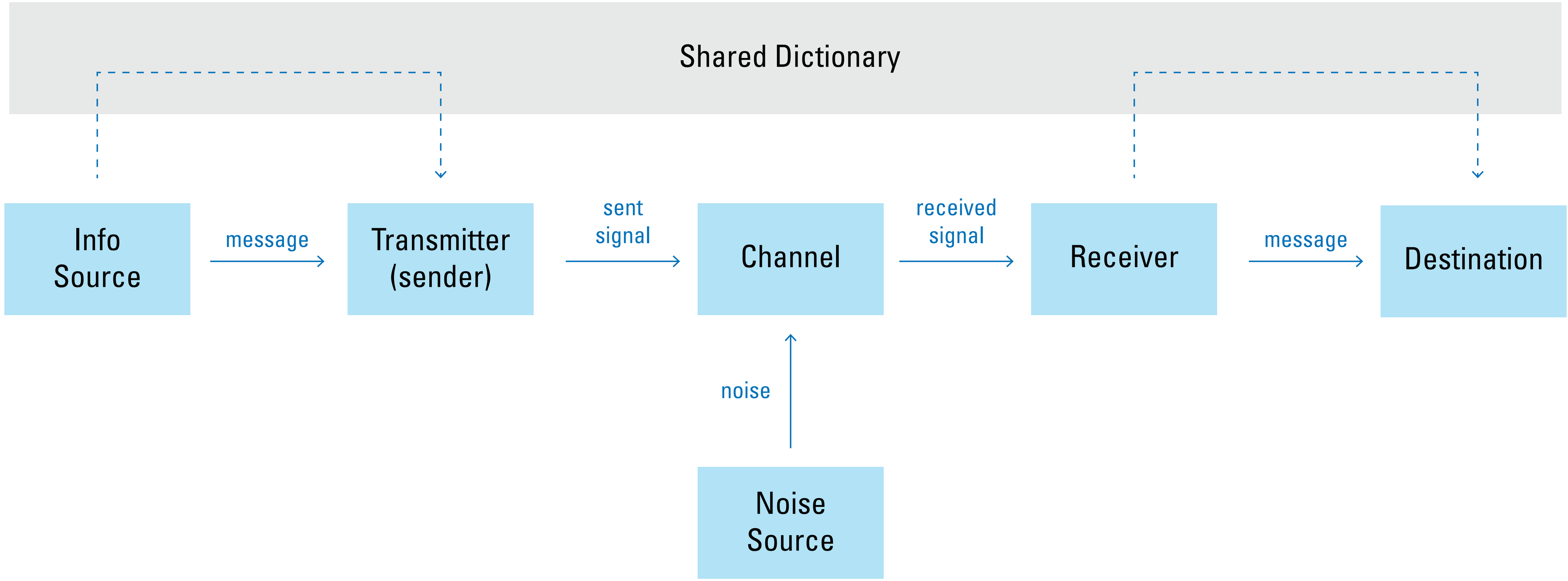
Grid (matrix)



Grid (regularized)



Shannon's Mathematical Model of Communications

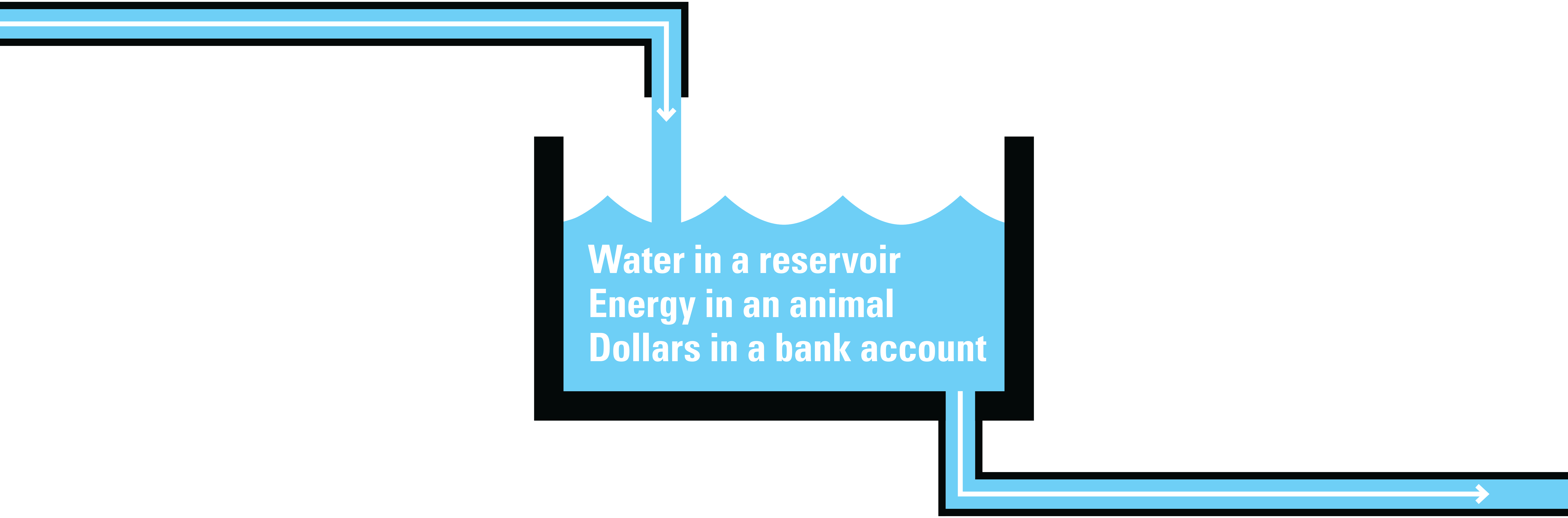


“A stock is the foundation of any system. … the elements … you can see, feel, count, or measure at any given time.

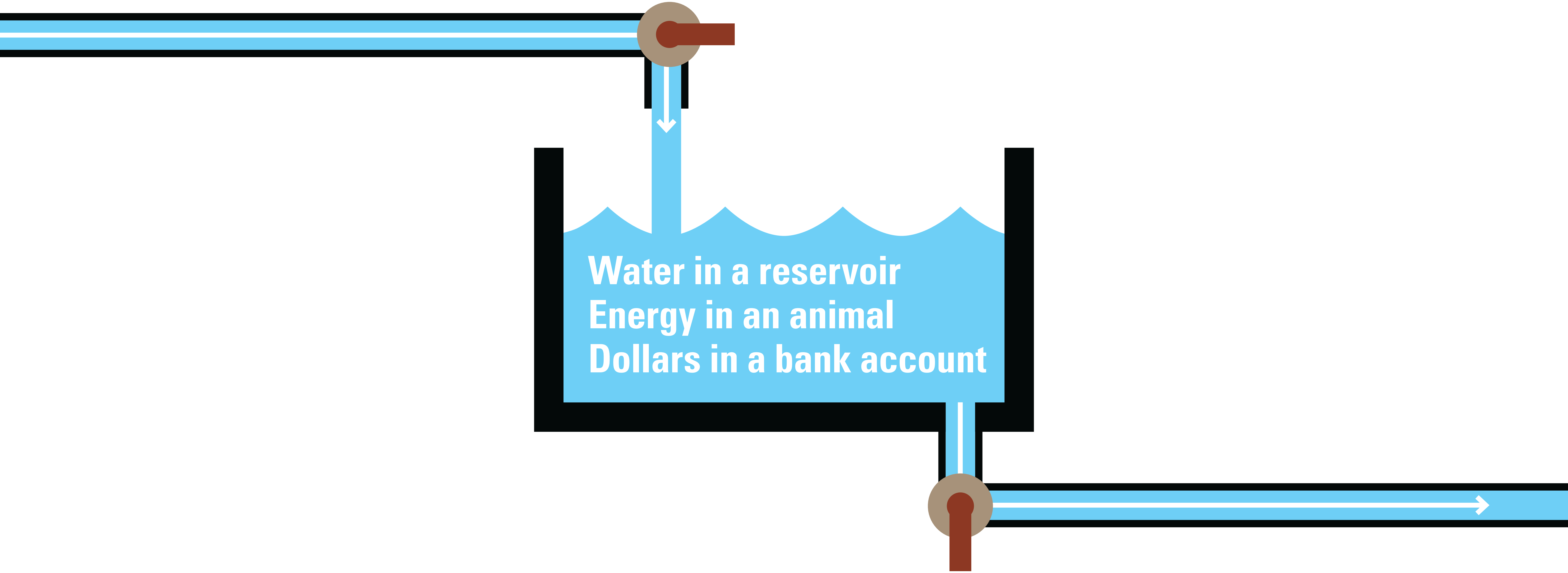
… an accumulation of material or information that has built up over time.
It may be the water in a bathtub, a population, the books in a bookstore,
the wood in a tree, the money in a bank, your own self-confidence.
A stock does not have to be physical. Your reserve of good will toward others
or your supply of hope that the world can be better are both stocks.”

— Donella Meadows

Dynamic equilibrium is a state of balance—
a resource that stays at the same level
even as it flows through a system.



In order to maintain dynamic equilibrium, ‘feedback’ from the stock must regulate inflow or outflow.



“Systems of information-feedback control are fundamental to all life and human endeavor, from the slow pace of biological evolution to the launching of the latest space satellite. . . . Everything we do as individuals, as an industry, or as a society is done in the context of an information-feedback system.”

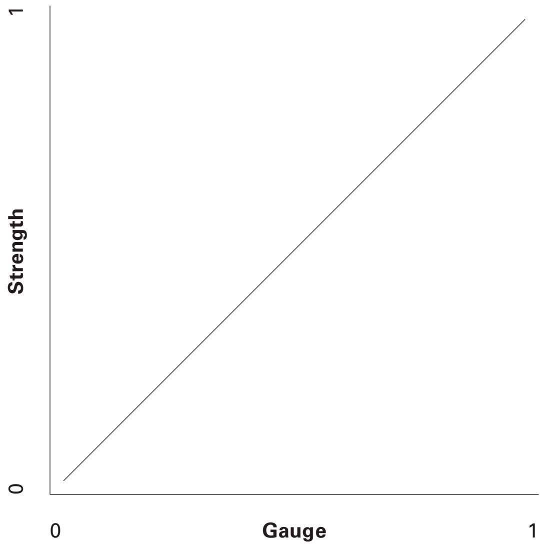
– Jay W. Forrester

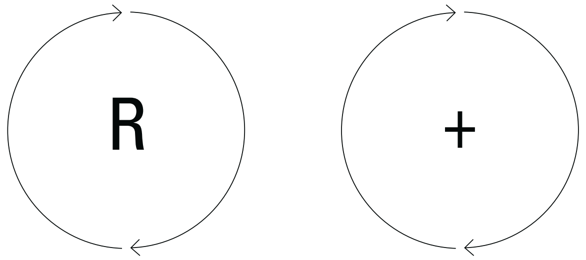
Feedback can be ‘positive’…

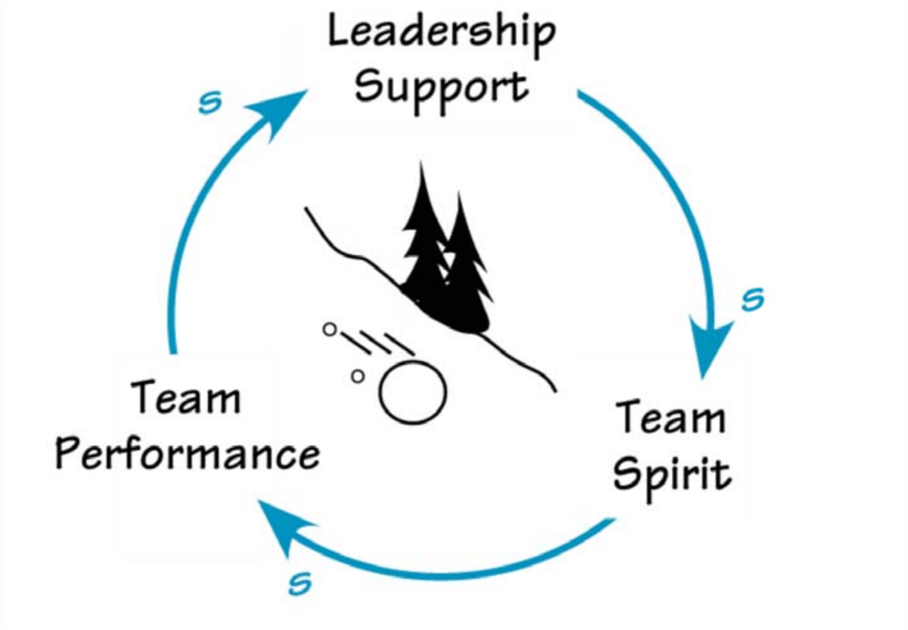
Positive Feedback (+) — a reinforcing loop (R) —
A increases B, and B increases A.

Proportional Relationships

For example, needle strength is proportional to Gauge.
Thin needles are weaker than thick ones.





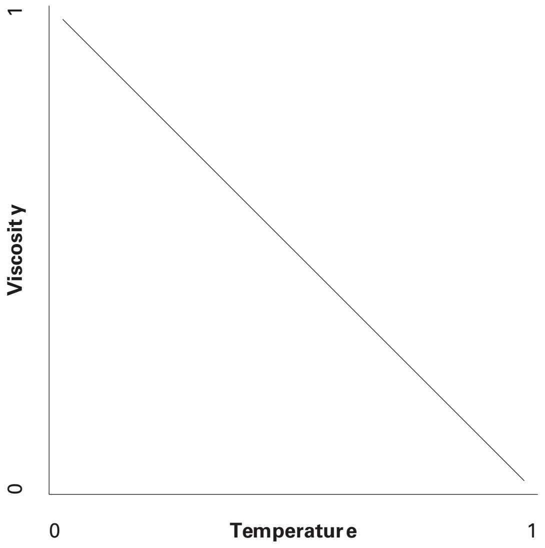


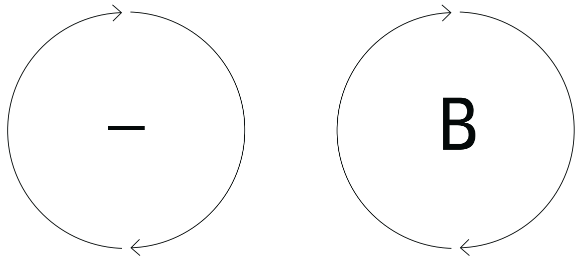
or ‘negative’.

