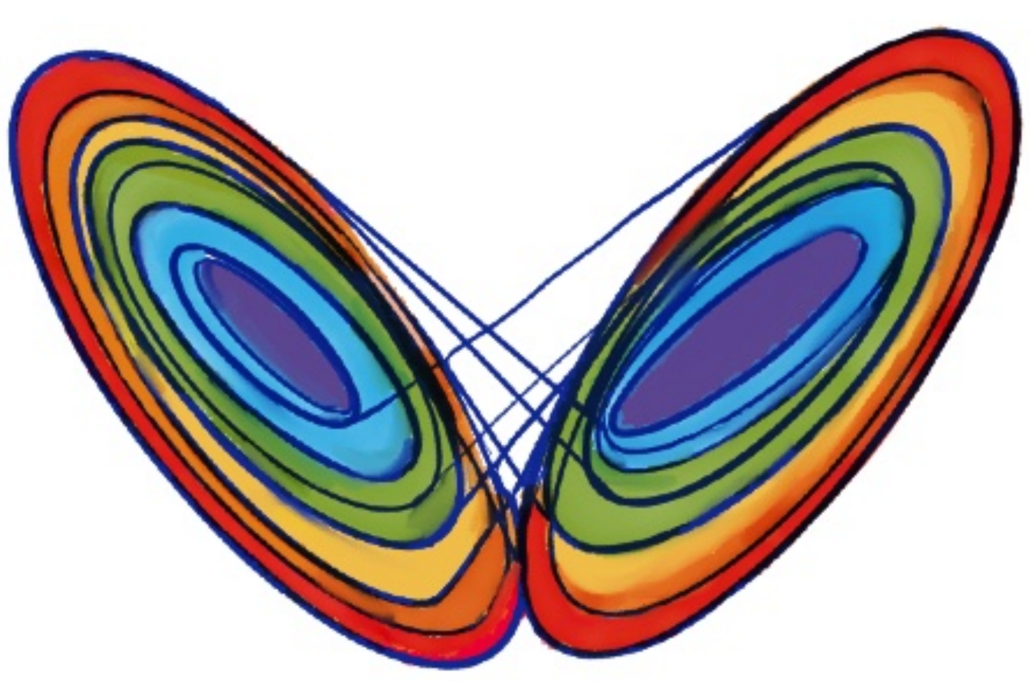


THE SCIENCE OF COMPLEXITY

By

Gitanjali Venkatraman

INTRODUCTION

REDUCTIONISM – UNDERSTANDING THE PARTS HELP UNDERSTAND THE WHOLE – HAS HELPED SCIENCE FLOURISH SINCE THE DAYS OF DESCARTES AND GALILEO.

ALONG COMES ANOTHER IDEA THAT SOMETIMES UNDERSTANDING THE PARTS DO NOT HELP IN WORKING OUT THE WHOLE.

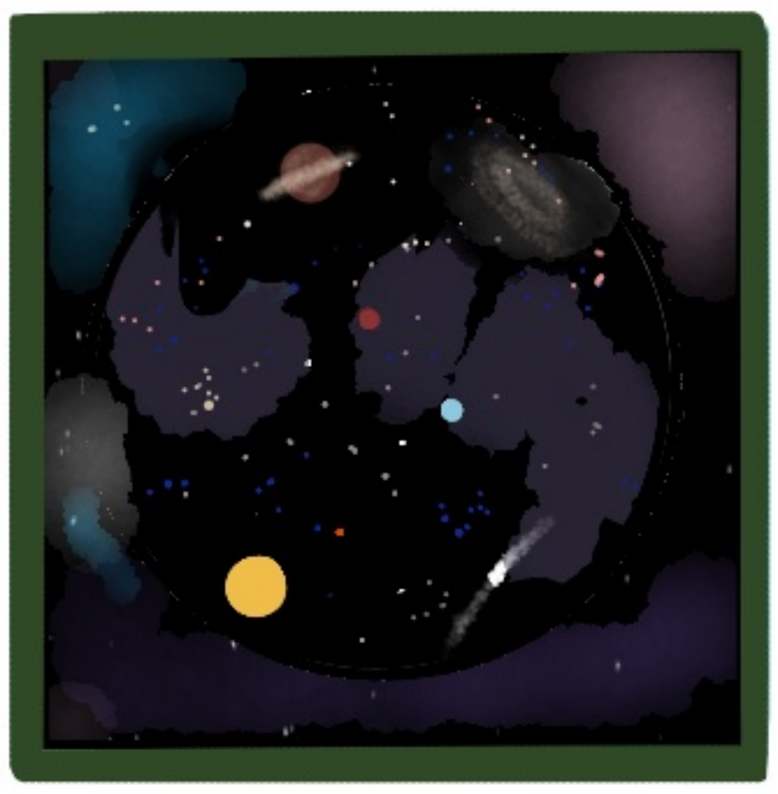
FOR EXAMPLE: THE WATER THAT MAKES THE WEATHER, THE CELLS THAT JOIN UP TO CREATE LIFE FORMS OR THE SHOPS THAT BUILD THE ECONOMY.

THIS IS COMPLEXITY, A NEW SCIENCE THAT HAS THE AUDACITY TO BRING SNOWFLAKES, PENDULUMS AND VIRUSES INTO THE SAME CONVERSATION.

WE STEP THROUGH THE LANDMARKS THAT HAVE BUILT THE SCIENCE AND THE PROBLEMS IT SEEKS TO TACKLE, KNOWING THAT THERE ARE SOME THINGS THAT CAN NEVER BE PRECISELY MEASURED OR PREDICTED.

SCOPE

THE PLACE TO START



THE UNIVERSE

IS

A

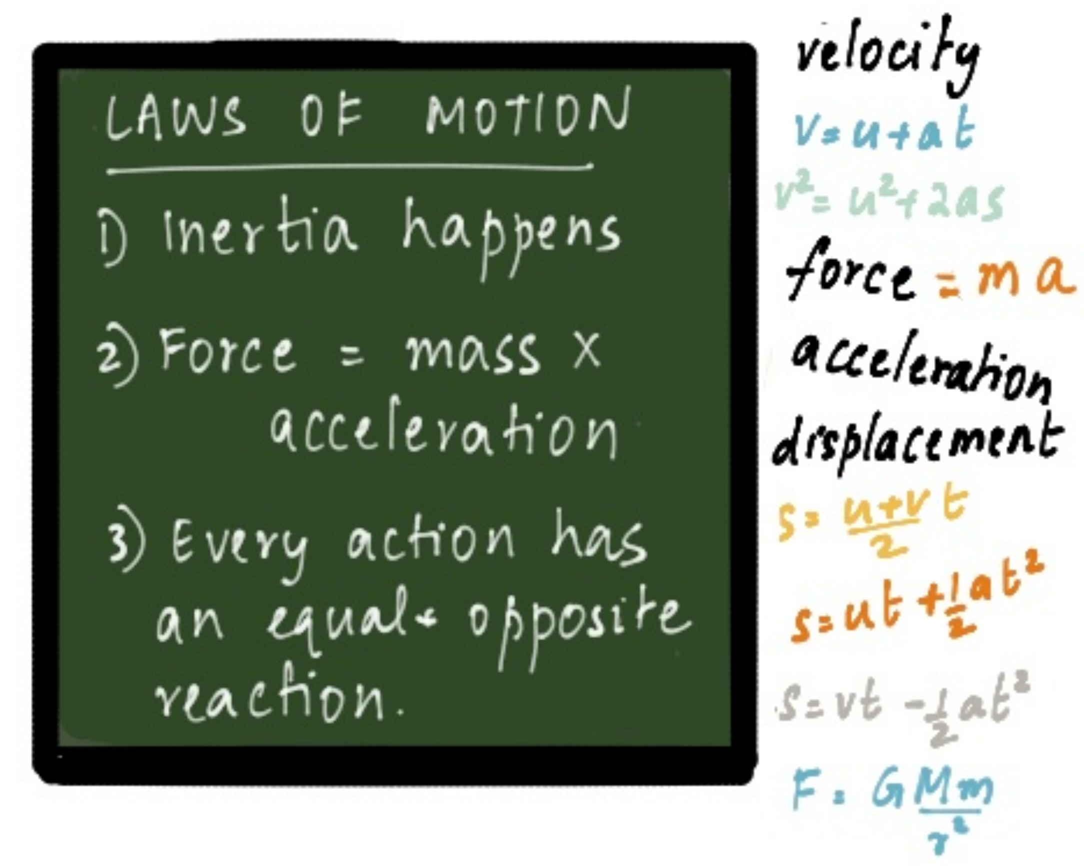
COMPLEX PLACE

ISAAC NEWTON

WAS ONE AMONG

MANY WHO HELPED

MAKE SENSE OF IT.



HIS EQUATIONS

PERFECTLY DESCRIBE

MOVEMENT ON EARTH

AND IN THE SKIES

THIS DETERMINISM WAS SO APPEALING THAT PHYSICIST PIERRE-SIMON LAPLACE IS THOUGHT TO HAVE DESCRIBED AN ALL-KNOWING DEMON :

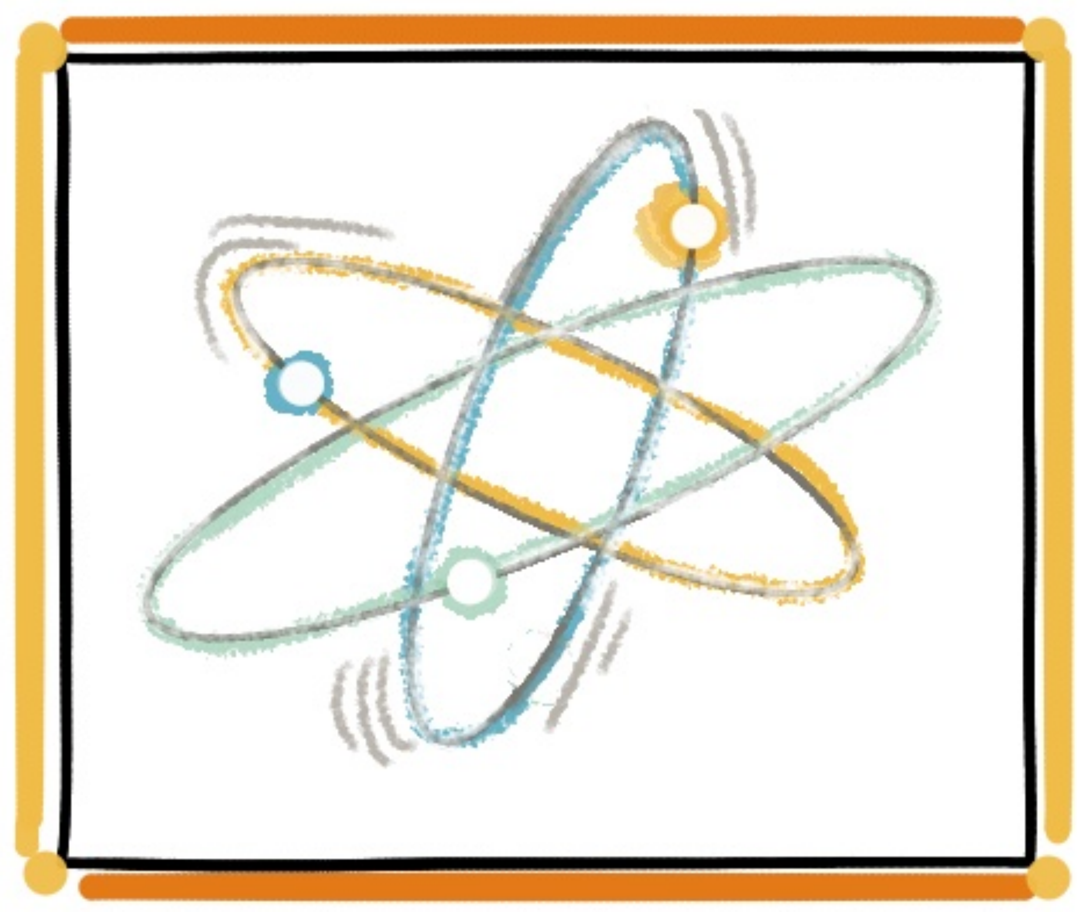
> "An intellect which at any given moment knew all of the forces that animate nature and positions of the beings .... for such an intellect nothing could be uncertain and future just like past would be present before its eyes."

EXCEPT...

NOT EVERYTHING IN THE UNIVERSE CAN BE EXPLAINED THIS WAY.

FOR EXAMPLE:

QUANTUM MECHANICS



THE SUBATOMIC WORLD DEFIES IDEAS OF CERTAINTY AND MEASUREMENT UNLIKE CLASSICAL PHYSICS

PREDICTING THE WEATHER

THE NOTION OF CHAOS WHERE APPROXIMATE MEASUREMENTS DO NOT PREDICT APPROXIMATE, BUT WILDLY DIFFERENT OUTCOMES.

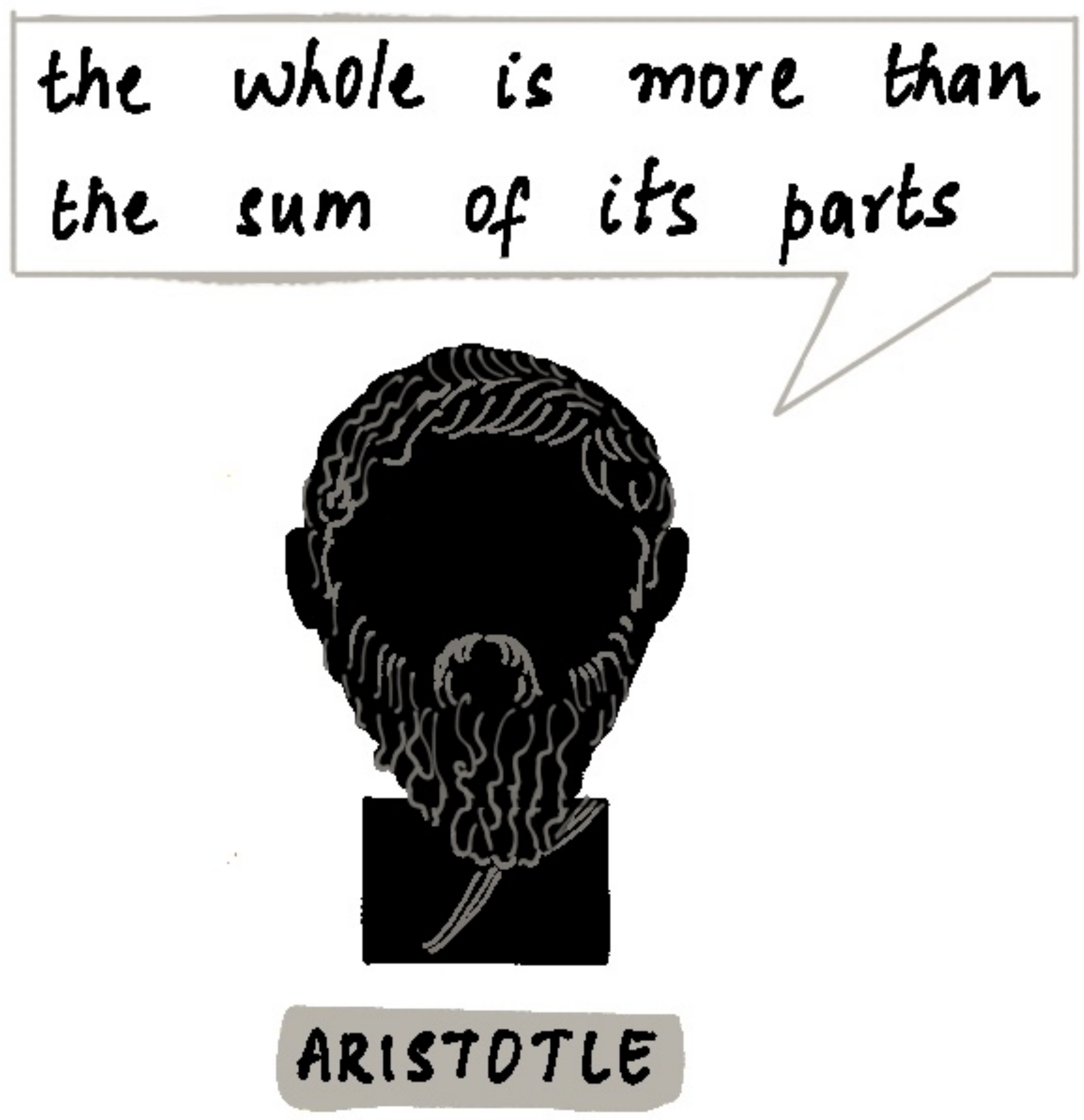
UNDERSTANDING NATURAL PHENOMENON LIKE THE WEATHER, SWARM BEHAVIOUR OF CREATURES LIKE ANTS LED TO A NEW SCIENCE.
THE SCIENCE OF COMPLEXITY

THE SCIENCE

COMPLEXITY CAN BE THOUGHT OF AS ASKING THE OPPOSITE QUESTION TO REDUCTIONISM.

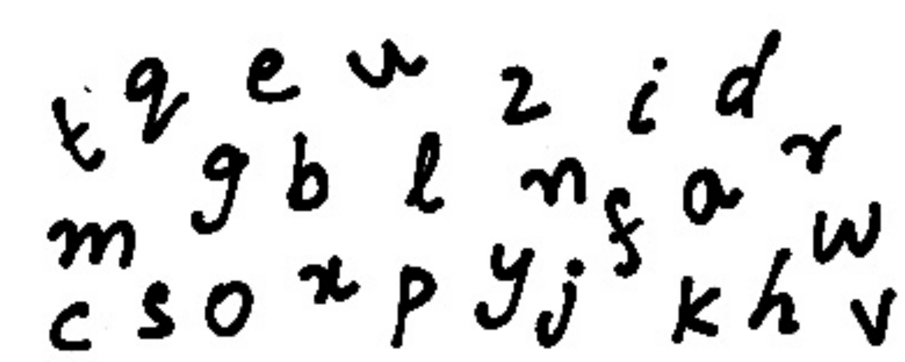
GIVEN THE INTERACTING PARTS
WHAT MAKES THE WHOLE WORK?

THIS QUOTE SUMS IT UP



FOR EXAMPLE

PARTS



WHOLE

ALSO KNOWN AS

- COMPLEX SYSTEM SCIENCE
- PLECTICS

HAS APPLICATIONS IN

- INFORMATION THEORY
- GEOLOGY
- NEUROSCIENCE
- ECONOMICS
- BIOLOGY . . . . . .

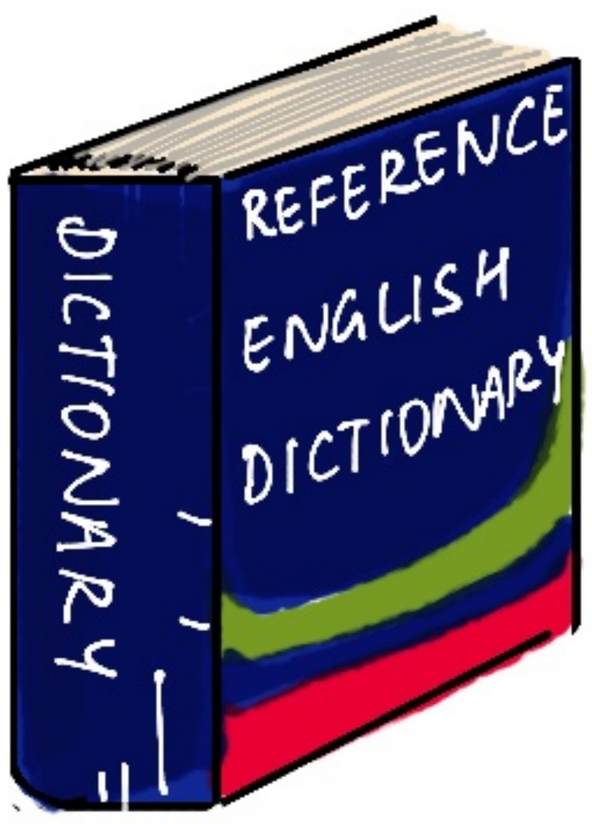
THE FIELD TOOK OFF IN THE 1980s WITH THE DEVELOPMENT OF COMPUTERS TO PROCESS NUMBERS AND WITH ENOUGH GRAPHICS TO VISUALISE EXPERIMENTS

THE ESSENCE

EVERY DISCIPLINE HAS A DIFFERENT NOTION OF COMPLEXITY AND MEASURES IT DIFFERENTLY. HERE WE WILL TRY AND UNDERSTAND WHAT COMPLEXITY IS ALL ABOUT.

COMPLEXITY : DEFINITION

IT IS QUITE A DIFFICULT TASK TO DEFINE COMPLEXITY AS A SCIENCE. COMPLEXITY TO COMPUTER SCIENTISTS IS NOT WHAT COMPLEXITY IS TO BIOLOGISTS.

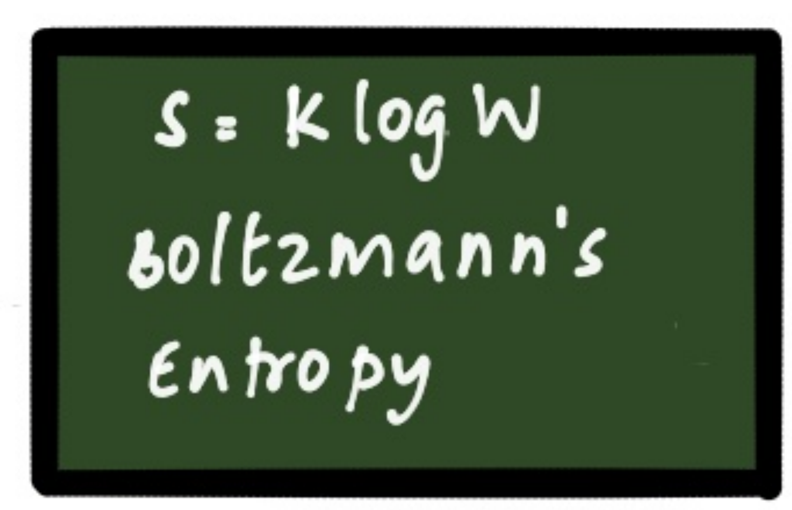


A DICTIONARY DEFINITION OF 'COMPLEXITY'

> *'the state of having many parts and being difficult to understand or find an answer to'*

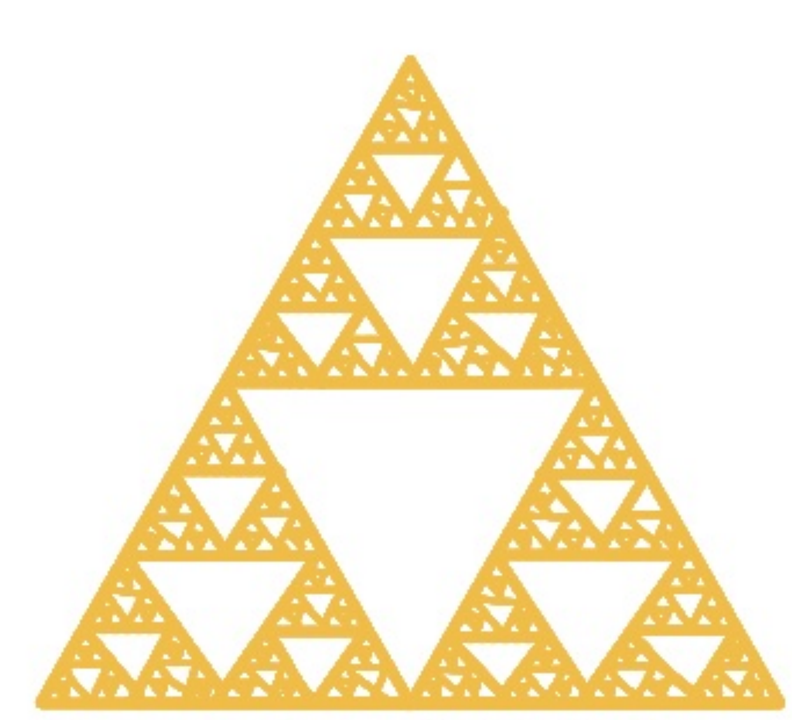
A PAPER BY SETH LLOYD LISTS THREE QUESTIONS THAT HELP TO MEASURE COMPLEXITY OF THE SUBJECT

- MEASURES BASED ON HOW HARD TO DESCRIBE
  - e.g. INFORMATION
  - ENTROPY



- MEASURES BASED ON HOW HARD TO CREATE
  - e.g. COMPUTATIONAL COMPLEXITY
  - COST

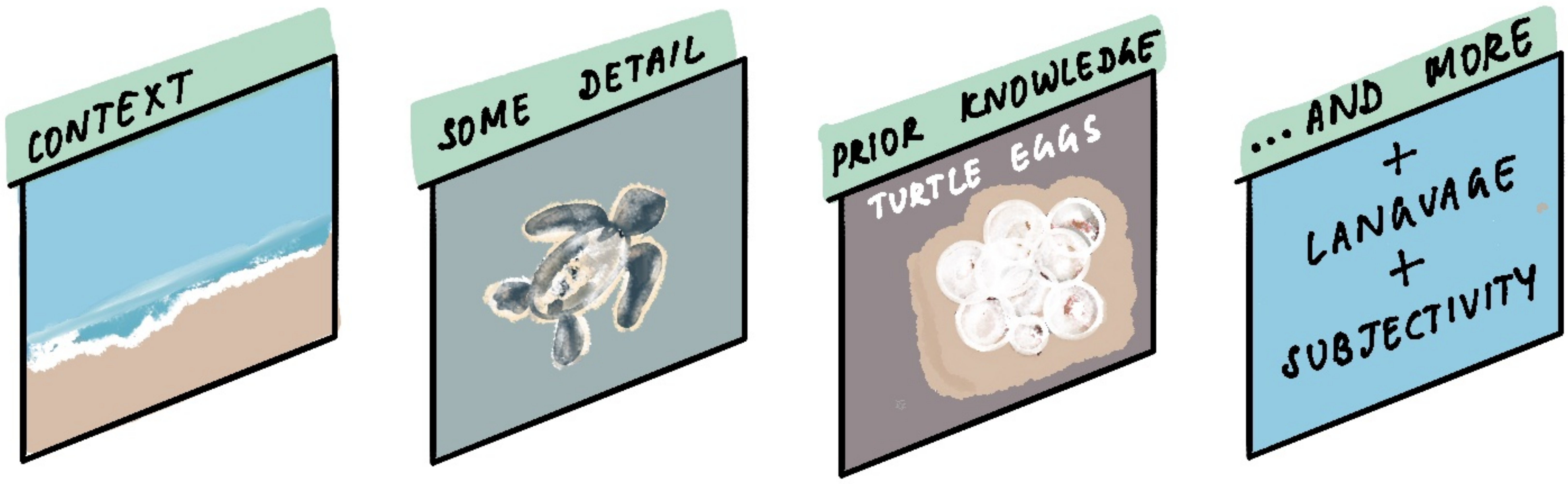
- MEASURES BASED ON DEGREE OF ORGANISATION
  - e.g. HIERARCHICAL COMPLEXITY
  - FRACTAL DIMENSION



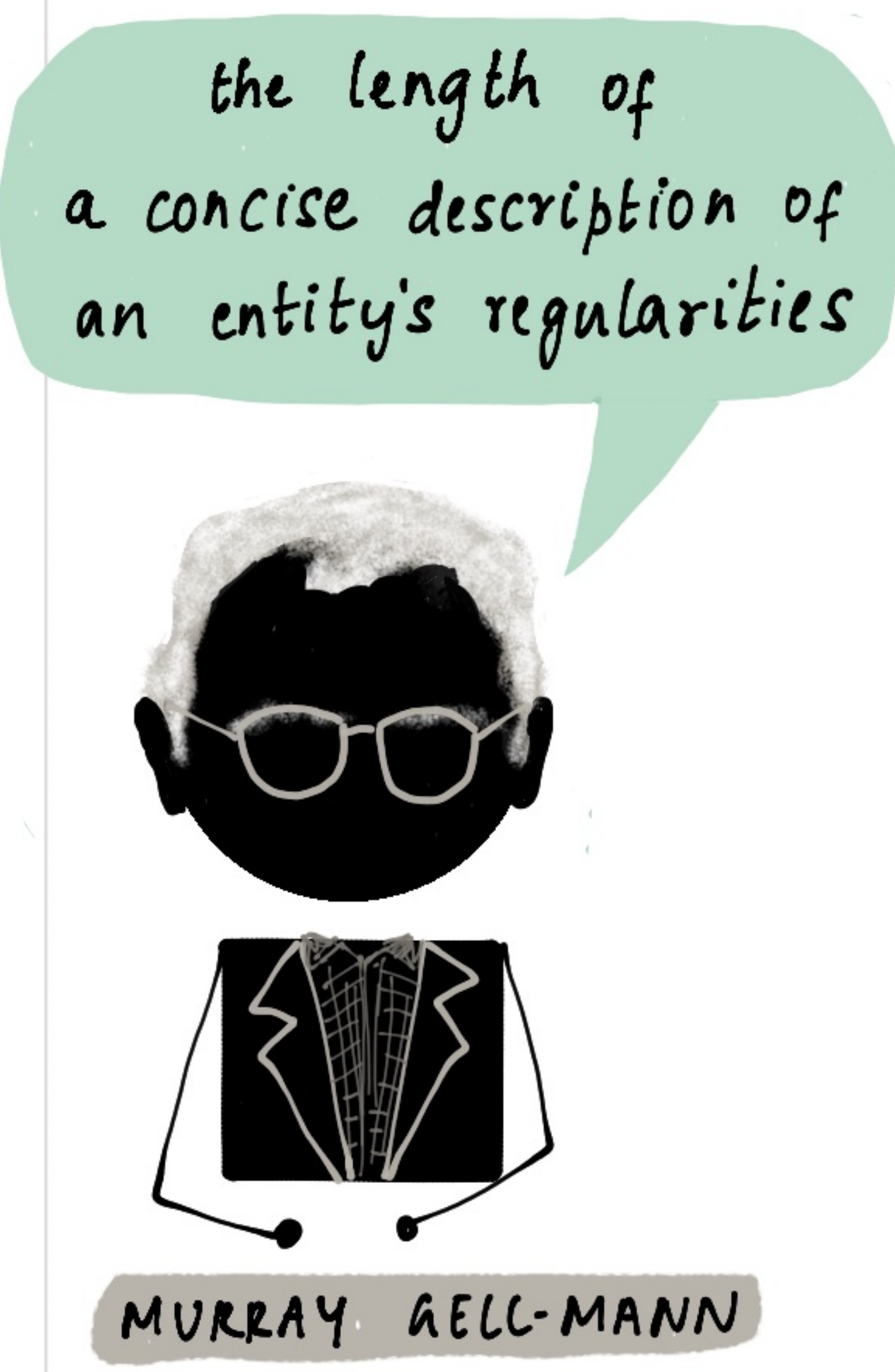
SIERPINSKI TRIANGLE

COMPLEXITY & ORDER

ALTHOUGH VARIOUS SCIENTIFIC FIELDS MEASURE COMPLEXITY IN DIFFERENT WAYS, UNDERSTANDING THE COMPLEXITY OF THE TOPIC MAY NEED



ANOTHER MEASURE OF COMPLEXITY IS:



RANDOM

no regularities

5 3 3 3 6 0 5 3 5
6 1 8 3 7 8 1 3 2
6 3 7 4 2 9 7 1 8
0 6 8 1 4 9 6 1 3

UNIFORM

fully regular

0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0

Effective complexity → ZERO

THUS, COMPLEXITY OCCURS BETWEEN TOTAL ORDER AND TOTAL DISORDER

COMPLEX SYSTEMS

SYSTEMS WHERE A SIZEABLE NUMBER OF FACTORS ARE INTERRELATED INTO AN ORGANIC WHOLE

-WARREN WEAVER

THE QUESTIONS

WARREN WEAVER

THE PROBLEMS THAT CANNOT BE SOLVED EITHER

- BY MANAGING THE RELATIONSHIPS BETWEEN A HANDFUL OF VARIABLES

OR

- BY EMPLOYING STATISTICAL METHODS TO COPE WITH MILLIONS OF VARIABLES

...WEAVER DESCRIBES THESE QUESTIONS AS THE SUBJECT OF COMPLEXITY

WHY DOES SALT WATER FAIL TO SATISFY THIRST?

DO COMPLEX PROTEIN MOLECULES KNOW HOW TO DUPLICATE THEIR PATTERN?

IS A VIRUS A LIVING ORGANISM?

ON WHAT DOES THE PRICE OF WHEAT DEPEND?

WHY IS ONE CHEMICAL SUBSTANCE A POISON WHILE ANOTHER WITH THE SAME ATOMS REARRANGED IS COMPLETELY HARMLESS?

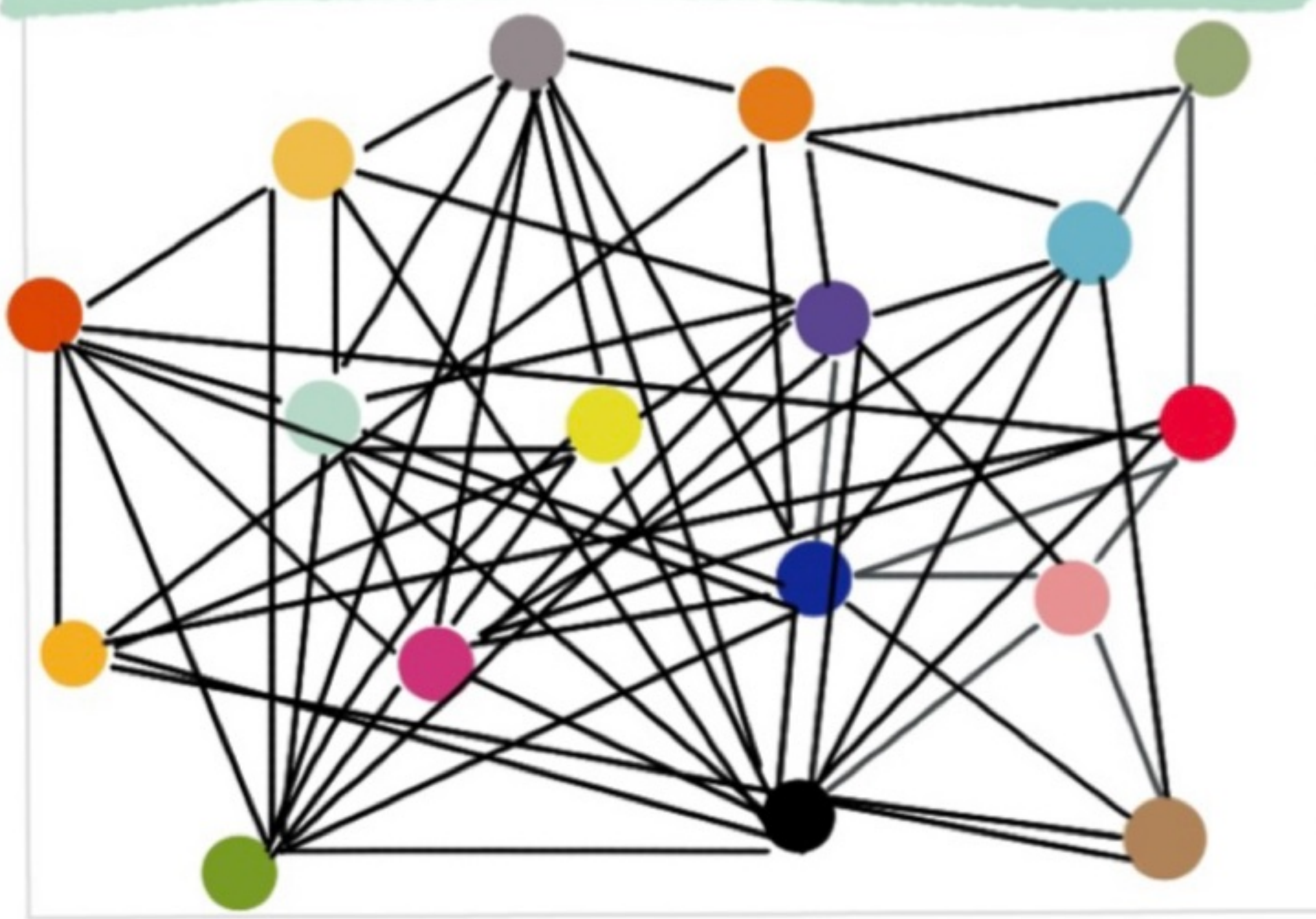
HOW CAN CURRENCY BE STABILISED?

HOW CAN WE EXPLAIN THE BEHAVIOUR PATTERNS OF A LABOUR UNION?

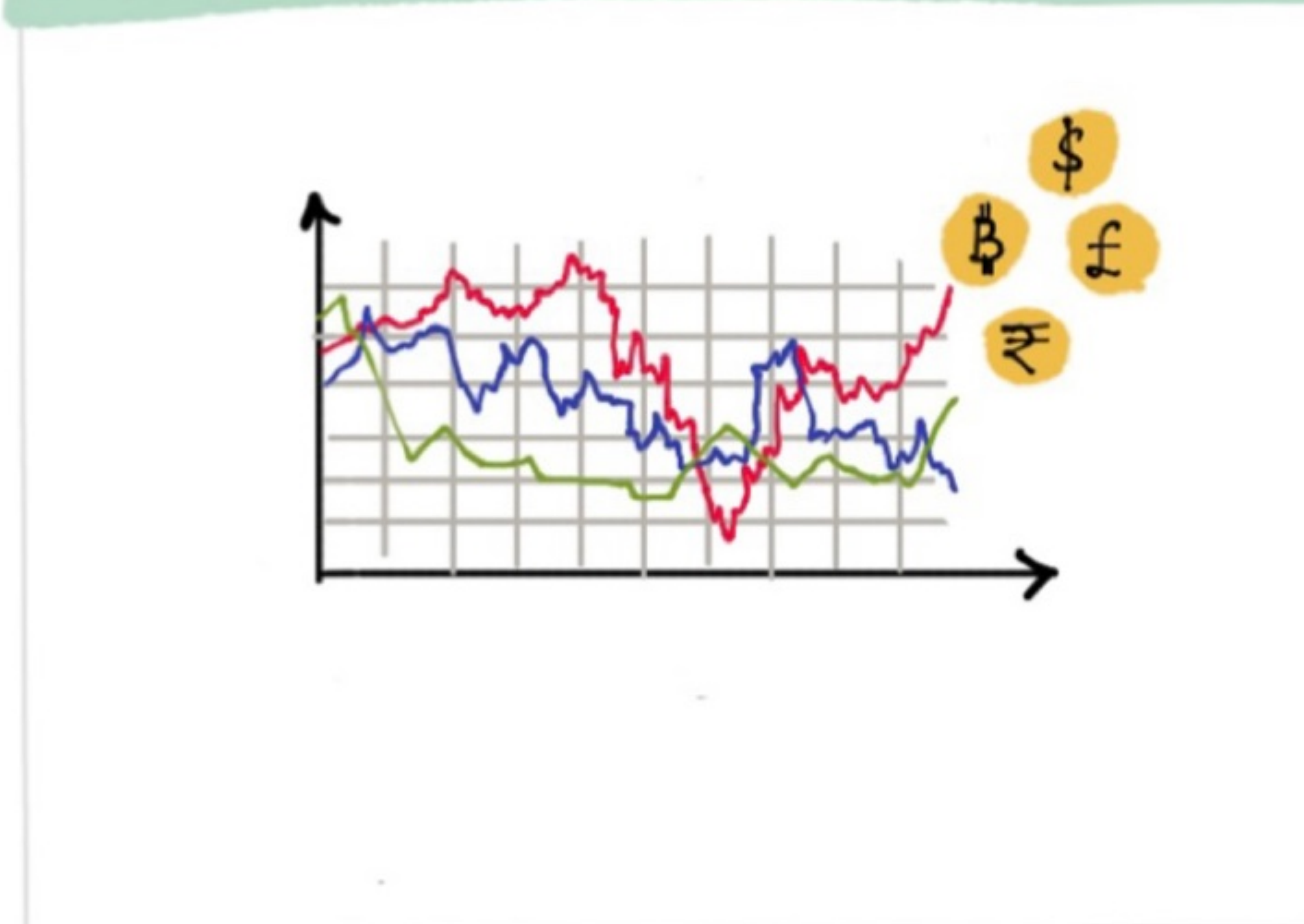
WHAT SACRIFICES OF SELFISH INTEREST WILL MOST EFFECTIVELY CONTRIBUTE TO A STABLE, DECENT AND PEACEFUL WORLD?

EXAMPLES OF COMPLEX SYSTEMS

SOCIAL NETWORKS

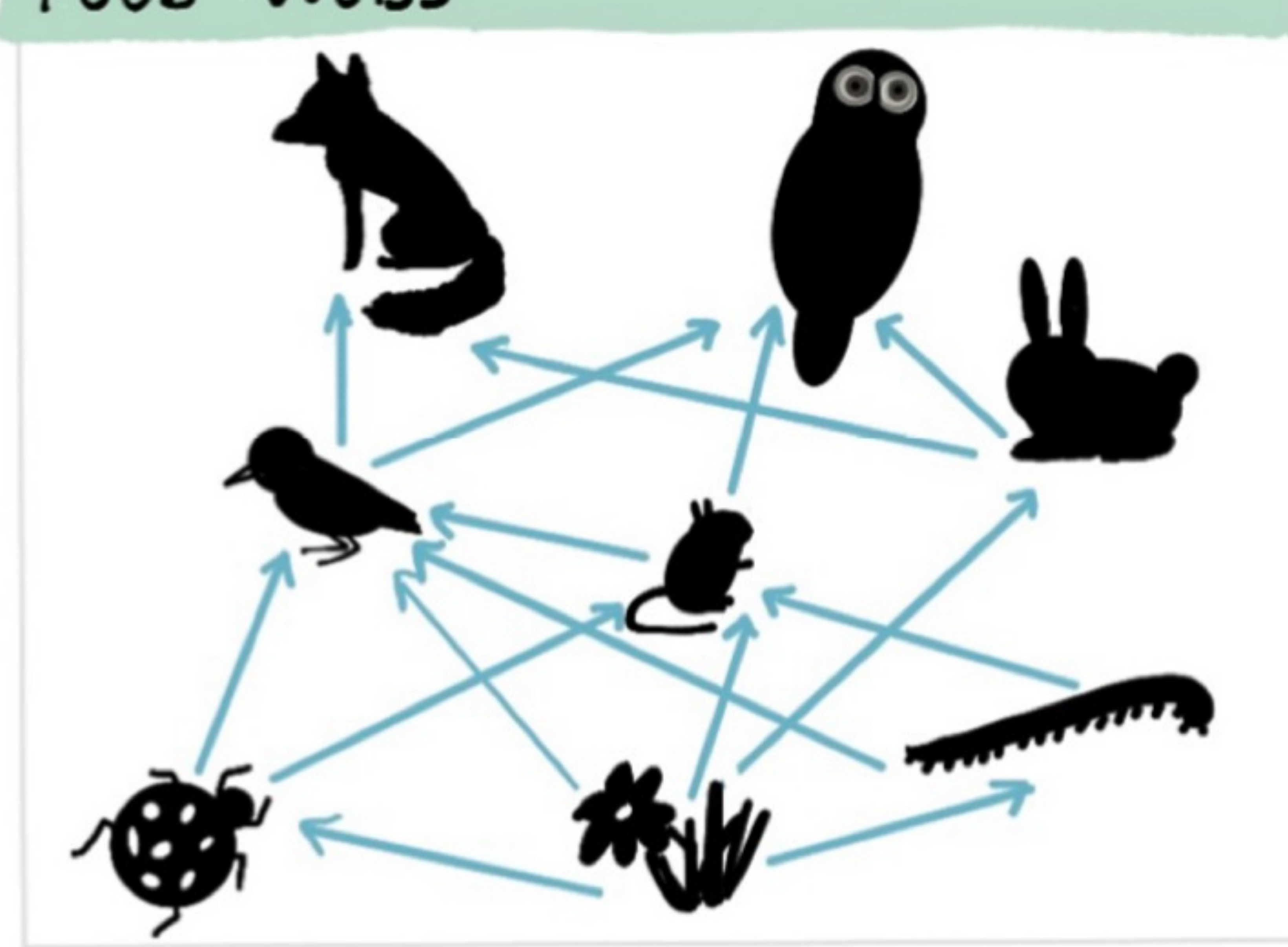


ECONOMIES



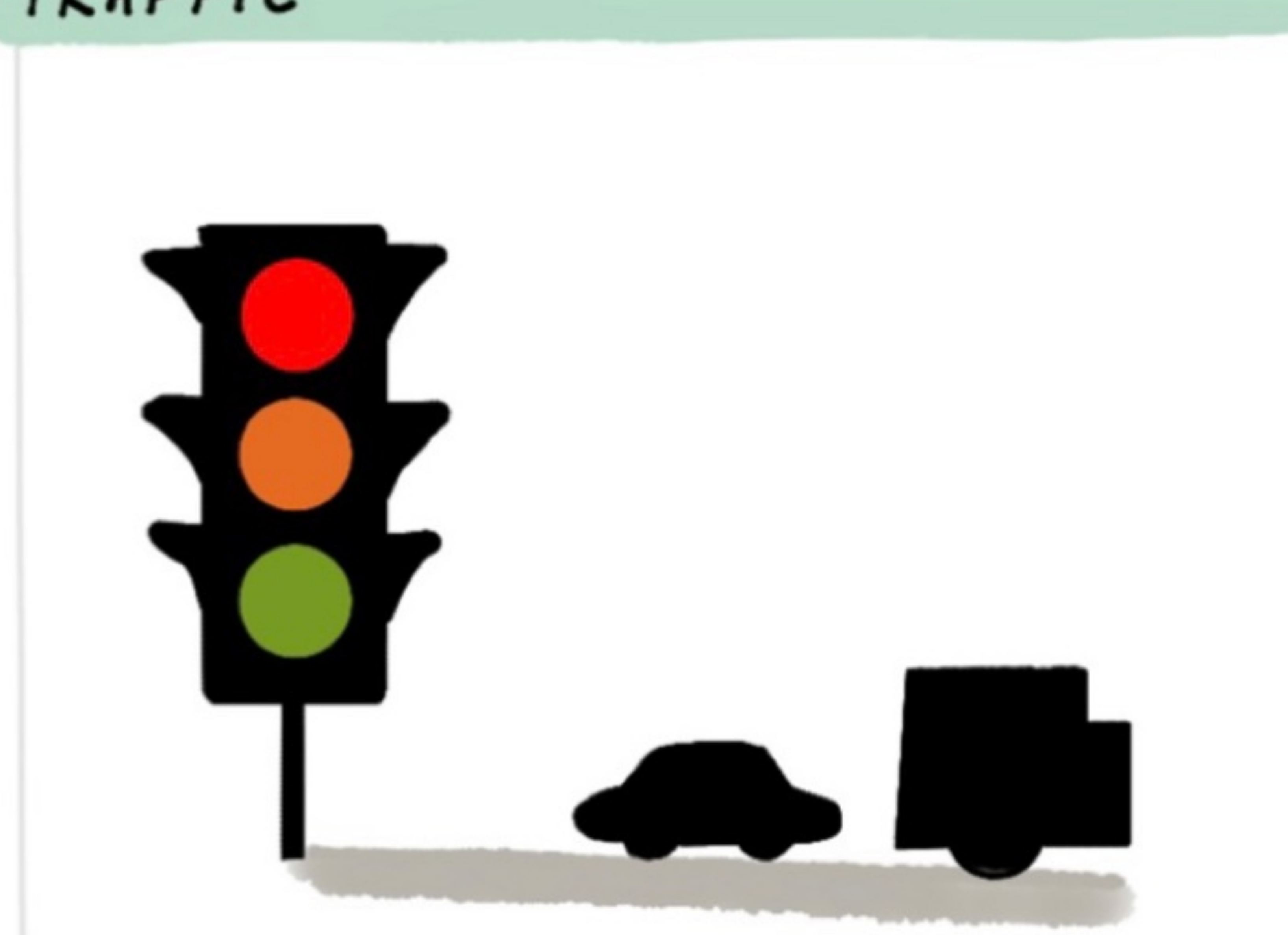
TERMITE COLONIES

FOOD WEBS



IMMUNE SYSTEM

TRAFFIC



SOME COMMON FEATURES

COMPLEX SYSTEMS HAVE SOME COMMON FEATURES. THEY HAVE:

SIMPLE COMPONENTS

- SIMPLER THAN THE

INTERACTIONS

- THE PARTS ARE INTERDEPENDENT AND INTERACT WITH EACH O BASED ON SIMPLE RULES

NO CENTRALISED CONTROL

- THEY ARE SELF ORGANISING

EMERGENT BEHAVIOUR

- THE COLLECTIVE BEHAVIOURS ADAPT AND EVOLVE AND ARE EVEN CHAOTIC AS THE SYSTEM LEARNS FROM ITS ENVIRONMENT

MAKING THE WHOLE GREATER THAN THE PARTS

EMERGENCE

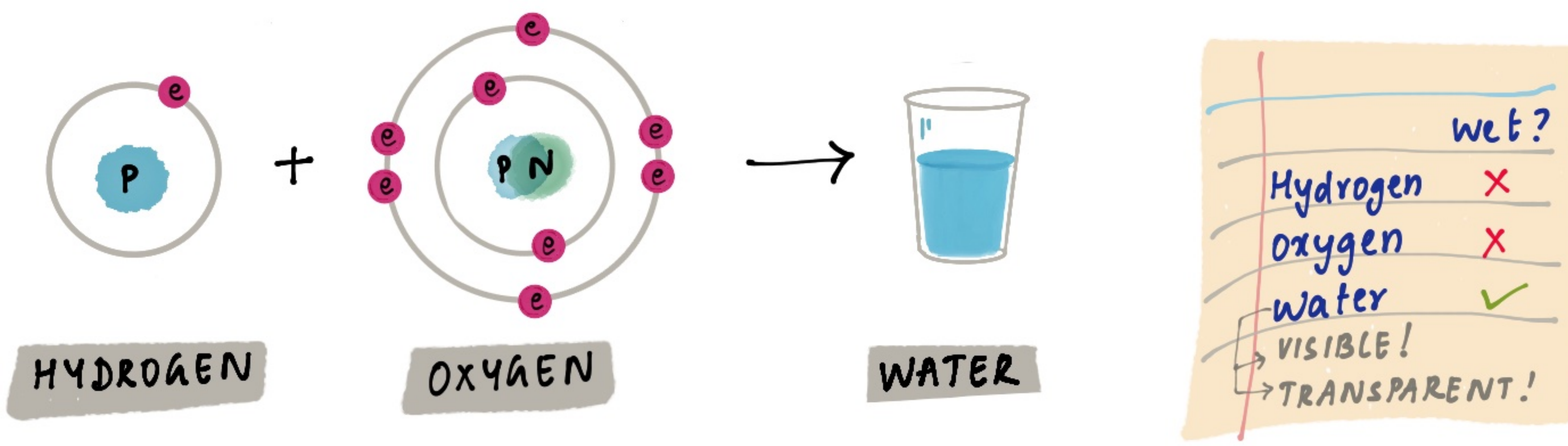
EMERGENT BEHAVIOUR IS AN ESSENTIAL REQUIREMENT FOR CALLING A SYSTEM COMPLEX

- JOHN HOLLAND

WETNESS IS A PROPERTY OF WATER - NOT ITS CONSTITUENTS

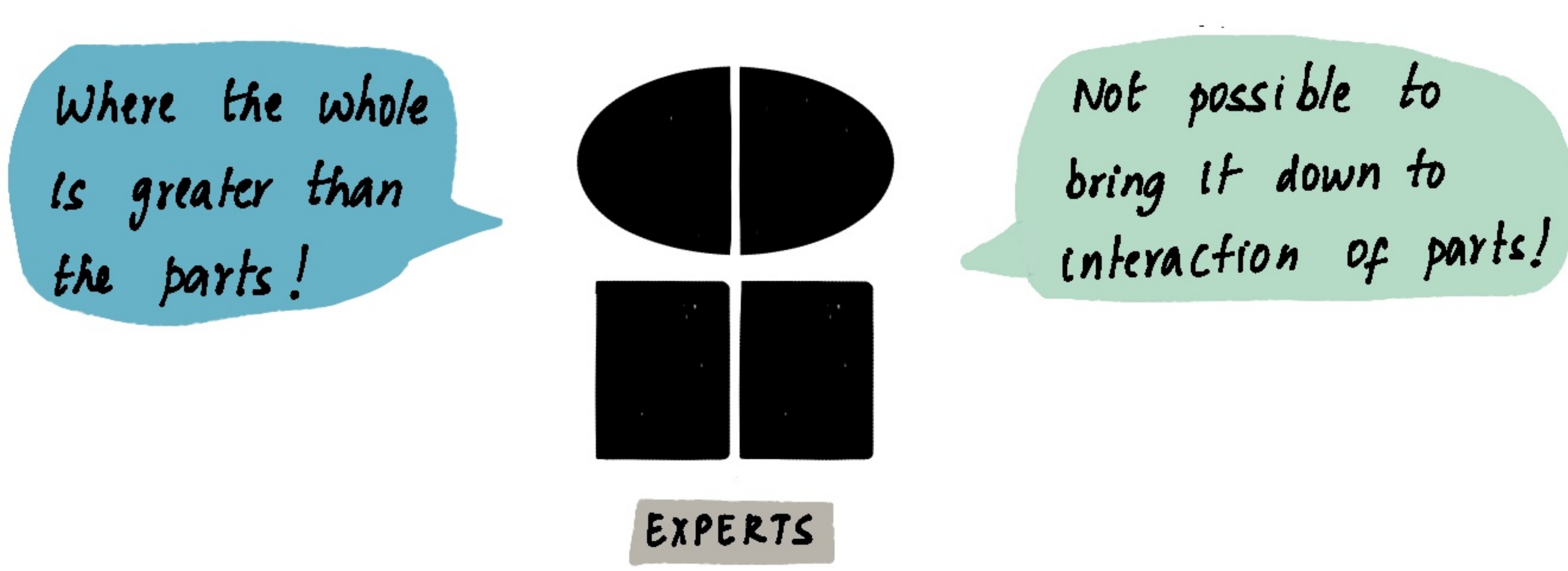
THIS EMERGENT PROPERTY SHOWS UP AT THE 'HIGHER' LEVEL.

THUS EMERGENCE AND HIERARCHY ARE CLOSELY LINKED.



EACH LEVEL HAS ITS OWN INTERESTING BEHAVIOURS, BUT IS DRIVEN BY THE RULES OF THE PREVIOUS LEVEL.

EMERGENCE IS ALSO NOT EASILY DEFINED



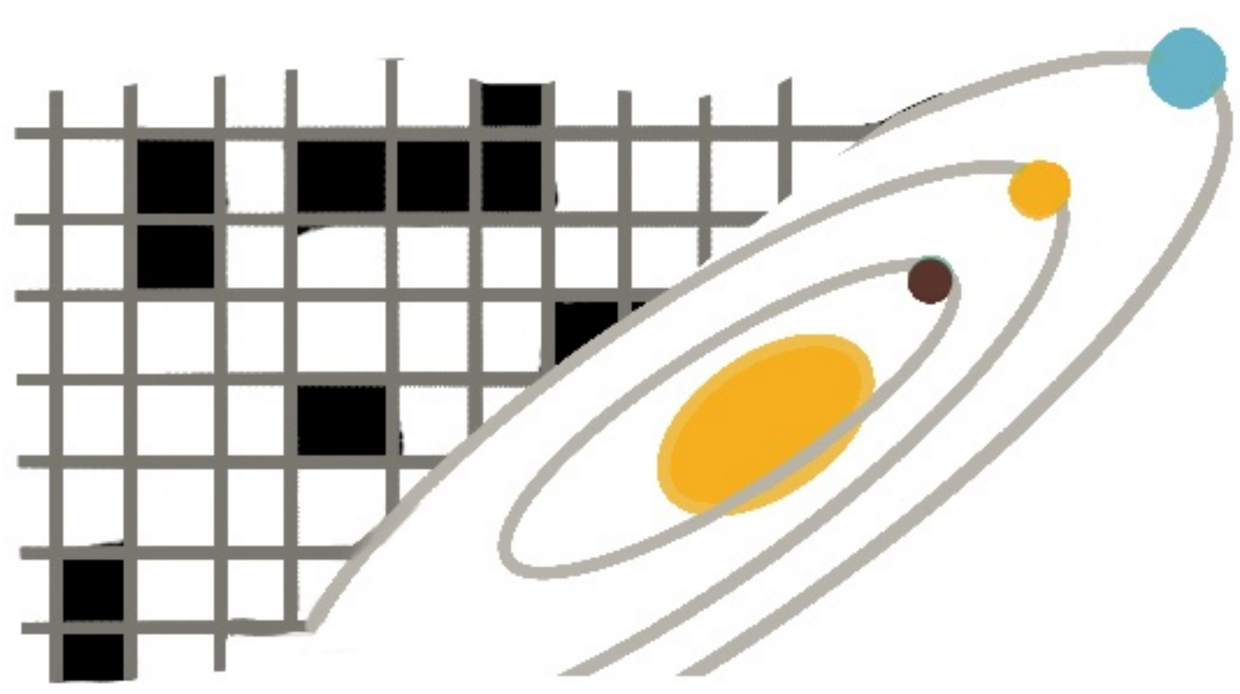
TECHNIQUES TO STUDY EMERGENT BEHAVIOURS COME FROM MANY DISCIPLINES. HOWEVER, THE CHALLENGE REMAINS THAT THE RULES/PATTERNS OBSERVED NEED TO BE CONSISTENT ACROSS MANY COMPLEX SYSTEMS.

TWO PATHS

THERE ARE TWO DIFFERENT KINDS OF EMERGENCE STUDIED – THROUGH EXAMINING:

COMPLEX PHYSICAL SYSTEMS CPS

GRID LIKE STRUCTURES OR INANIMATE OBJECTS



- GOVERNED BY PHYSICAL LAWS SPELT OUT BY RULES/EQUATIONS
- THE PARTS STAY THE SAME
- MOST INTERACTIONS ARE BETWEEN NEAREST NEIGHBOURS
- THE POSITION/STATE CHANGES

COMPLEX ADAPTIVE SYSTEMS CAS

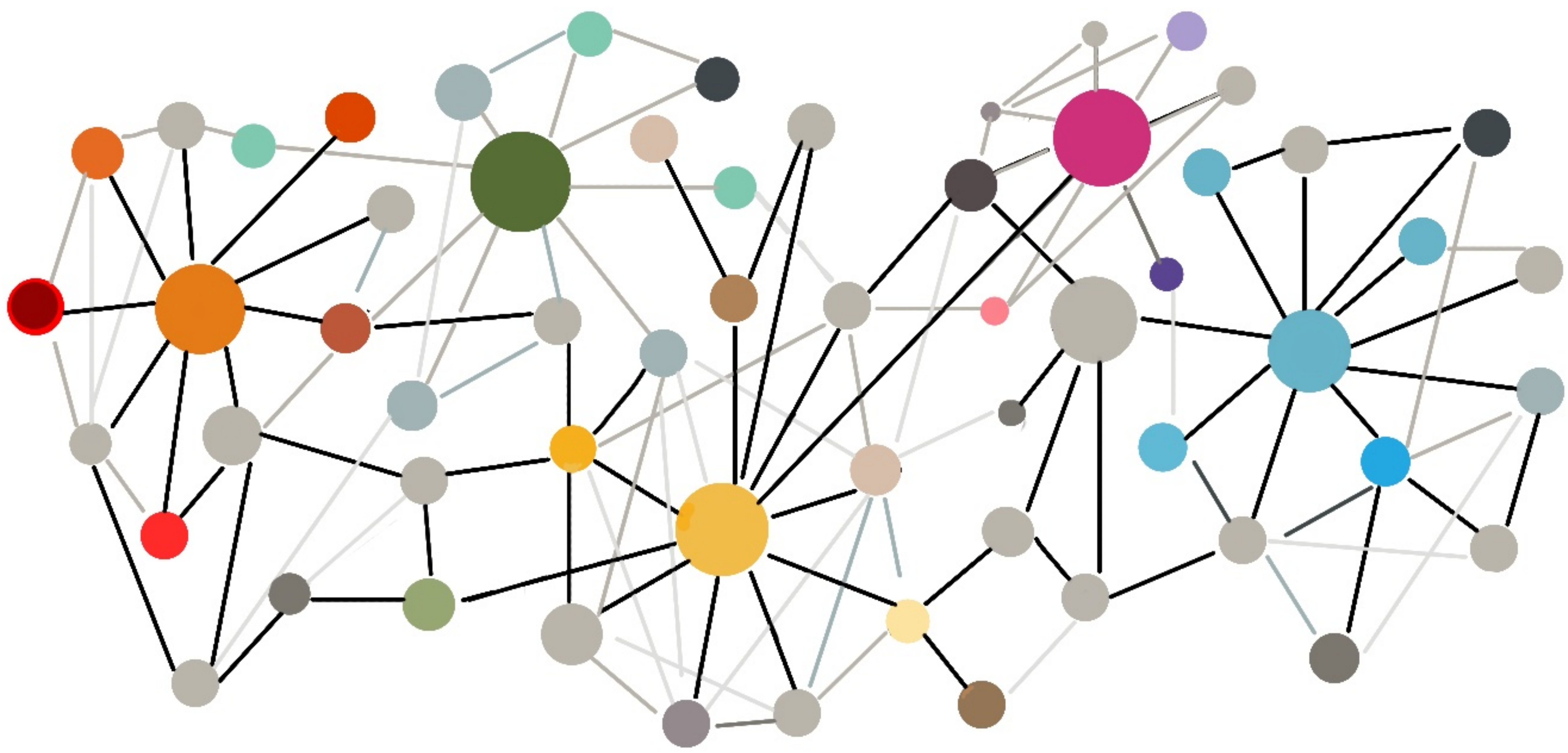
BIOLOGICAL, SOCIO-CULTURAL OR ECONOMIC SYSTEMS

- BEHAVIOUR DEPENDS ON OTHER ELEMENTS
- THE PARTS – CALLED AGENTS – LEARN AND ADAPT
- AGENTS INTERACT WITH EACH OTHER FORMING NETWORKS AND FEEDBACK LOOPS.
- THE ADAPTATION OVER TIME RESULTS IN DIVERSITY

THE NON-ADDITIVITY OF EMERGENCE PRESENTS A MATHEMATICAL DIFFICULTY AND THERE IS NOT YET AN OVERARCHING THEORY OF COMPLEX SYSTEMS

NETWORKS - 1

NETWORK SCIENCE HAS GROWN AS A FIELD OF ITS OWN. IT STUDIES THE PROPERTIES OF A NETWORK & RELATIONSHIPS BETWEEN THE NODES. THE INTENT IS TO USE A COMMON LANGUAGE TO DESCRIBE DIFFERENT NETWORKS AND SHARE LEARNINGS

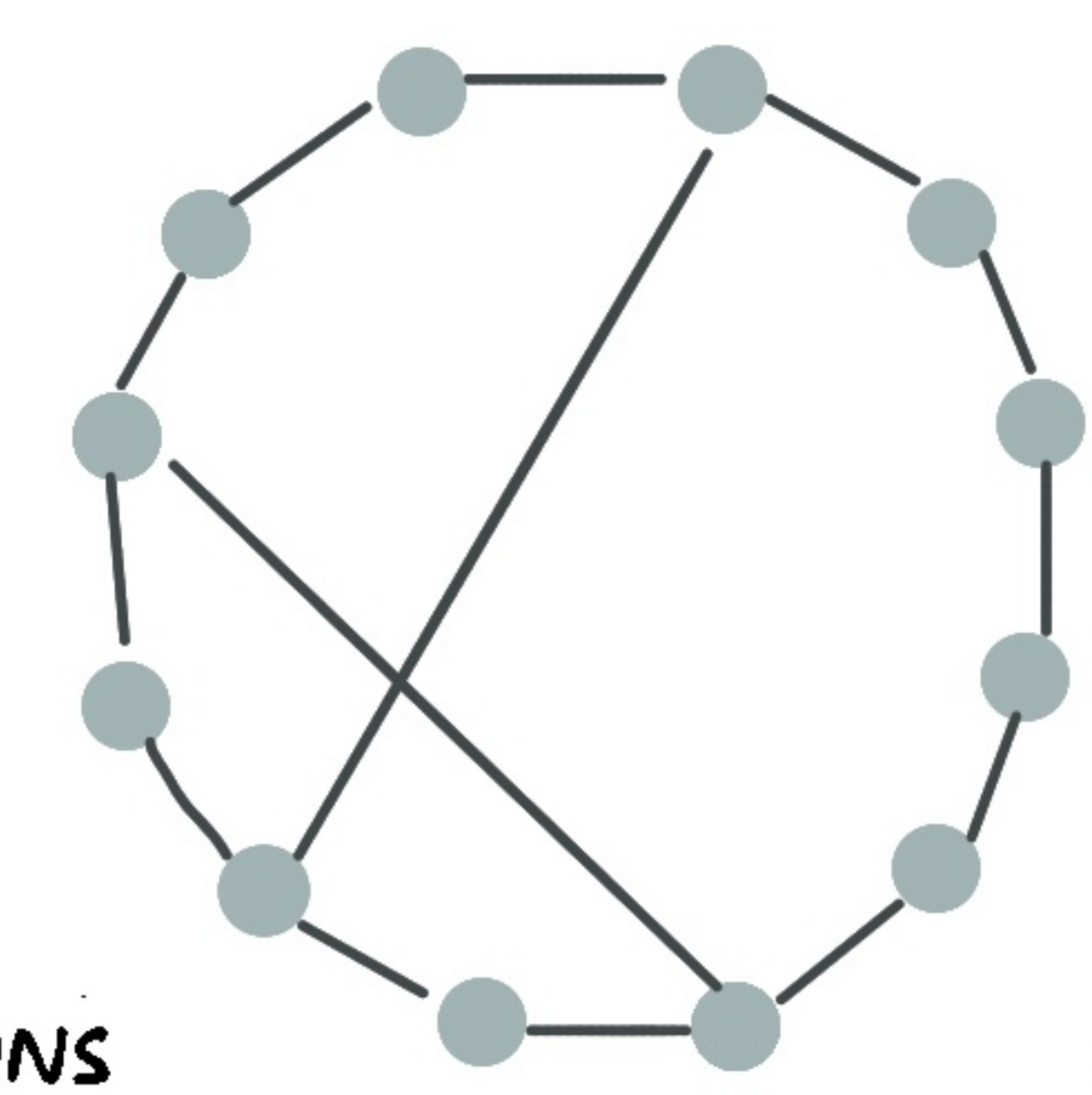


DEGREE / FANOUT

THE NUMBER OF CONNECTIONS OF A NODE

HUB

A NODE WITH A HIGH DEGREE



PATH LENGTH

NUMBER OF CONNECTIONS IN THE SHORTEST PATH BETWEEN TWO NODES

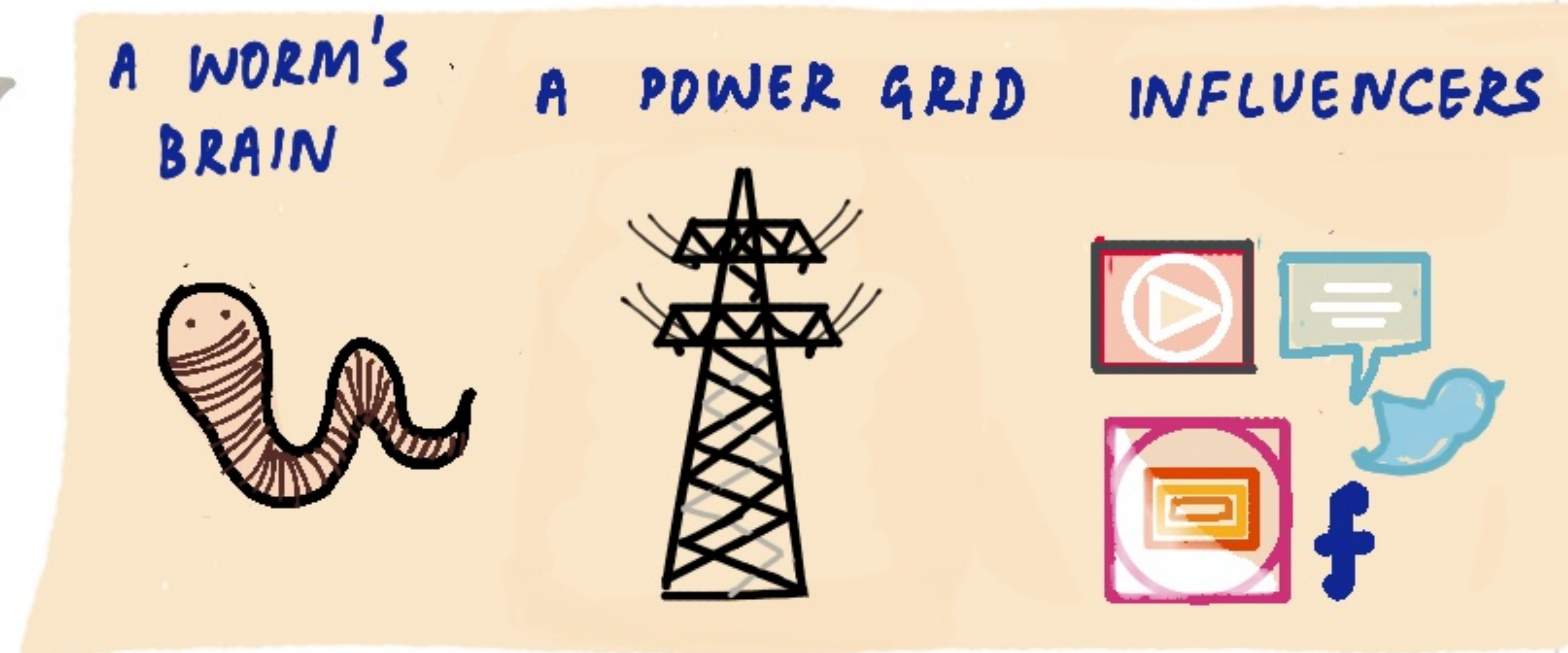
CLUSTER

A MOSTLY SEPARATE INTERCONNECTED SET OF NODES

NETWORKS - 2

SMALL WORLD NETWORK

A SMALL NUMBER OF HIGH DEGREE NODES AND HIGH CLUSTERING



THIS ENSURES A SHORT(ISH) AVERAGE PATH LENGTH AND ENABLES INFORMATION TO TRAVEL QUICKER AND CHEAPER.

SCALE FREE NETWORK

A TYPE OF SMALL WORLD NETWORK
FOR EXAMPLE, THE WORLD WIDE WEB.

STRUCTURE

- SMALL # OF HIGH DEGREE NODES
- NODES WITH A WIDE RANGE OF DEGREES
- SELF SIMILAR

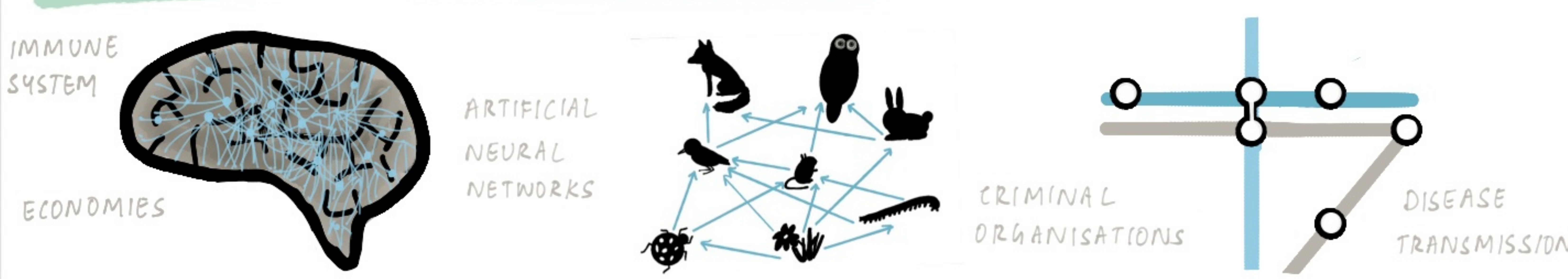
FEATURE

REMOVING A NODE (COMPUTER/PAGE) DOESN'T AFFECT ITS OPERATION

FAILURE

REMOVING ONE OR MORE HUBS WILL HAVE BIG CONSEQUENCES

EVERYDAY EXAMPLES OF NETWORKS



NEURAL NETWORKS — FOOD WEBS — TRANSPORT NETWORKS

THIS STUDY WILL HELP US BETTER UNDERSTAND THE STRENGTHS & VULNERABILITIES OF OUR OWN NATURAL AND ORGANISED NETWORKS

BUILDING THE SCIENCE

LET US TAKE A LOOK AT THE SCIENCES THAT COME TOGETHER IN THE QUEST FOR A UNIFIED THEORY OF COMPLEXITY.

GOALS

COMPLEXITY SCIENCES STUDY BOTH COMPLEX PHYSICAL SYSTEMS AND COMPLEX ADAPTIVE SYSTEMS. THE INTENTION IS TO USE LEARNINGS FROM ONE TO BETTER UNDERSTAND THE OTHER.

MELANIE MITCHELL

ACCORDING TO MELANIE MITCHELL, AT SANTA FE INSTITUTE THE TWO GOALS OF COMPLEXITY ARE:

- CROSS DISCIPLINARY INSIGHTS FROM DEVELOPING MATHEMATICAL AND COMPUTATIONAL TOOLS

MATHEMATICS

STATISTICS

COMPUTATION

APPLY THESE TO A COMPLEX PHYSICAL/ADAPTIVE SYSTEM TO

- GET INSIGHTS
- COMPARE WITH ANOTHER COMPLEX SYSTEM

- A GENERAL THEORY OF COMPLEXITY

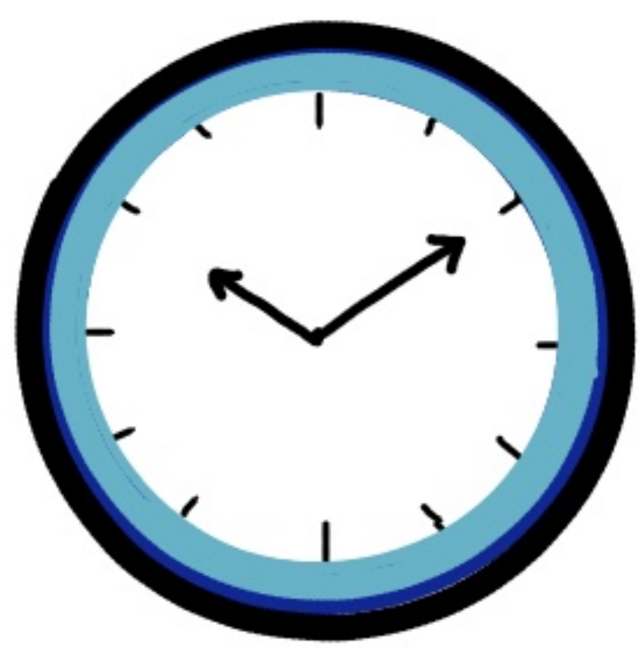
TO UNIFY THE SCIENCES THAT MAKE UP COMPLEXITY

(THE HOLY GRAIL + CONTROVERSIAL GOAL)

CORE DISCIPLINES

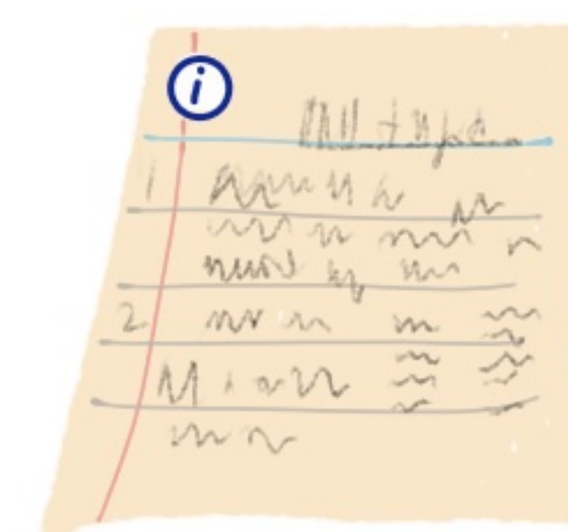
COMPLEXITY BRINGS TOGETHER ASPECTS OF OTHER SCIENCES

DYNAMICS



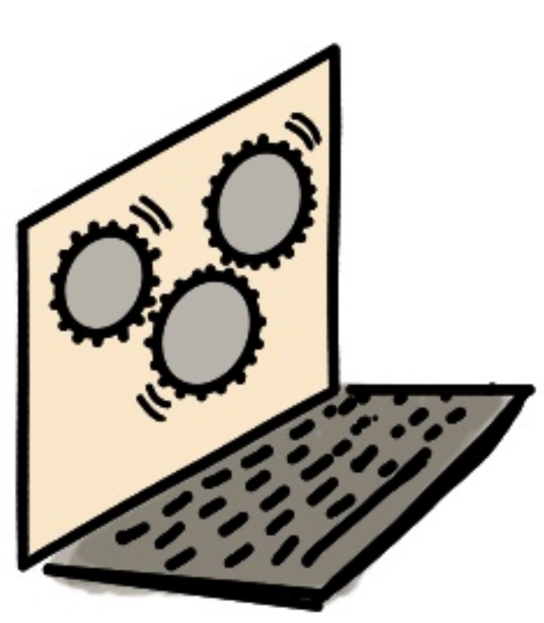
HOW AND WHY THINGS CHANGE OVER TIME

INFORMATION



SIGNALS EXCHANGED WITHIN THE SYSTEM

COMPUTATION



HOW THE INFORMATION IS PROCESSED/INTERPRETED

EVOLUTION

HOW SYSTEMS ADAPT AND LEARN FROM THE CHANGING ENVIRONMENT

DYNAMICS

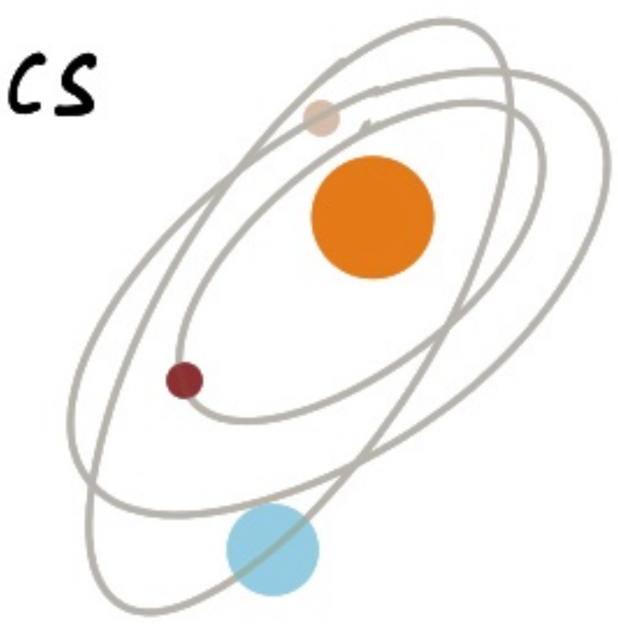
HELPS TO DESCRIBE THE NATURE OF
CHANGE IN A COMPLEX SYSTEM

ALL ABOUT DYNAMICS

DYNAMICS IS ABOUT HOW THINGS CHANGE OVER TIME

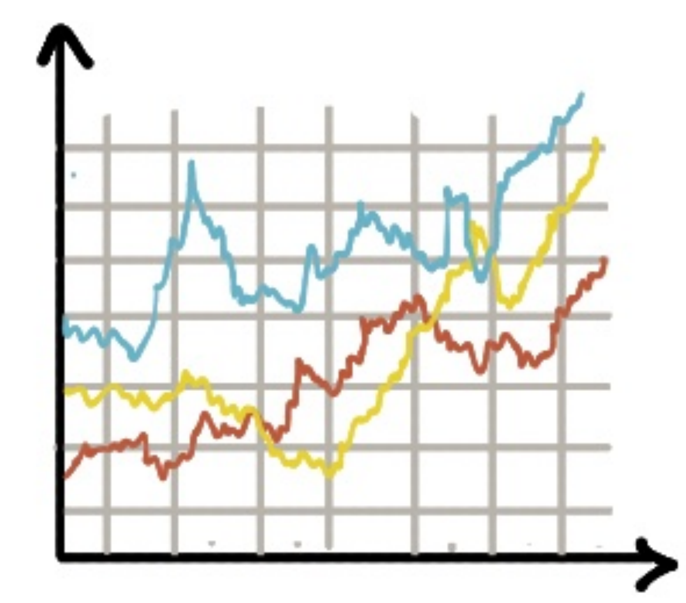
THERE ARE MANY KINDS OF DYNAMICS UNDER STUDY

ORBITS



GROUPS

STOCK PRICES



WHILE THERE ARE MATHEMATICAL TOOLS TO STUDY CHANGE AND MAKE PREDICTIONS, NOT ALL DYNAMICAL SYSTEMS ARE EASY TO PREDICT.