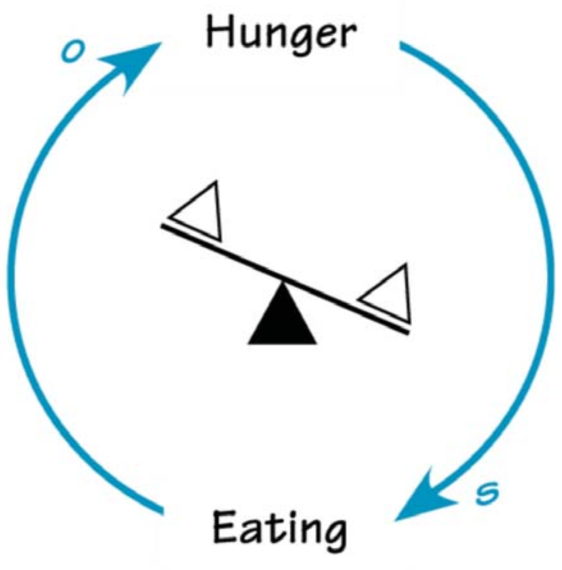
Negative Feedback (-) — a balancing loop (B) —
A increases B, and B decreases A.

Inverse Relationships

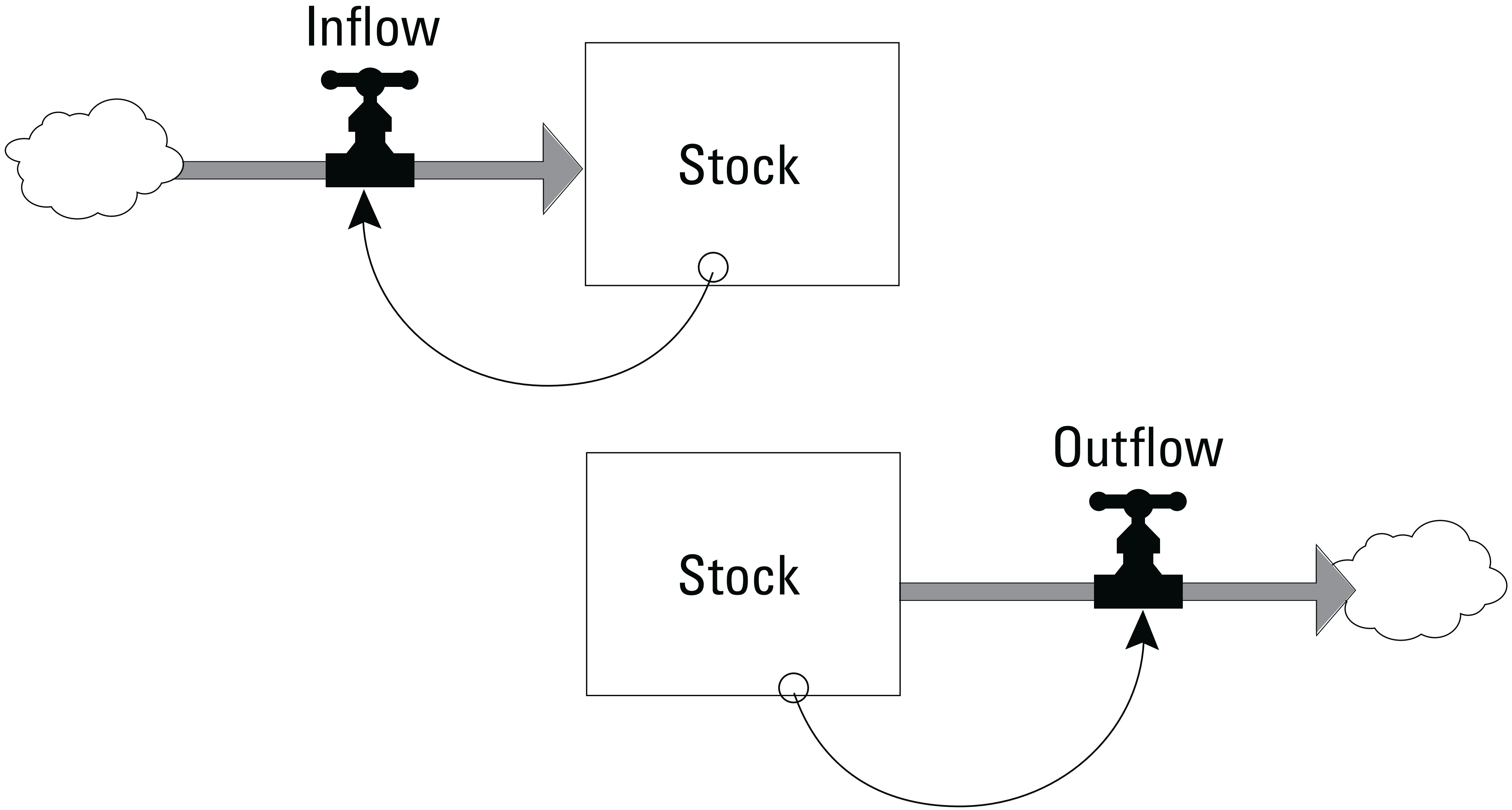
For example, the viscosity of a compound is inversely proportional to temperature. Cold compounds are thicker and more viscous then warm ones.



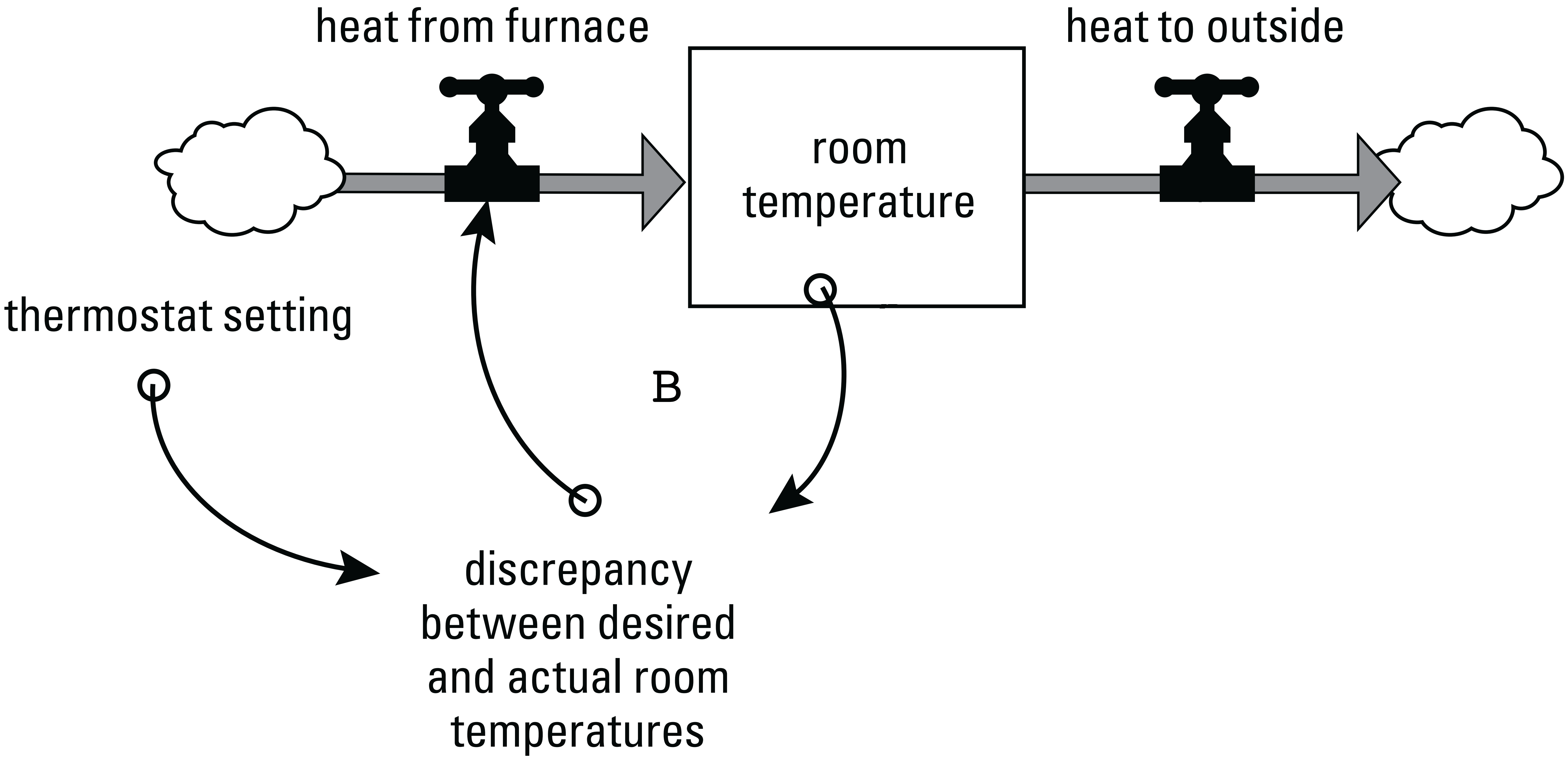




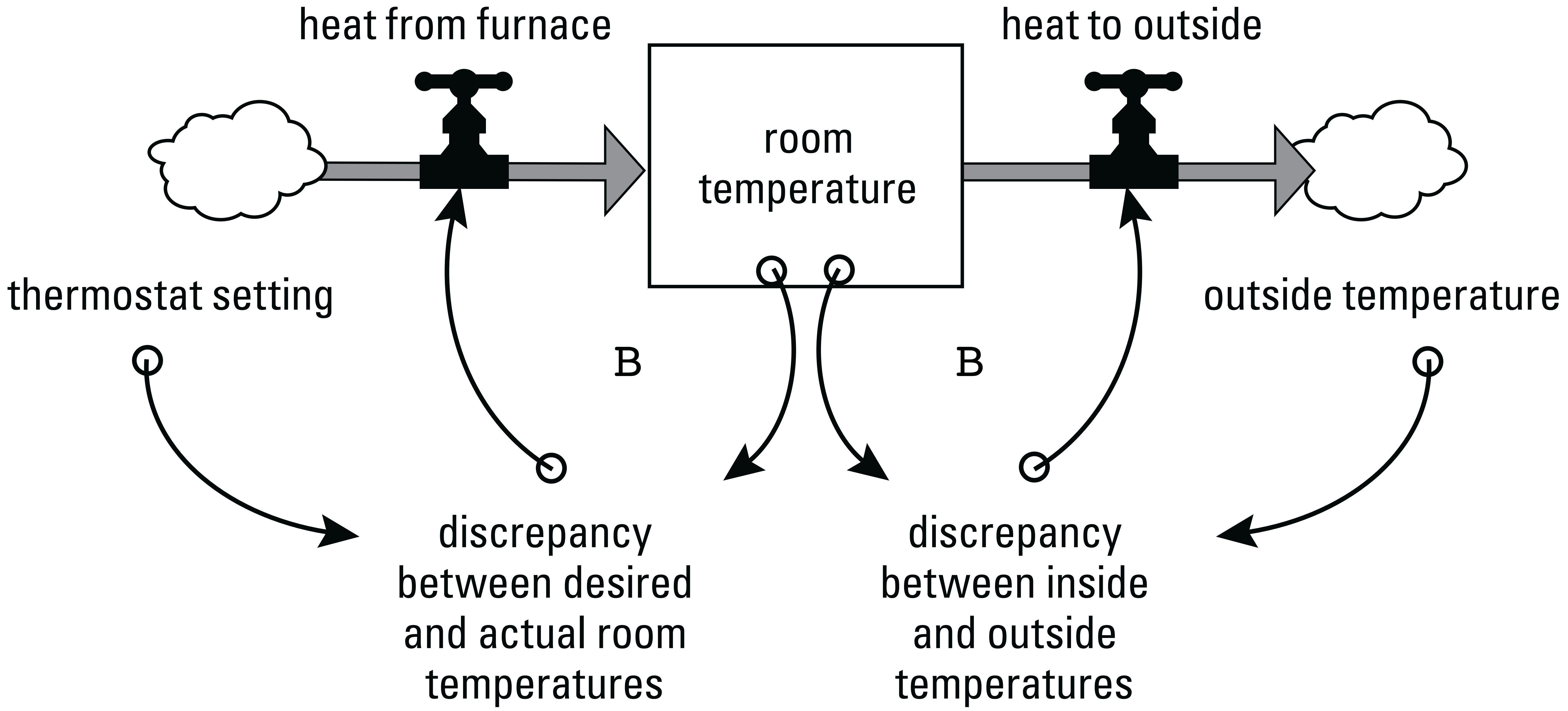
In Meadow's view, **"A feedback loop is formed when changes in a stock affect the flows into or out of that same stock."**