.... *Calculus Algebra Topology Differential Equations* ....

COMPLEX BEHAVIOURS IN DYNAMICAL SYSTEMS COULD BE THE RESULT OF

ITERATION → REPEATING THE SAME BEHAVIOURS OVER AND OVER

NON-LINEARITY → WHERE THE WHOLE IS NOT THE SUM OF THE PARTS

CHAOS → SENSITIVE DEPENDENCE ON INITIAL CONDITIONS

WE WILL NOW LOOK AT EACH OF THESE COMPLEX BEHAVIOURS

ITERATION

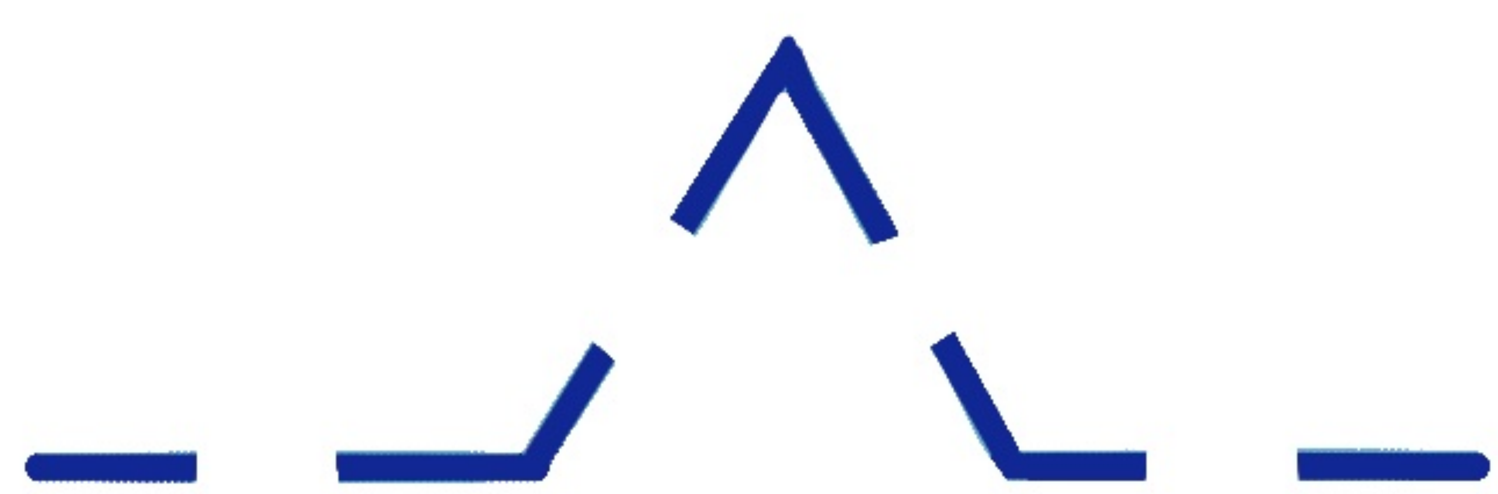
REPEATING THE SAME BEHAVIOURS PRODUCES COMPLEX PATTERNS.

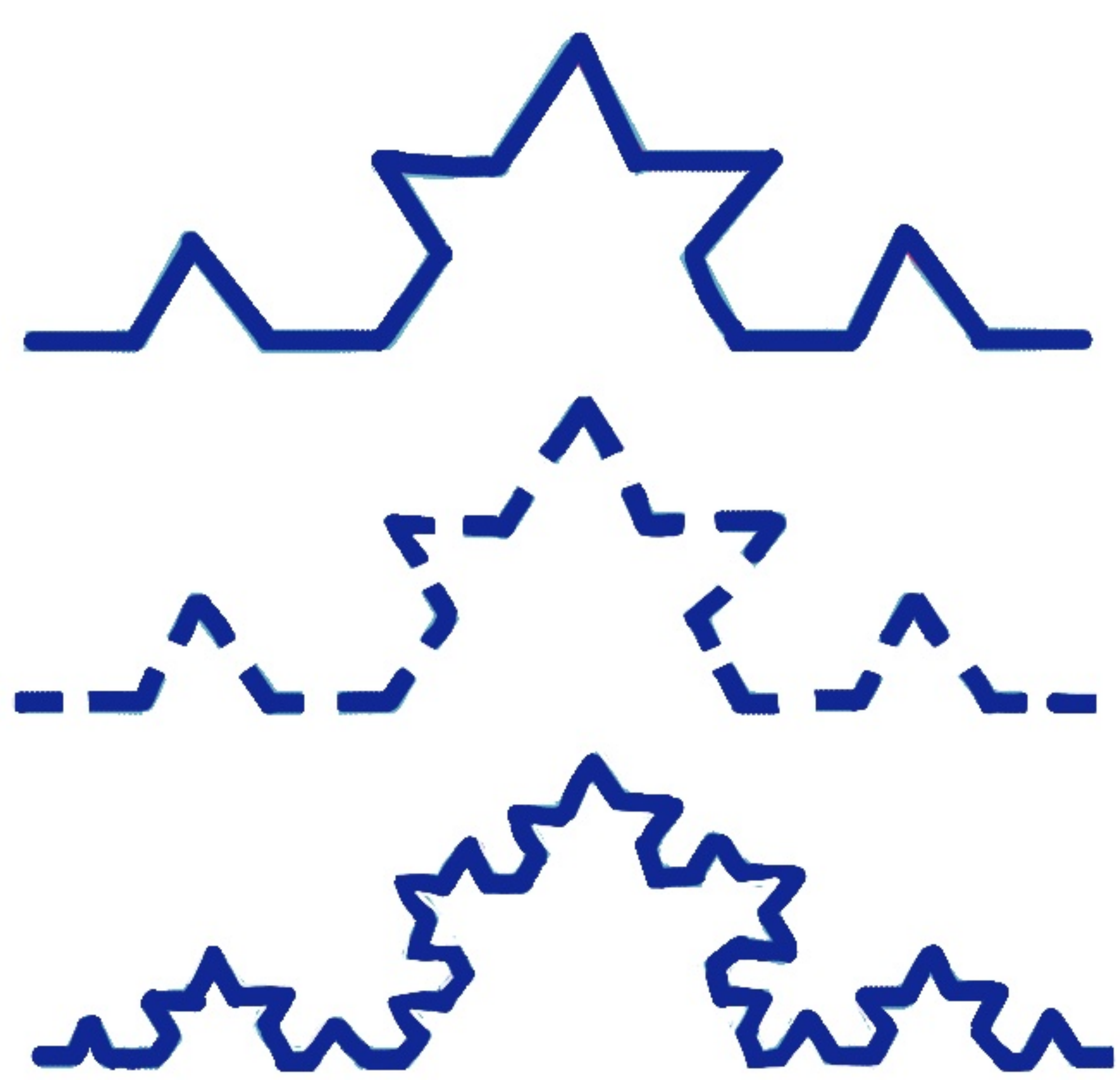
HERE IS A LINE

REMOVE THE MIDDLE ONE THIRD SEGMENT

FILL THE GAP WITH TWO LINES SO EACH.. ..IS THE LENGTH OF THE REMOVED SEGMENT

REPEAT FOR EACH SEGMENT

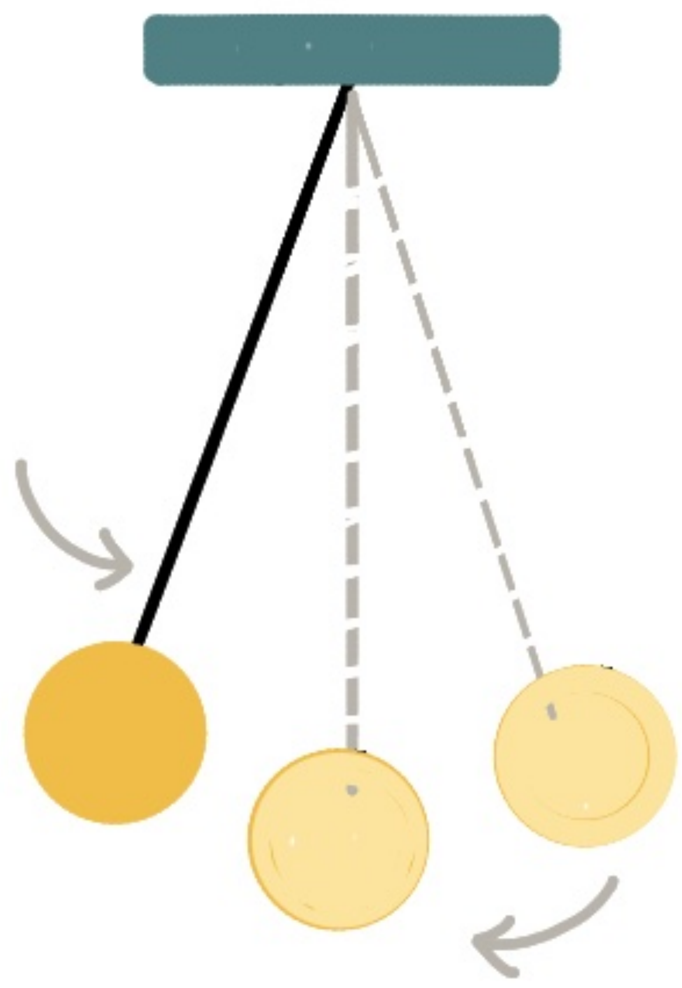




THIS IS A KOCH CURVE, A SELF SIMILAR PATTERN – A FRACTAL

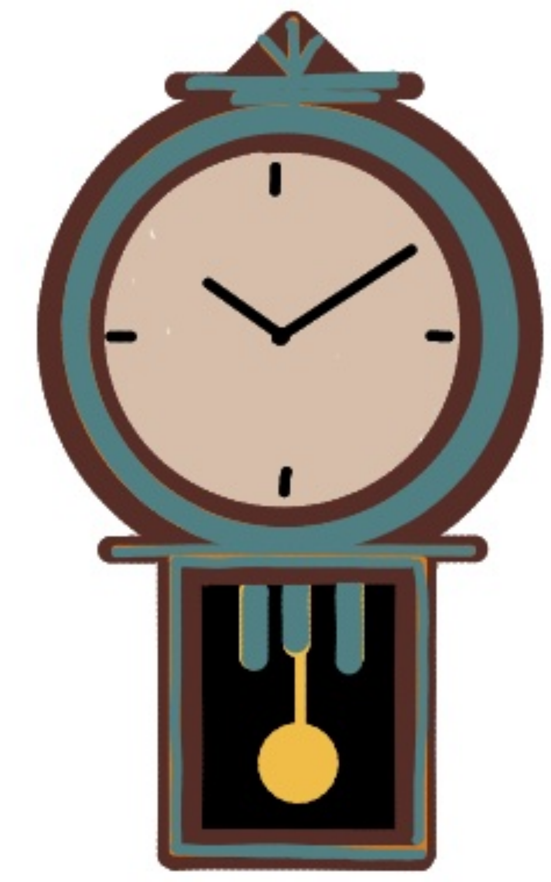
NON LINEARITY

A SIMPLE PENDULUM



A SYSTEM WITH
A STRING FIXED ON ONE END AND
A WEIGHT ATTACHED TO THE OTHER.

THE MOTION IS PREDICTABLE
EVERY RUN.



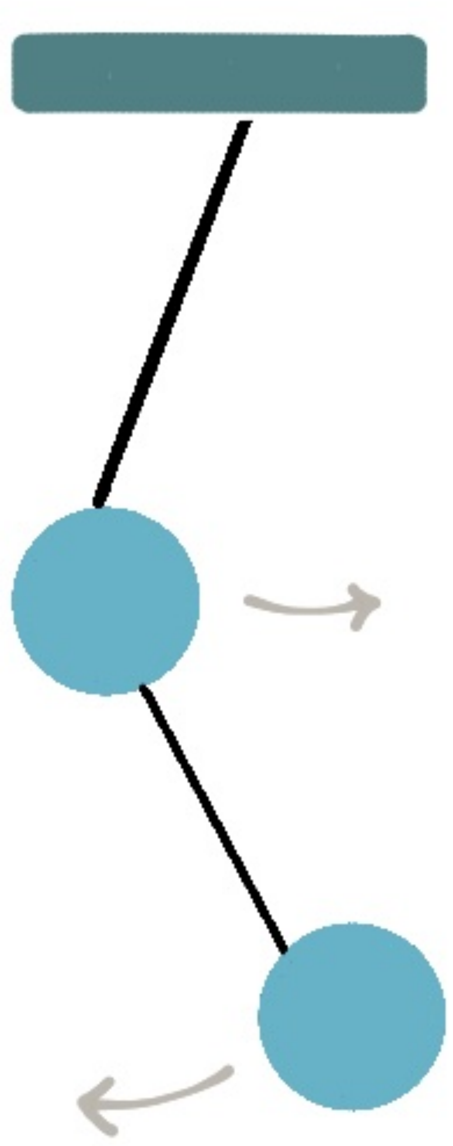
THE EQUATIONS TO CALCULATE THE FREQUENCY...

Period $T = 2\pi\sqrt{\frac{L}{g}}$

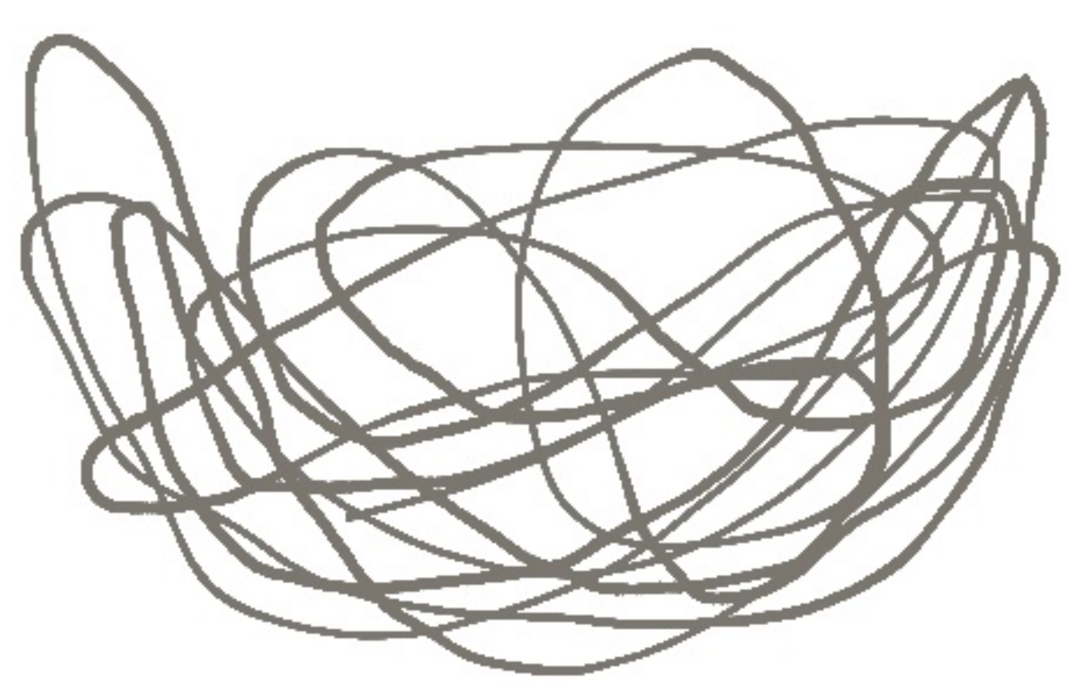
Frequency $f = \frac{1}{2\pi}\sqrt{\frac{g}{L}}$

...AND PERIOD OF ITS MOTION ARE SOLVABLE BY HAND

A DOUBLE PENDULUM IS CHAOTIC



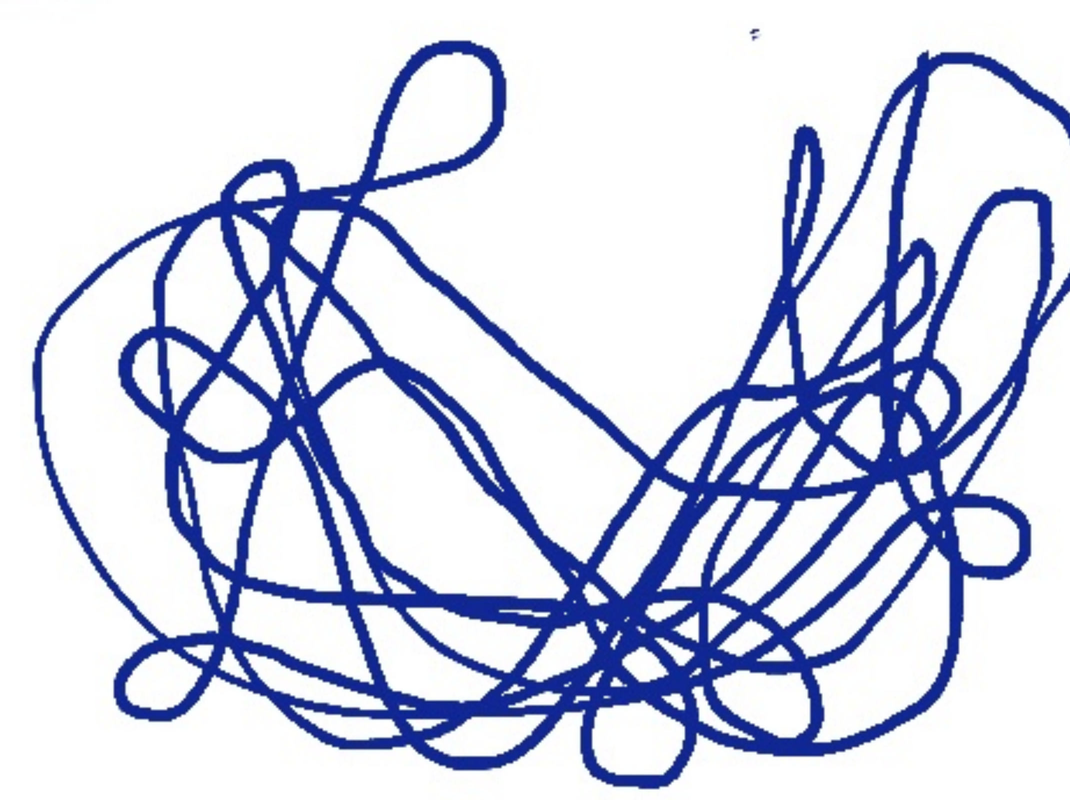
A PENDULUM WITH A PENDULUM ATTACHED TO IT.



PATH-1

THE PATH TRACED LOOKS RANDOM AND UNPREDICTABLE

NEEDS A COMPUTER TO SOLVE EQUATIONS



PATH-2

A SECOND RUN TRACES OUT A VERY DIFFERENT PATH

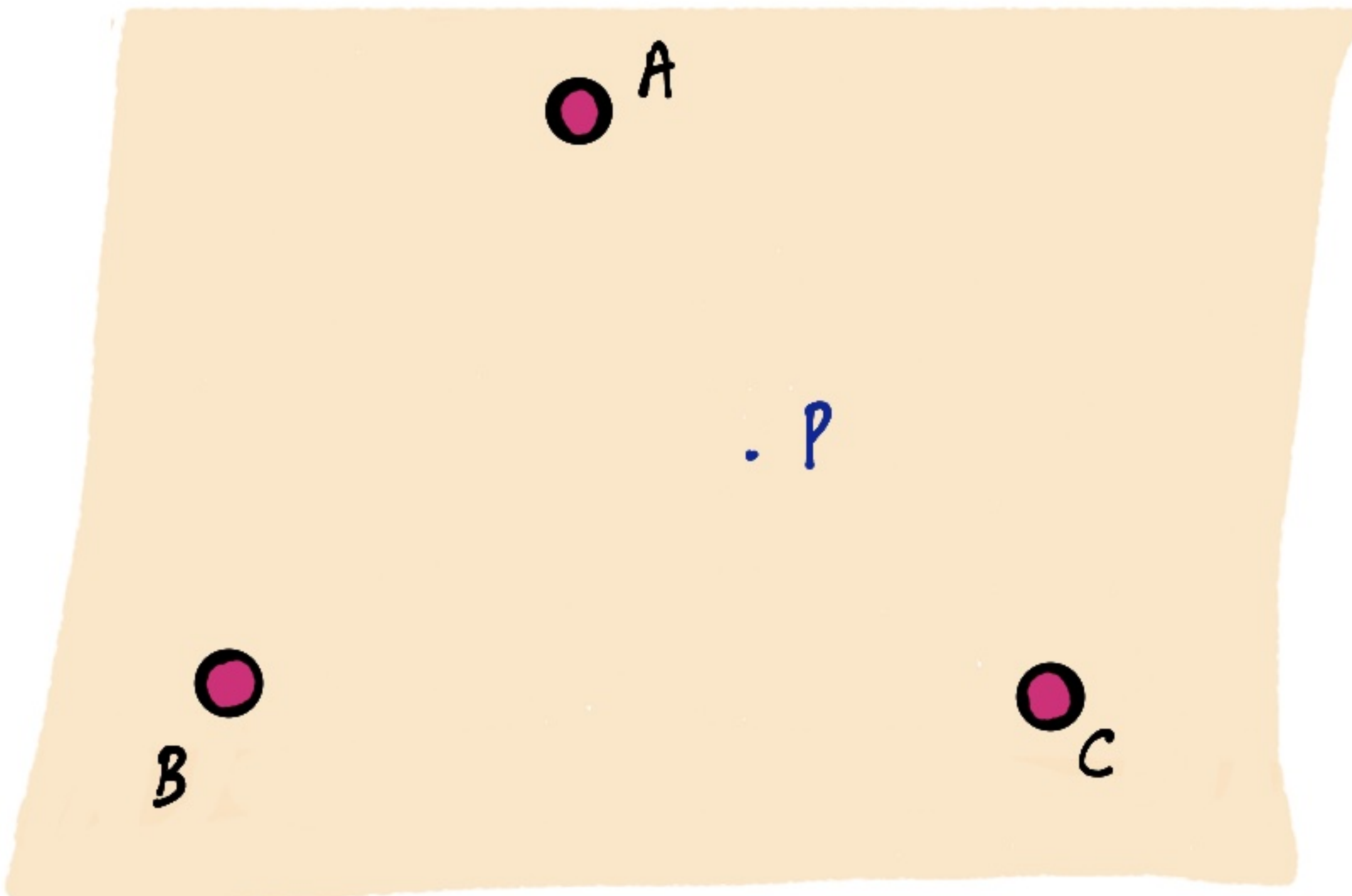
SMALL DIFFERENCE IN INITIAL CONDITIONS

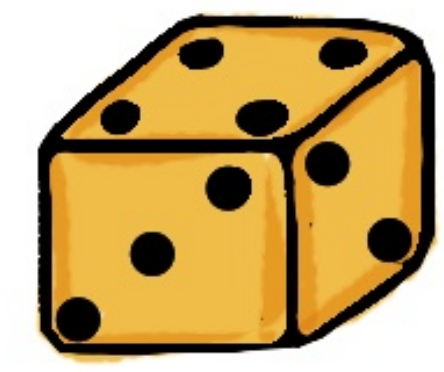
THE NON LINEARITY OF DYNAMIC SYSTEMS CAN BE THOUGHT OF AS:

MOTION OF 2 SIMPLE PENDULUMS $\neq$ MOTION OF 1 DOUBLE PENDULUM

CHAOTIC OR FRACTAL?

DRAW THREE DOTS A, B AND C. MARK A RANDOM POINT P FROM WHERE TO START. USE A DIE TO PLOT OTHER POINTS

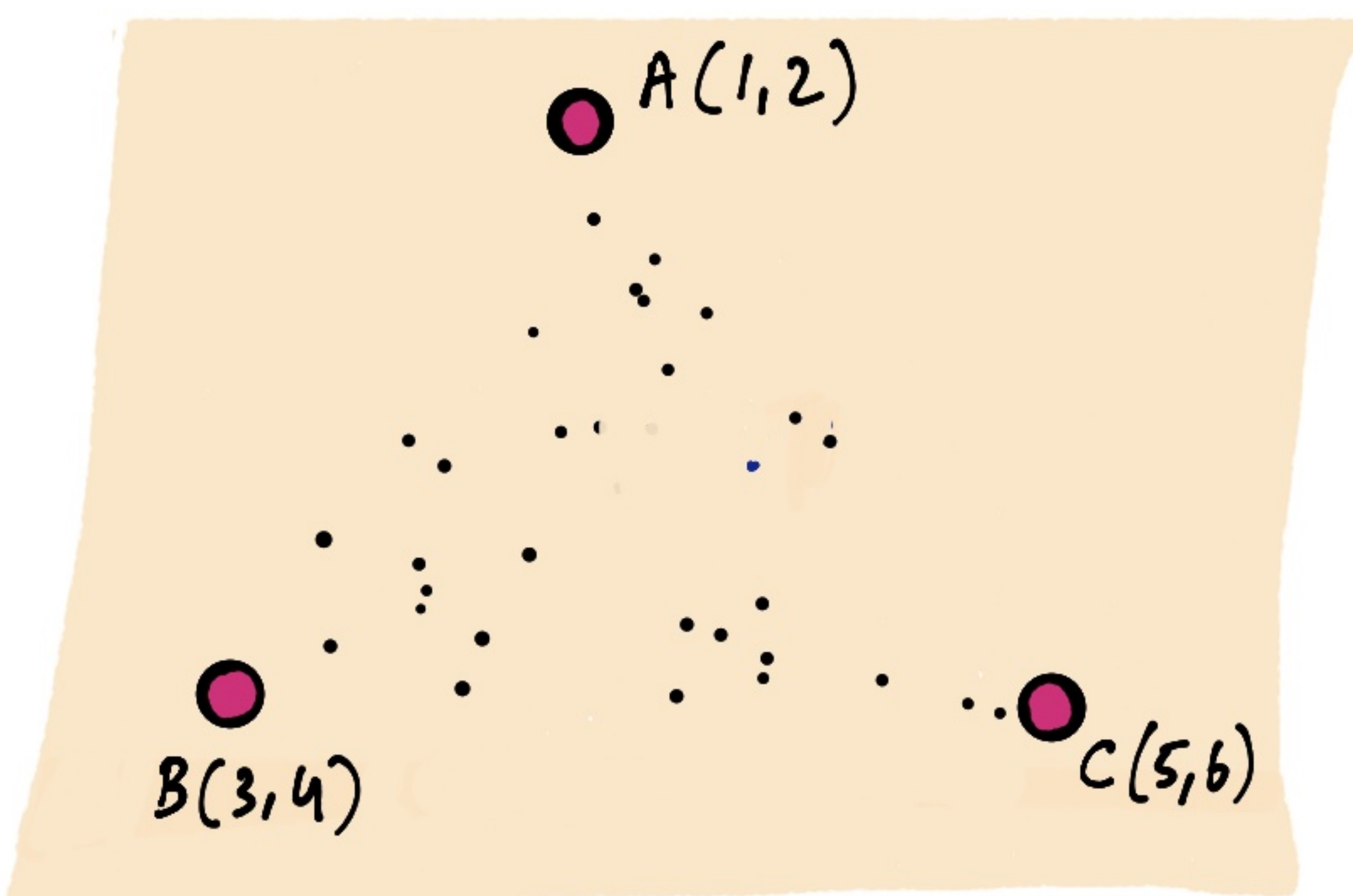




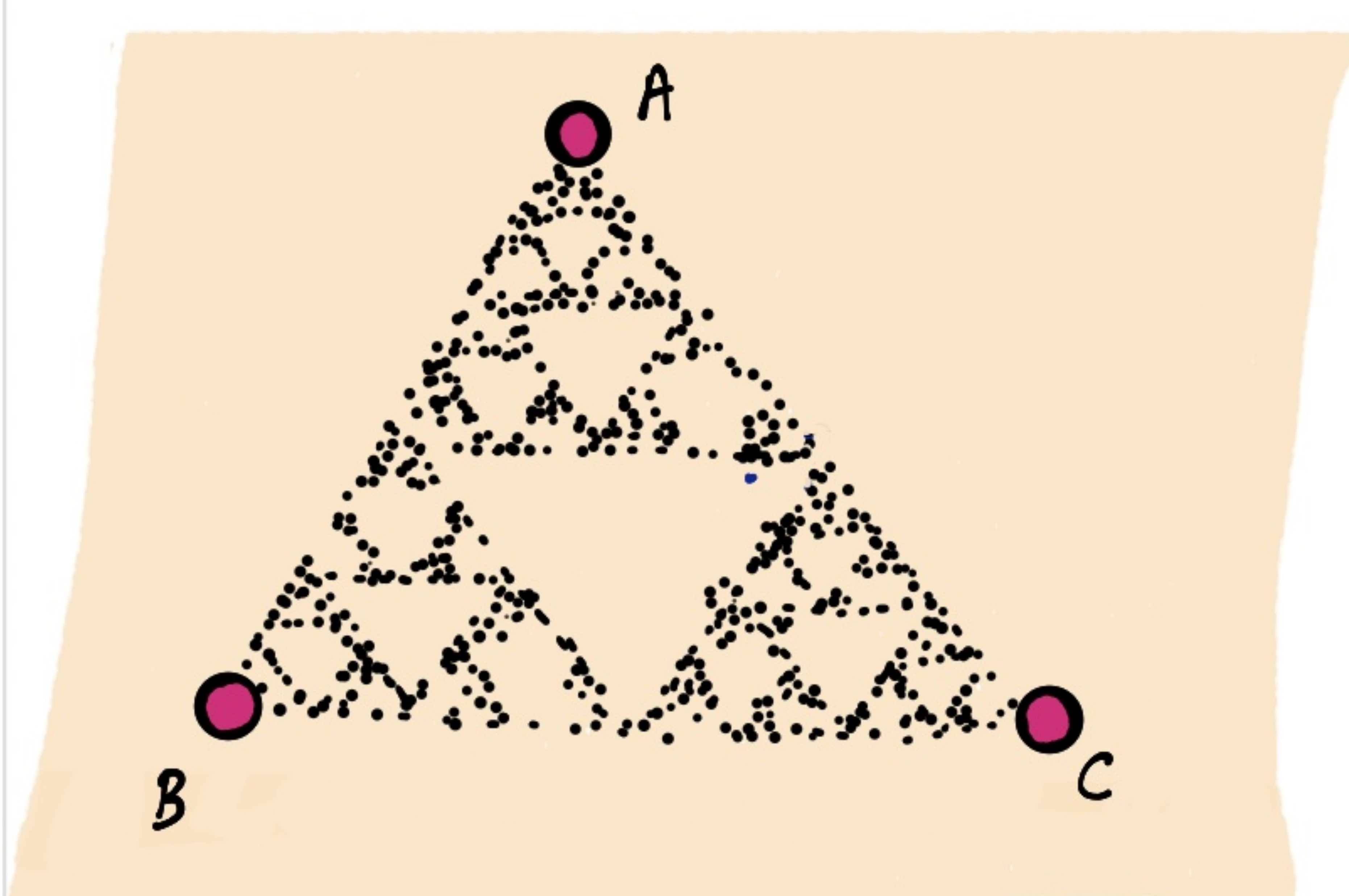
(1,2) → MOVE HALFWAY TO A

(3,4) → MOVE HALFWAY TO B

(5,6) → MOVE HALFWAY TO C



WHAT STARTS OFF AS RANDOM DOTS BEGINS TO LOOK MORE STRUCTURED WITHIN A FEW HUNDRED ITERATIONS



THIS SET OF RULES TENDS TOWARDS A PATTERN CALLED AN ATTRACTOR. THE PATTERN IS A FAMOUS FRACTAL: THE SIERPINSKI TRIANGLE

CHAOS & POINCARÉ

NEWTON'S EQUATIONS DESCRIBE THE MOTION OF PLANETS ACCURATELY ONLY IN THE CASE WHERE THERE ARE EXACTLY TWO BODIES.

IN THE LATE 1800s:

MATHEMATICIAN HENRI POINCARÉ ATTEMPTED TO DESCRIBE THE MOTION OF 3 BODIES USING NEWTON'S LAWS OF MOTION AND GRAVITATION FROM THEIR INITIAL POSITIONS AND VELOCITIES.

POINCARÉ DIDN'T SUCCEED

My work had a serious error

I had to withdraw my paper...

... paying a huge amount of money

HENRI POINCARÉ

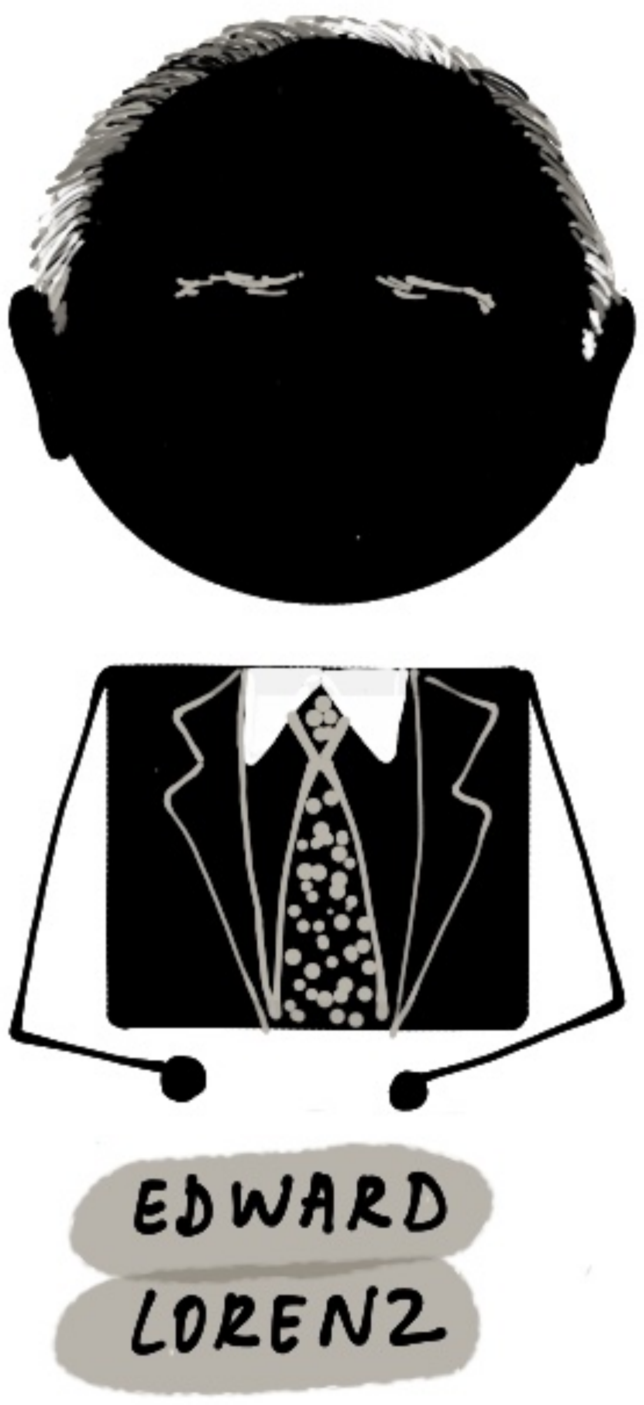
BUT HE CAME TO THE REALISATION THAT

WE CAN KNOW THE INITIAL CONDITIONS OF ANY EVENT ONLY APPROXIMATELY

SMALL DIFFERENCES IN THE INITIAL CONDITIONS PRODUCE VERY GREAT ONES IN THE FINAL PHENOMENA

POINCARÉ'S WORK LAID THE FOUNDATION OF CHAOS THEORY

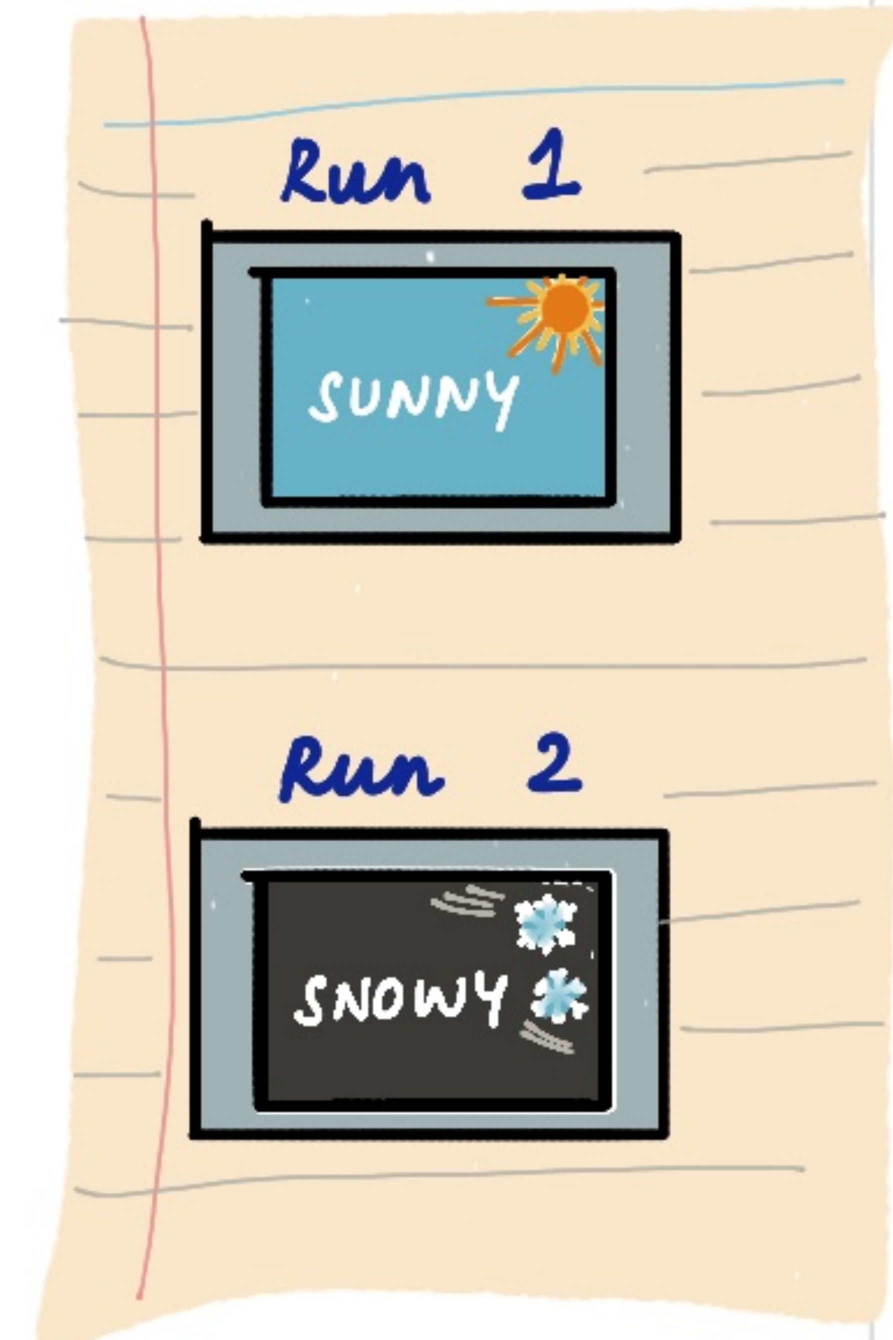
UNPREDICTABLE AS WEATHER



METEOROLOGIST EDWARD LORENZ WAS SIMULATING ON HIS COMPUTER, A SIMPLE MODEL OF THE ATMOSPHERE

in only twelve equations!

ON THE SECOND RUN, HE FOUND THAT THE RESULTS WERE VERY DIFFERENT

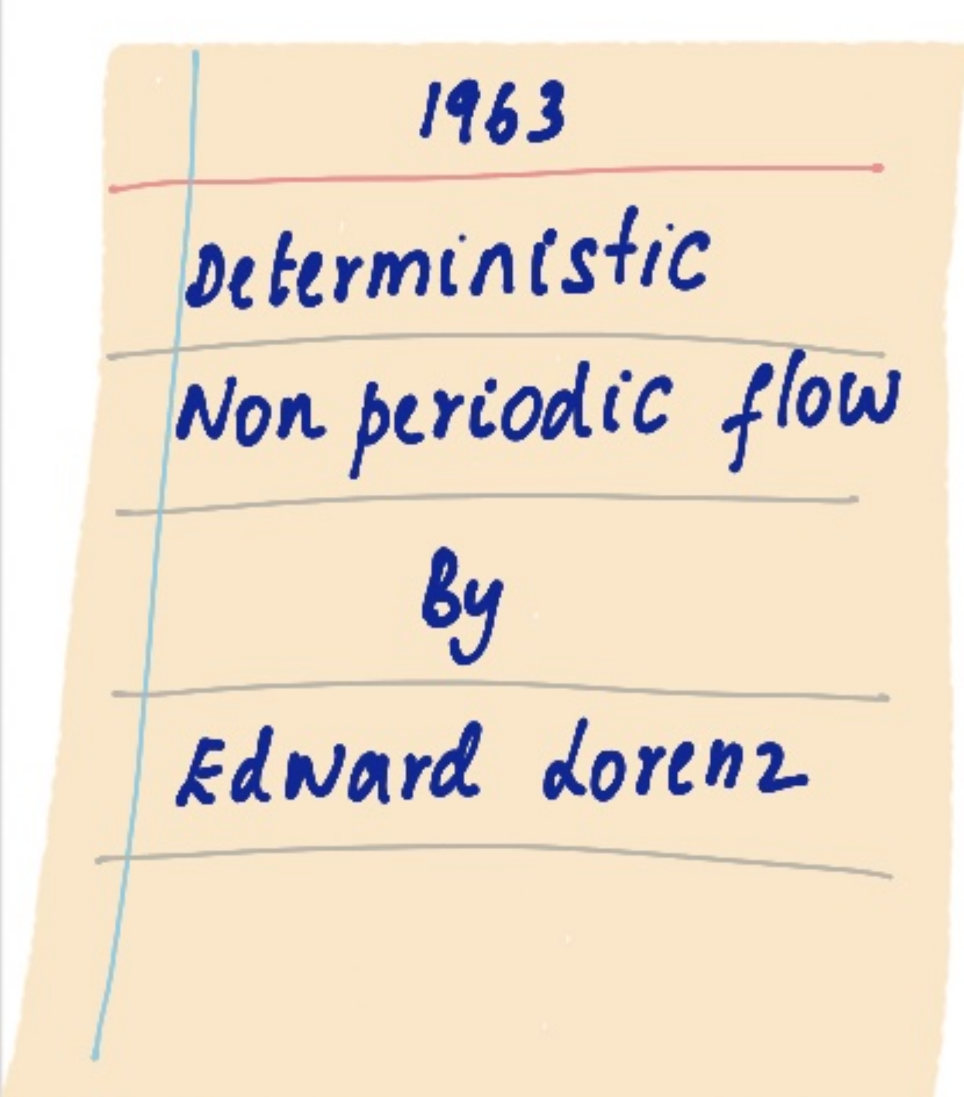


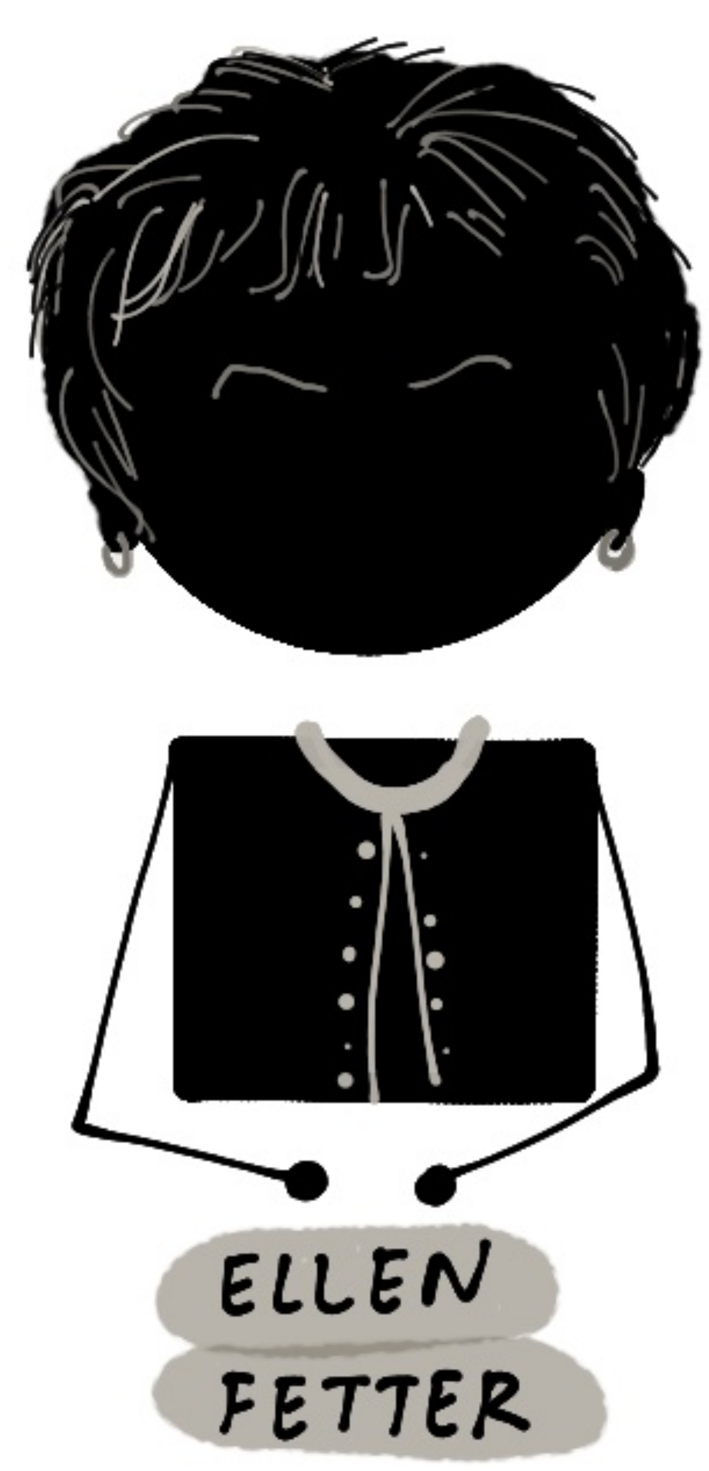
THE SECOND RUN HAD A DIFFERENT INPUT VALUE IN ONE OF THE DECIMAL PLACES DUE TO ROUNDING.

Temperature : 27.084271°

Temperature : 27.084°

SMALL CHANGES AMPLIFIED IN THIS DETERMINISTIC SYSTEM RESULTING IN 'CHAOTIC' BEHAVIOUR



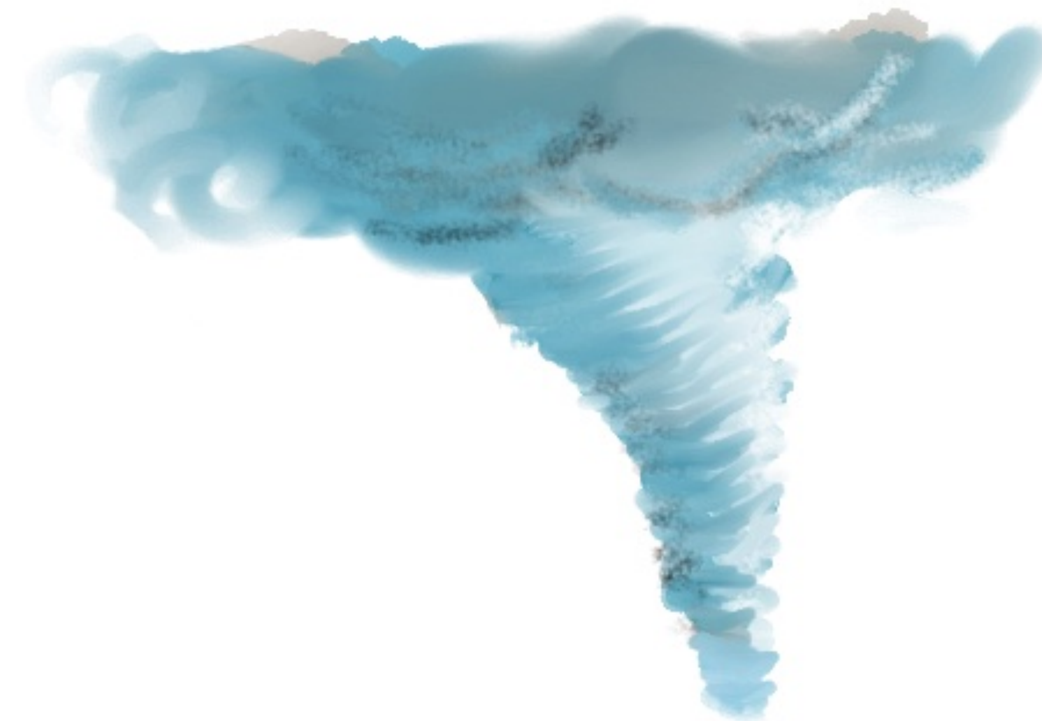


LORENZ PURSUED THIS RESEARCH WITH HELP FROM HAMILTON AND FETTER AND PUBLISHED HIS OBSERVATIONS IN A PAPER

THE BUTTERFLY EFFECT

CHAOS IS THE SENSITIVE DEPENDENCE ON INITIAL CONDITIONS

APPARENTLY CAPABLE OF SETTING OFF
A TORNADO IN TEXAS
BY THE FLAPPING OF
A BUTTERFLY'S WINGS IN BRASIL

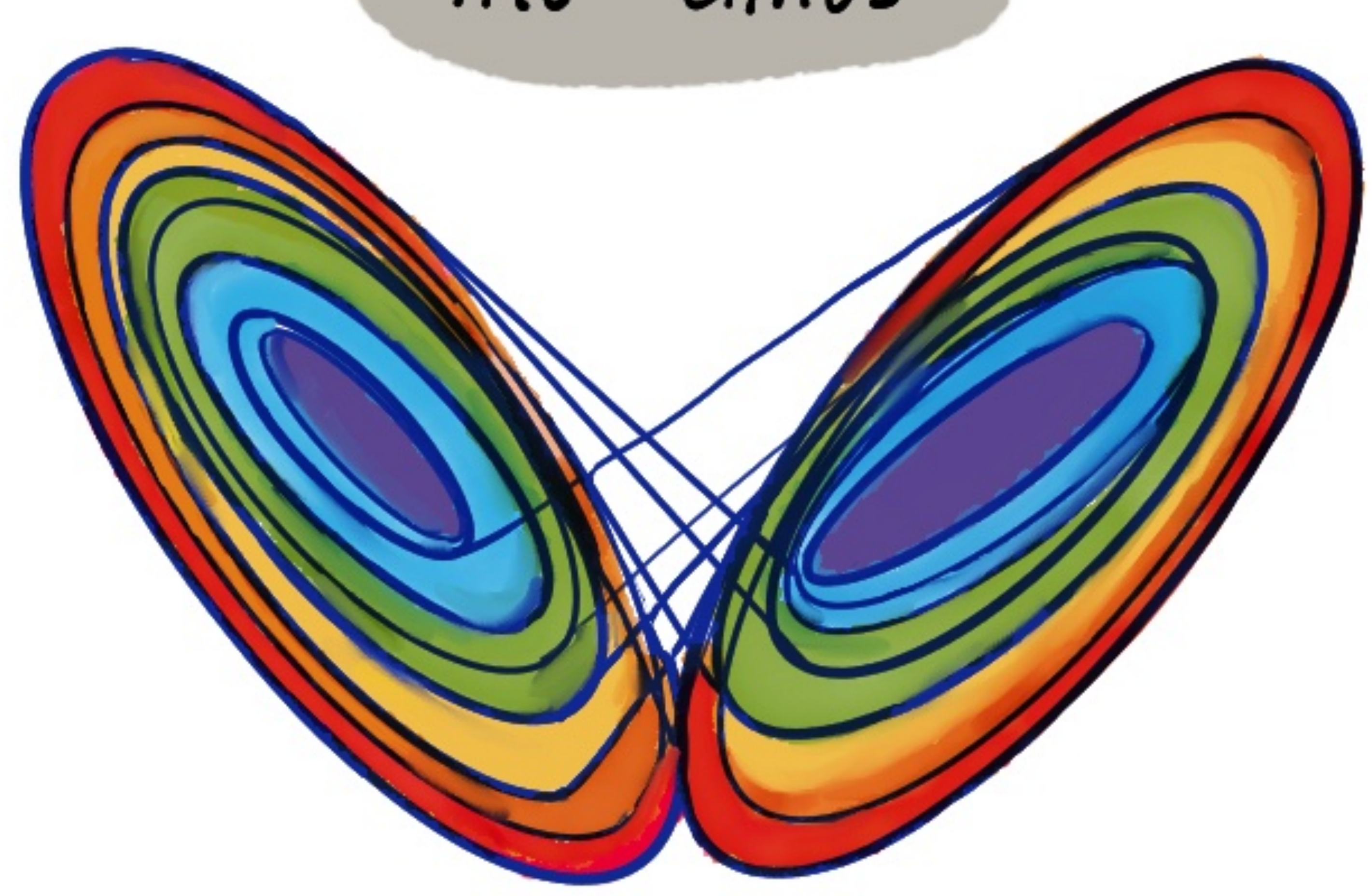


THIS PHENOMENON THAT LORENZ WROTE ABOUT CAME TO BE POPULAR AS THE BUTTERFLY EFFECT.

LORENZ NOTICED THAT THE SOLUTIONS TO A SET OF 3 OF THOSE EQUATIONS TAKE THE SHAPE OF CURVED LINES LOOPING AROUND TWO "CENTRES".

THE 'CHAOS'

NEVER RETRACES THE SAME PATH



CALLED THE LORENZ ATTRACTOR

LOOKS LIKE THE WINGS OF A BUTTERFLY

FORMS AN ORDERLY PATTERN

TWO PATHS STARTING NEAR EACH OTHER CAN DIVERGE, ONE SEPARATING OFF TO THE RIGHT HALF AND THE OTHER TO THE LEFT, CAUSING THE UNPREDICTABILITY BETWEEN THE TWO RUNS

DETERMINISTIC CHAOS – I

$$x_{n+1} = \lambda x_n (1 - x_n)$$

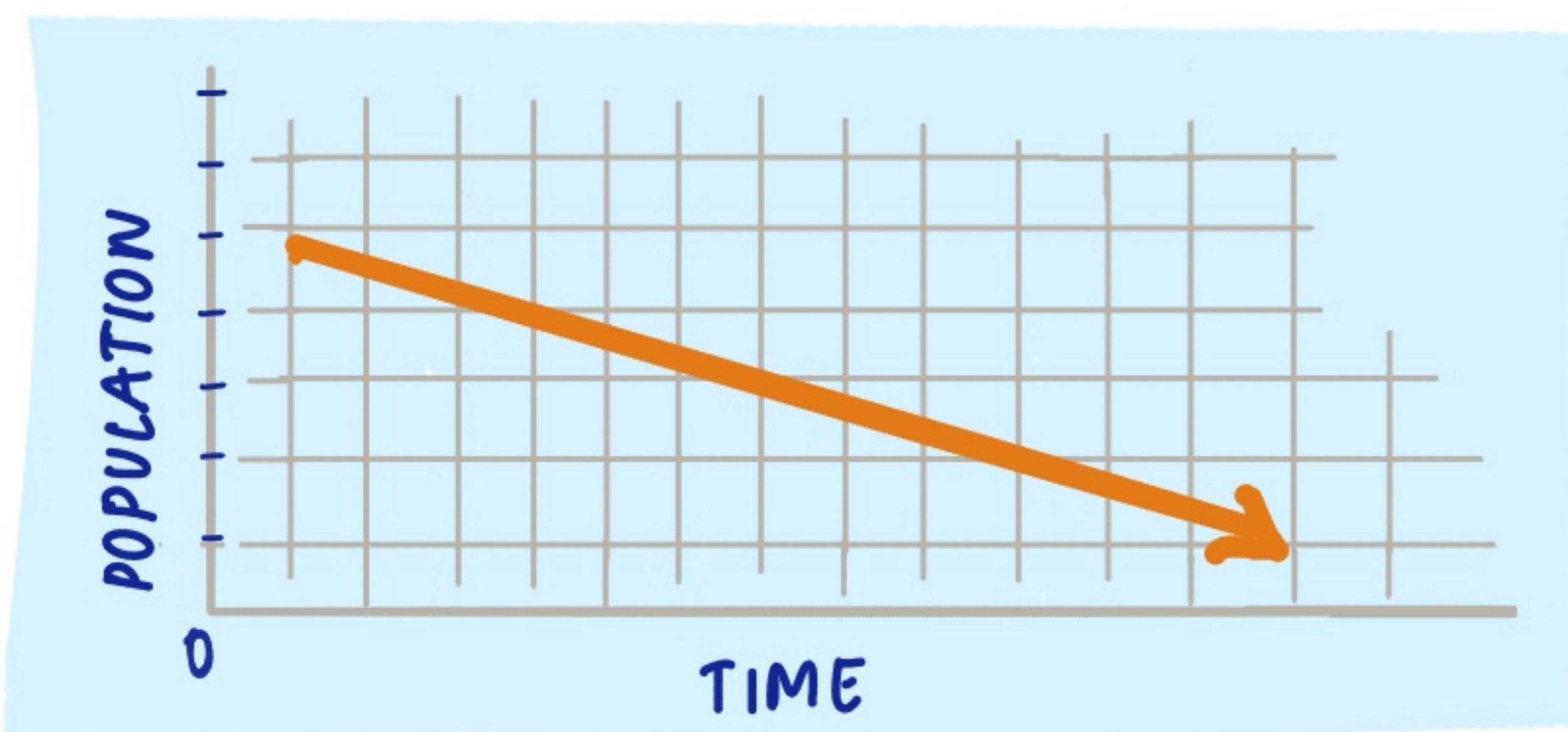
x = POPULATION $\quad$ $n+1$ = NEXT YEAR

λ = GROWTH RATE $\quad$ n = THIS YEAR

→ from a paper by Robert May

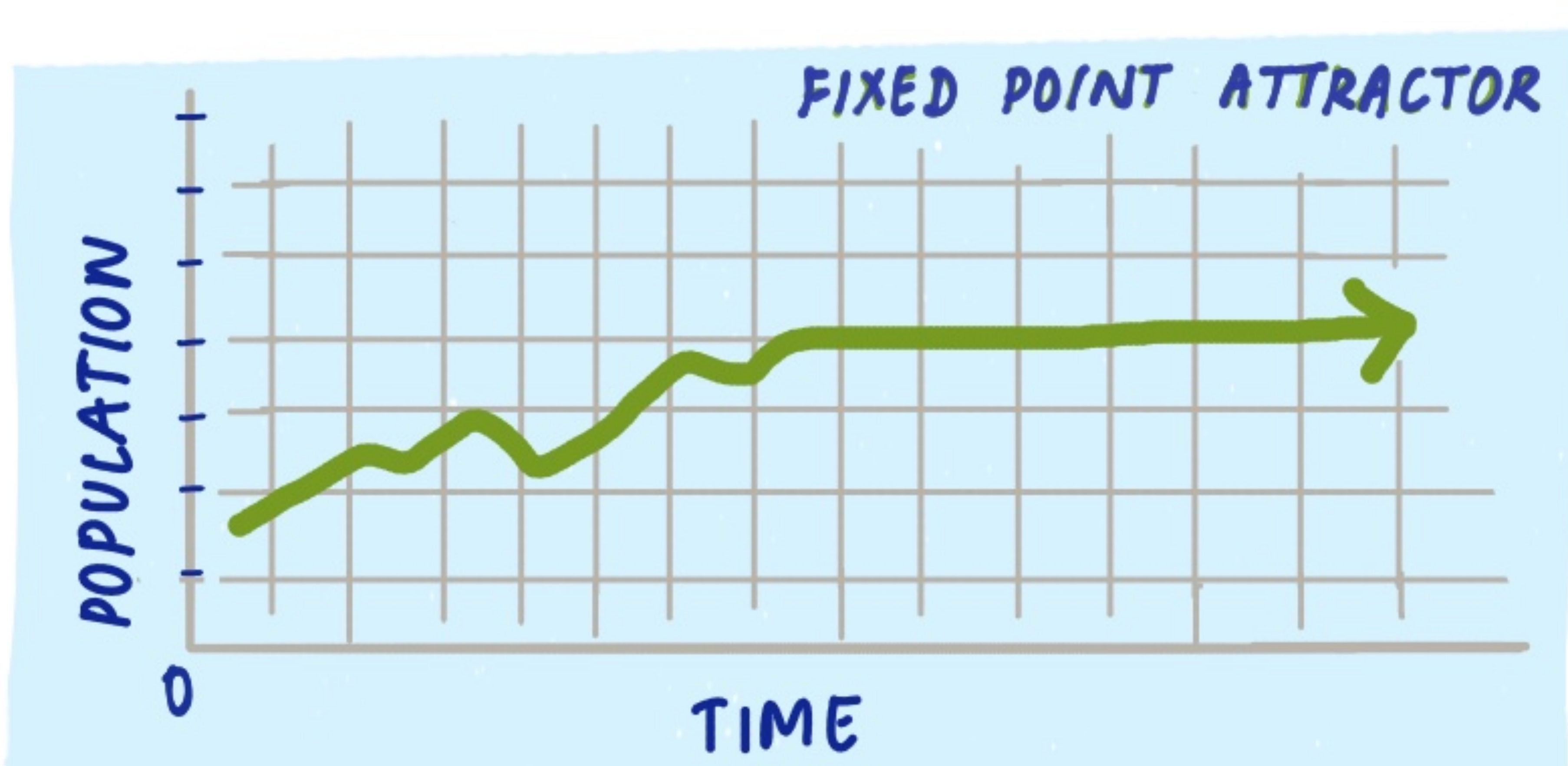
THIS IS AN EQUATION THAT MODELS POPULATION GROWTH

IF THE GROWTH RATE IS BETWEEN 0 – 1



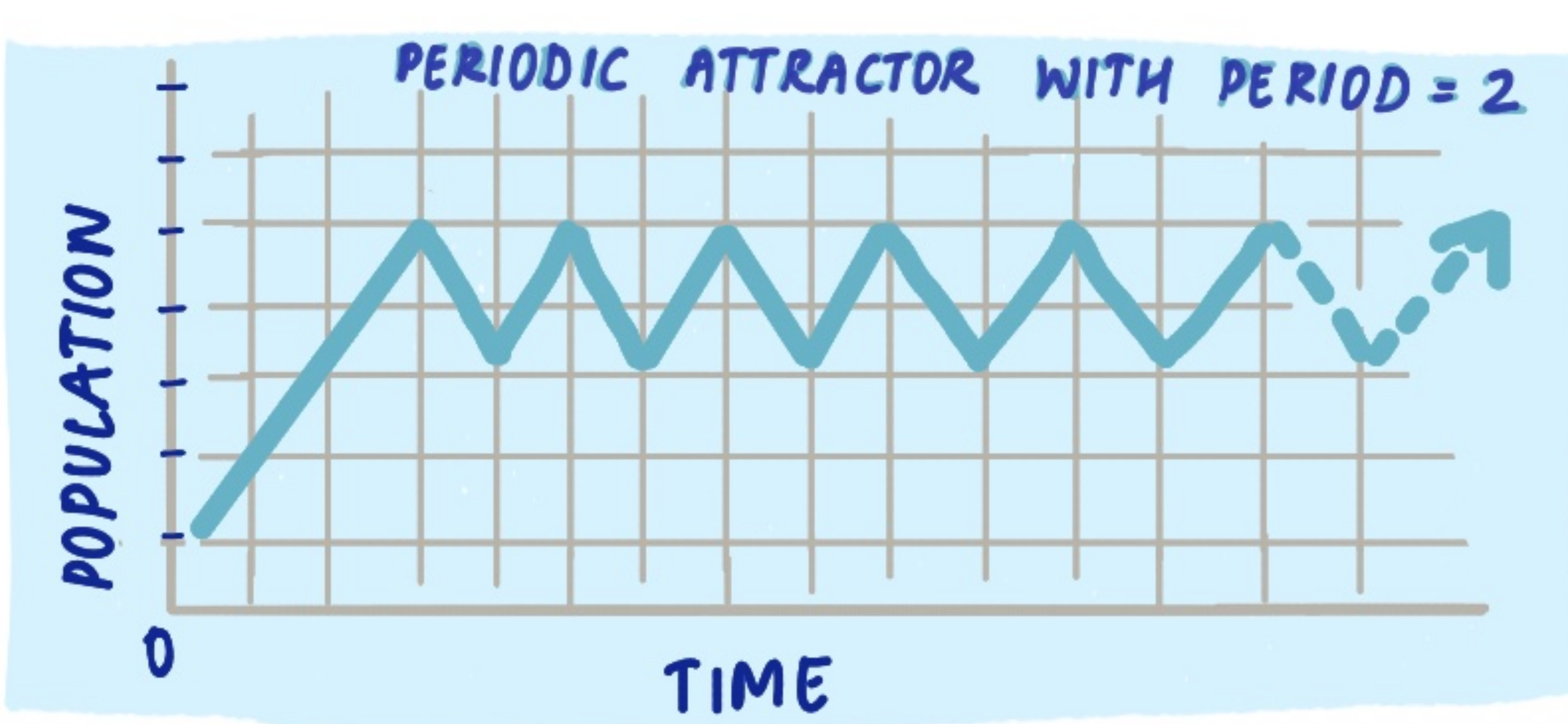
THE POPULATION DIES OUT OVER A FEW GENERATIONS

FOR SOME GROWTH RATES ABOVE 1



THE POPULATION STABILISES OVER A FEW GENERATIONS

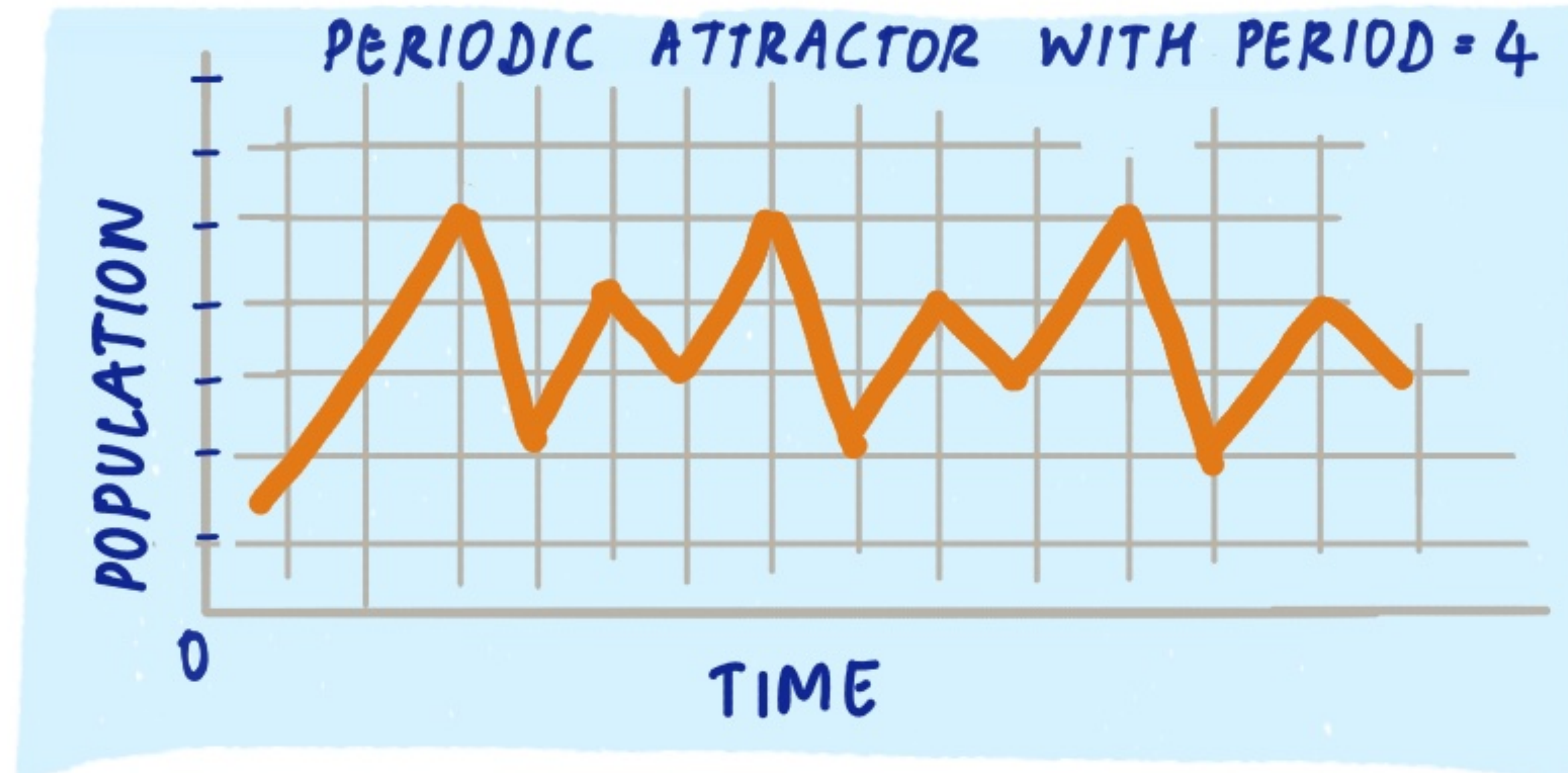
FOR HIGHER GROWTH RATES AROUND 3·2



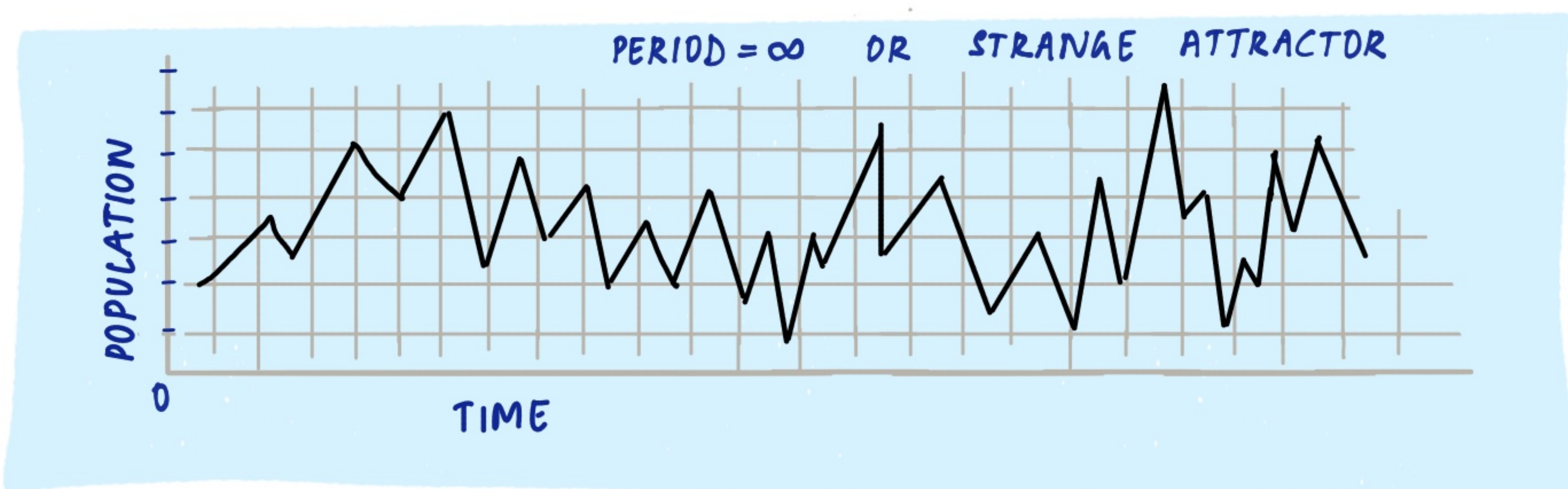
THE POPULATION OSCILLATES BETWEEN 2 STABLE VALUES EVERY ALTERNATE GENERATIO

DETERMINISTIC CHAOS – 2

AS λ INCREASES BY FURTHER SMALL AMOUNTS, THE PERIOD GOES TO 4, 8, 16, 32 ETC.



FINALLY, AT A CERTAIN VALUE OF GROWTH RATE, CLOSE TO 4, THE POPULATION DOES NOT SEEM TO BE CYCLING THROUGH ANY PREDICTABLE SET OF VALUES AT ALL.



A RERUN OF THE POPULATION MODEL NOW WOULD VARY SIGNIFICANTLY

AN EQUATION WHICH USED TO MAKE ACCURATE PREDICTIONS IS NOW IMPOSSIBLE TO PREDICT. THIS IS CALLED DETERMINISTIC CHAOS.