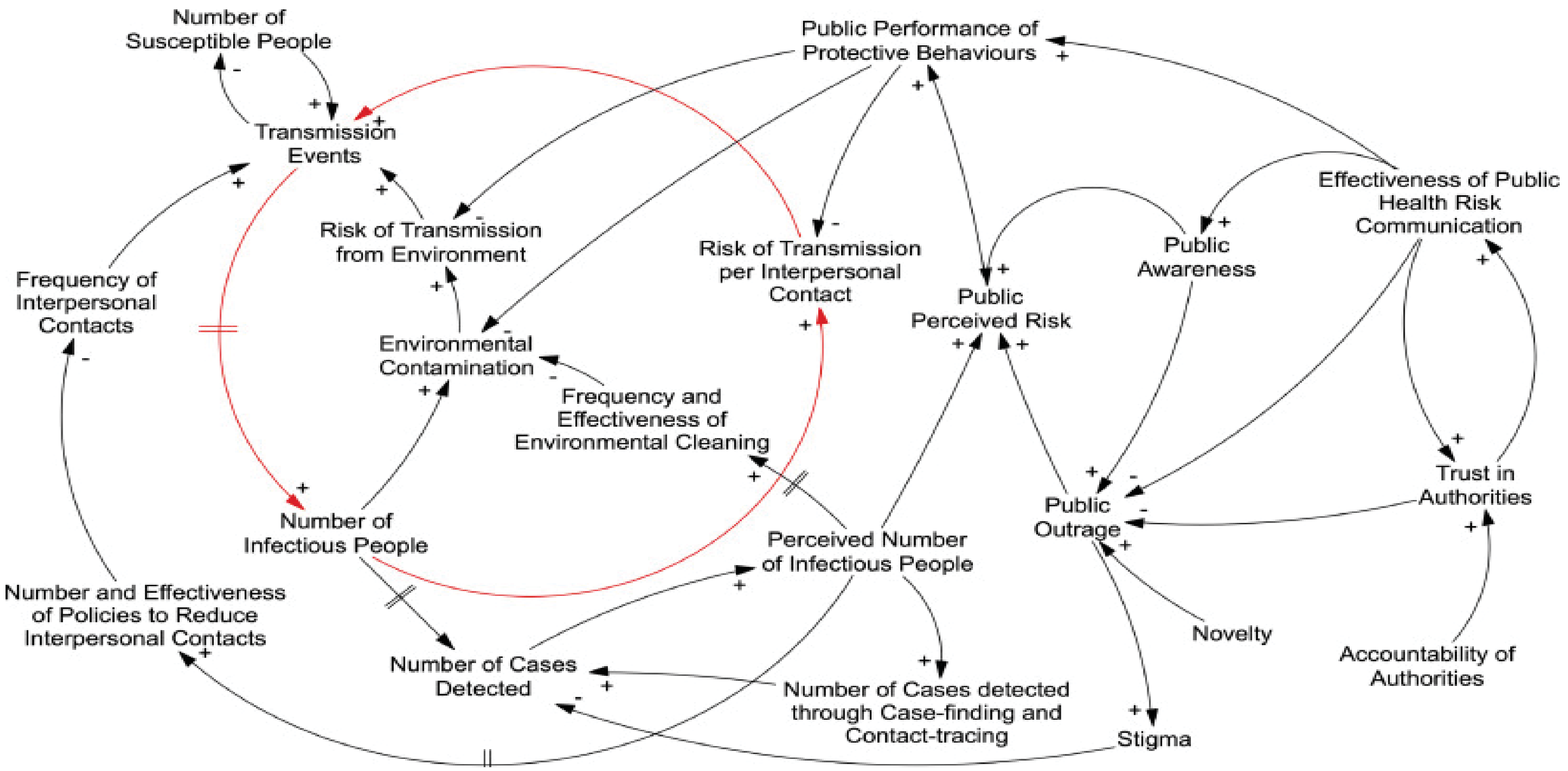
Meadows: **“Room temperature regulated by a thermostat and furnace.”**



Meadows: **"Room temperature is *also* regulated by outside temperature."**



Meadows' language of 'balancing' and 're-inforcing' loops has developed into a 'formalism' called Causal Loop Diagrams (CDLs).



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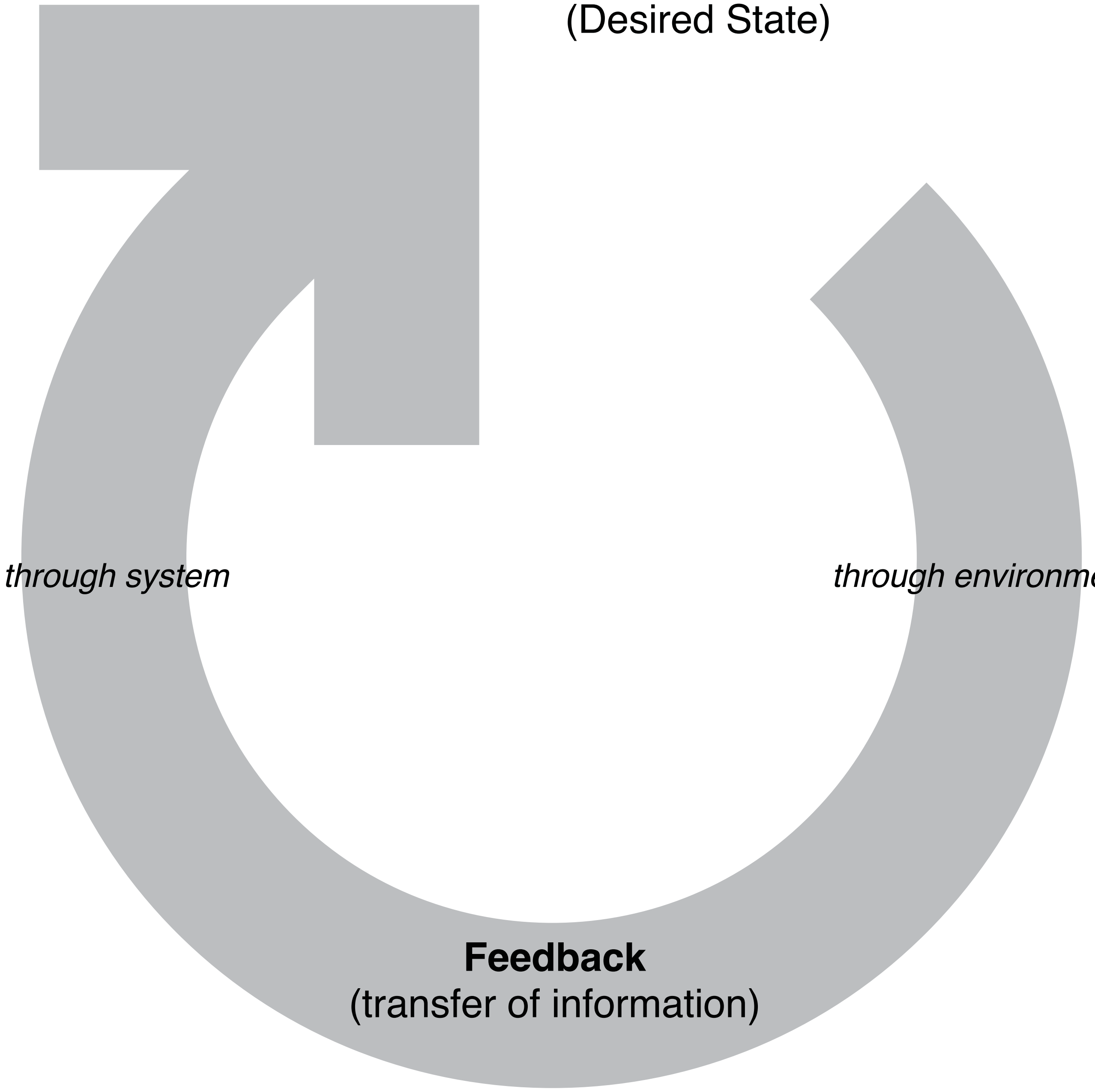
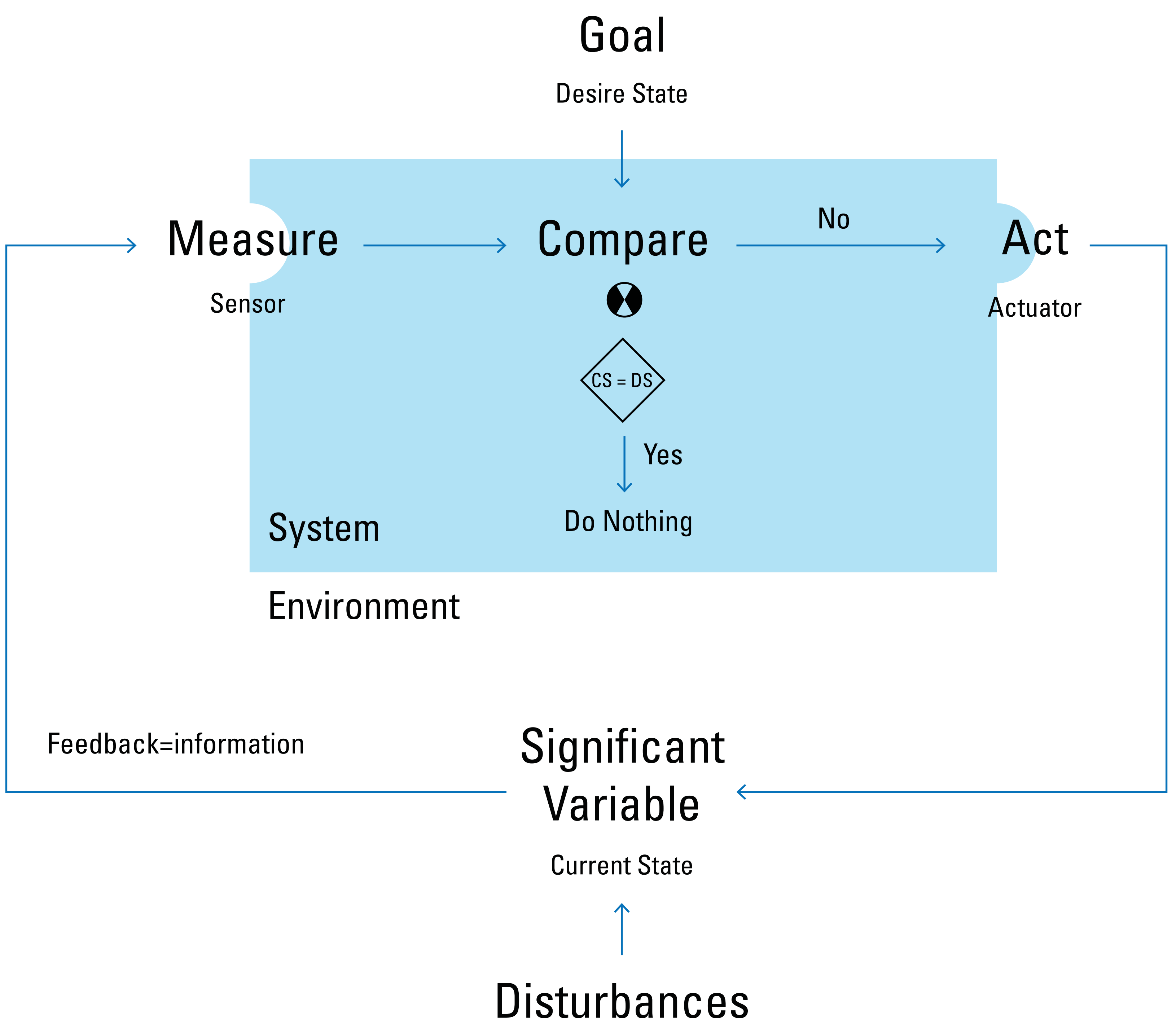
Feedback: Basics



Feedback Loop Framework



Self-regulating systems may be:

Mechanical (+ digital)

- Float valve, as in a toilet
- Flyball governor, as on a steam engine
- Thermostat, in HVAC, refrigerators, etc.
- Cruise control, maintaining speed
- Cruise control, maintaining speed
- Auto-pilot, maintaining direction
- Auto-focus, in cameras
- Fire control systems, targeting missiles

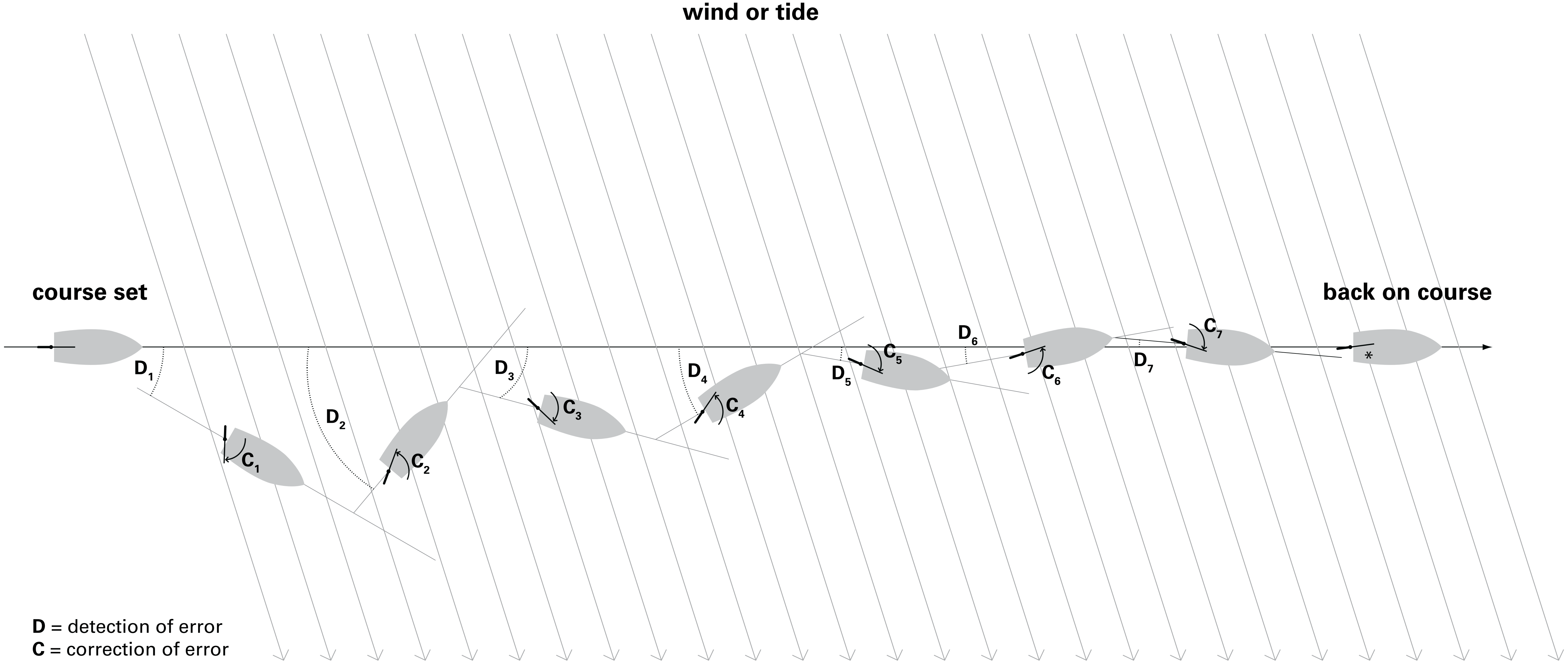
Biological (chemical), i.e., homeostasis

- Body temperature
- Blood pressure
- Blood glucose level
- 02 level
- Hydration level
- Salt levels, (NaCl, KCl, etc.
- Population in a stable ecology

Social (cultural + linguistic)

- Norms + their enforcement
- Laws + government
- Rules in games + sports
- Markets (supply + demand of goods)
- Maintaining services (infrastructure)
- Managing organizations
- Designing products

Cybernetics as steering — Staying "on course"



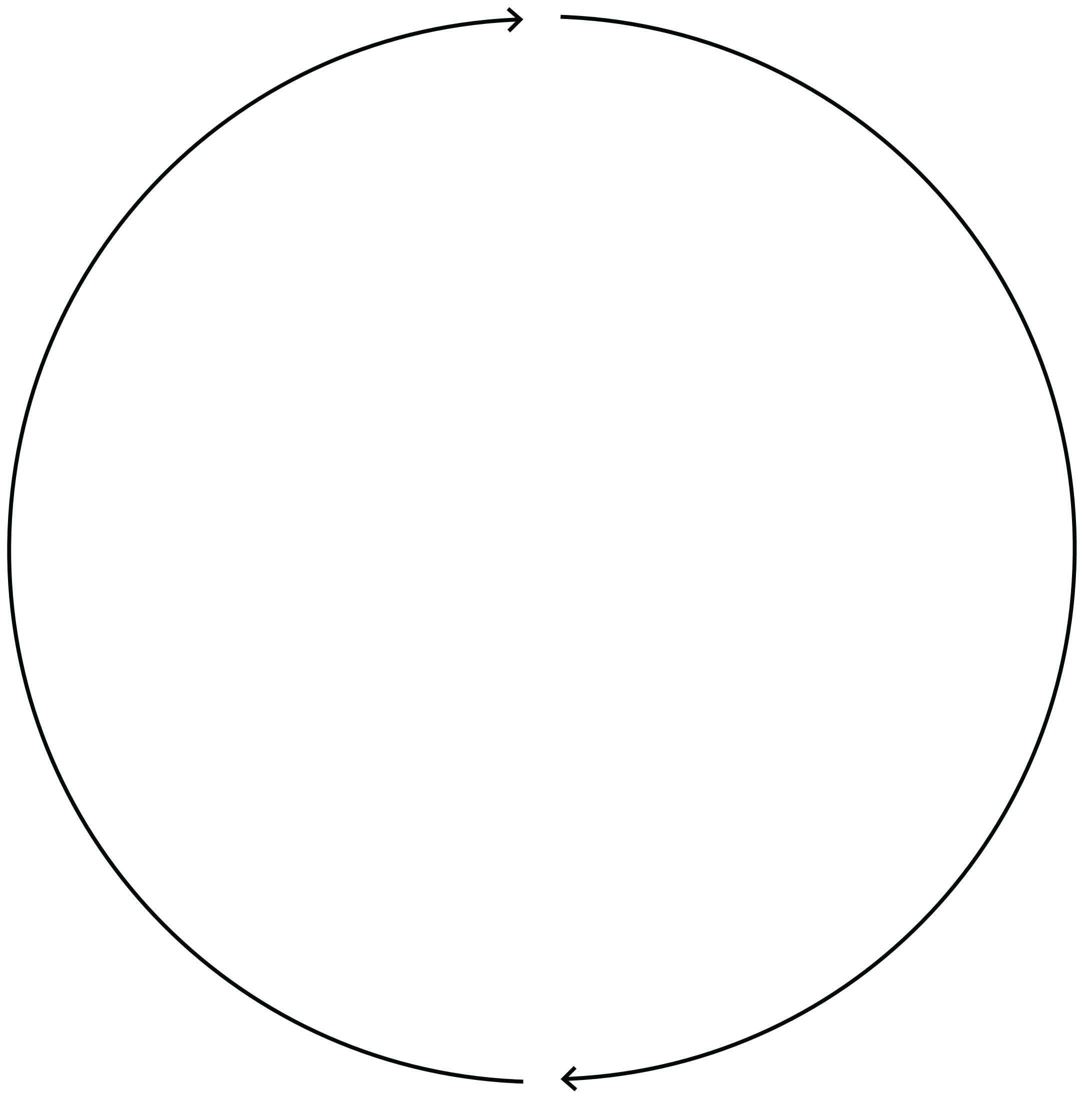
D = detection of error
C = correction of error

*Rudder needs to be maintained at a slight starboard angle (left turn) to compensate for wind and tide.

Steering as feedback loop: detection and correction of error.

D = Detection of error

compares current heading
with desired heading



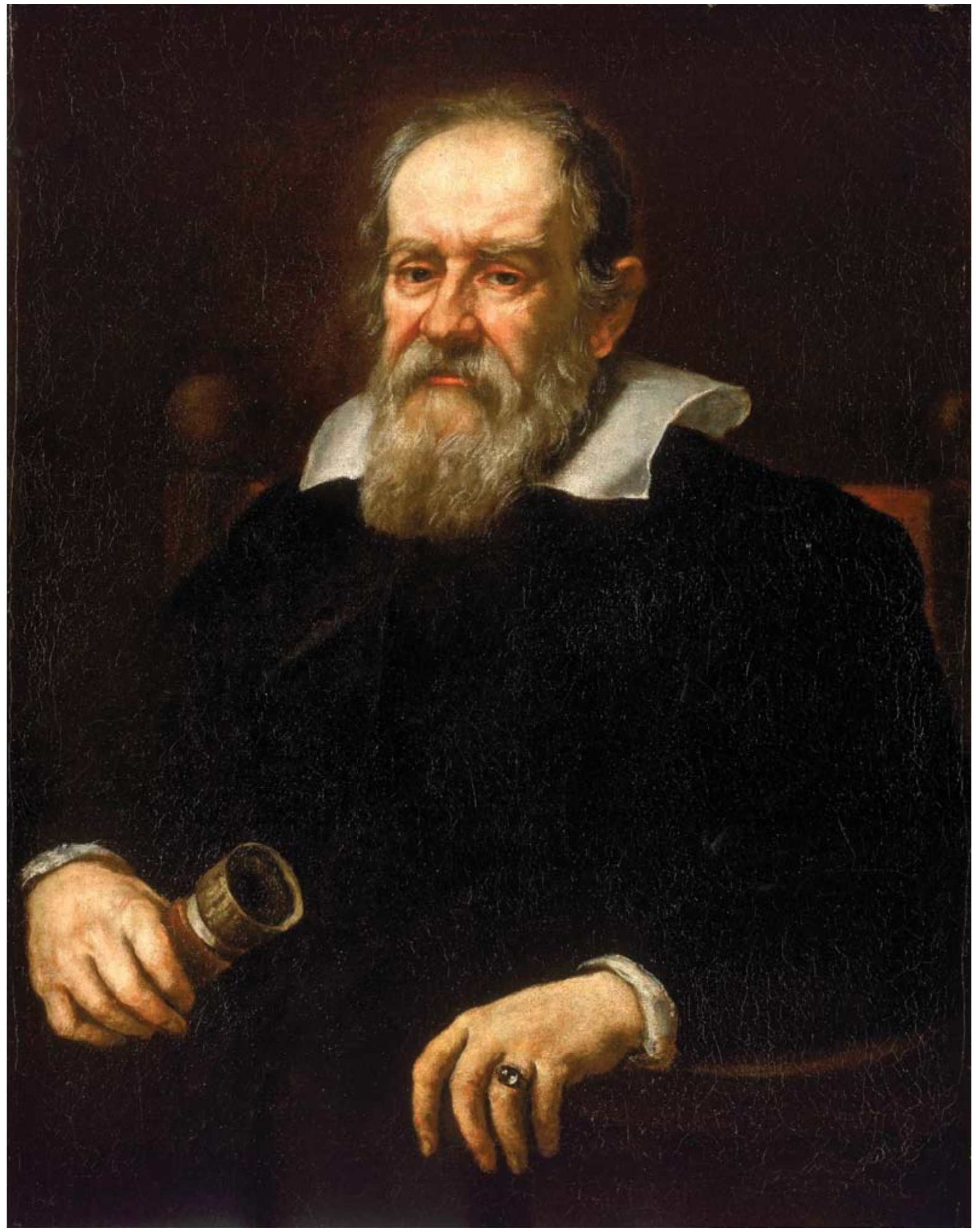
C = Correction of error

adjust rudder to correct heading

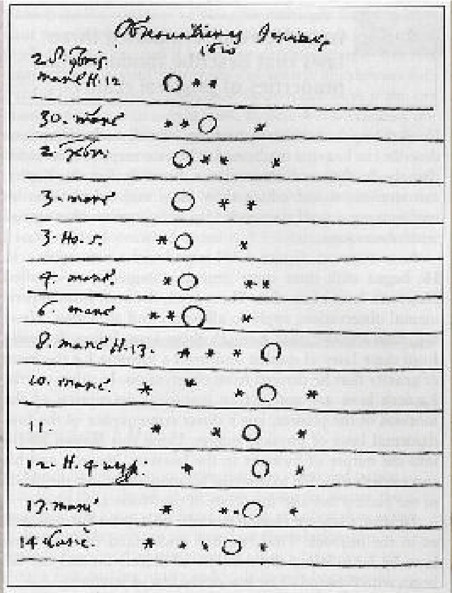
Measurement
How do we detect error?

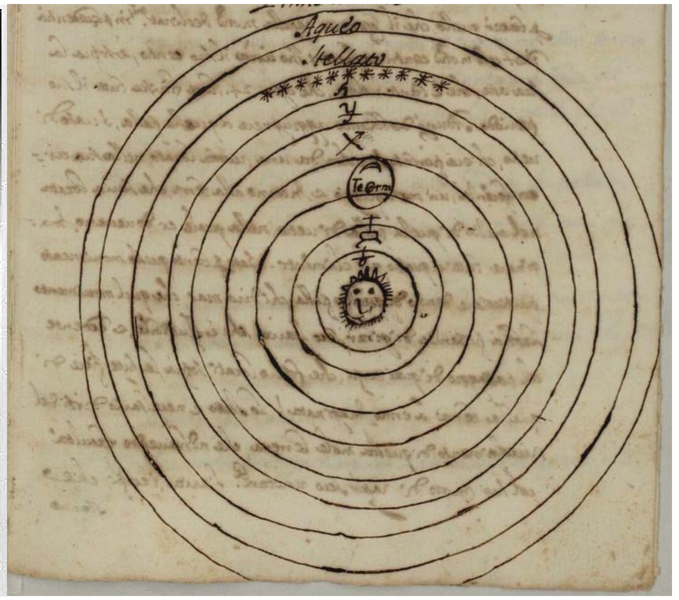
Measurement is a form of observation, for example,

Galileo's observations of the satellites of Jupiter caused a revolution in astronomy: a planet with smaller planets orbiting it did not conform to the principles of Aristotelian cosmology.
– Galileo Galilei, 1564-1642



Jupiter's moons and Heliocentrism



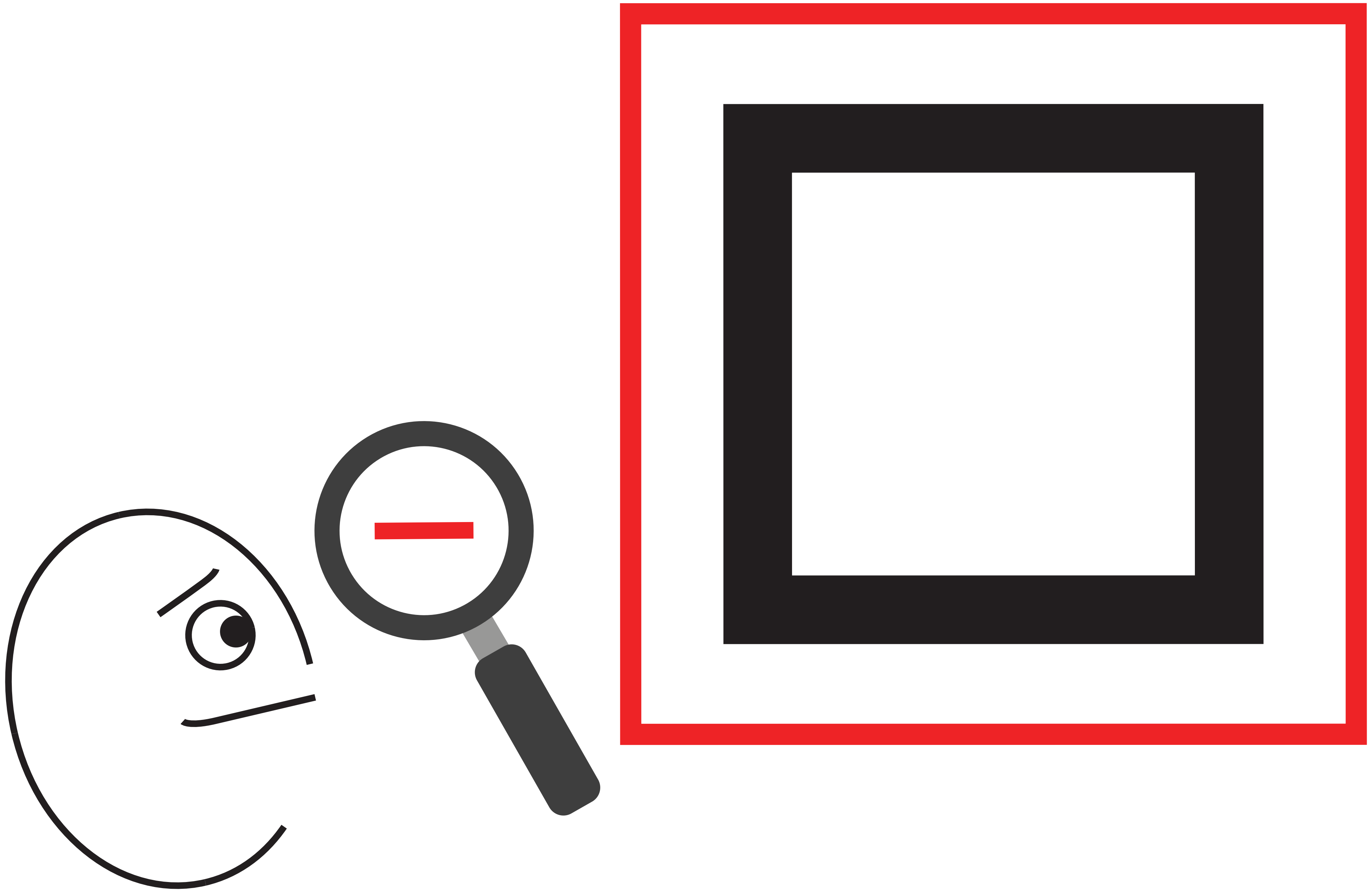


Building an Instrument → observing → recording → tabulating → analyzing → modeling