UNIVERSALITY IN CHAOS

① ROUTE TO CHAOS	② RATE OF PERIOD DOUBLING
This period doubling route to chaos is also seen in other chaotic systems	The period doubles 4.669201... times faster than last time This is the Feigenbaum Constant

INFORMATION

HELPS US BETTER UNDERSTAND SELF ORGANISATION
IN A COMPLEX SYSTEM

A HISTORY

INFORMATION THEORY HAS ITS ORIGINS IN THERMODYNAMICS, A BRANCH OF PHYSICS DEALING WITH HEAT, WORK AND MOTION

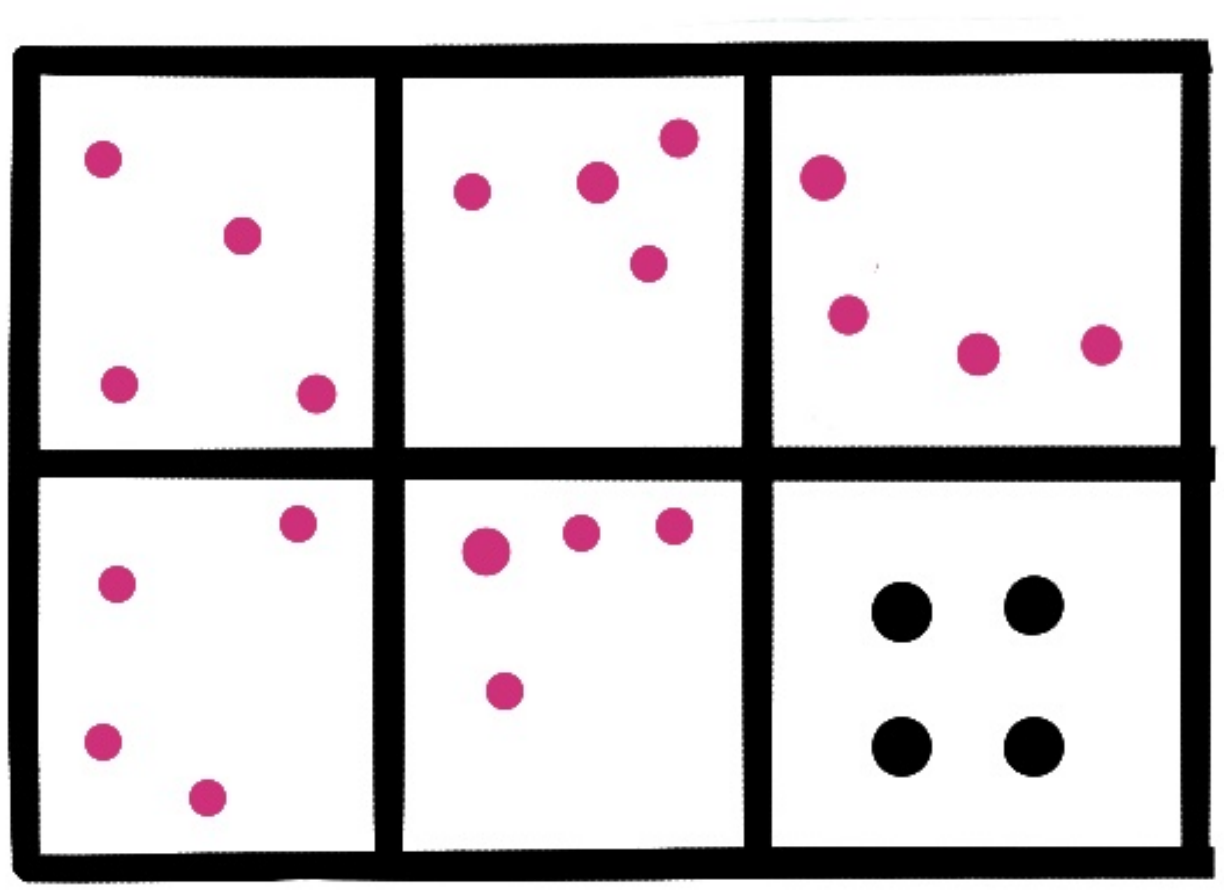
THERE ARE SOME FUNDAMENTAL LAWS OF THERMODYNAMICS

LAW 1 ENERGY IN THE UNIVERSE IS FIXED → Energy cannot be created or destroyed

LAW 2 ANY UNUSABLE ENERGY INCREASES THE DISORDER OR ENTROPY OF THE UNIVERSE → Order turns to disorder unless work is done

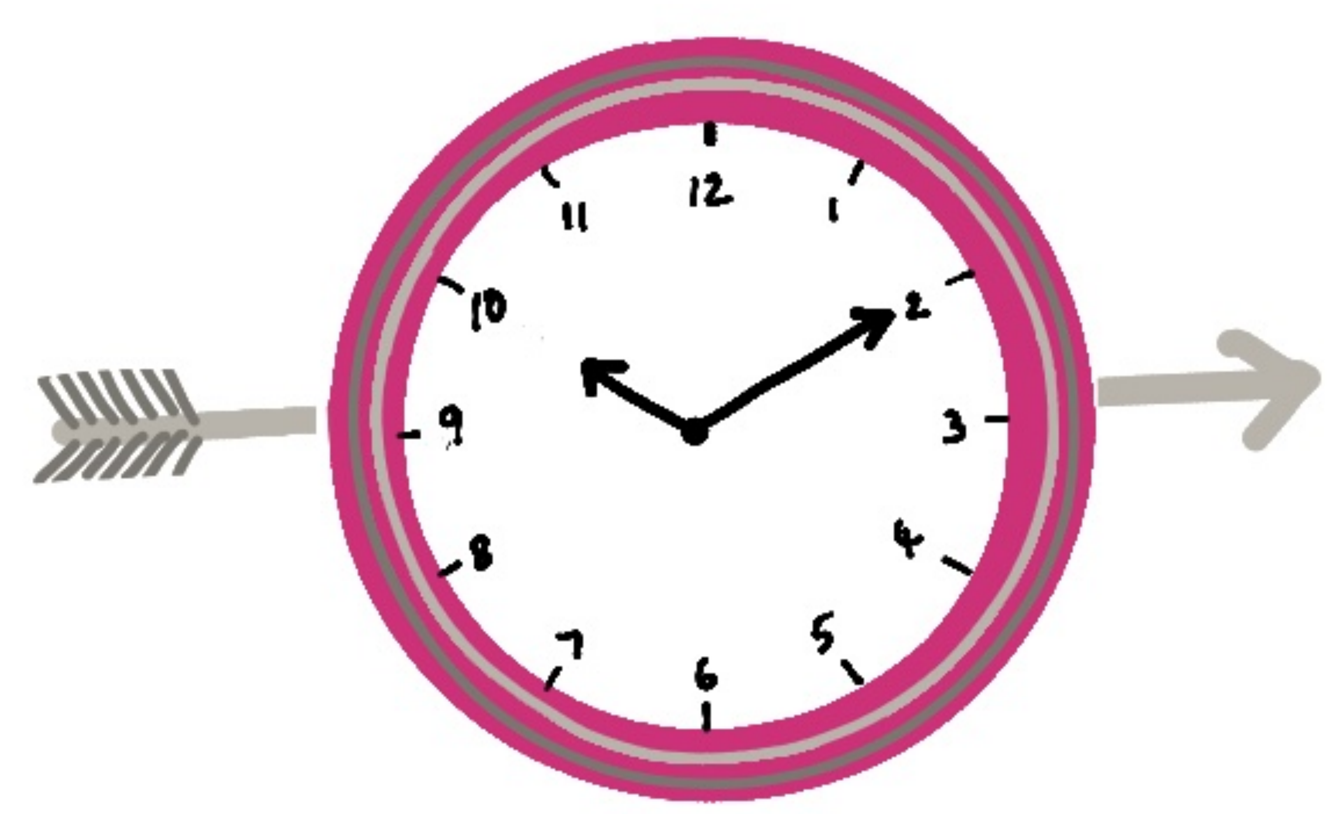
OUR FOCUS IS THE SECOND LAW WHICH IS INVIOLABLE

ENTROPY IS CONNECTED TO PROBABILITY



THERE ARE MORE WAYS TO ACHIEVE DISORDER THAN THERE ARE TO ACHIEVE ORDER

ENTROPY TELLS US THAT TIME HAS A DIRECTION



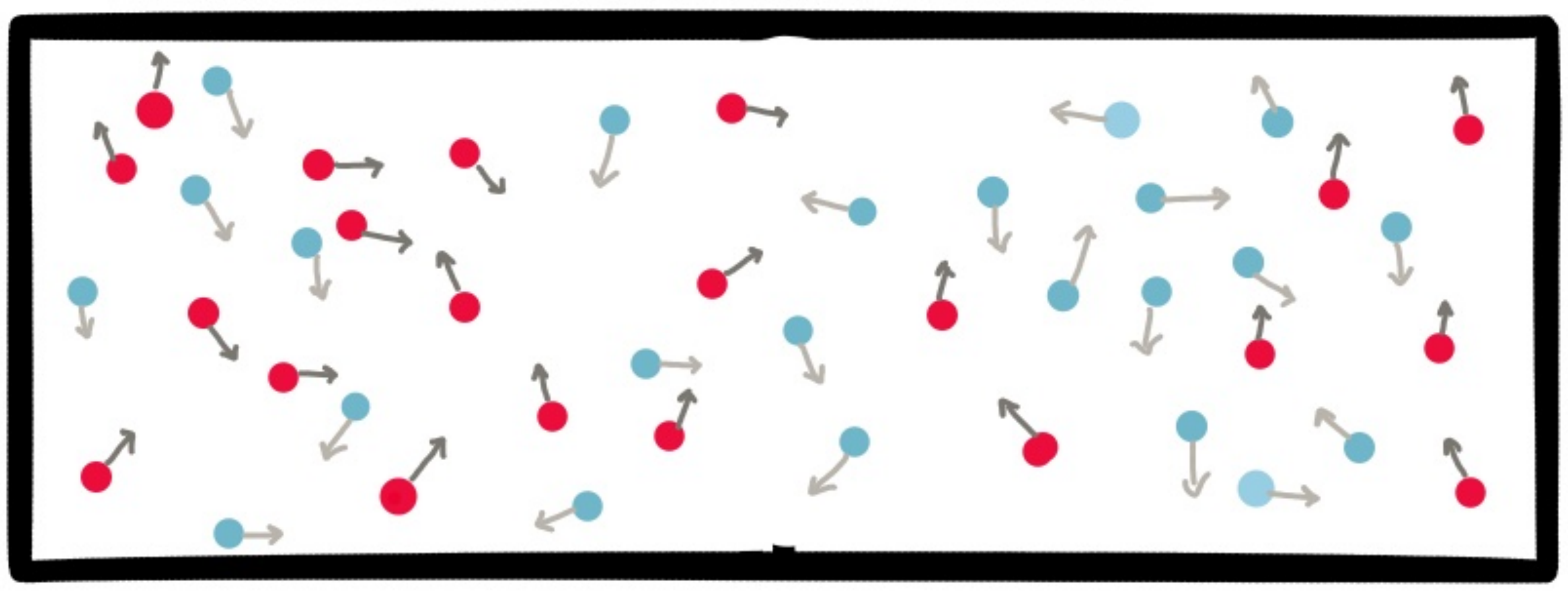
IN THE DIRECTION OF INCREASING ENTROPY

JAMES CLERK MAXWELL WONDERED IN A FAMOUS THOUGHT EXPERIMENT IN 1867 INVOLVING A DEMON, IF THE SECOND LAW COULD BE VIOLATED

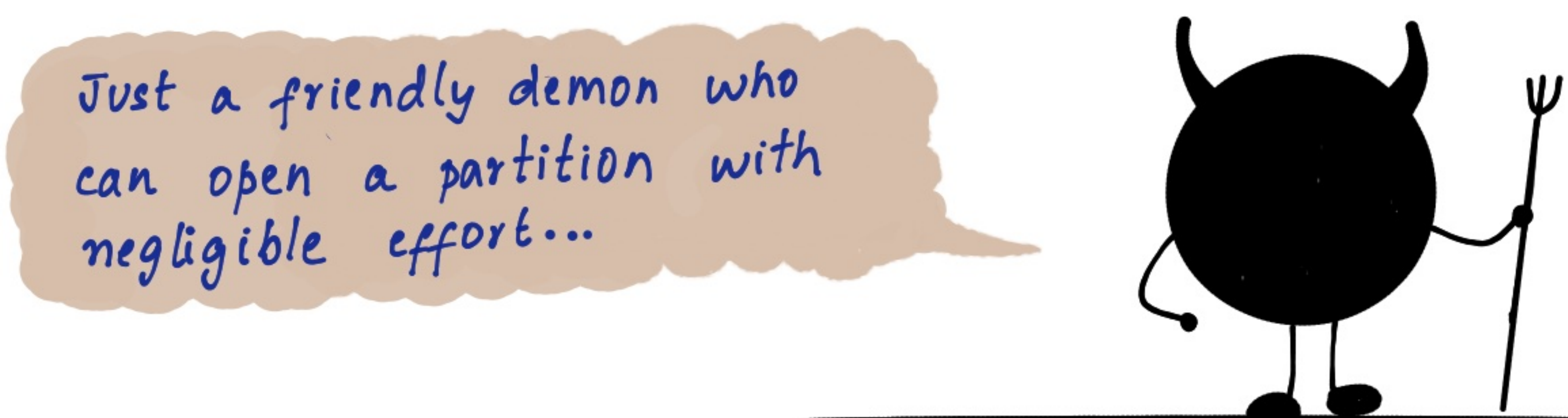
MAXWELL'S DEMON

MAXWELL KNEW THAT HEAT WAS THE MOTION OF MOLECULES.

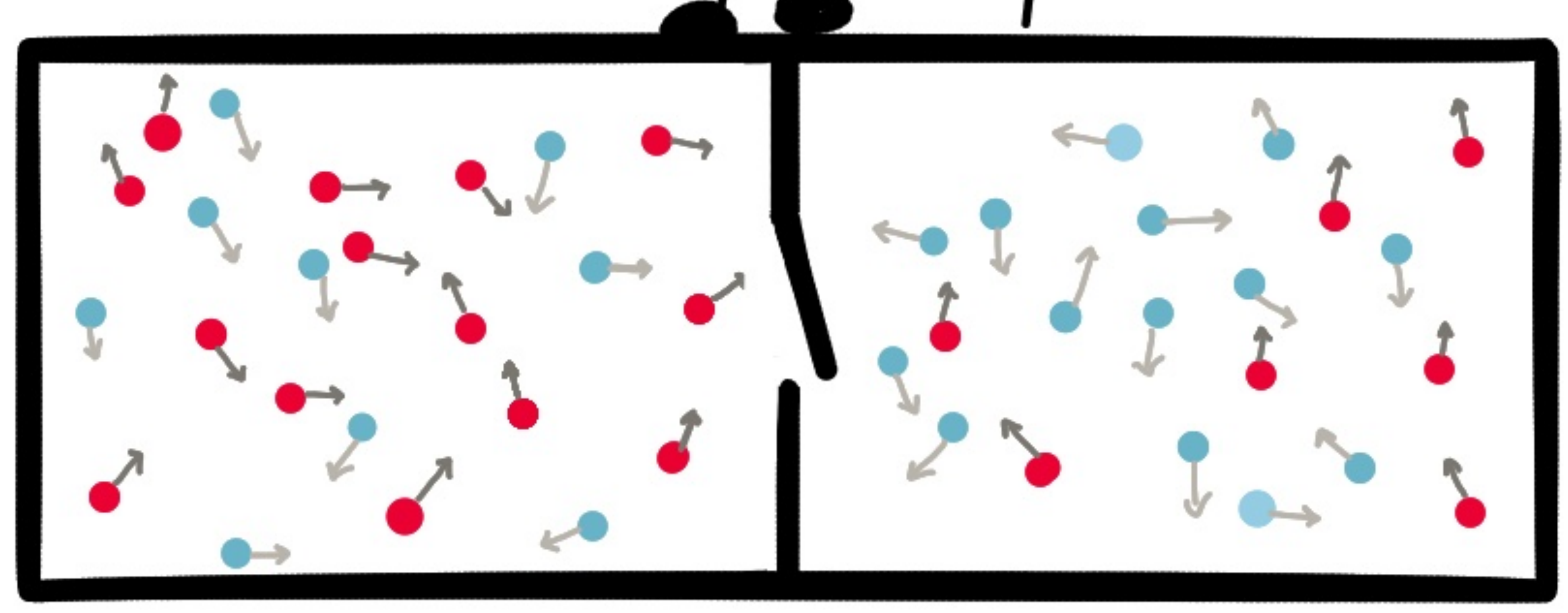
HOTTER MOLECULES MOVED FASTER AND COOLER ONES MOVED SLOWER.

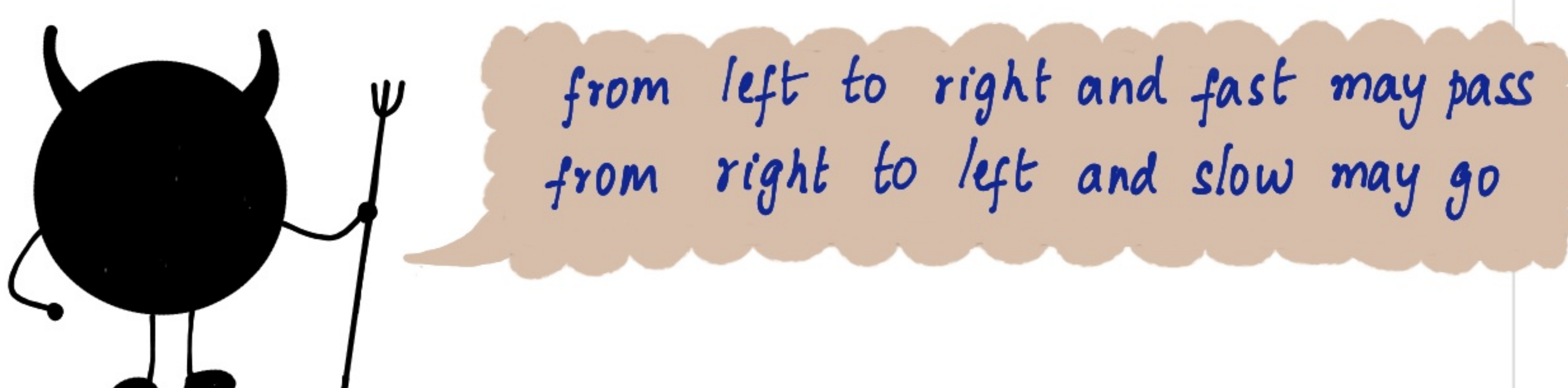


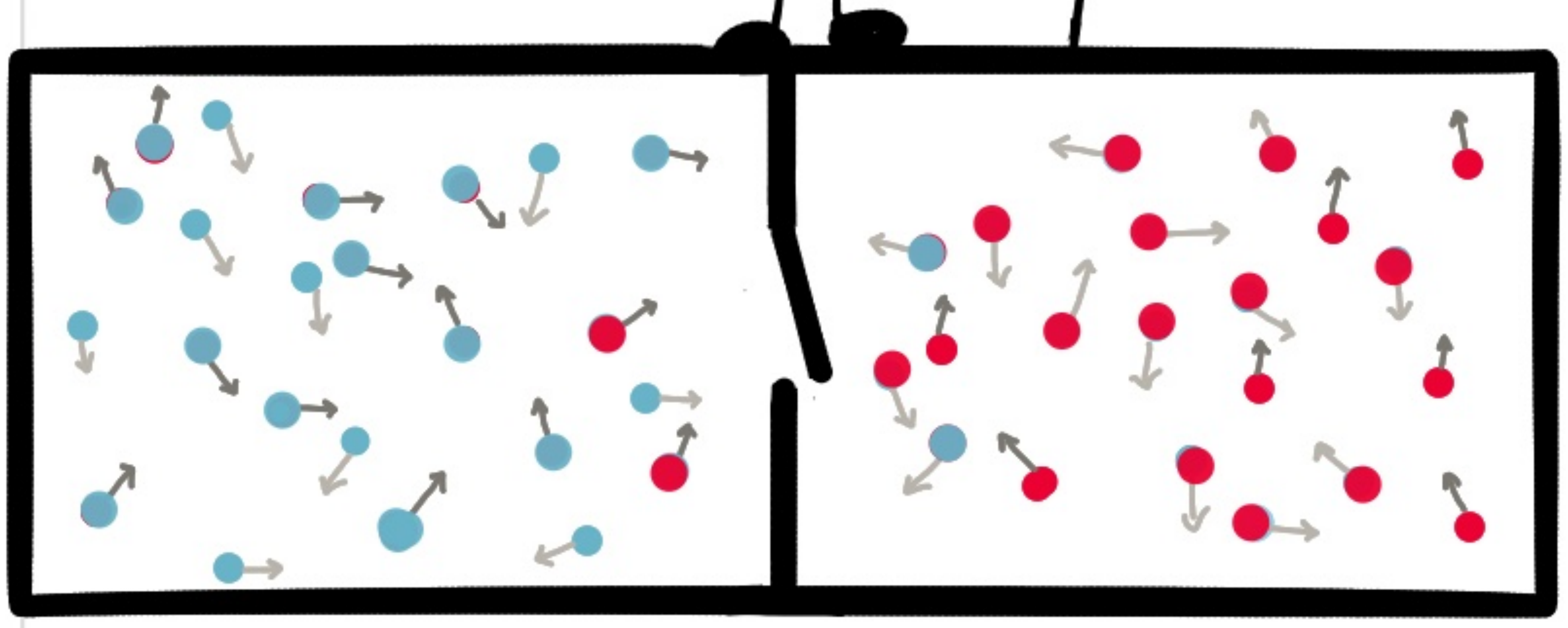
MAXWELL IMAGINED THAT IT MIGHT BE POSSIBLE TO SEPARATE THE COOL AND HOT AIR JUST WITH INFORMATION ABOUT IT



A DEMON IN CHARGE OF A PARTITION WOULD OBSERVE AND REMEMBER THE SPEEDS OF ALL MOLECULES







ORDER WOULD BE CREATED WITH JUST INFORMATION AND NO WORK DONE

WHAT IS INFORMATION AND DOES IT VIOLATE THE SECOND LAW?

WHAT IS INFORMATION?

AN ABSTRACT MASS-NOUN USED TO DENOTE ANY AMOUNT OF DATA, CODE OR TEXT THAT IS STORED, SENT, RECEIVED OR MANIPULATED IN ANY MEDIUM

— PLATO.STANFORD.EDU

THE RESOLUTION OF UNCERTAINTY

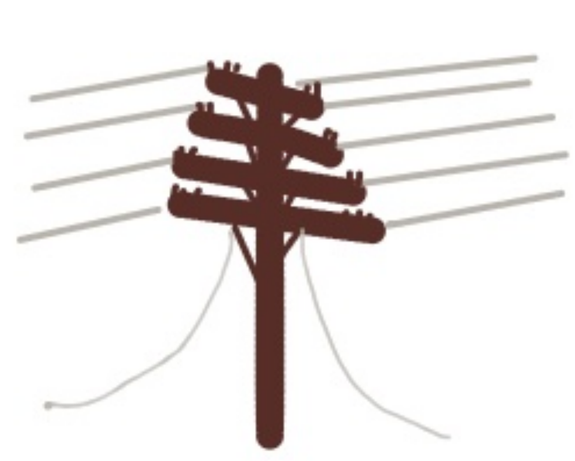
— WIKIPEDIA

ASIDE FROM THE SPOKEN WORD, HUMANS HAVE INVENTED MANY WAYS TO EXCHANGE INFORMATION

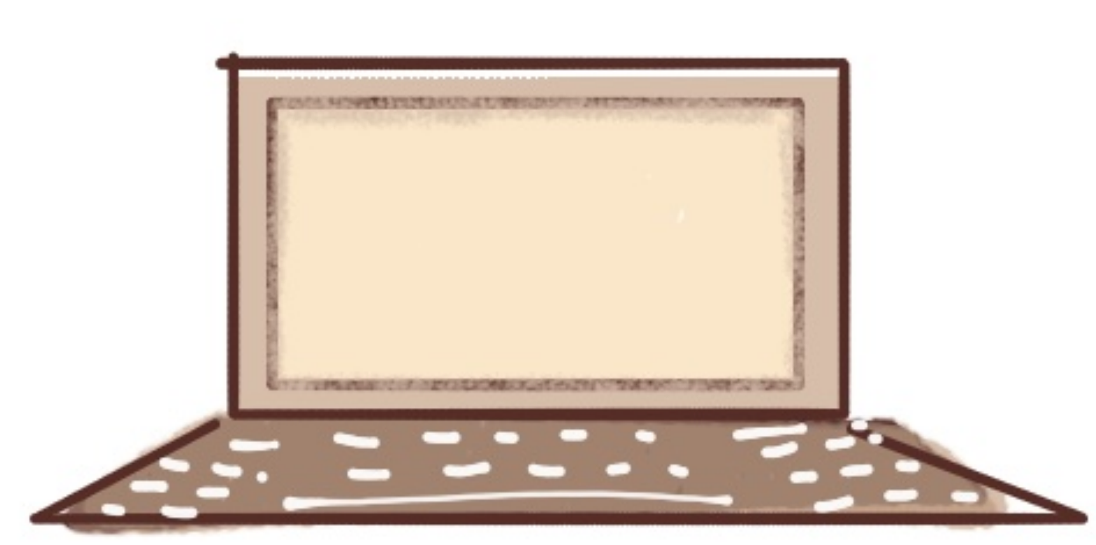
CLAY TABLET

PUNCH CARDS

PRINTED WORDS



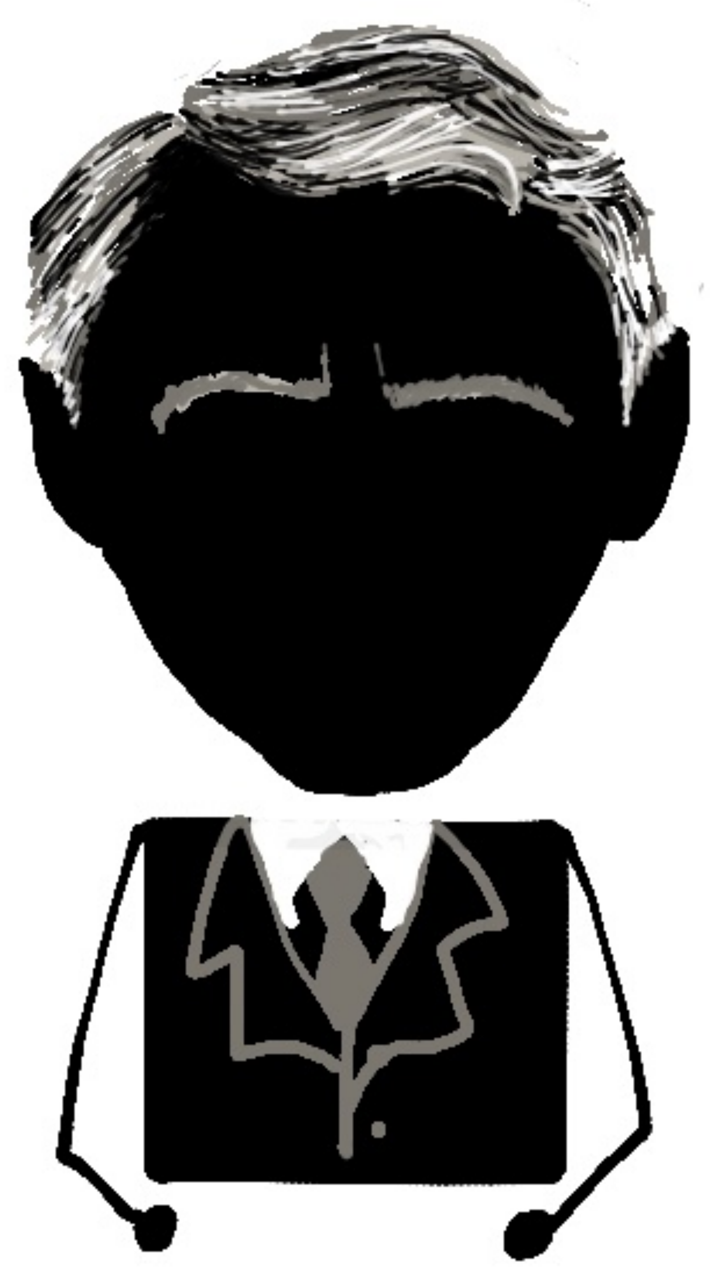
TELEGRAPH



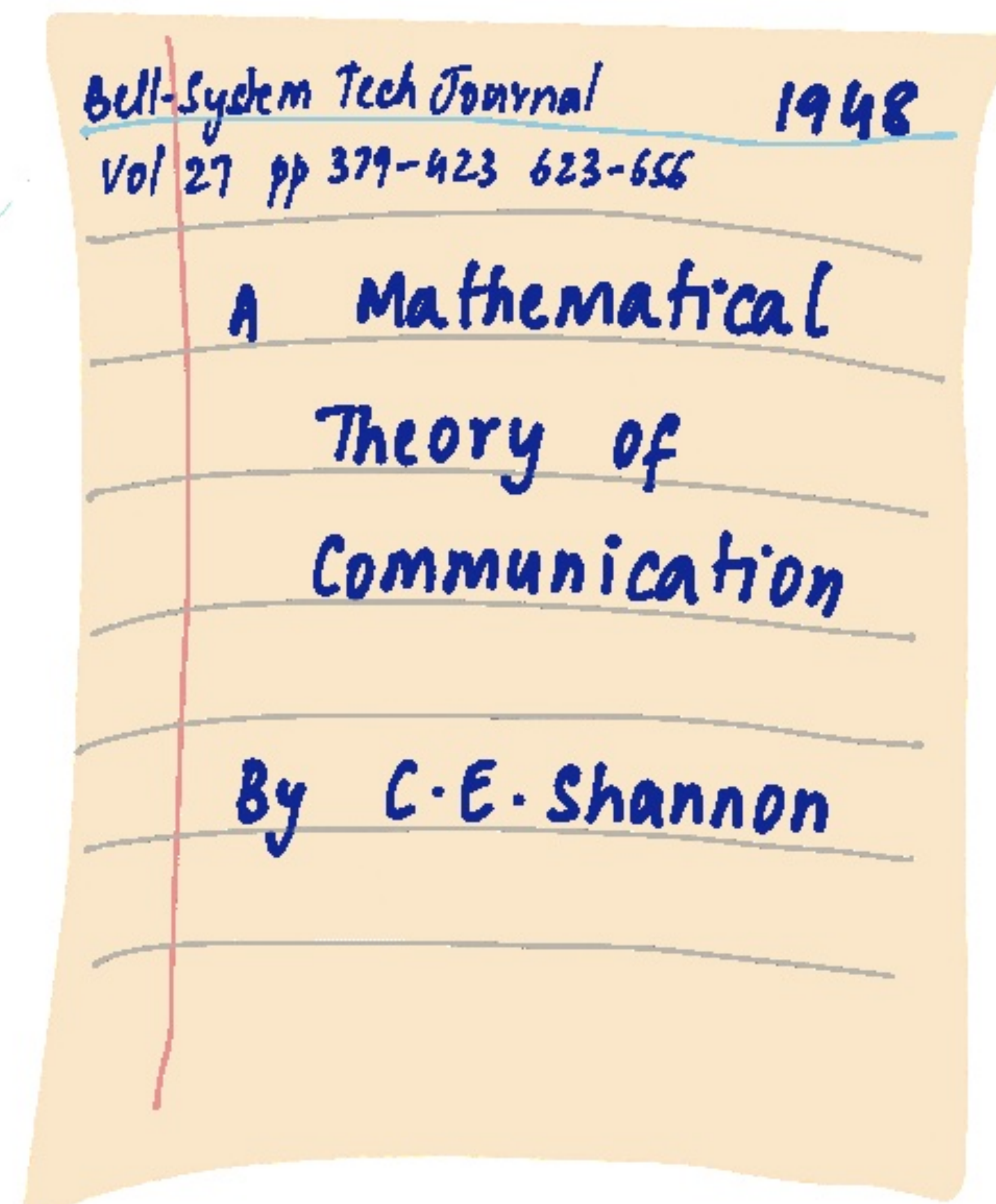
COMPUTERS

MEASURING INFORMATION

CLAUDE SHANNON, MATHEMATICIAN, WAS INTERESTED IN THE EFFICIENT TRANSFER OF SIGNALS THROUGH TELEPHONE WIRES.



CLAUDE SHANNON
BELL LABS



THROUGH THE PAPER HE WROTE, SHANNON:

INTRODUCED THE SMALLEST UNIT OF INFORMATION

A BIT -
SHORT FOR BINARY DIGIT

0	1

THE BIT UNDERPINS MODERN COMPUTATION

QUANTIFIED HOW WE CAN MEASURE INFORMATION

SAY FOR A COIN TOSS

PROBABILITY OF
- HEADS = P(H) = 1/2
- TAILS = P(T) = 1/2

INFORMATION CONTENT:

$$= -\left[P(H)\log_2 P(H) + P(T)\log_2 P(T)\right]$$

$$= -\left[\frac{1}{2}\log_2\frac{1}{2} + \frac{1}{2}\log_2\frac{1}{2}\right]$$

$$= 1 \text{ bit}$$

ON INFORMATION CONTENT

INFORMATION CONTENT IN A MESSAGE

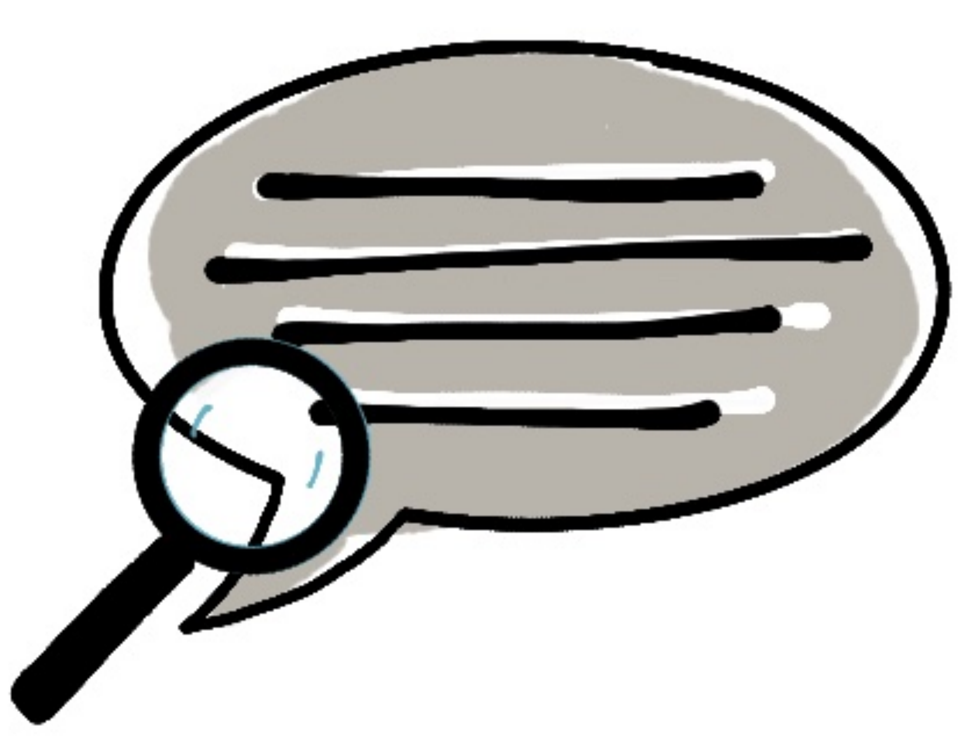
IS RELATED TO THE PROBABILITIES OF ITS SYMBOLS OR OUTCOMES

A MESSAGE WITH HIGHER INFORMATION CONTENT

INFORMATION CONTENT IS THE OPTIMAL BITS NEEDED TO ENCODE

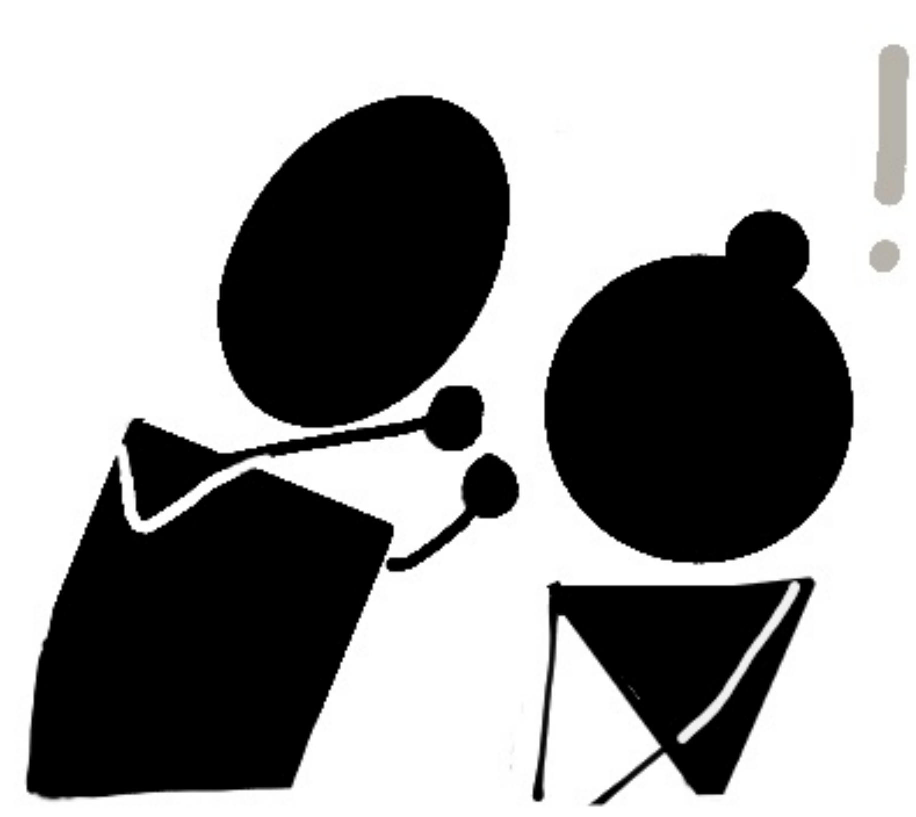
IS LESS COMPRESSIBLE

THE MEANING



IS IRRELEVANT

THE QUANTITY OF INFORMATION



IS ABOUT HOW UNEXPECTED IT IS

THUS THE ROLL OF A DIE

HAS MORE SURPRISE THAN A COIN TOSS

WITH THIS, SHANNON HAD LAID THE FOUNDATIONS FOR A NEW BRANCH OF STUDY CALLED INFORMATION THEORY

WHAT OF THE DEMON?

MAXWELL'S DEMON HAD TROUBLED SCIENTISTS FOR NEARLY A CENTURY

THERE NOW SEEMED TO BE A VALID EXPLANATION THAT MAXWELL'S DEMON DID NOT VIOLATE THE SECOND LAW OF THERMODYNAMICS

- LEO SZILARD
- LÉON BRILLOUIN
- ROLF LANDAUER
- CHARLES BENNETT

IN THEORY:

THERE IS A METHOD TO	AND NOT CHANGE ENTROPY
DETECT MOLECULE VELOCITIES	✓
OPEN PARTITIONS	✓
STORE INFORMATION	✗
ERASE INFORMATION	✗

THE DEMON LEARNS ABOUT THE HOT AND COOL AIR MOLECULES

All information needs to be carried by a physical 'thing'...