Bernard Scott's Principles of Observation:

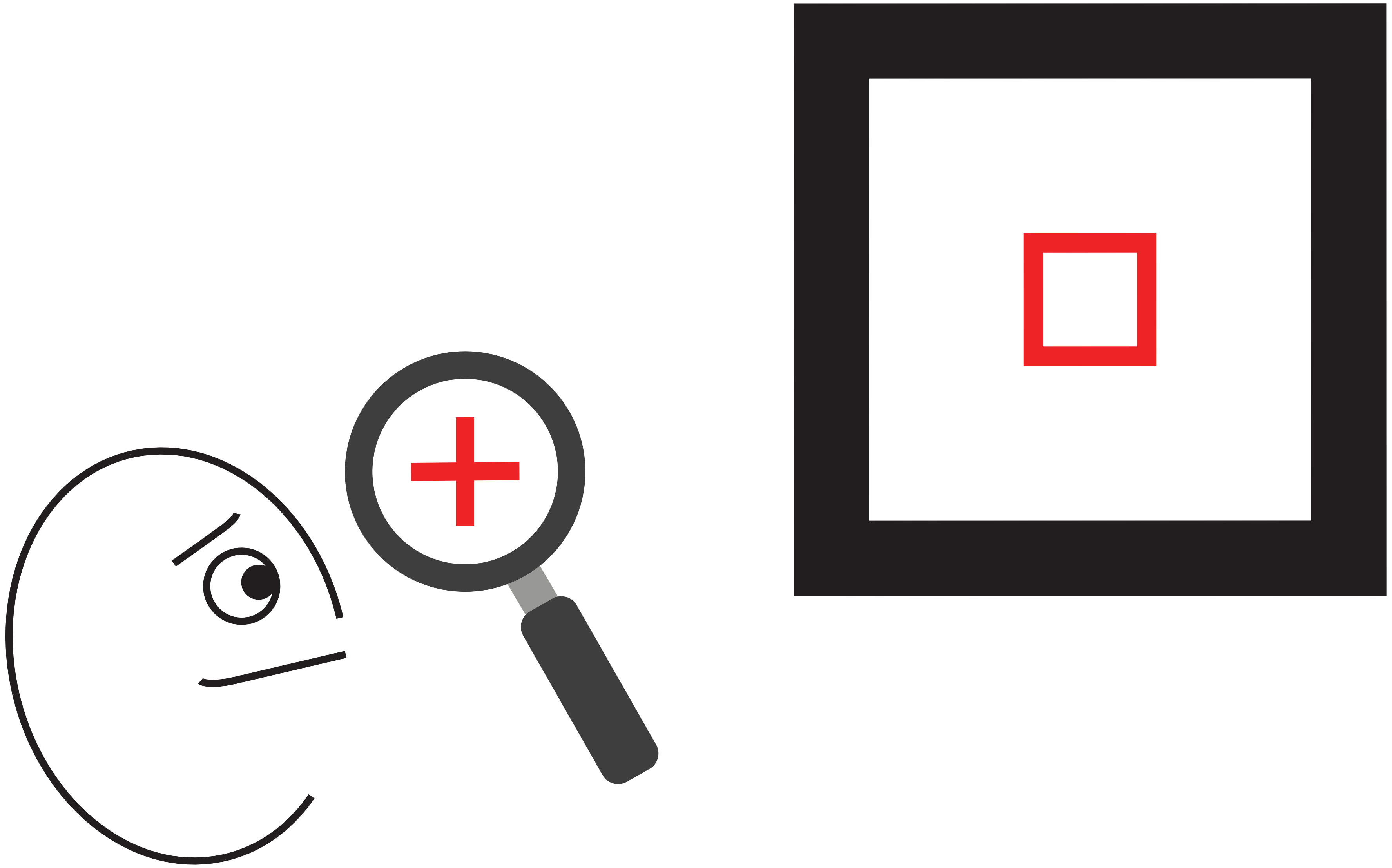
1. There is always a bigger idea.

Sometimes you need to zoom out to see the full picture.

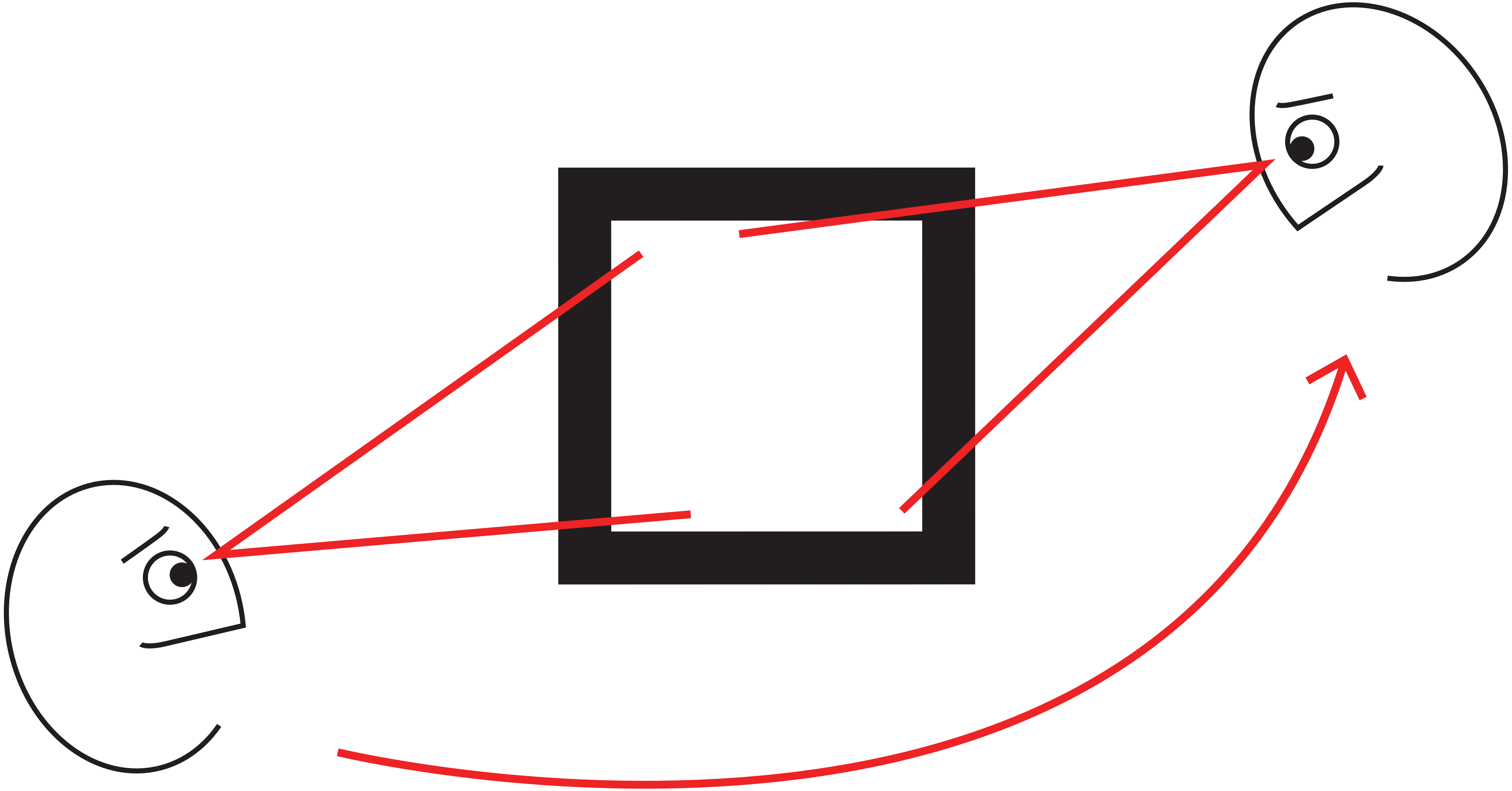


2. There is always another level of detail.

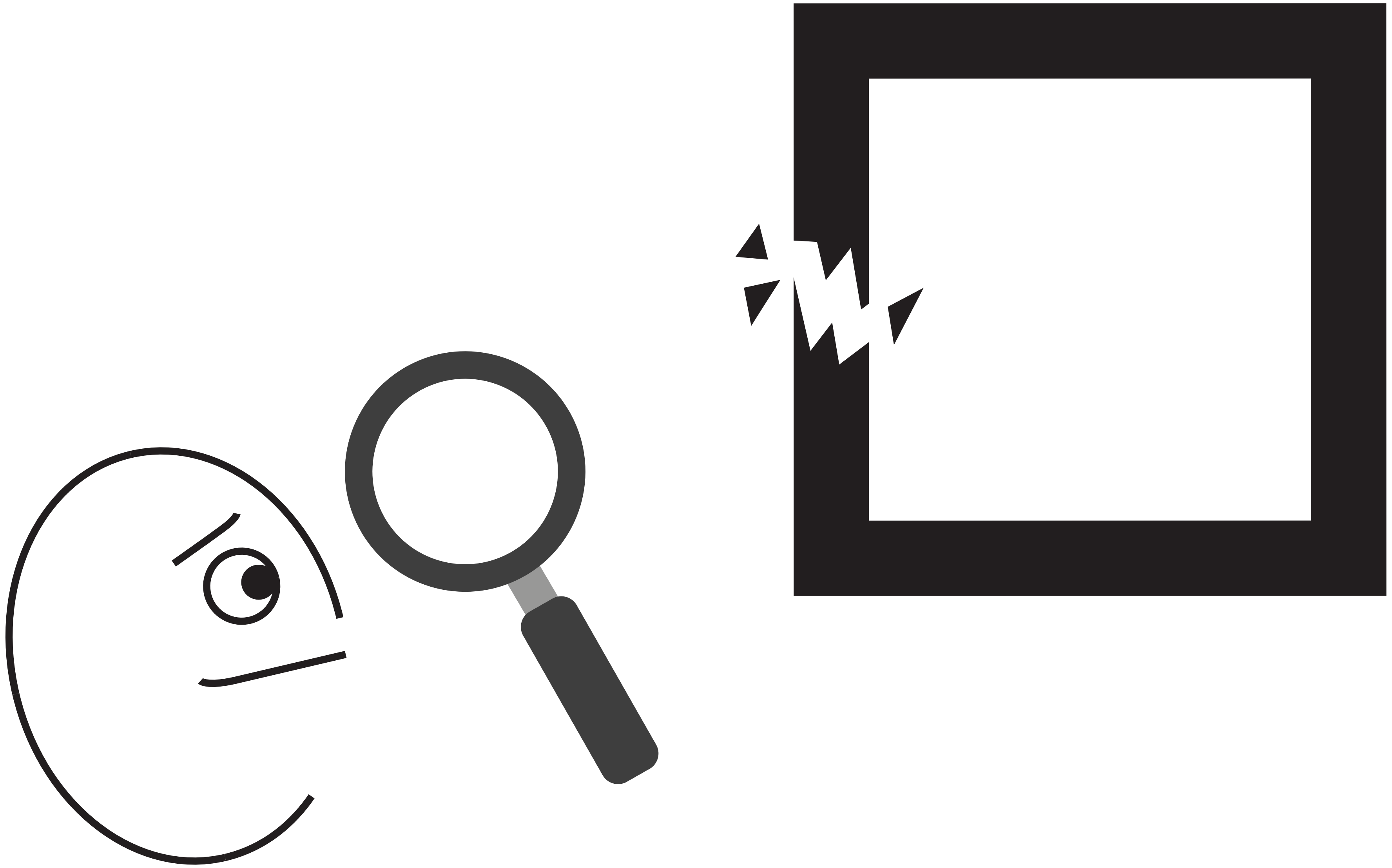
Zooming in can help.



3. There is always another perspective.



4. There is always error.



5. There is always the unexpected.

What can we observe? or ‘sense’?

- Shape, position, movement
- Contrast or change
- Color (hue, value, saturation)
- Sound (pitch, tone, volume)
- Smell and taste
- Temperature and wetness
- Texture and solidity (resistance)
- Our position in space + changes to it

These qualities may be enhanced by tools, such as the telescope or microscope.

Also, other qualities, which we cannot sense, may be ‘mapped’ onto those we can sense, for example, infrared may be mapped to RGB.

In that way, the invisible may be made visible.

These images of the DCP Pegasus gas plant in Midkiff, Texas, show a gas leak that would otherwise be invisible to the naked eye. By using a transfer function, we are able to create a mapping in order to make the data understandable.

In order to turn an observation into a measurement, we need a scale. Scales are arbitrary — matters of convention, agreements.

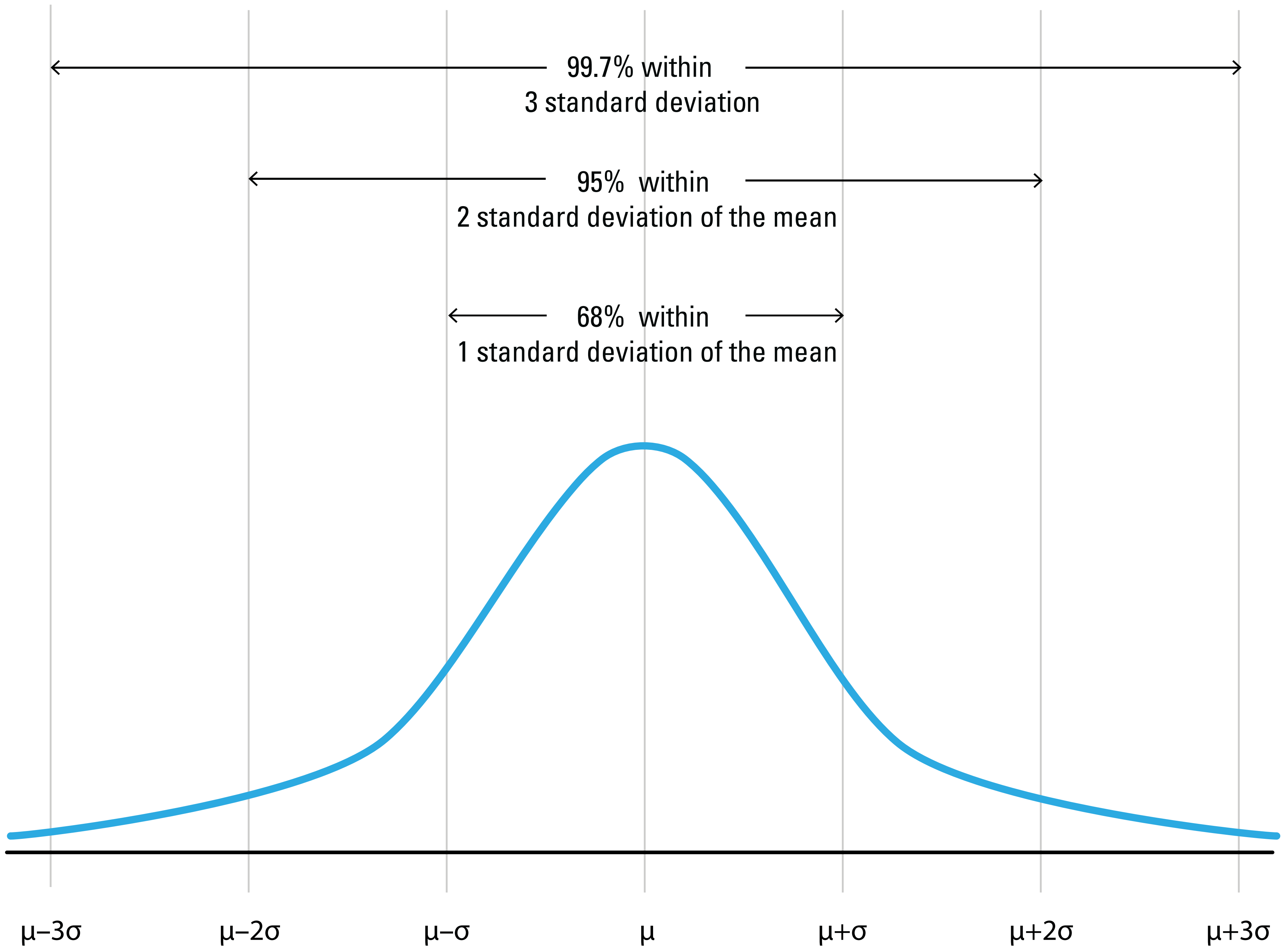
INCHES =	YARDS =	YARDS =	METERS
4 1/2"	1/8 yard	.125 yard	.114 meters
9"	1/4 yard	.25 yard	.229 meters
13 1/2"	3/8 yard	.375 yard	.343 meters
18"	1/2 yard	.5 yard	.457 meters
22 1/2"	5/8 yard	.625 yard	.572 meters
27"	3/4 yard	.75 yard	.686 meters
31 1/2"	7/8 yard	.875 yard	.8 meters
36"	1 yard	1 yard	.914 meters
40 1/2"	1 1/8 yard	1.125 yard	1.029 meters
45"	1 1/4 yard	1.25 yard	1.143 meters
49 1/2"	1 3/8 yard	1.375 yard	1.257 meters
54"	1 1/2 yard	1.5 yard	1.372 meters
58 1/2"	1 5/8 yard	1.625 yard	1.486 meters
63"	1 3/4 yard	1.75 yard	1.6 meters
67 1/2"	1 7/8 yard	1.875 yard	1.715 meters
72"	2 yards	2 yards	1.829 meters

What can we measure?

- Length - meter (m)
- Time - second (s)
- Amount of substance - mole (mole)
- Electric current - ampere (A)
- Temperature - kelvin (K)
- Luminous intensity - candela (cd)
- Mass - kilogram (kg)

- Magnetism - gauss
- Energy - Joule (J)

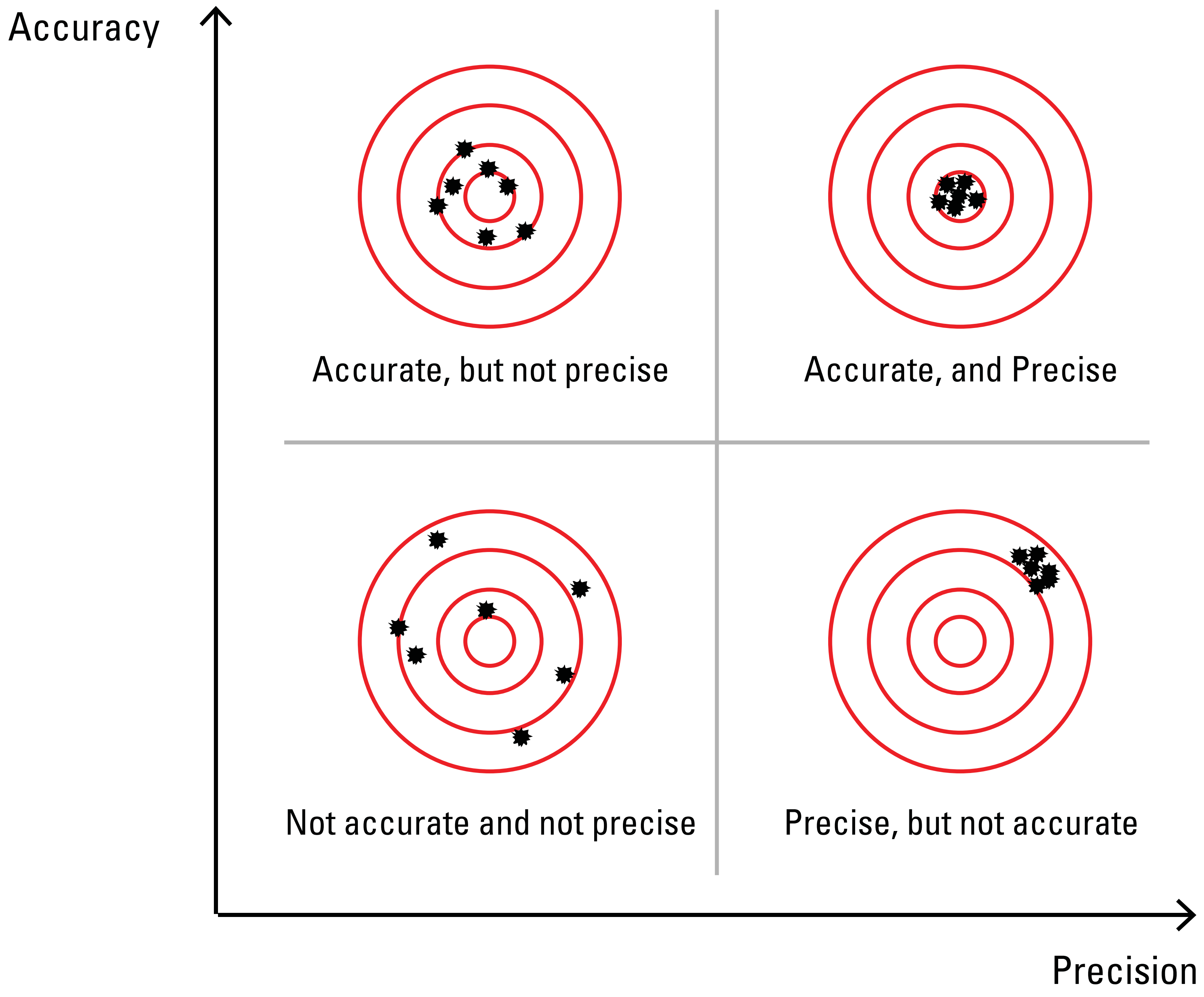
Gauss normal distribution / Bell Curve



Accuracy + Precision

Accuracy = how close a measurement is to the true or accepted value

Precision = how close two adjacent measures can be (also, how many decimal places are available)



Confusion Matrix or Error Matrix

Disease (or Gold Standard)

Test Result	+	–	
+	True Positive (TP) eqv. with hit	False Positive (FP) eqv. with false alarm, Type I error	Total Positive
–	False Negative (FN) eqv. with miss, Type II error	True Negative (TN) eqv. with correct rejection	Total Negative
	Total Diseased	Total Healthy	

accuracy (ACC)

$$\mathrm{ACC} = \frac{\mathrm{TP}+\mathrm{TN}}{\mathrm{P}+\mathrm{N}} = \frac{\mathrm{TP}+\mathrm{TN}}{\mathrm{TP}+\mathrm{TN}+\mathrm{FP}+\mathrm{FN}}$$

precision or positive predictive value (PPV)

$$\mathrm{PPV} = \frac{\mathrm{TP}}{\mathrm{TP}+\mathrm{FP}} = 1 - \mathrm{FDR}$$

sensitivity, recall, hit rate, or true positive rate (TPR)

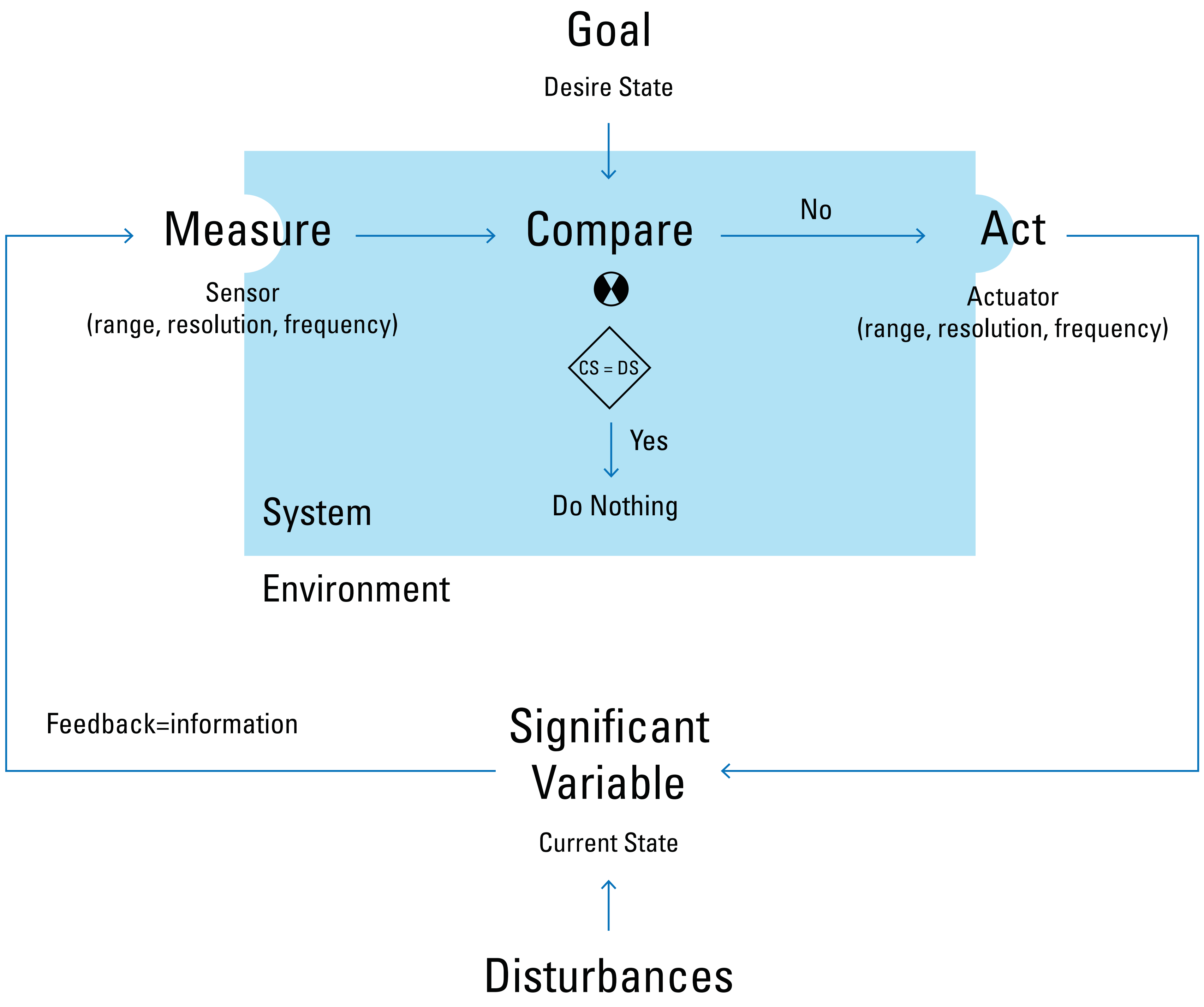
$$\mathrm{TPR} = \frac{\mathrm{TP}}{\mathrm{P}} = \frac{\mathrm{TP}}{\mathrm{TP}+\mathrm{FN}} = 1 - \mathrm{FNR}$$

specificity, selectivity or true negative rate (TNR)