THE KNOWLEDGE ALTERS THE STATE OF ITS MEMORY

THE DEMON REDUCES DISORDER IN THE BOX

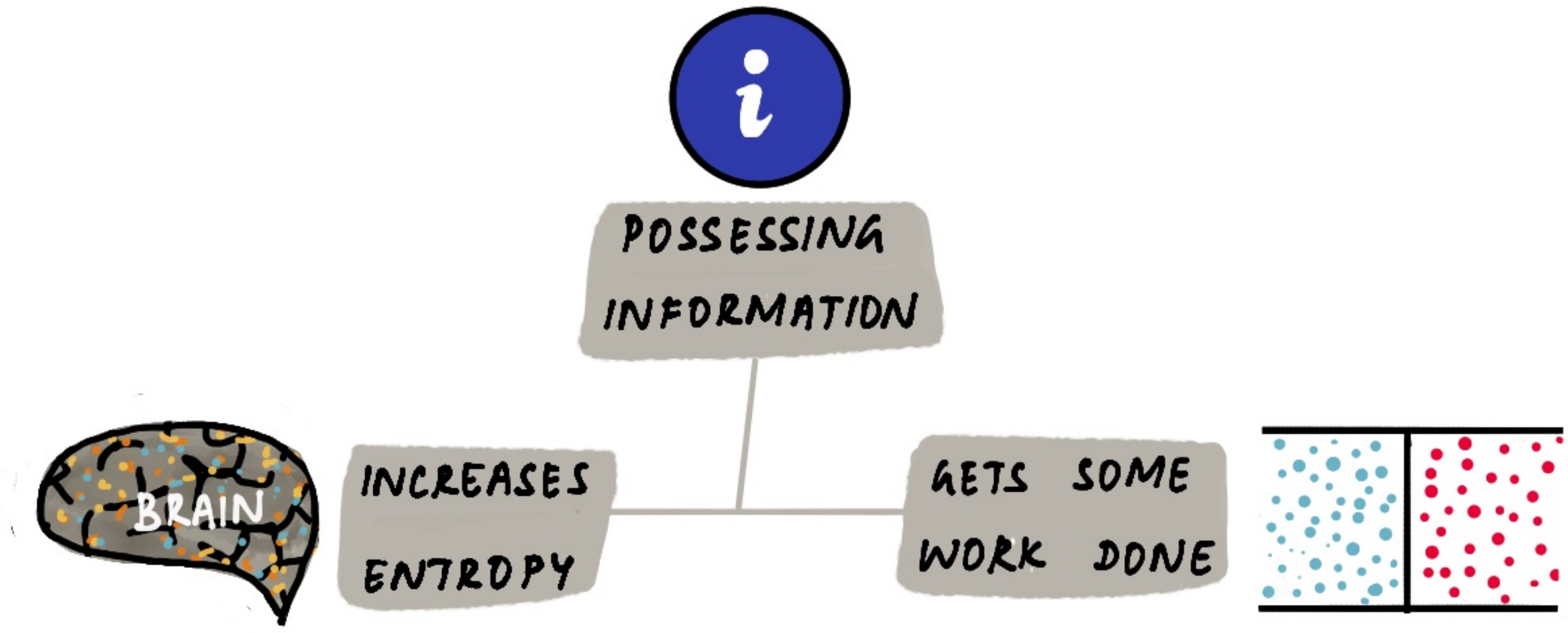
...A thought, a book, sounds or pictures..

ITS OWN MEMORY HAS NOW INCREASED ENTROPY

ERASING OR RESETTING MEMORY RELEASES ENTROPY

INFORMATION & COMPLEXITY

THE EXPLANATION TO MAXWELL'S THOUGHT EXPERIMENT SHOWS US THE PROFOUND LINK BETWEEN ENTROPY AND INFORMATION



INFORMATION IS PART OF THE PHYSICAL WORLD AND IT OBEYS THE LAWS OF PHYSICS JUST LIKE EVERYTHING ELSE

— JIM AL-KHALILI

INFORMATION IS AS KEY TO COMPLEXITY AS ENERGY IS TO PHYSICS

— JIM CRUTCHFIELD

THE NEW AREAS OF RESEARCH

- BUILD ON SHANNON INFORMATION
- INVESTIGATE OTHER KINDS OF INFORMATION
- INFORMATION PROCESSING IN NATURAL SYSTEMS

COMPUTATION

THE IDEA THAT COMPLEX SYSTEMS CAN FIND AND CONSUME INFORMATION

WHAT IS COMPUTATION?

A COMPUTATION IS A PROCESS THAT OBEYS FINITELY DESCRIBABLE RULES

– RUDY RUCKER

COMPUTATION IS WHAT A COMPLEX SYSTEM DOES WITH INFORMATION TO SUCCEED/ADAPT IN ITS ENVIRONMENT

– MELANIE MITCHELL

ALL PHYSICAL SYSTEMS CAN BE THOUGHT OF AS REGISTERING AND PROCESSING INFORMATION.
HOW ONE WISHES TO DEFINE COMPUTATION WILL DETERMINE YOUR VIEW OF WHAT COMPUTATION CONSISTS OF

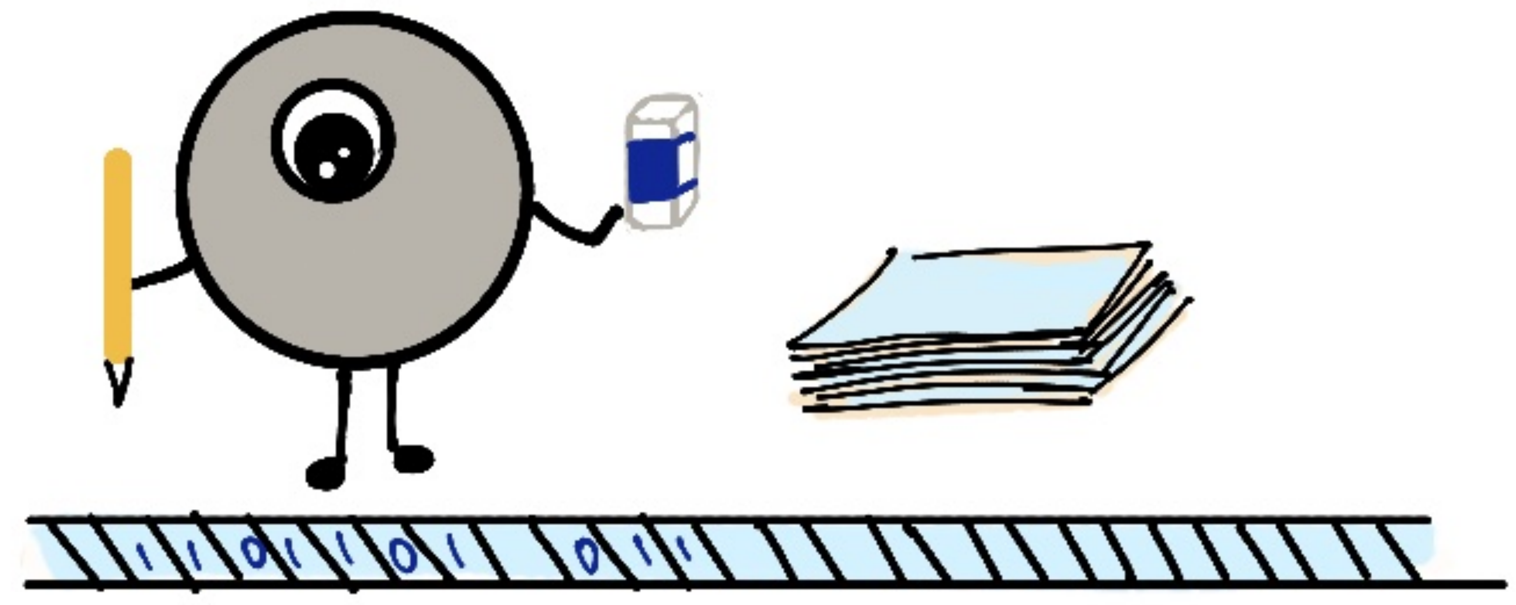
– SETH LLOYD

THE PURPOSE OF COMPUTATION IS INSIGHT, NOT NUMBERS

– RICHARD HAMMING

IDEAS IN COMPUTATION

WE ARE FAMILIAR WITH THE IDEA THAT COMPUTATION IS THE STEPS CARRIED OUT BY A TURING MACHINE



FROM THIS MODEL OF COMPUTATION STEMMED THE IDEA OF COMPUTATIONAL COMPLEXITY - THE RESOURCES NEEDED TO RUN A PROGRAM

Read 'The Story of Quantum Computing' from thoughtworks.com for more detail

ANOTHER POIGNANT IDEA THAT CAME ABOUT WAS THE CONCLUSION OF THE DECIDABILITY PROBLEM

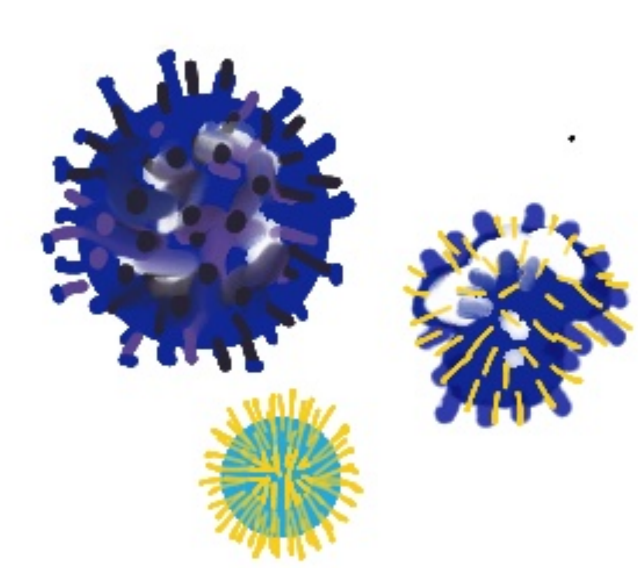
IS THERE A TURING MACHINE TO DECIDE IF A TURING MACHINE WOULD HALT OR RUN FOREVER?

IN SHORT, THE ANSWER TO THE DECIDABILITY PROBLEM IS NO, LEAVING US TO CONCLUDE THAT THERE ARE SOME ANSWERS WE CAN NEVER COMPUTE

Read 'A Tribute to Turing' from thoughtworks.com for more detail

PROCESSES IN NATURE CAN ALSO BE THOUGHT OF AS COMPUTATION

NUTRIENTS TRANSPORT SYSTEM IN PLANTS

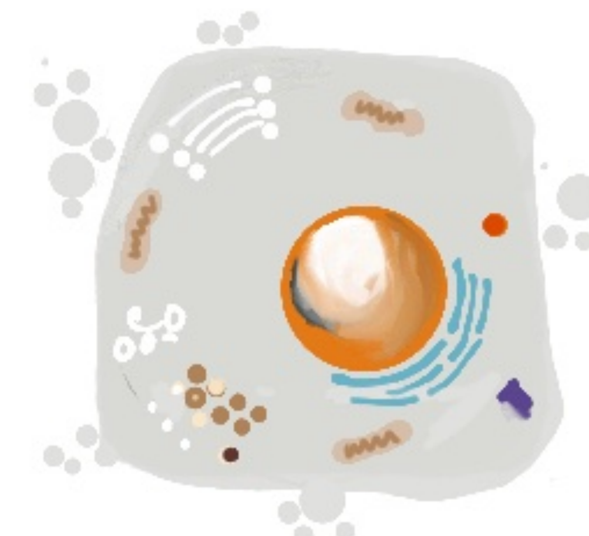


HUMAN IMMUNE SYSTEM

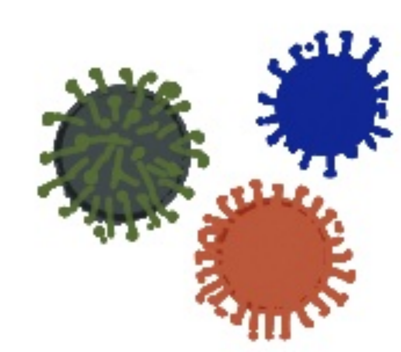
WHAT DOES NATURE COMPUTE?

CELLS HAVE THE ABILITY TO STORE AND PROCESS INFORMATION AND IN THIS RESPECT, CELLS AND COMPUTERS ARE OFTEN COMPARED.

THE LIVING BEING, BE IT A CELL OR ANT, HAS RECEPTORS



IT CAN SENSE THE ENVIRONMENT WITH THIS



WHEN THE RECEPTOR ENCOUNTERS AN INTERESTING OBJECT, IT EMITS A SIGNAL

THE OTHER LIVING BEINGS IN THE VICINITY SENSE THE SIGNAL AND REACT TO IT

PRODUCTION OF MORE CELLS TO FIGHT INTRUDERS

SCENT TRAIL GATHERS A LARGE GROUP OF ANTS

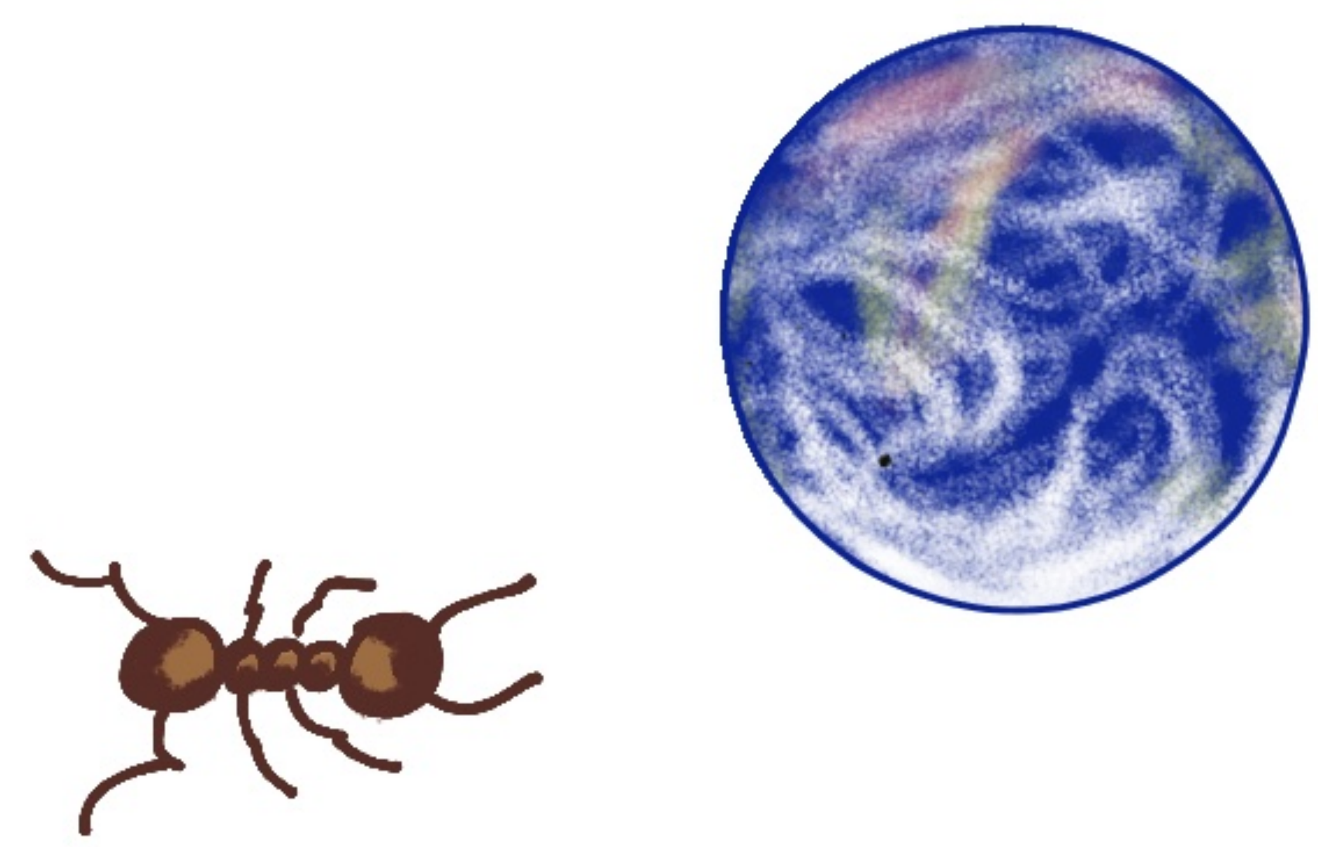
THE INFORMATION IS THE DISTRIBUTION OR CONCENTRATION OF

WHITE BLOOD CELLS

ANTS IN THE TRAIL

PROCESSING INFORMATION

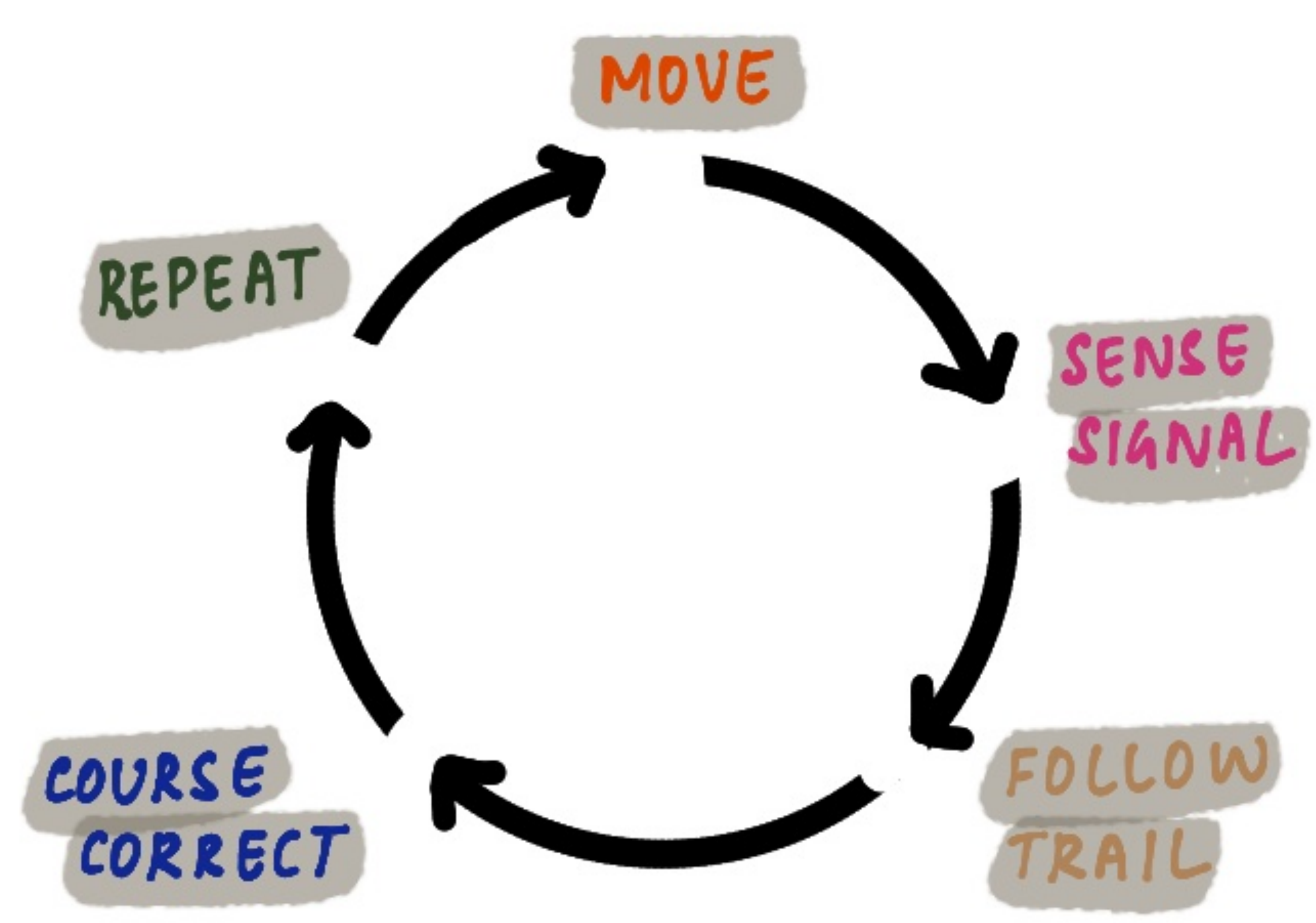
THE INDIVIDUAL IS TOO SMALL TO UNDERSTAND THE WHOLE SYSTEM



SO IT TAKES IN RANDOM SAMPLES

SAMPLING BECOMES LESS RANDOM AS SIGNALS GET MORE FREQUENT

THE INFORMATION CAN BE THOUGHT OF AS FEEDBACK LOOPS



FEEDBACK LOOPS ACT LIKE A THERMOSTAT

FEEDBACK LOOPS RECIRCULATE SIGNALS & RESOURCES

MEANING OF INFORMATION

EXPLORING THE NOTION OF

THE MEANING OF INFORMATION

IS ALSO AN EXPLORATION

OF CONSCIOUSNESS

OR THE SELF

TO WHO INFORMATION

MUST MAKE SENSE

THIS TOPIC IS BEYOND THE SCOPE OF THIS BOOK.

EVOLUTION

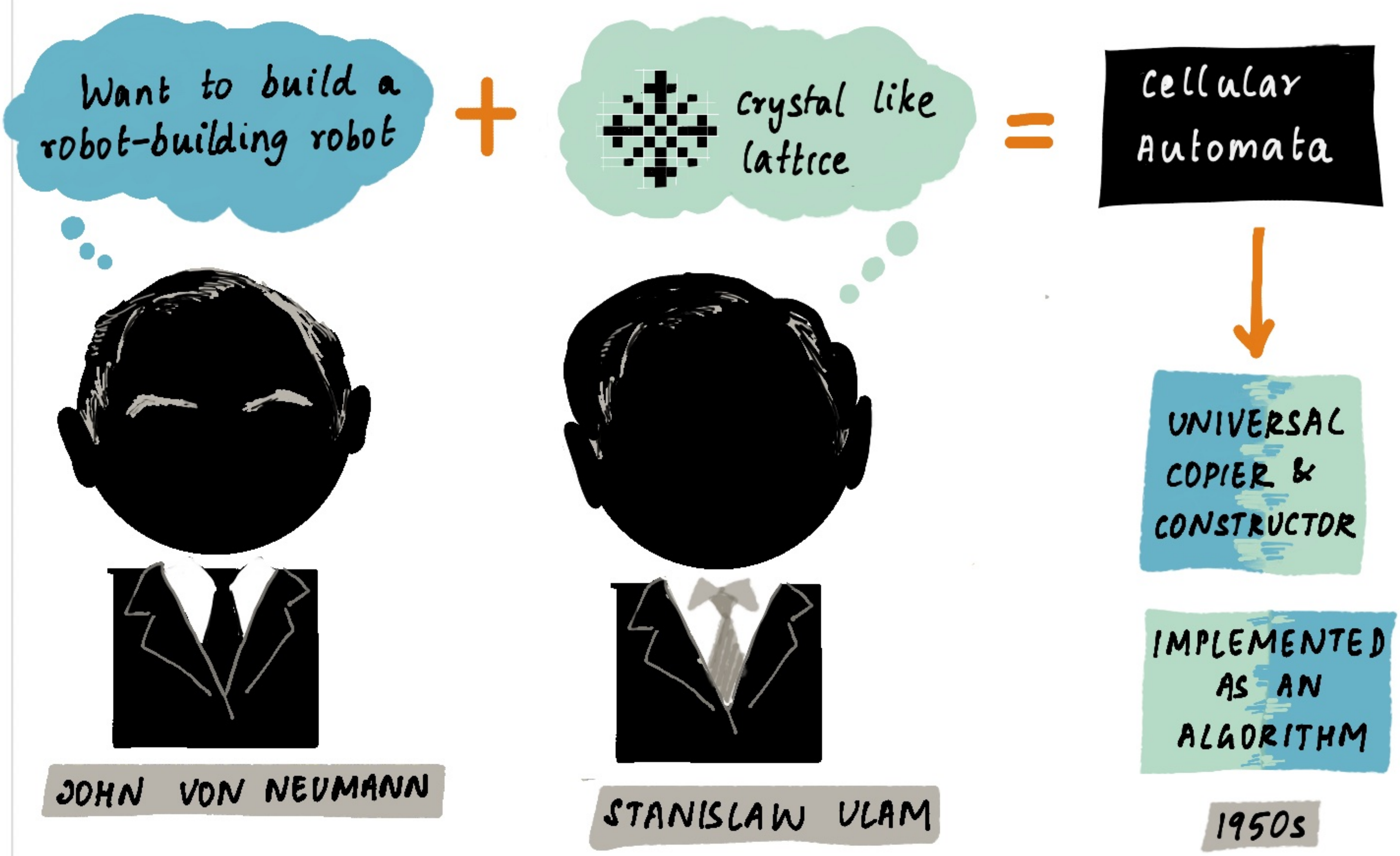
THE ABILITY OF A SYSTEM TO LEARN, GROW, ADAPT AND THRIVE IN A CHANGING ENVIRONMENT

A NEW CAPABILITY

IN THE 1950s, STARTING FROM ALAN TURING, MANY PEOPLE WONDERED ABOUT THE CONNECTION BETWEEN MIND AND MACHINE

CAN BIOLOGICAL PROCESSES BE TRANSLATED INTO A MECHANISTIC ONE?

THE AIM, AS IT HAS BEEN FOR CENTURIES ACROSS MANY CIVILISATIONS, WAS TO CREATE A SELF OPERATING MACHINE – OR AUTOMATON.



whether self-reproduction is enough to call a machine or program alive or conscious is a topic for a whole other book

THE NEXT QUESTION: CAN THE PROGRAM LEARN AND EVOLVE IN AN ENVIRONMENT?

EVOLUTION

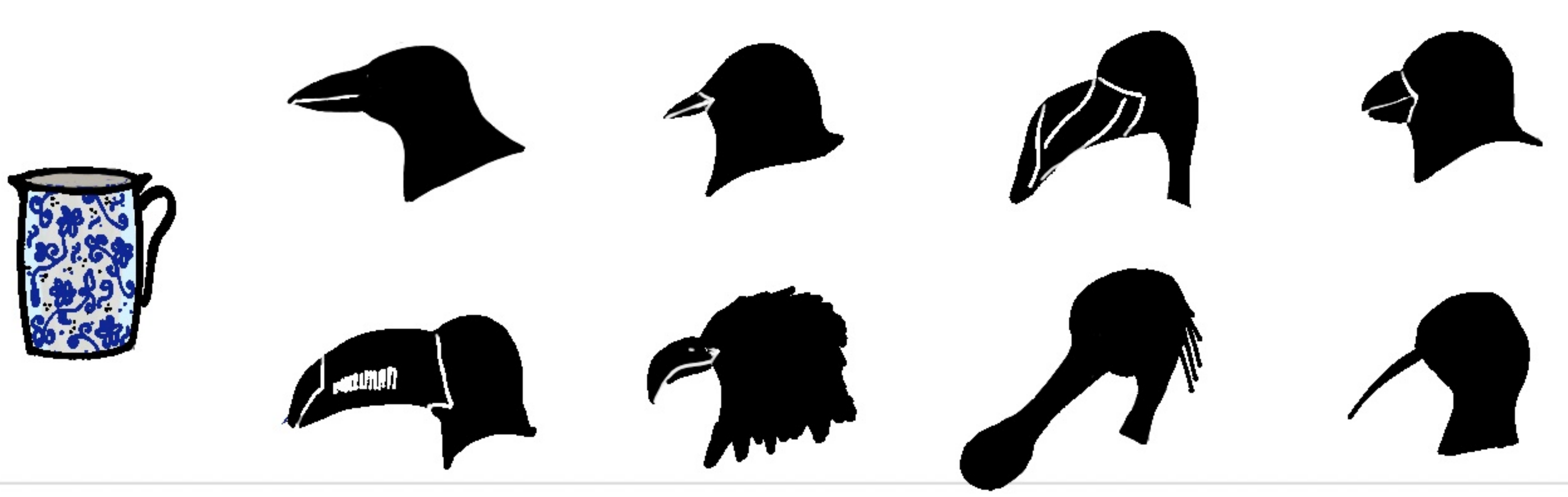
EVOLUTION IS THE CHANGE IN CHARACTERISTICS OF A POPULATION OVER TIME. THE CHARACTERISTICS THAT GIVE AN INDIVIDUAL SOME ADVANTAGE ARE PASSED ON THROUGH THE PROCESS OF NATURAL SELECTION TO THE NEXT GENERATIONS

NATURAL EVOLUTION: A REMINDER

Charles Darwin's theory of evolution by natural selection:

- Individuals have large variations for a characteristic ← Variation
- Those most suited to the environment are more likely to survive and breed ← Survival of the fittest
- The characteristics that helped survival will be passed on to the next generation ← Heredity + random mutations

THE BEST BEAK FOR THE JOB IS:



EVOLUTIONARY COMPUTATION

EVOLUTION IN COMPUTATION DRAWS IDEAS FROM EVOLUTION IN NATURE

IT USES SIMILAR CONCEPTS SUCH AS SELECTION, REPRODUCTION, CROSSOVER AND MUTATION TO EVOLVE NEW 'GENERATIONS' FROM RANDOMLY CHOSEN POSSIBLE SOLUTIONS.

PIONEERS IN THE FIELD

- DAVID FOGEL
- JOHN H HOLLAND → *came up with* → GENETIC ALGORITHMS
- INGO RECHENBERG
- HANS-PAUL SCHWEFEL

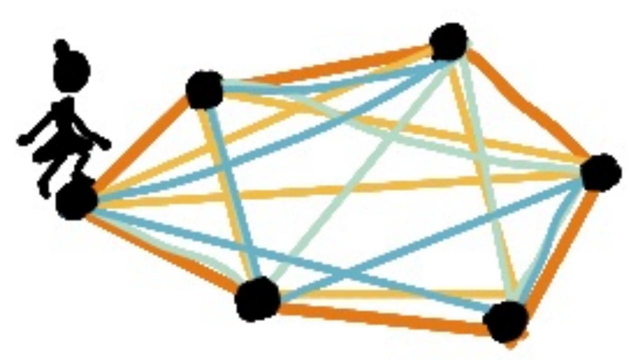
TECHNIQUES

- EVOLUTIONARY ALGORITHMS
- GENETIC ALGORITHMS
- GENETIC PROGRAMMING
- GRAMMATICAL EVOLUTION

SUITABLE TO

- EXPLORE A LARGE SEARCH SPACE
- SOLVE OPTIMISATION PROBLEMS

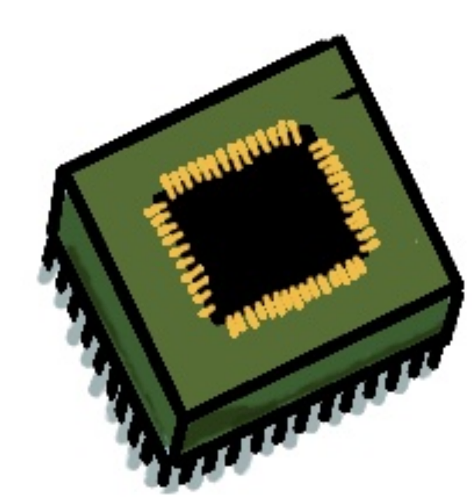
SOME APPLICATIONS



TRAVELLING SALESPERSON PROBLEMS

GAME PLAYING

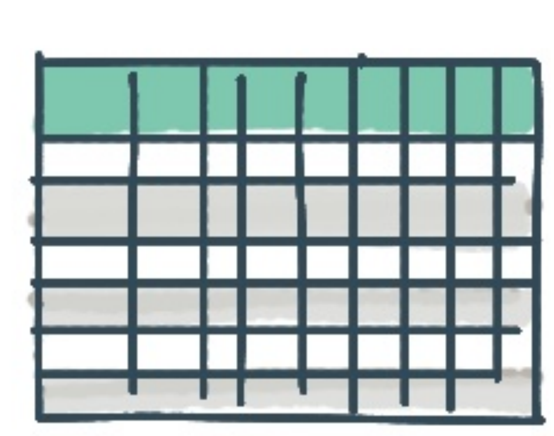
DNA/GENE ANALYSIS



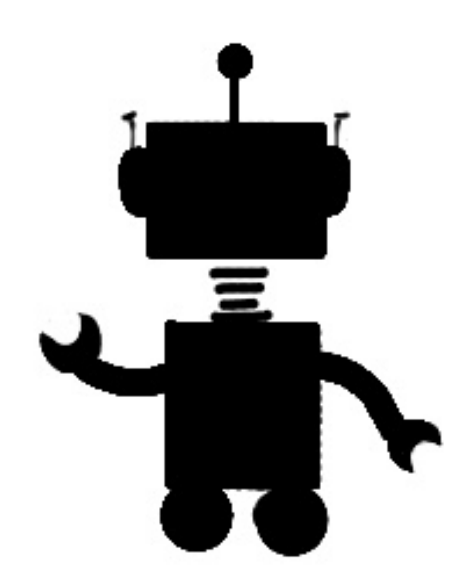
HARDWARE DESIGN

ENCRYPTION CODE BREAKING

MACHINE LEARNING



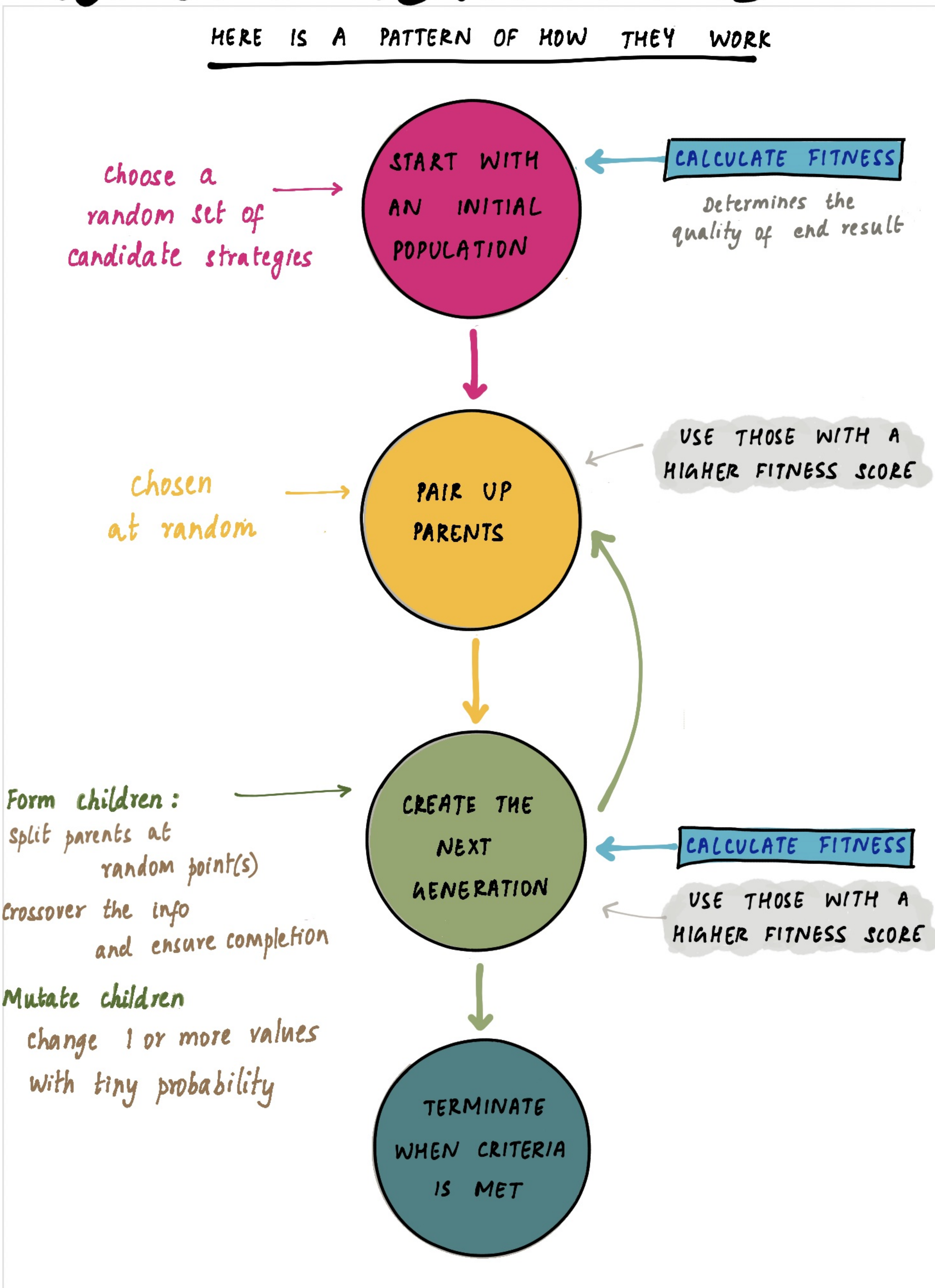
SCHEDULING



ROBOTICS

THIS IS NOW A SUB-FIELD IN ARTIFICIAL INTELLIGENCE AS WELL.
LET US NOW LOOK AT GENETIC ALGORITHMS – A WELL KNOWN TECHNIQUE

GENETIC ALGORITHMS



EXAMPLE: ROUTE PLANNING

PROBLEM FIND THE SHORTEST ROUTE BETWEEN A SET OF CAKE SHOPS WHERE YOU VISIT EVERY CAKE SHOP ONLY ONCE.

INITIAL POPULATION

SOME POSSIBLE ROUTES

A B C D E F G — 1
A C G B D F E — 2
B F A E G C D — 3
G D A C B E F — 4
F A E G B D C — 5
C G E B A D C — 6

FITNESS CALCULATION

THIS WILL BE THE TOTAL TIME FROM START TO END FOR EACH ROUTE.