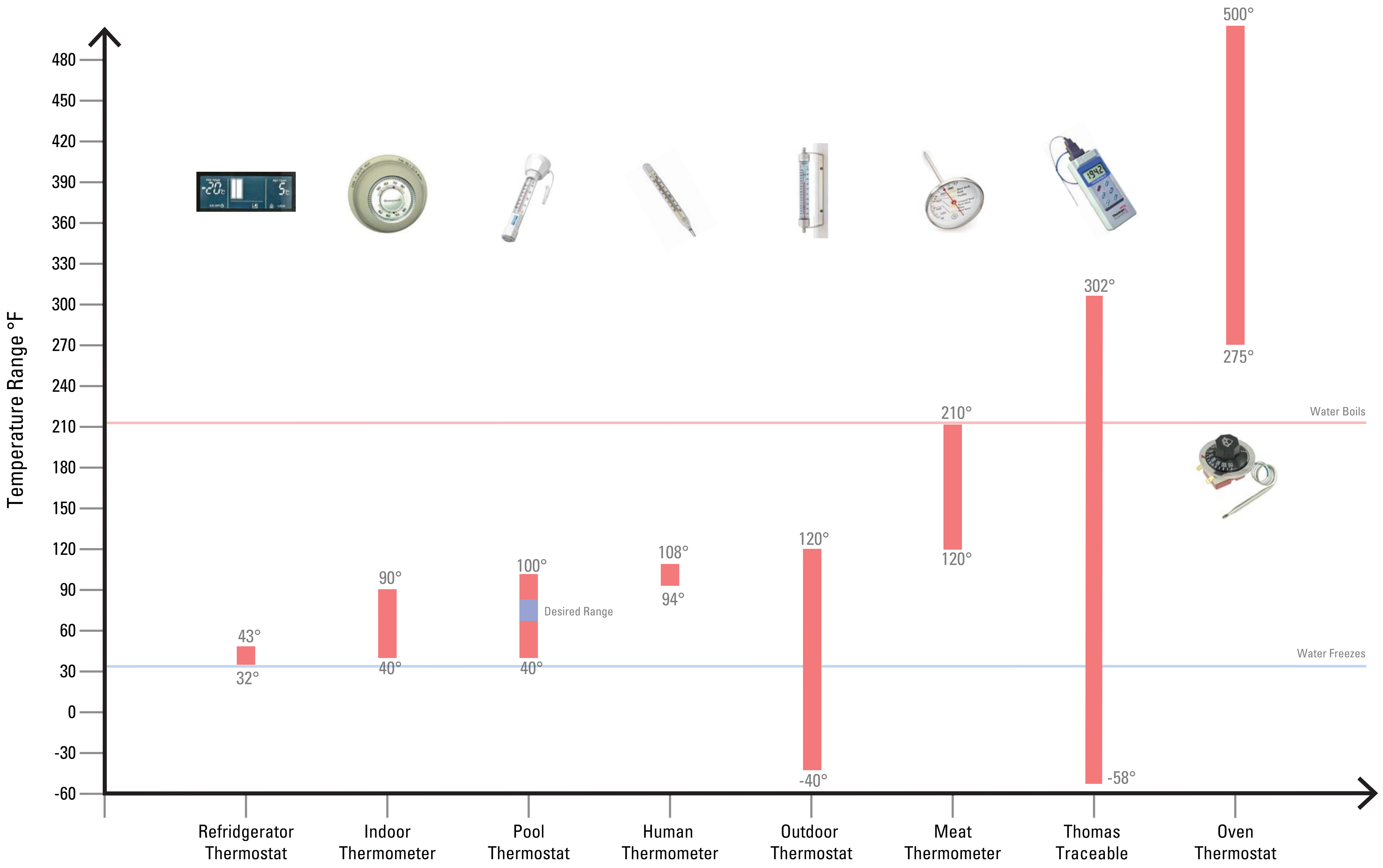
$$\mathrm{TNR} = \frac{\mathrm{TN}}{\mathrm{N}} = \frac{\mathrm{TN}}{\mathrm{TN}+\mathrm{FP}} = 1 - \mathrm{FPR}$$

Adding specificity to feedback models: Range, Resolution, and Frequency

The effectiveness of a control system's sensor and actuator depend on their range, resolution, and frequency.

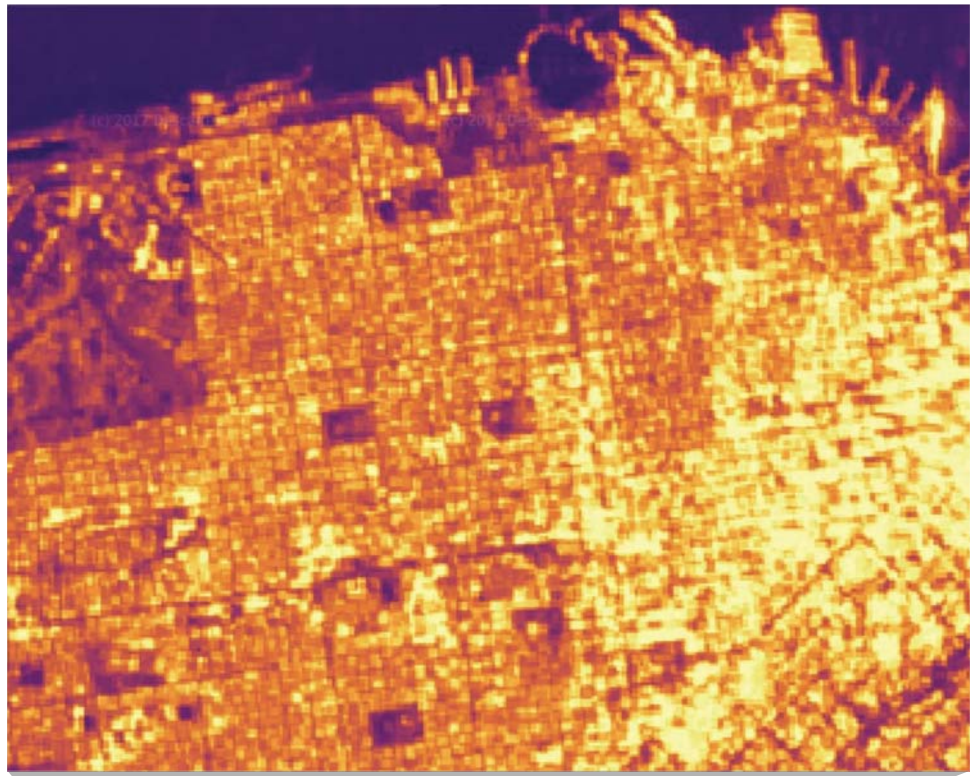


Thermometers measure different ranges, depending on their uses.

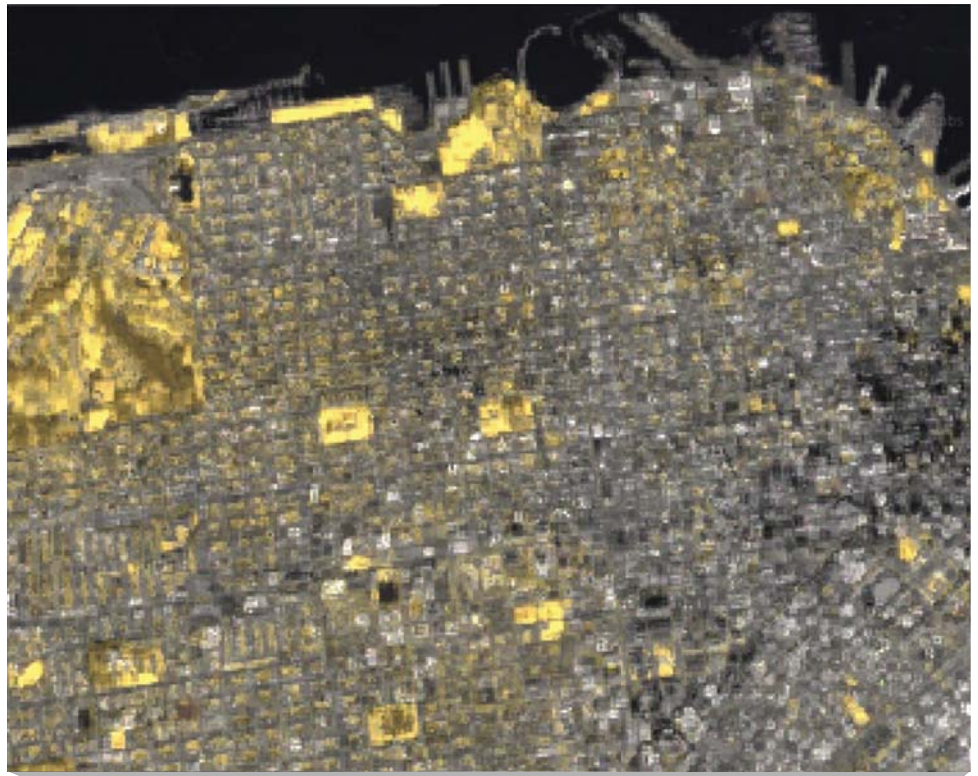


Range defines the extent or limits of a system's measurement or action.