PAIR UP PARENTS

PAIRING COULD BE RANDOM

1 – Parent 1 — A B C D E F G
4 – Parent 2 — G D A C B E F

CREATE NEXT GENERATION

PAIRING ① AND ④ GIVE

Parent 1	A B	C D E	F G
Parent 2	G D	A C B	E F

CROSSOVER - SWAP AT POINTS OF SPLIT

child 1	_ _	A C B	_ _
child 2	_ _	C D E	_ _

FILL NON-DUPLICATE INFO OF ORIGINAL

child 1	_ _	A C B	F G
child 2	G _	C D E	_ F

ENSURE CHILD INFO IS COMPLETE

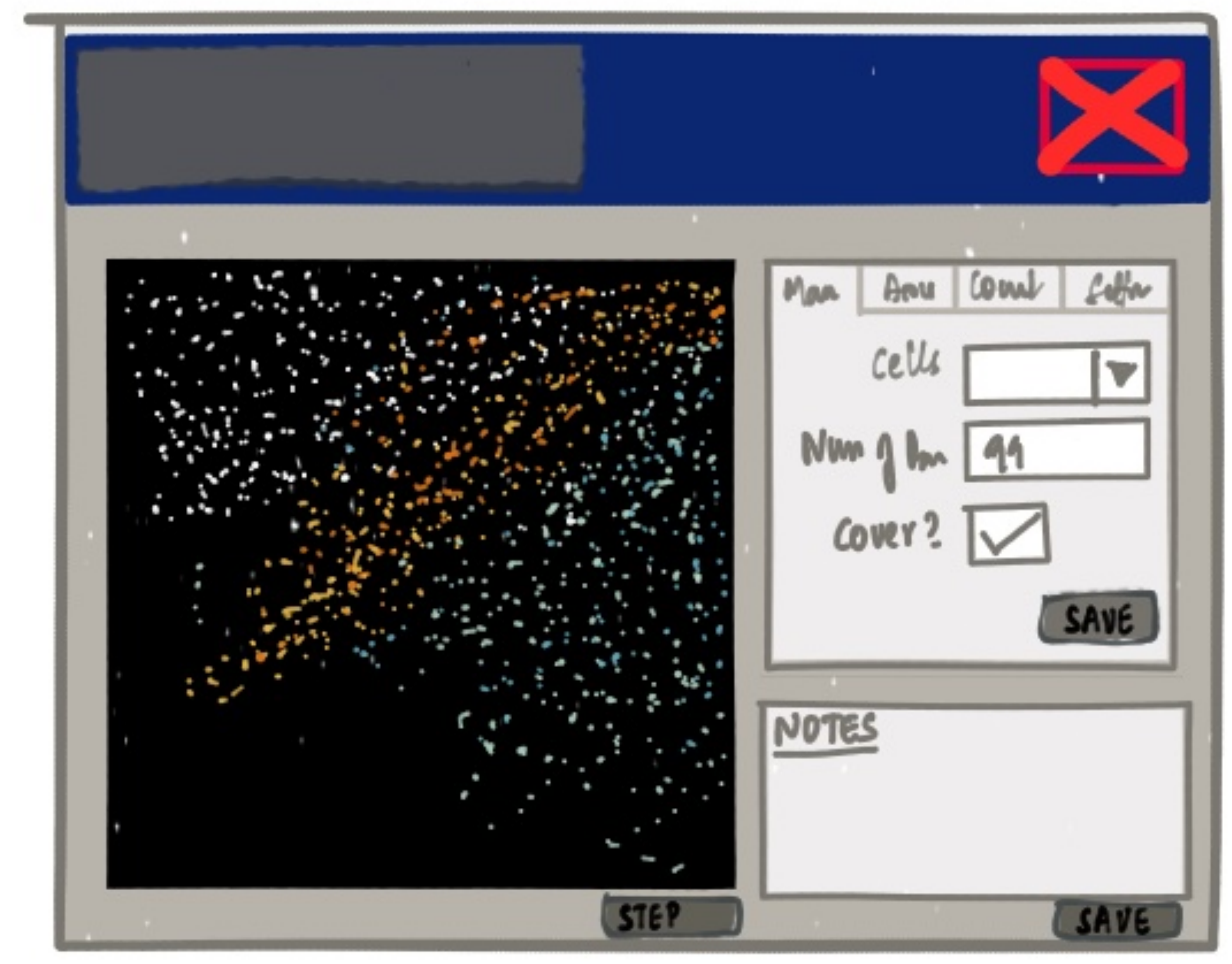
child 1	D E	A C B	F G
child 2	G B	C D E	A F

TERMINATE

DEFINE CRITERIA FOR POPULATION SIZE, FITNESS SCORE ETC

SIMULATING COMPLEX SYSTEMS

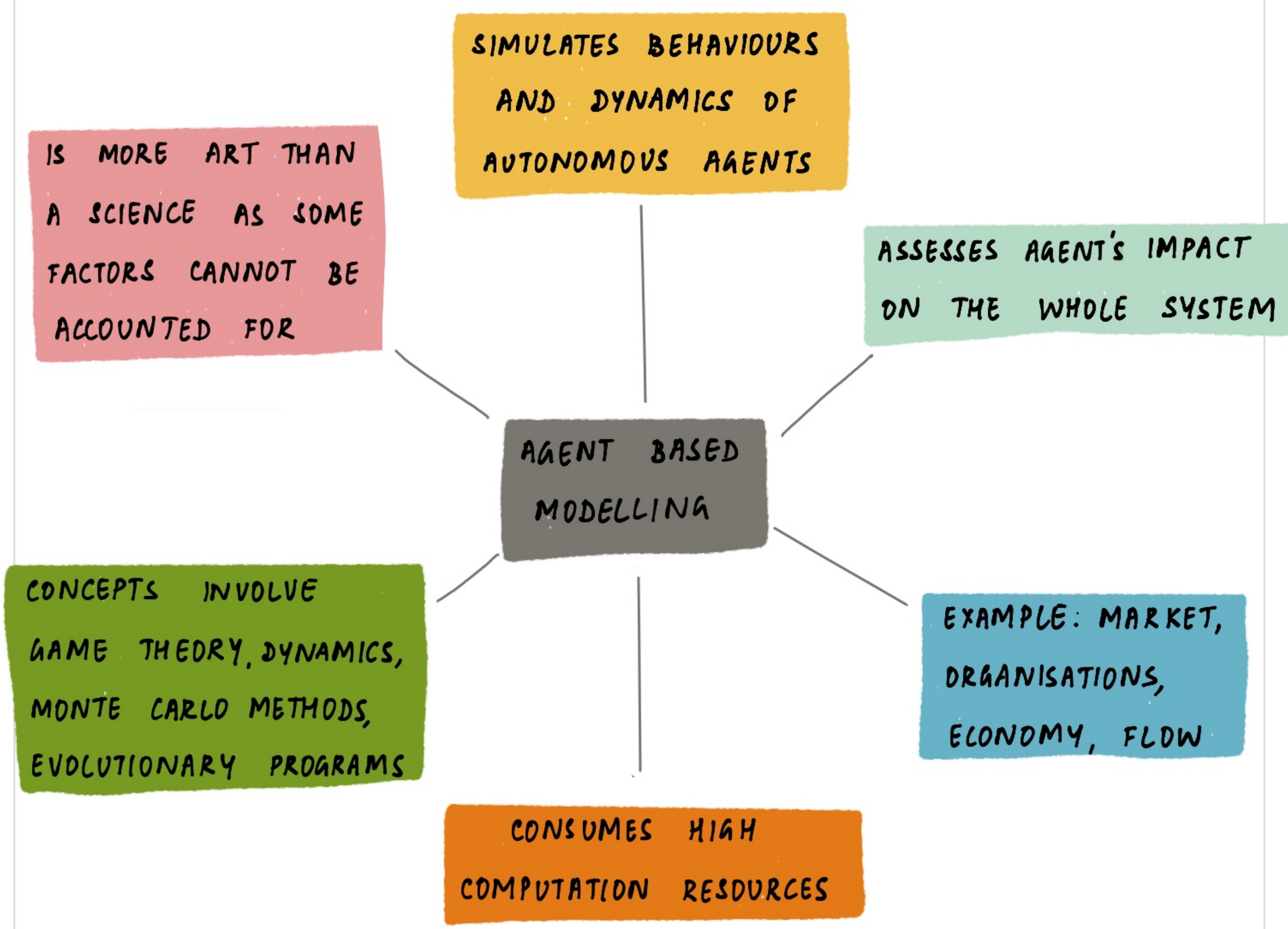
AS WITH OTHER SCIENCES, COMPLEX SYSTEMS ALSO RELY ON MAKING REPRESENTATIONS OF VARIOUS CONCEPTS IN CODE.



THESE ARE CALLED MODELS.

THE RESULTS WHICH CAN BE REPLICATED ARE MORE USEFUL AND CAN BE BETTER UTILISED TO CHECK INFERENCES OF THE RESULTS.

AN EXAMPLE OF A METHOD OF SIMULATION

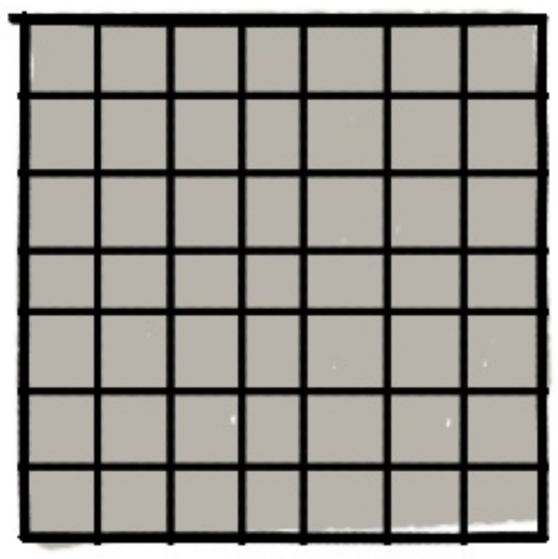


CELLUCAR AUTOMATA

A COMMONCY USED MODELLING TOOL IN COMPLEX SYSTEMS

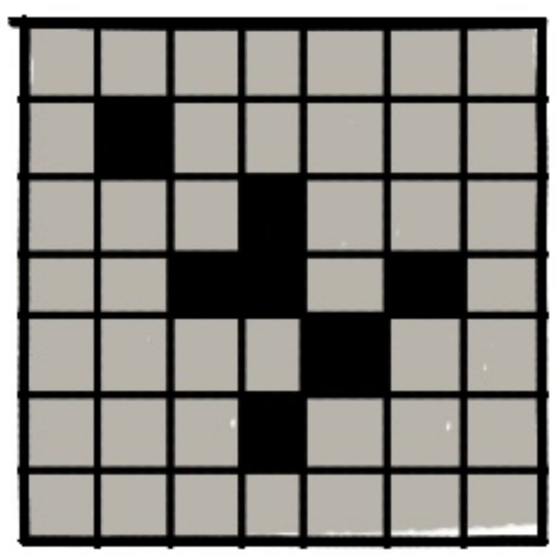
CELLULAR AUTOMATA - CA

CELLULAR AUTOMATA (AUTOMATON - SINGULAR FORM) ARE COMPLEX SYSTEMS WHERE TIME AND SPACE ARE DISCRETE.



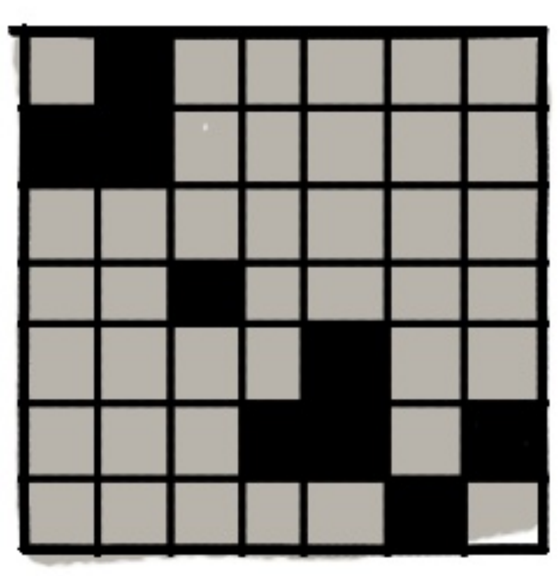
A CELLULAR AUTOMATON CONSISTS OF A GRID OF CELLS

one, two or more dimensions

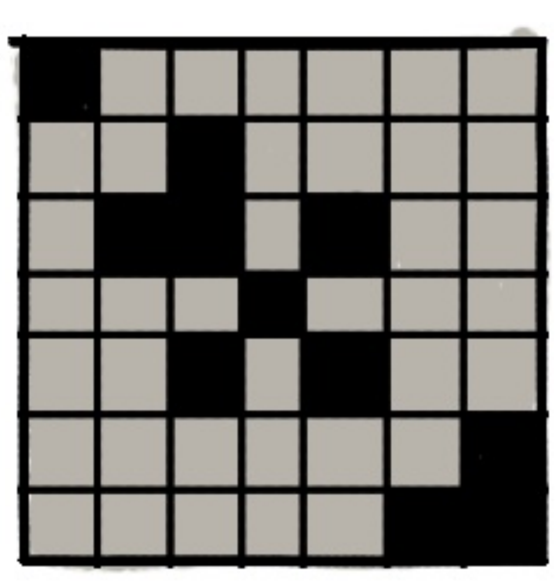


EACH CELL IS IN A STATE OUT OF MANY POSSIBLE STATES. HERE, ON OR OFF

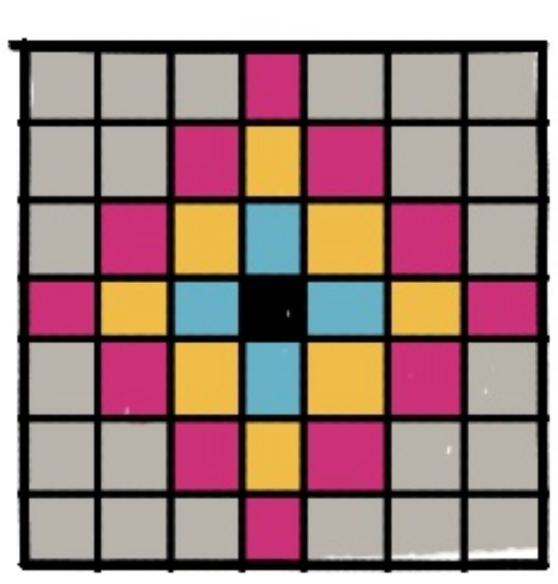
two or more states



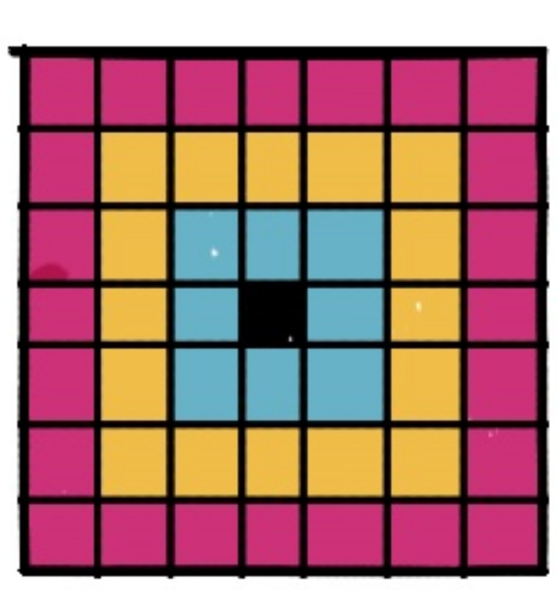
THE STATE OF EACH CELL EVOLVES CONTINUOUSLY DEPENDING ON RULES



USUALLY, THE RULES ARE BASED ON THE STATES OF NEIGHBOURING CELLS.



THIS IS THE VON NEUMANN NEIGHBOURHOOD FOR THE BLACK CELL



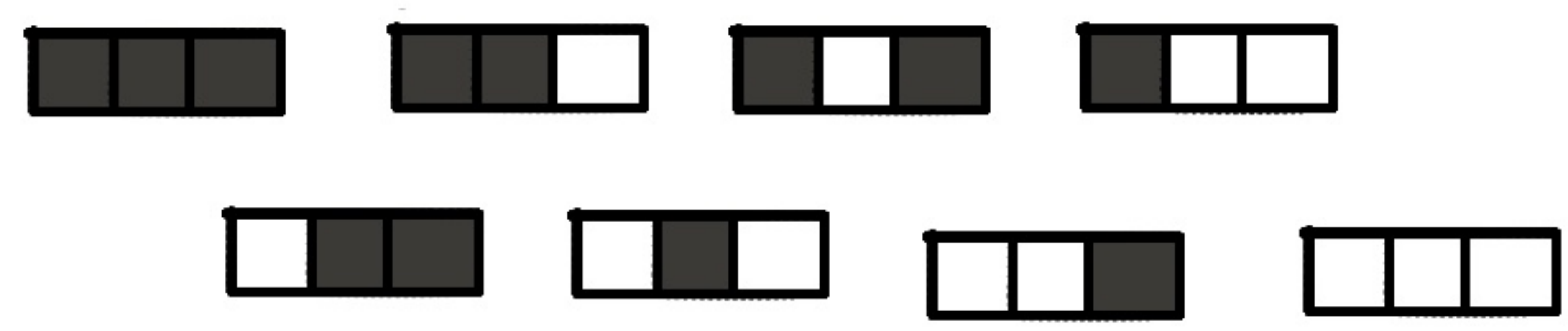
THIS IS THE MOORE NEIGHBOURHOOD FOR THE BLACK CELL

ONE DIMENSION

ELEMENTARY CELLULAR AUTOMATA ARE ONE DIMENSIONAL.

THE NEXT STATE OF A CELL IS DECIDED BY THE STATE OF THE CELL ITSELF AND ITS TWO IMMEDIATE NEIGHBOURS.

8 POSSIBLE ARRANGEMENTS FOR 3 CELLS WITH 2 STATES →



HOW TO DEFINE A CELLULAR AUTOMATON

- LIST POSSIBLE NEIGHBOURHOODS FOR EACH CELL
- DEFINE OUTCOME / NEXT STATE OF THE CELL IN THE MIDDLE

NEIGHBOURHOODS	NEXT STATE	
■■■	☑ ON	☐ OFF
■■□	☑ ON	☐ OFF
■□■	■ ON	☑ OFF
■□□	■ ON	☑ OFF
□■■	☑ ON	☐ OFF
□■□	☑ ON	☐ OFF
□□■	■ ON	☑ OFF
□□□	■ ON	☑ OFF

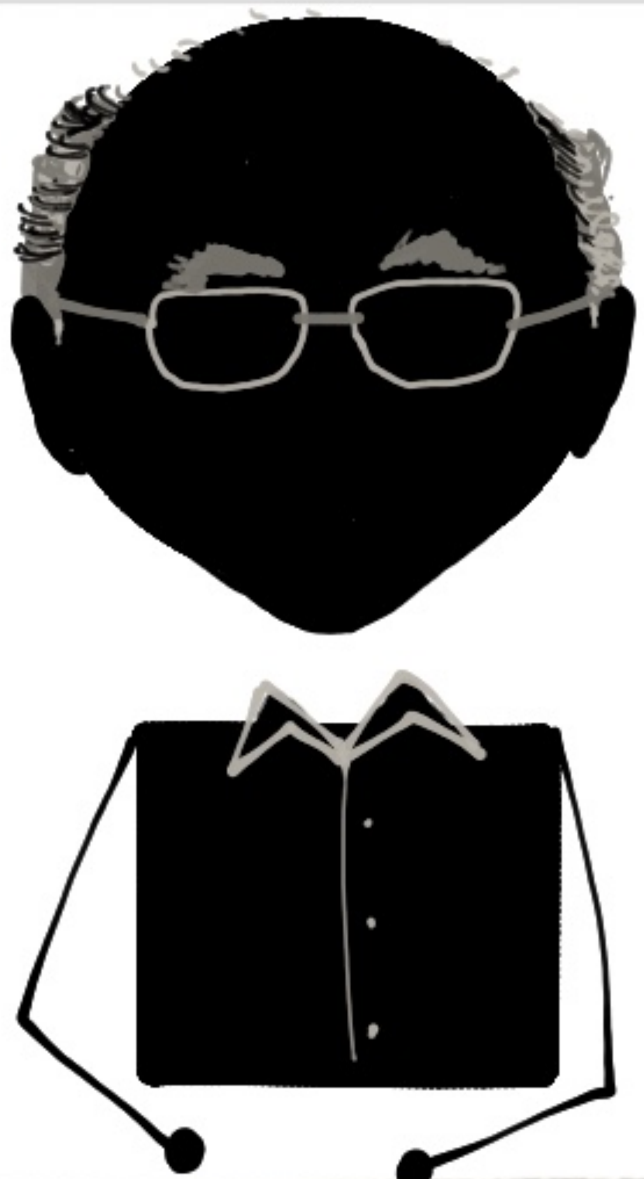
Two outcomes per neighbourhood

NUMBER OF POSSIBLE ELEMENTARY CELLULAR AUTOMATA $= 2 \times 2 \times 2 \times 2 \times 2 \times 2 \times 2 \times 2$

$= 2^8$

$= 256$

WOLFRAM & CA

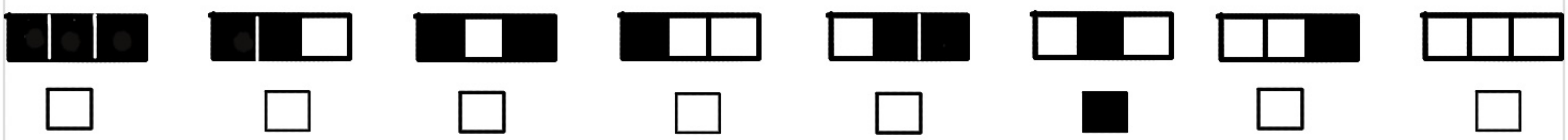


STEPHEN WOLFRAM

STEPHEN WOLFRAM, MATHEMATICIAN AND COMPUTER SCIENTIST, STUDIED ELEMENTARY CELLULAR AUTOMATA IN GREAT DETAIL.

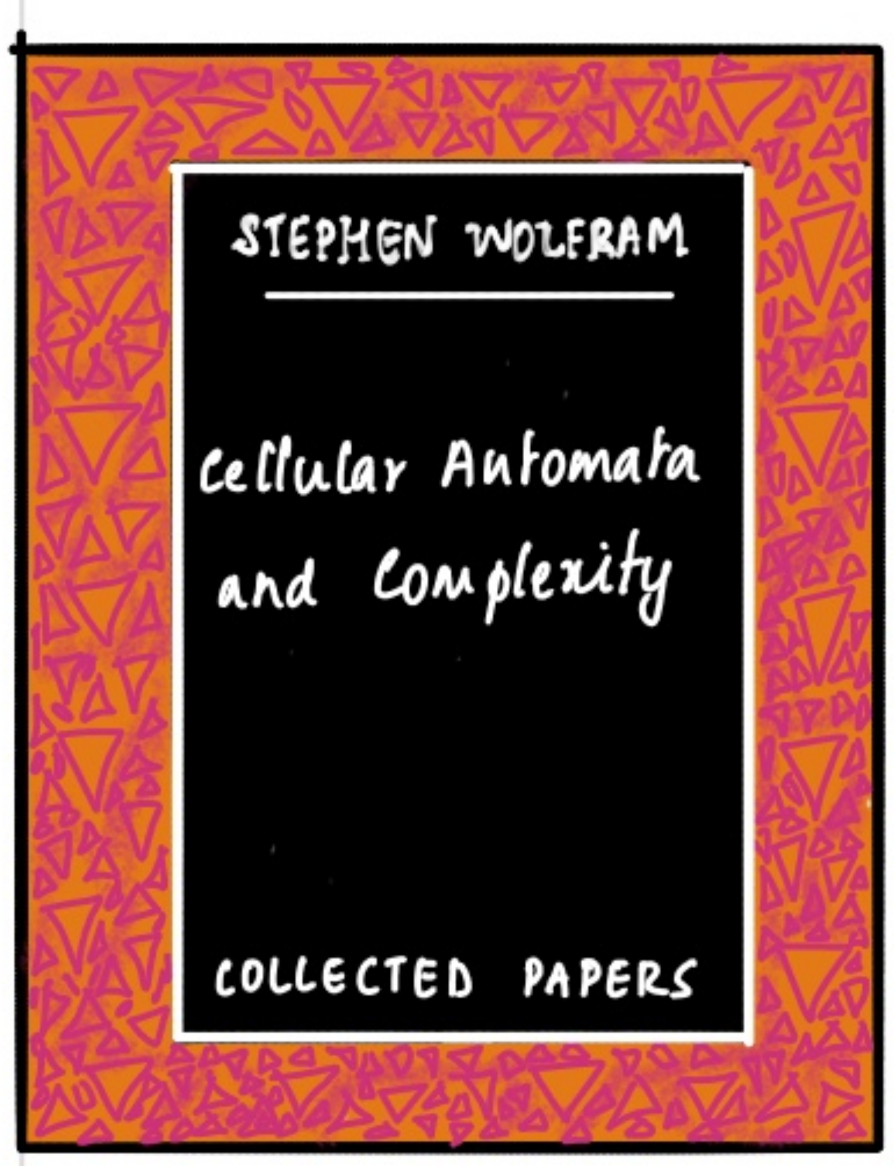
HE PROPOSED A NUMBERING SCHEME - WOLFRAM CODE - TO ASSIGN TO EACH OF THE 0 - 255 RULES.

THE SCHEME IS DEFINED IN THIS ORDER



0	0	0	0	0	1	0	0

THE OUTCOME 00000100 IS CONVERTED FROM DECIMAL TO BINARY. THIS STRING OF DIGITS IS THE BINARY EQUIVALENT OF NUMBER 4. THIS IS THE WOLFRAM CODE

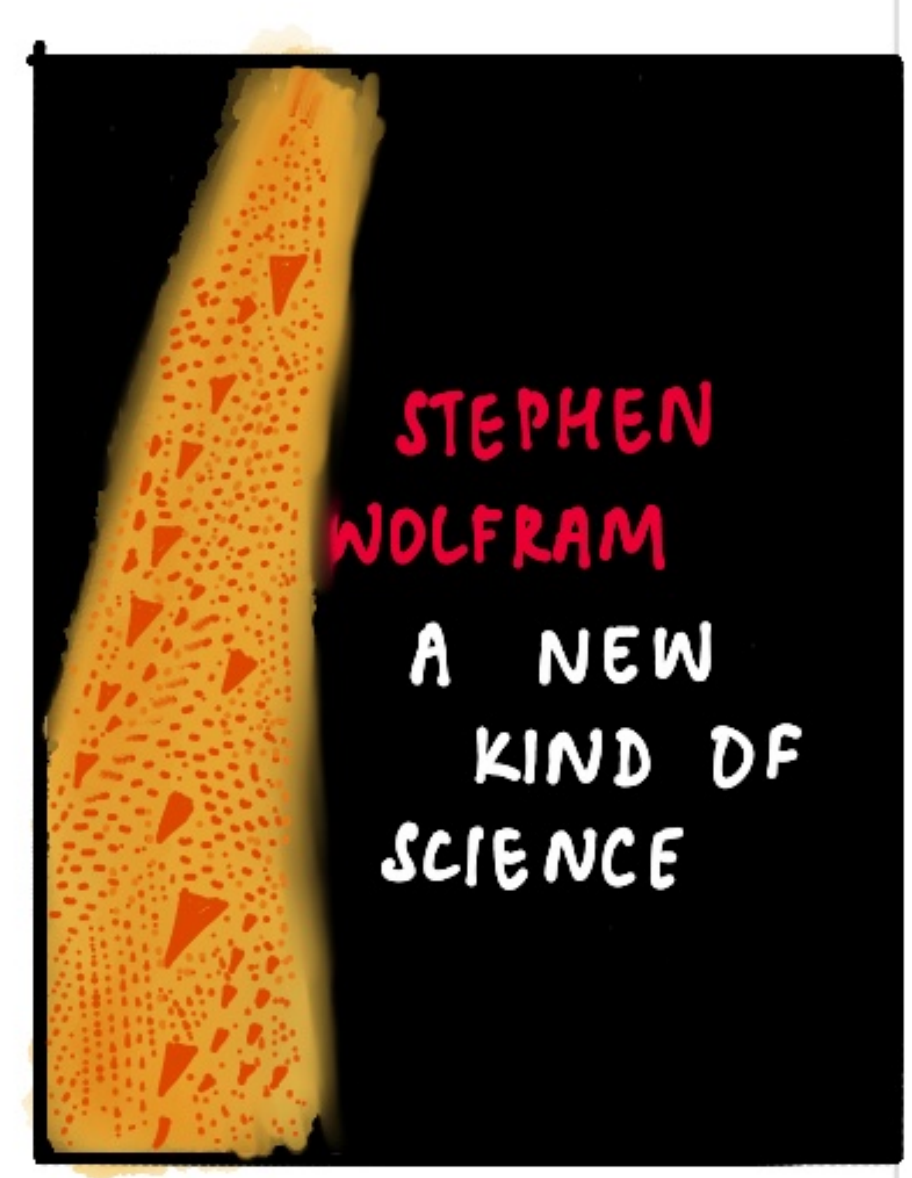


WOLFRAM USED THESE SIMPLE RULES AND STUDIED THE

- FIXED
- OSCILLATING
- CHAOTIC

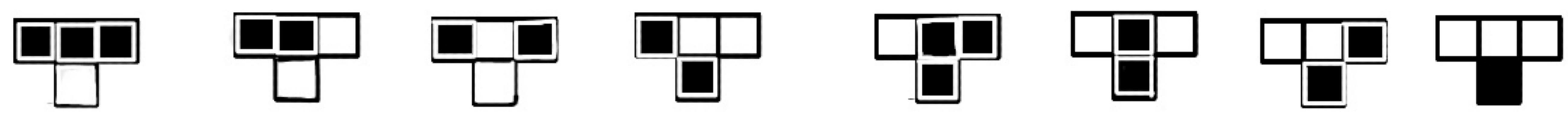
PATTERNS

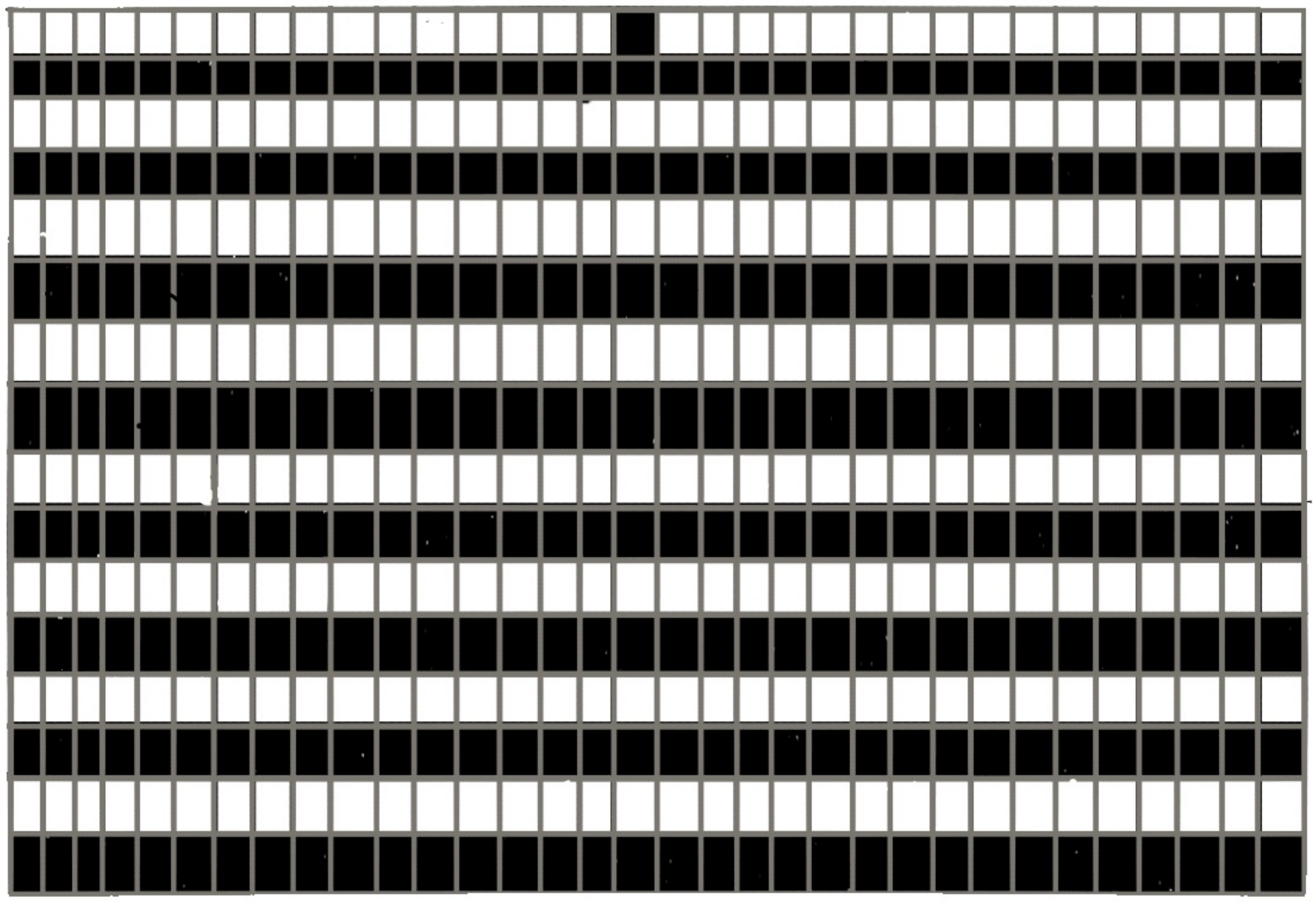
THAT EVOLVED FROM THEM.



LET US LOOK AT SOME OF THESE PATTERNS AND UNDERSTAND WHAT MAKES THESE STRUCTURES POWERFUL ENOUGH TO MODEL COMPLEX SYSTEMS

EXAMPLE - RULE 31





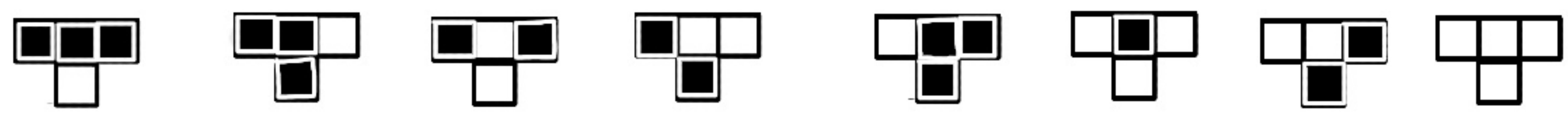
LET US START WITH A SINGLE 'ON' CELL FOR ALL EXAMPLES

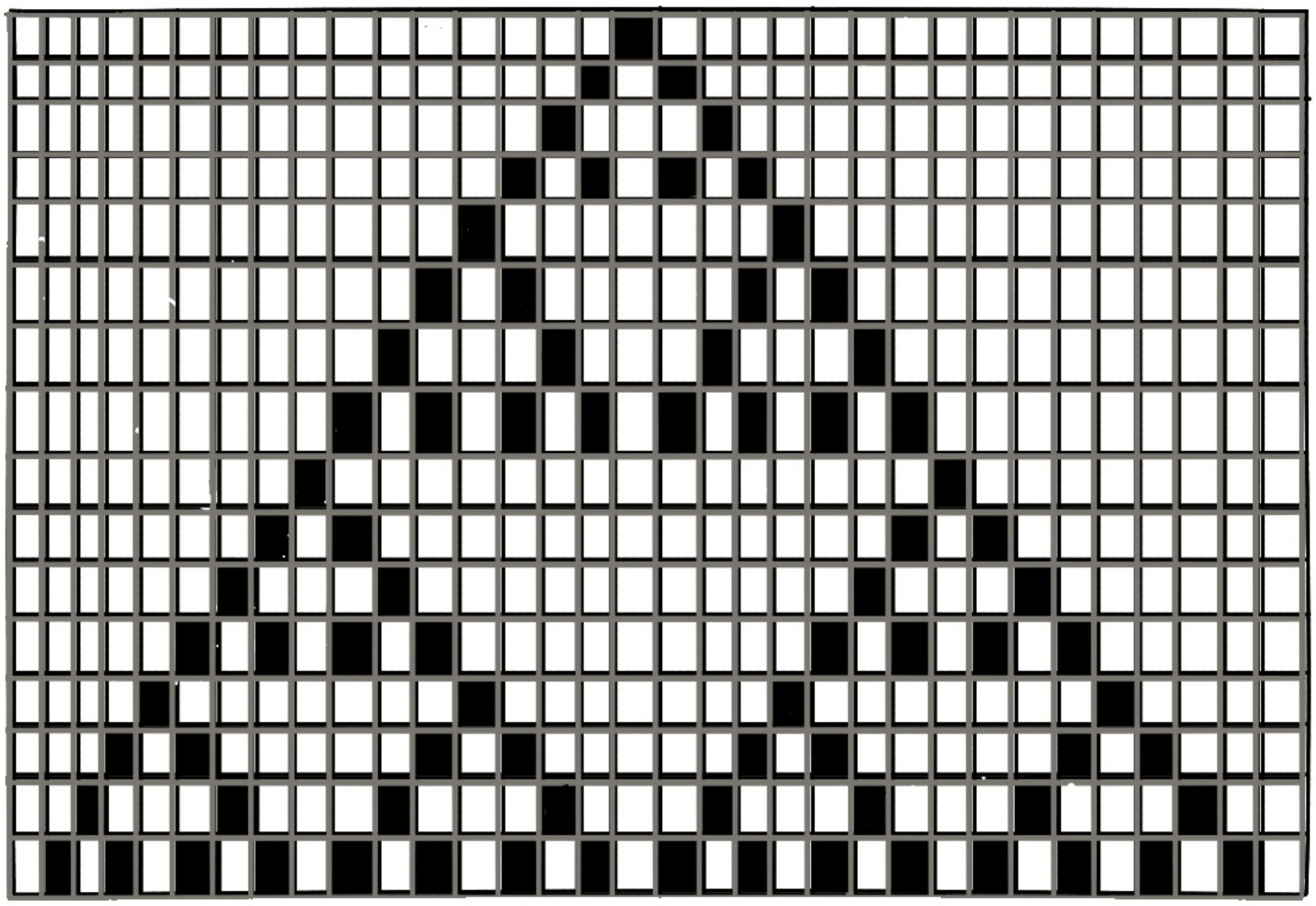
- THIS RULE VERY QUICKLY SETTLES INTO A SIMPLE OSCILLATING PATTERN

- SOME RULES PRODUCE A FIXED POINT PATTERN SUCH AS RULE 77

search for '1D Elementary Cellular Automata' an online simulator from elife-asu.github.io

EXAMPLE - RULE 90



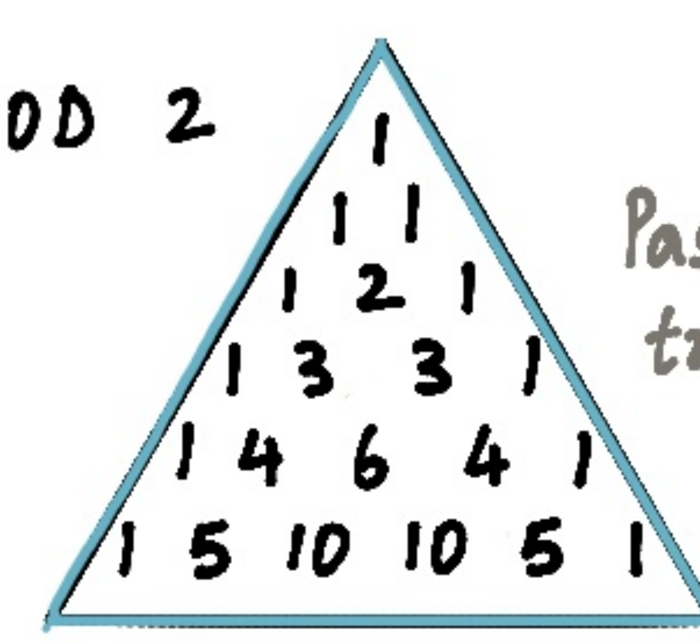


- IT FORMS A SIERPINSKI TRIANGLE FRACTAL PATTERN

- THIS IS ALSO PASCAL'S TRIANGLE MOD 2

  0 FOR EVEN NUMBERS

  1 FOR ODD NUMBERS

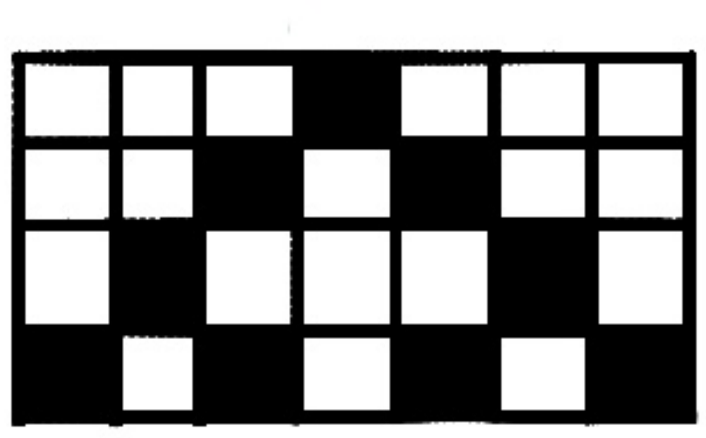


Pascal's triangle

- THE NEXT VALUE OF A CELL IS THE XOR OF ITS NEIGHBOURS

X	Y	X ⊕ Y
1	1	0
0	0	0
1	0	1
0	1	1

XOR Truth table

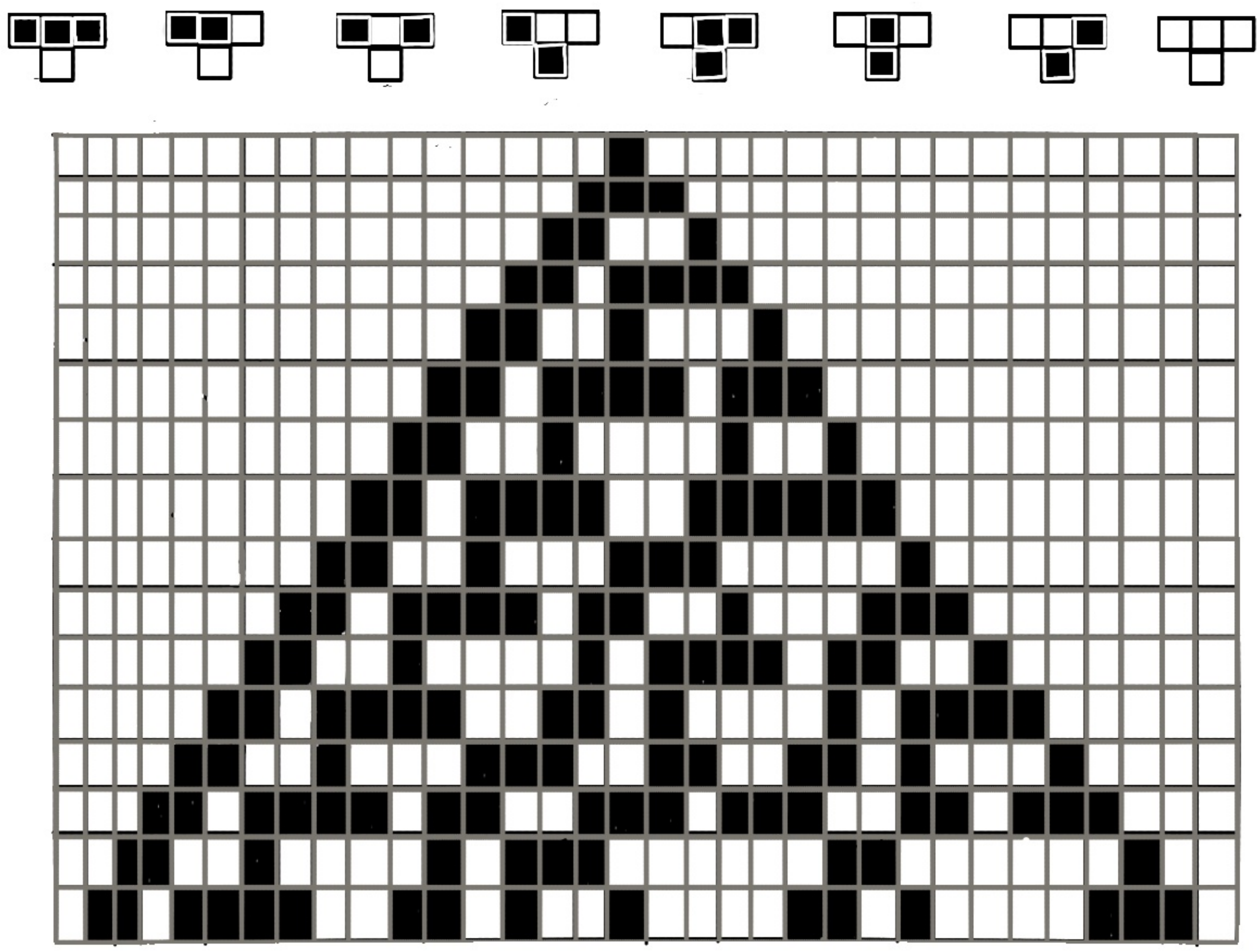


XOR = ⊕
EXCLUSIVE OR

0	0	0	1	0	0	0
0	0	1	0	1	0	0
0	1	0	0	0	1	0
1	0	1	0	1	0	1

NEXT VALUE OF 0 = 1 ⊕ 0 = 1
NEXT VALUE OF 1 = 0 ⊕ 0 = 0
NEXT VALUE OF 0 = 0 ⊕ 1 = 1

EXAMPLE - RULE 30



- DISPLAYS NON-REPEATING CHAOTIC BEHAVIOUR
- USED AS A (PSEUDO) RANDOM NUMBER GENERATOR
- PROPOSED USE IN PUBLIC KEY CRYPTOGRAPHY

  GIVEN THE RULES:

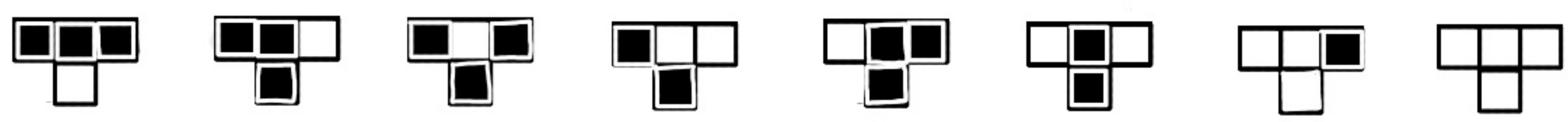
  EASY TO WORK OUT THE NEXT STEP

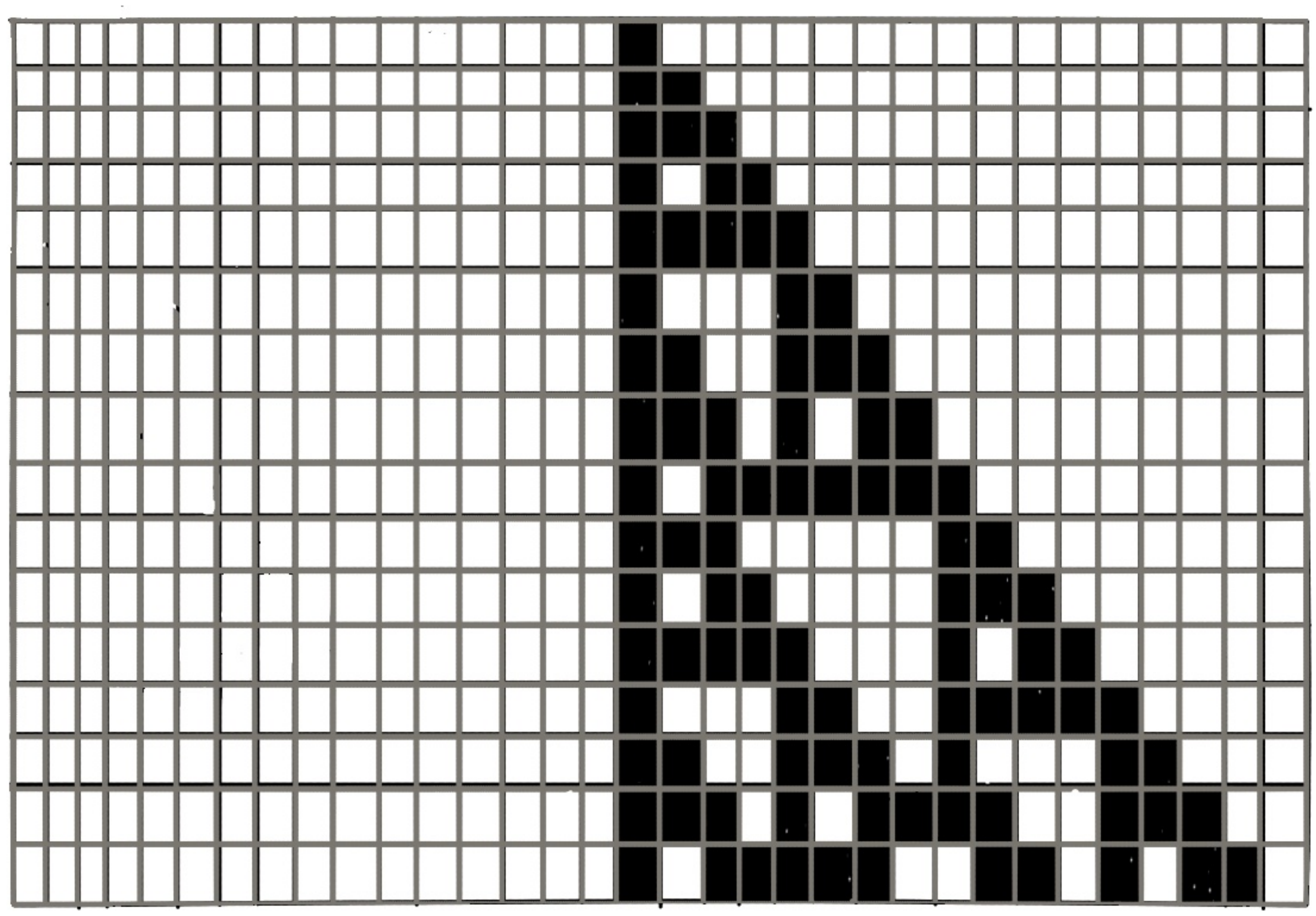
  HARD TO WORK OUT THE PREVIOUS STEP

- DISPLAYS SENSITIVE DEPENDENCE TO INITIAL CONFIG
- "CENTRAL TO HOW COMPLEXITY GETS MADE IN NATURE" (REF TO SIMPLE RULES GIVING COMPLEX BEHAVIOUR)

  – STEPHEN WOLFRAM WRITINGS.

EXAMPLE - RULE 124





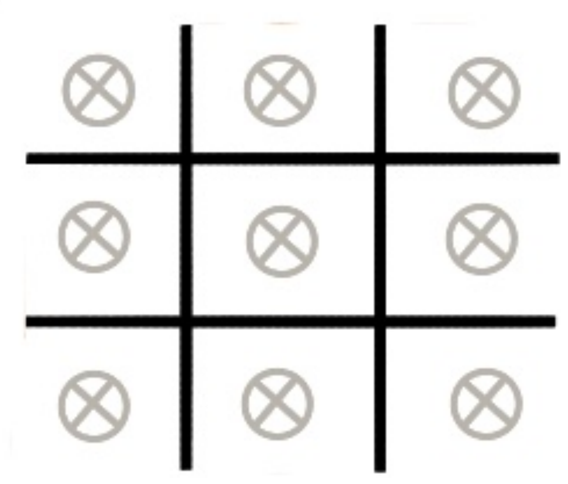
- IS THE MIRROR IMAGE OF THE MORE FAMOUS* RULE 110
- IS PROVED TO BE TURING COMPLETE (ALSO RULE 110)

  SEARCH ONLINE FOR A DEMO OF RULE 110 MARBLE COMPUTER
- DISPLAYS STRANDS OF LONG-LIVED COMPLEX STRUCTURES.

* Rule 124 was more of a personal choice

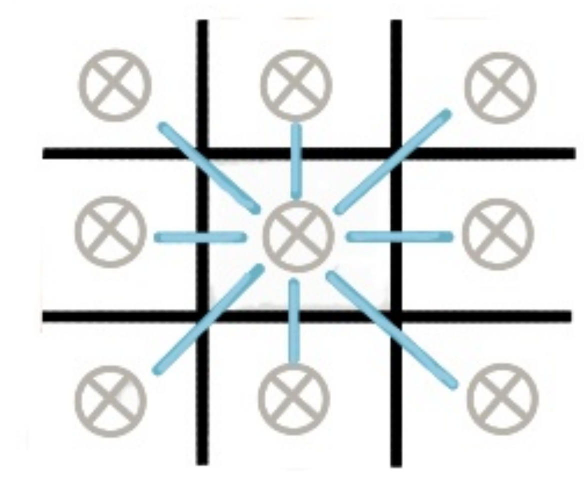
TWO DIMENSIONS

CELLULAR AUTOMATA IN TWO DIMENSIONS NEED



AN INITIAL STATE

RULES



A DEFINED NEIGHBOURHOOD

HERE ARE SOME TWO DIMENSIONAL CELLULAR AUTOMATA

BRIAN'S BRAIN

RAKE

IMMIGRATION

SEEDS

SEDIMENTAL

GAME OF LIFE

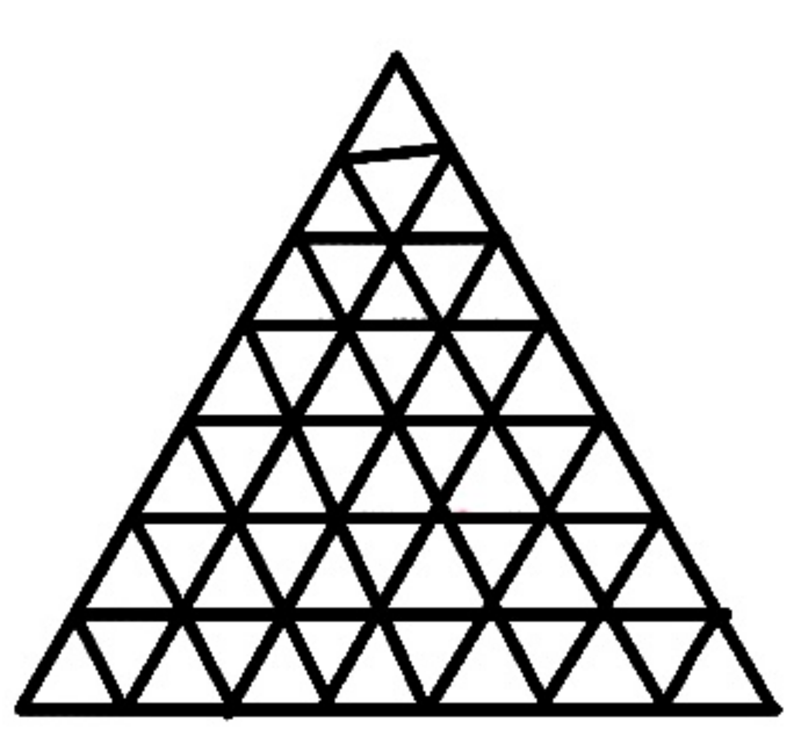
STAR WARS

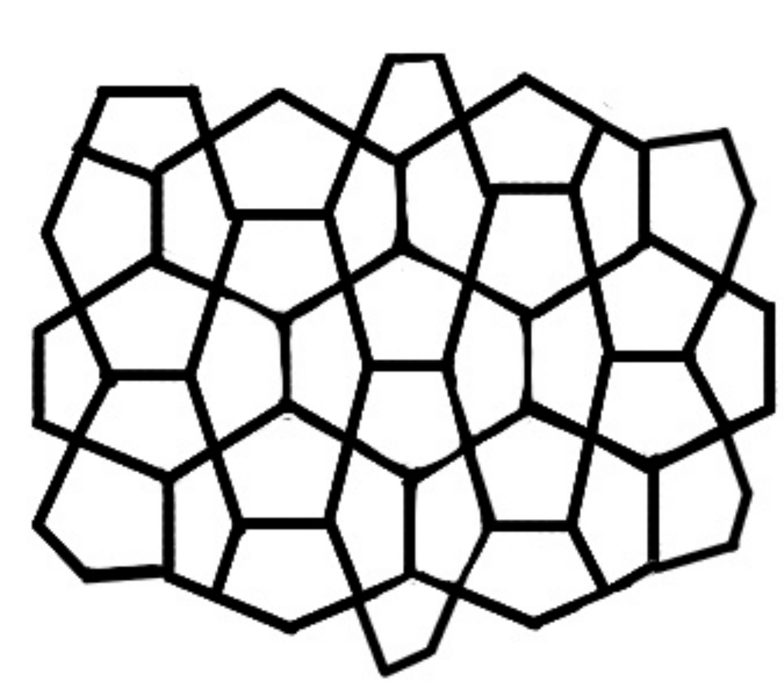
BOMBERS

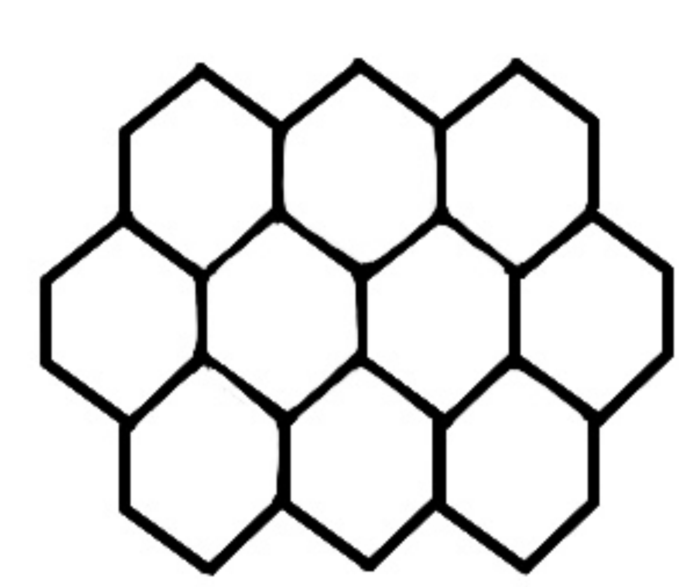
HIGHLIFE

WIREWORLD

INTERESTINGLY, THE GRIDS COULD BE NON-SQUARES. THEY COULD BE TRIANGLES, PENTAGONS OR HEXAGONS. (EVEN ON PENROSE TILES! WORK BY PROF SUSAN STEPNEY)







THE WHOLE GRID IS UPDATED AT ONCE FOR EACH TIME STEP.

THE GAME OF LIFE

JOHN CONWAY

THE MOST WELL KNOWN OF CELLULAR AUTOMATA HAS TO BE THE GAME OF LIFE DESIGNED BY JOHN CONWAY IN 1970.

IN THE GRID, CELLS ARE IN ONE OF

ALIVE ■ STATE

DEAD □ STATE

GAME OF LIFE : RULES

BIRTH

- A DEAD CELL WITH 3 LIVE NEIGHBOURS COMES ALIVE

DEATH

- A LIVE CELL WITH 1 OR 0 LIVE NEIGHBOURS DIES

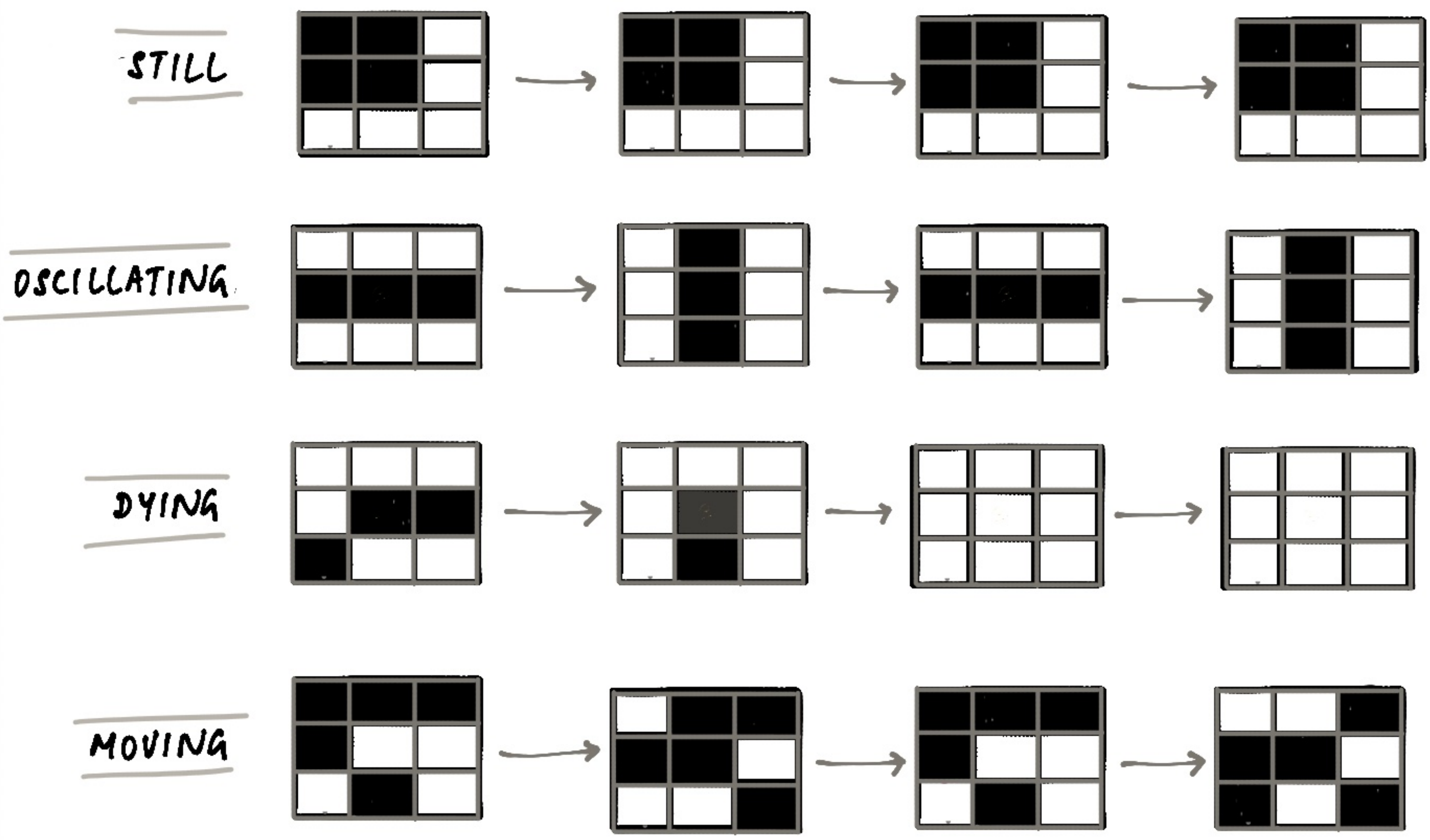
- A LIVE CELL WITH 4 OR MORE LIVE NEIGHBOURS DIES

SURVIVAL

- A LIVE CELL WITH 2 OR 3 LIVE NEIGHBOURS STAYS ALIVE

THE COMPLEXITY

THE GAME OF LIFE IS A VERY WELL THOUGHT OUT SET OF RULES THAT CAN EVOLVE MANY TYPES OF PATTERNS -



THIS SHAPE GLIDED ACROSS THE GRID PROMPTING A SEARCH FOR MORE SUCH 'CREATURES'.

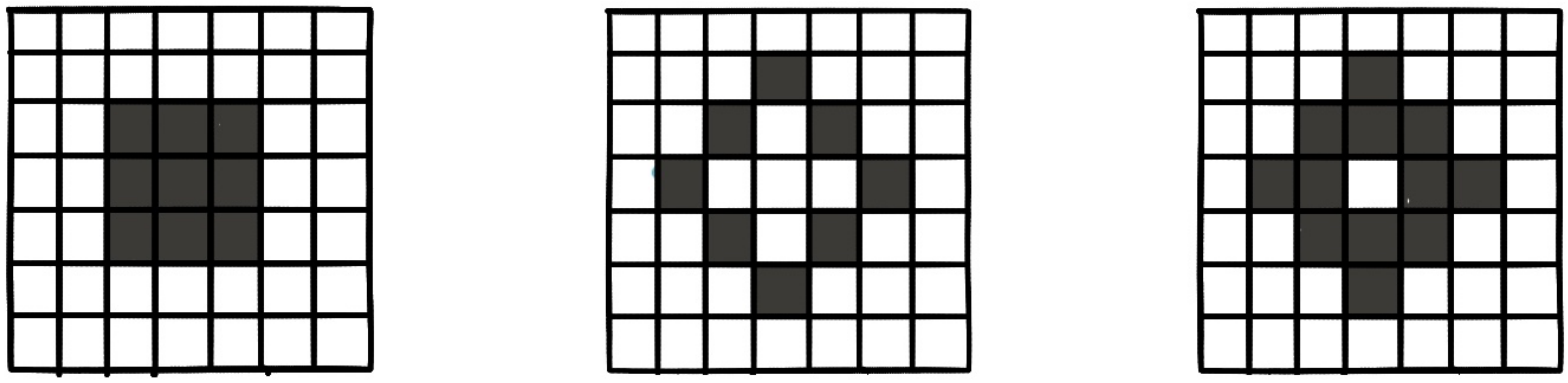
MORE COMPLEX SHAPES AND UNPREDICTABLE PATTERNS INTERACT AND UNFOLD, ALL DEPENDING ON THE INITIAL STATES OF THE CELLS.

THE EMERGENCE AND SELF ORGANISATION THAT CONWAY INTENDED TO DEMONSTRATE - THE UNPREDICTABILITY - IS NOT RANDOM BECAUSE LIFE OBEYS CERTAIN RULES.

UNSURPRISINGLY, LIFE HAS ITS OWN LEXICON AND COMMITTED GROUPS OF ENTHUSIASTS.

check out playgameoflife.com

THE LEGACY



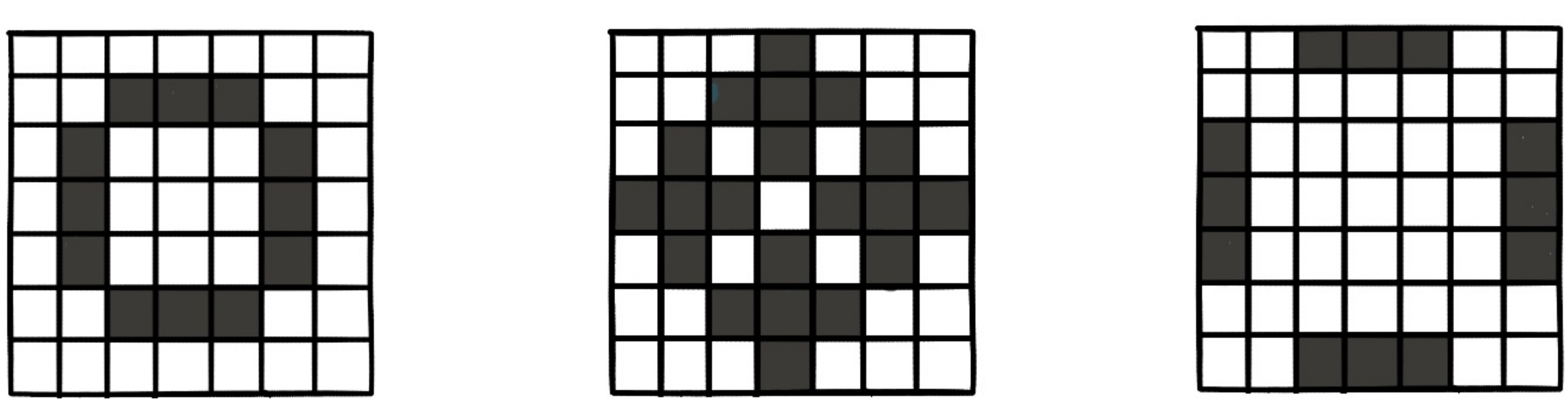
GAME OF LIFE CONTINUES TO BE POPULAR SINCE IT WAS FIRST PUBLISHED IN MARTIN GARDNER'S COLUMN IN SCIENTIFIC AMERICAN ABOUT 50 YEARS AGO.

THERE ARE PATTERNS ON THE GRID THAT CAN EMULATE COUNTERS AND LOGIC GATES IN PROGRAMMING.

THE GAME OF LIFE IS PROVED AS TURING COMPLETE & UNDECIDABLE

LIFE IS A VERY EASY TO UNDERSTAND EXAMPLE OF EMERGENT COMPLEXITY

LIFE HELPS US UNDERSTAND HOW PATTERNS IN NATURE CAN DEVELOP AND THAT IT IS POSSIBLE THAT COMPLEX FORMS CAN ARISE FROM THE SIMPLE WITHOUT BEING EXPLICITLY PROGRAMMED TO DO SO.



CA ARE IDEAL FOR:

AS WE HAVE SEEN EARLIER, LIKE ANY OTHER COMPLEX SYSTEM, CELLULAR AUTOMATA ARE ALSO

- ✓ SIMPLE INTERACTING COMPONENTS
- ✓ CAPABLE OF PROCESSING INFORMATION
- ✓ WITH NO CENTRAL CONTROL &
- ✓ DISPLAY COMPLEX BEHAVIOUR FROM SIMPLE RULES

COMPLEX SYSTEMS HAVE SOME COMMON FEATURES. THEY HAVE:

SIMPLE COMPONENTS

- SIMPLER THAN THE WHOLE

INTERACTIONS

- THE PARTS ARE INTERDEPENDENT AND INTERACT WITH EACH OTHER BASED ON SIMPLE RULES

NO CENTRALISED CONTROL

- THEY ARE SELF ORGANISING

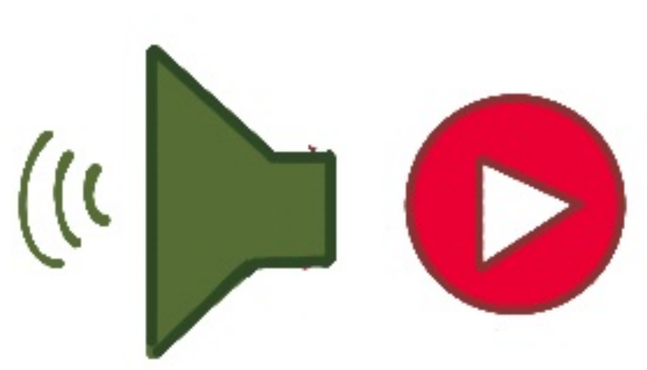
EMERGENT BEHAVIOUR

- THE COLLECTIVE BEHAVIOURS ADAPT AND EVOLVE AND ARE EVEN CHAOTIC AS THE SYSTEM LEARNS FROM ITS ENVIRONMENT

MAKING THE WHOLE GREATER THAN THE PARTS

CELLULAR AUTOMATA CAN BE USED TO:

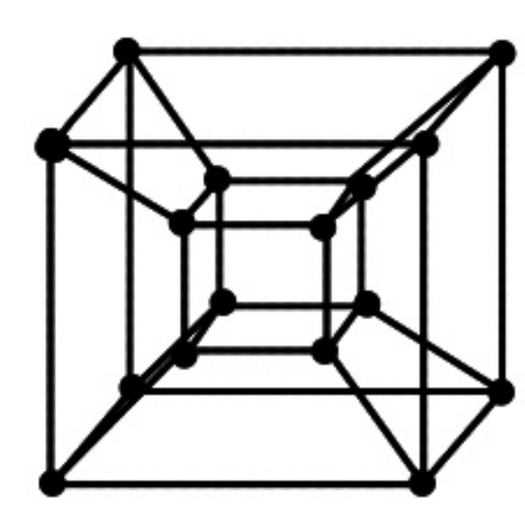
CREATE AUDIO/ VISUAL CONTENT



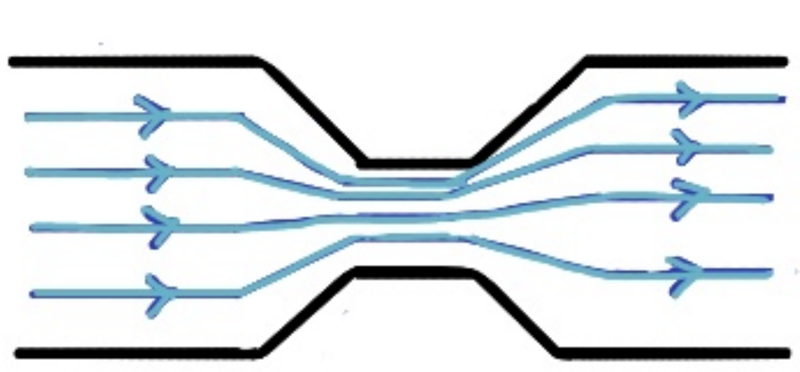
GENERATE PSEUDO RANDOM NUMBERS

9	5	4	3	6	8	9	0
1	6	3	2	1	9	7	9
2	1	7	9	6	0	2	8
8	7	3	5	4	4	4	7
4	8	0	5	2	5	6	6
2	4	1	0	1	0	4	2

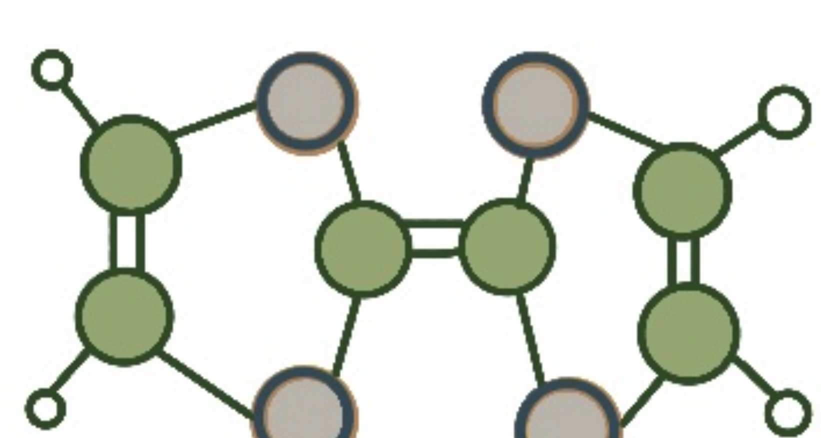
BUILD PARALLEL COMPUTERS



MODEL PHYSICAL SYSTEMS



BUILD MOLECULAR COMPUTERS



SIMULATE BIOLOGICAL PROCESSES

A BRIEF OUTLOOK

COMPLEXITY IS A VERY YOUNG SCIENCE STILL TRYING TO ESTABLISH ITS ROOTS.

ON ONE HAND, THERE IS RESEARCH AND COMPUTING RESOURCES BEING INVESTED IN COMPLEXITY SCIENCES. IT HAS GENERATED MUCH INTEREST THROUGH IDEAS IN ARTIFICIAL INTELLIGENCE, CELLULAR AUTOMATA, ARTIFICIAL LIFE ETC.

ON THE OTHER, THERE IS SKEPTICISM AND DOUBT ABOUT THE GOALS AND THE BASIC BUILDING BLOCKS FOR THIS SCIENCE.

COMPLEXITY HAS APPLICATIONS SUCH AS DESIGNING EVACUATION ROUTES AND MODELLING TRAFFIC PATTERNS.

IT IS FULL OF POSSIBILITIES – DEVELOPING A COMMON VOCABULARY TO ACCURATELY DEFINE THE PHENOMENA, A NEW TYPE OF MATHEMATICS TO DEPICT THE INTERACTIONS, AND IMPORTANTLY, THE CYCLE OF HYPOTHESIS AND TESTING.

WILL COMPLEXITY HELP US GAIN SIGNIFICANT INSIGHT INTO OUR WORLD? WILL A DIFFERENT NEWTON COME ALONG AND INVENT A HYPERCALCULUS TO BUILD A UNIFIED THEORY?

ONLY TIME WILL TELL.

MORE TO EXPLORE

THIS IS BY NO MEANS AN EXHAUSTIVE LIST. COMPLEXITY SCIENCE HAS AFFECTS MANY FIELDS. IT IS GROWING AND IT EMBRACES NUMEROUS CONCEPTS.

HERE ARE A HANDFUL

- GAME THEORY, PRISONER'S DILEMMA
- MANDELBROT SETS (FRACTALS)
- NORBERT WIENER'S CYBERNETICS
- ALAN TURING'S MORPHOGENESIS
- NOAM CHOMSKY'S UNIVERSAL GRAMMAR
- ANALOGIES AND LEARNING – M. MITCHELL'S COPYCAT PROGRAM

MY REFERENCES

Online Courses

Introduction to Complexity complexityexplorer.org
Analysing Complexity - coursera.org

Books

Chaos: Making a new science - James Gleick
Complexity: A guided tour - Melanie Mitchell
Complexity a very short introduction - John H Holland
Complex Systems latest - quantamagazine.org/tag/complex-systems

Papers/Articles

Simplicity and complexity in the description of nature: Murray Gell-Man - iscte-iul.pt
What is Complexity? - Murray Gell-Man - complexity.martinsewell.com
Measures of Complexity - Seth Lloyd - mit.edu
Science and Complexity - Warren Weaver -
A Brief History of Systems Science, Chaos and Complexity - resilience.org
Chaos - plato.stanford.edu
What are complex systems - cssociety.org
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Chaos

Double Pendulum demo - myphysicslab.com
Video: Butterflies, Chaos and Fractals - Professor Raymond Flood
Order from chaos: How to apply complexity theory at work - bbva.com
Video: Fractal Mathematics - Dr Ron Eglash youtube.com
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MY REFERENCES

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Paper: A Mathematical Theory of Communication - Claude Shannon
Entropy and Second Law - physics.bu.edu
Paper: Information Theory and the Digital Age - mit.edu