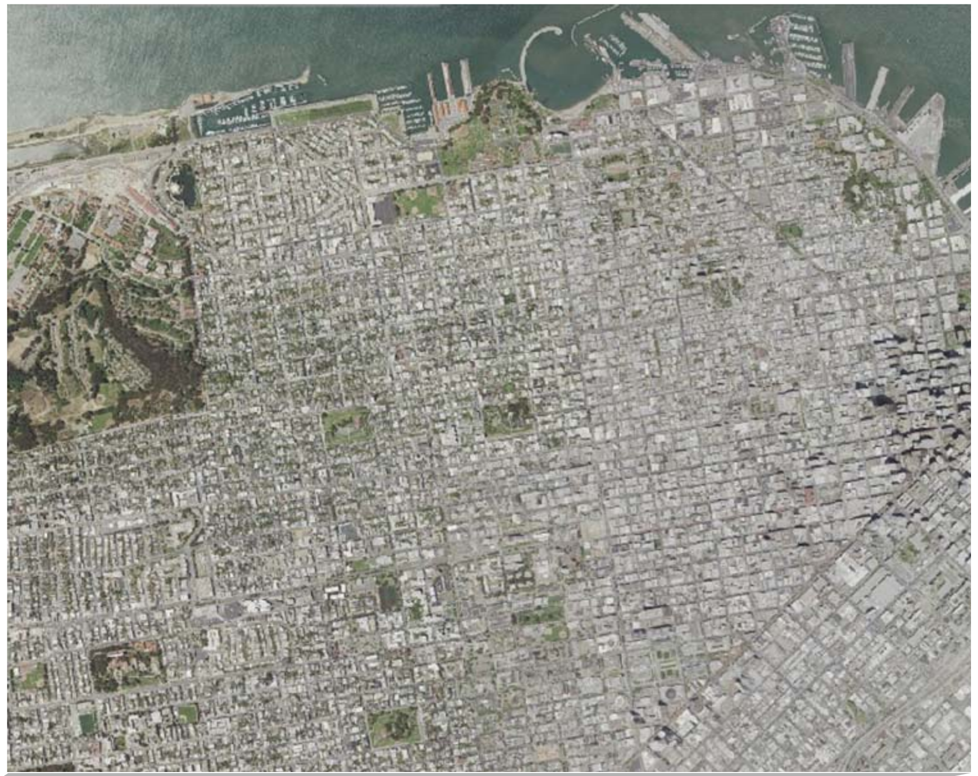
SAR sensing displayed as false color

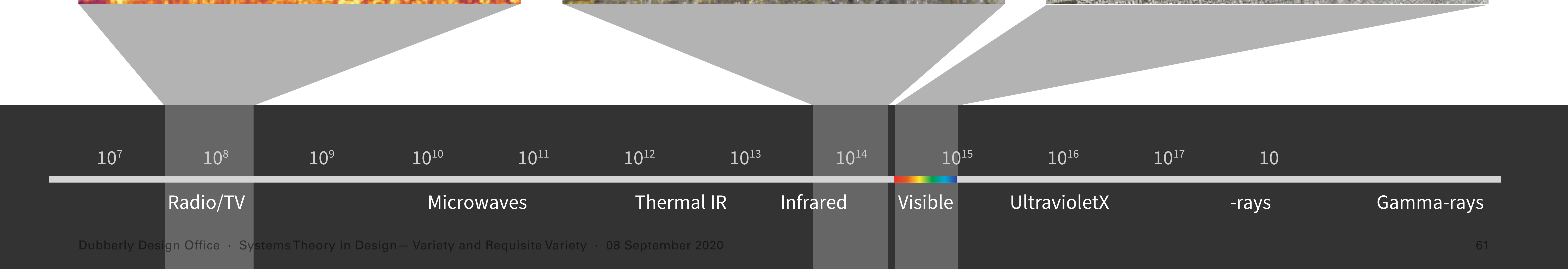


Red edge sensing displayed as false color



RGB sensing displayed as RGB

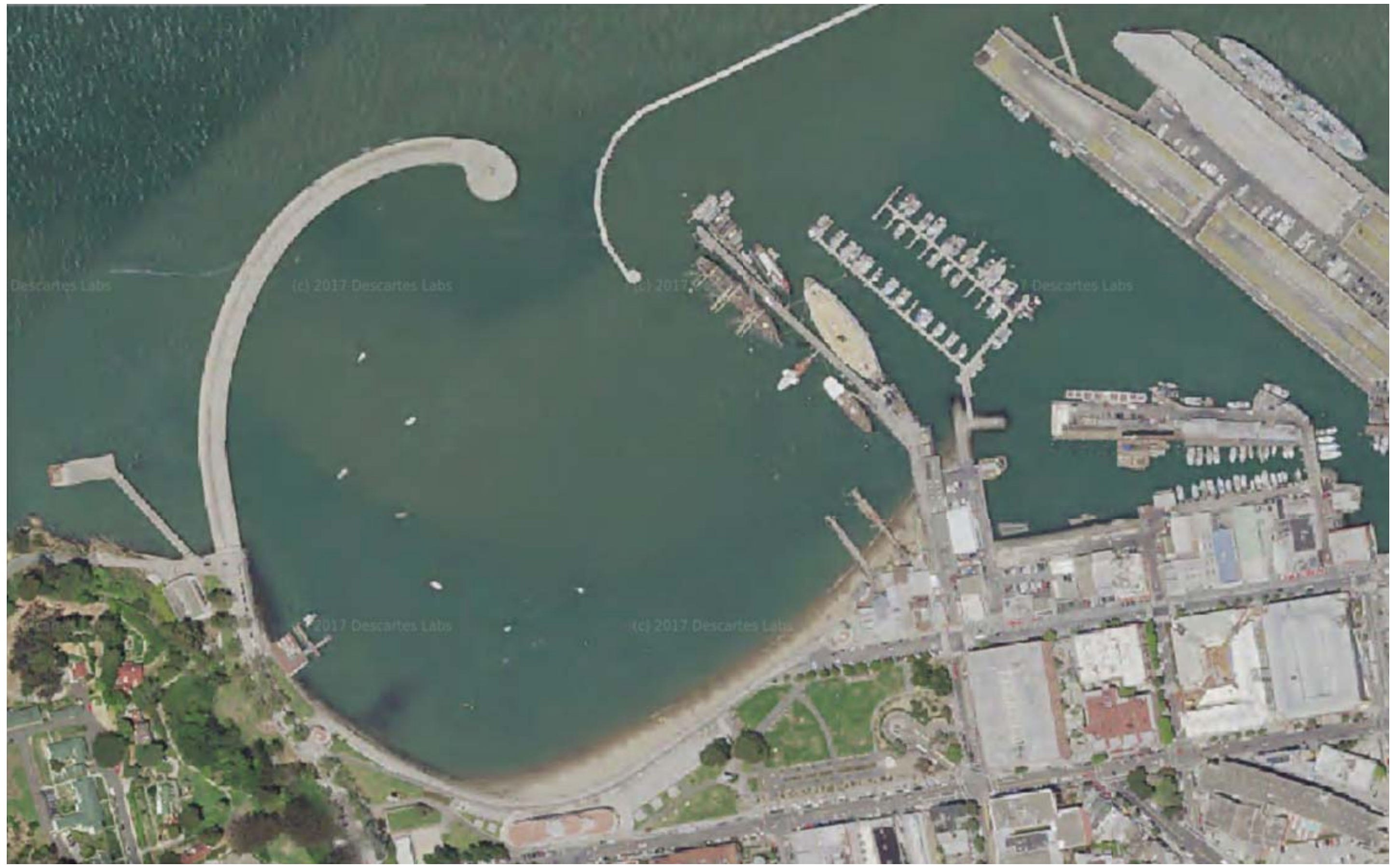




Resolution defines the ‘fineness’ or ‘grain’ of a system’s measurement or action.

Low resolution image (e.g., Landsat-8)

Each Landsat- 8 pixel covers a 30 by 30 meter area (98 by 98 feet), about the size of a baseball diamond.



High resolution image (e.g., NAIP- Aerial imagery)

Each NAIP pixel covers a 1 by 1 meter area (3.39 by 3.39 feet), about the side of the hood of your car.

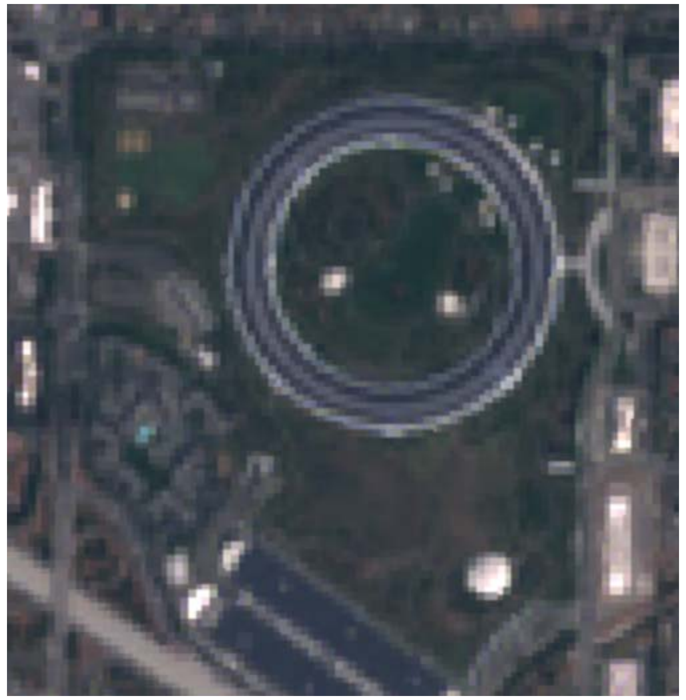
Frequency defines how often or quickly a system measures or acts.

The photographs below are a sequence of NAIP imagery, of the construction of Apple Park, each taken two years apart.

May 20, 2012

June 6, 2014

May 29, 2016



August 7, 2020
(Taken by Sentinel 2, 10 m/px resolution which is about an order of magnitude off from NAIP)

Variety

Ross Ashby defines ‘variety’ (technically) as “how many distinguishable elements [a set] contains.”*

For example, the set

c, b, c, a, c, c, c, a, b, c, b, b, a

contains many occurrences of the same letters,

but it contains only 3 unique letters:

a, b, c

Thus, it has a ‘variety’ of 3 elements.

Variety is a measure of information,

which Ashby explicitly maps to Shannon’s measure of

‘bits’.

For example,

a 24-bit image has more information (more variety)

than an 8-bit image.

The set of possibilities (the color space) of a 24-bit image

is much larger than that of an 8-bit image.

*Ross Ashby, “Introduction to Cybernetics,” page 124,1957.

Ashby added an important qualification:

"It will be noticed that
a set's variety is not an intrinsic property of the set:
the observer and his powers of discrimination may have to be specified
if the variety is to be well defined."

This idea — the importance of the role of the observer —
will become crucial in our later discussions systems.

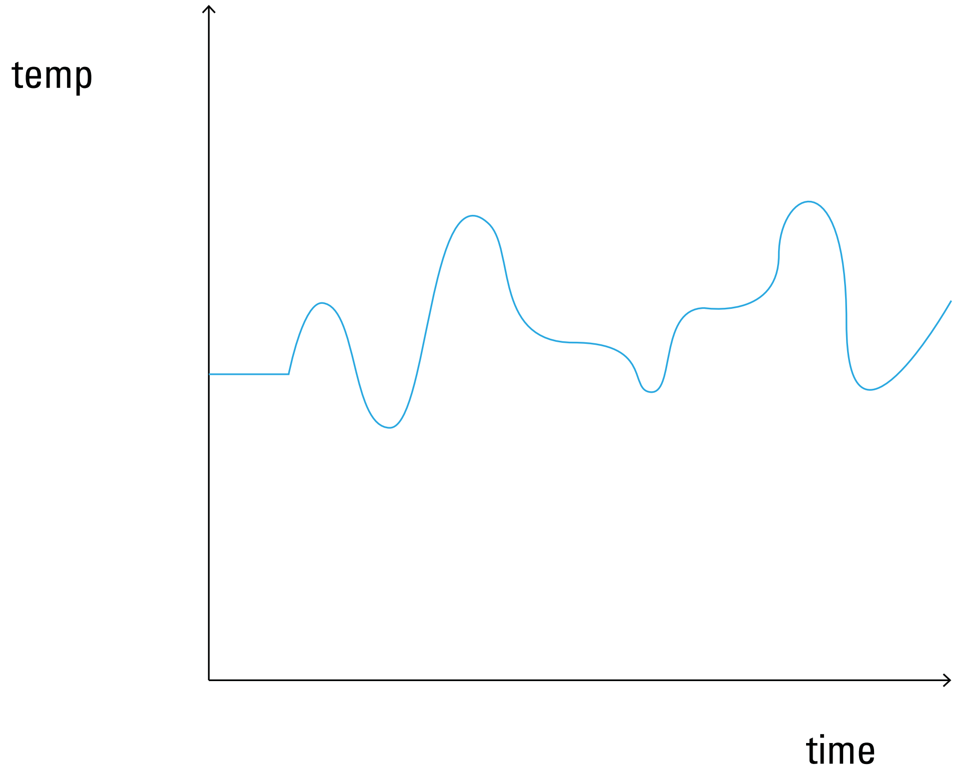
Ashby also introduces the idea of **'constraints'** — **'when the variety that exists under one condition is less than the variety that exists under another.'**

- Constraints may be slight or severe.
- The intensity of the constraint is shown by the reduction it causes in the number of possible arrangements — the extent to which it reduces variety.
- Constraints affect whether the components of a set act 'independently'.
  That is, they describe the 'degrees of freedom' available to the set.
- If all combinations are possible, then the number of degrees of freedom is equal to the number of components.
  If only one combination is possible, the degrees of freedom are zero.
- Ashby points out, "when a constraint exists advantage can usually be taken of it."
- An organism can adapt just so far as the world is constrained, and no further.
- Ashby also notes, learning is worthwhile only when the environment shows constraint.
- That something is 'predictable' implies that there exists a constraint.
- Machines may be described in terms of constraints — i.e., transformations.

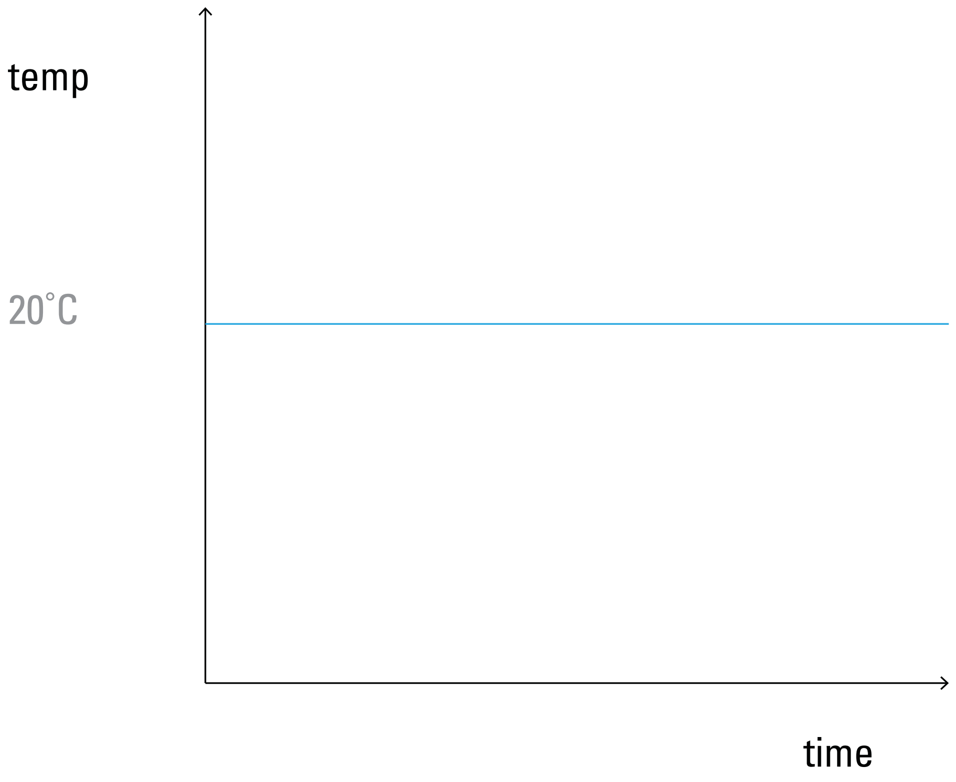
A key idea from Ashby is that **“Regulation blocks the flow of variety.”**

Disturbances present information to the system.

Without regulation, disturbances would transform the system.
That is, with no AC, hot weather will raise the indoor temperature.



With regulation, the information in the disturbance is blocked.
That is, if a system maintains indoor temperature at 20°C,
the indoor temperature tells us nothing about the weather outside.



**Thus, a system's variety is a measure of its capacity to resist disturbances —
that is, to maintain itself in a state of equilibrium.**

"In general, then, an essential feature of the good regulator is that it blocks the flow of variety from disturbances to essential variables."

The Law of Requisite Variety:
Variety destroys (or absorbs) variety.

"Only variety in a regulator can force down
the variety due to a disturbance."

When a system has enough variety to withstand (block)
or counteract (parry)
the variety of likely disturbances,
then that system may be said to have 'requisite variety'.

Describing the likely disturbances a system will face — and thus the variety it requires to overcome them — is a design task.

- The greater the range of disturbances, the more variety required for the regulator to maintain equilibrium.
- Of course, a regulator cannot have infinite variety; adding variety to a regulator increases its cost.
- The designers must decide which disturbances are likely, and what the project can afford.
- This is a cost-risk analysis.

Identifying likely disturbances and requisite variety are also important tasks in designing teams + organizations.

In a stable environment, organizations seek to increase efficiency; thus they reduce variety — (e.g., the language they use).

Reduced variety leaves the organization vulnerable to unforeseen disturbances, i.e., competitive innovation or ‘disruption’.

Re-introducing variety (e.g., new language, frameworks, methods) into an organization can be very difficult.

Three other ideas to consider:

What is ‘diversity’?
And why is it a good?

What is ‘resilience’?
And why is it a good?

What is ‘biocost’?
And why is it a bad?

Special thanks to
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Presentation posted at
systems.dubberly.com/variety_and_requisite_variety_20200908.pdf