University of Glasgow

Global to Local | Tectonics, Structural & Metamorphic Geology

LECT 2 | Firm Foundations

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WORLD CHANGING GLASGOW

Global2Local | Lesson Plan

Week	LECT | MON	LECT | TUE	LECT | WED	LECT | THU	LAB | M-T	LAB | W-F
INTRO 26/10/2020	–	–	**1 | Journey Across Scales**	2 | Firm Foundations	–	1 | Dimensional Analysis
UNIQUE EARTH 02/11/2020	3 | Planetary Formation	4 | Planetary Evolution	5 | Plate Boundaries	6 | Life Tectonics	2 | B-Y-O Planet	3 | Rock Deformation
DYNAMIC EARTH 09/11/2020	7 | Core Dynamics	8 | Mantle Dynamics	9 | Plate Dynamics	10 | Faulting & Folding	4 | Mantle Convection	5 | Faults & Folds
CONTINENTS 16/11/2020	11 | Collision & Orogeny	12 | Extension & Rifting	13 | Continental Metamorphism	14 | Topography & Erosion	6 | Metamorphic Rocks	7 | Structures & Textures
OCEANS 23/11/2020	15 | Formation	16 | Subduction	17 | Oceanic Metamorphism	18 | Hot Spots	8 | Metamorphic Rocks	9 | Tectonic Synthesis

Global2Local | Online Study Plan

Lecture Content

- *NO synchronous delivery*, work through in your own time (KEEP UP TO DATE!)
- Slides, video on **Moodle** one week before scheduled lecture
- Complete interactive tasks after each lecture (**Quiz**, **Padlet** link on Moodle)
- Ask and/or upvote questions online (**Slido** link on Moodle)

Lab Practicals

- Video, slides with instructions on Moodle on day of scheduled lab
- *Group-wise synchronous delivery* on **MS Teams** space as scheduled on timetable
- 15 min instructions on general channel at start (*not recorded!*)
- Work on Lab activities in existing Study Group channels (*not recorded!*)
- 15 min wrap-up at the end (*not recorded!*, video version available on Moodle after)
- Lab leader available throughout for questions, trouble shooting (*not recorded!*)

General Q&A

- drop-in session with GTA, Thursdays 9-10 am on Teams

Global2Local | Intended Learning Outcomes

INTRO | Firm Foundations

PART I – Scientific Method

- Scientific method: observations, experiments, models, theories
- Data, models, and theory: definition, relationships, applications
- Forward and inverse models: definition, limitations

PART II – Fundamental Laws & Processes

- Fundamental Laws of Nature: conservation laws, entropy production
- Transport processes: driving forces, resisting material properties
- Equilibrium and disequilibrium: static vs. dynamic, relevance of scale

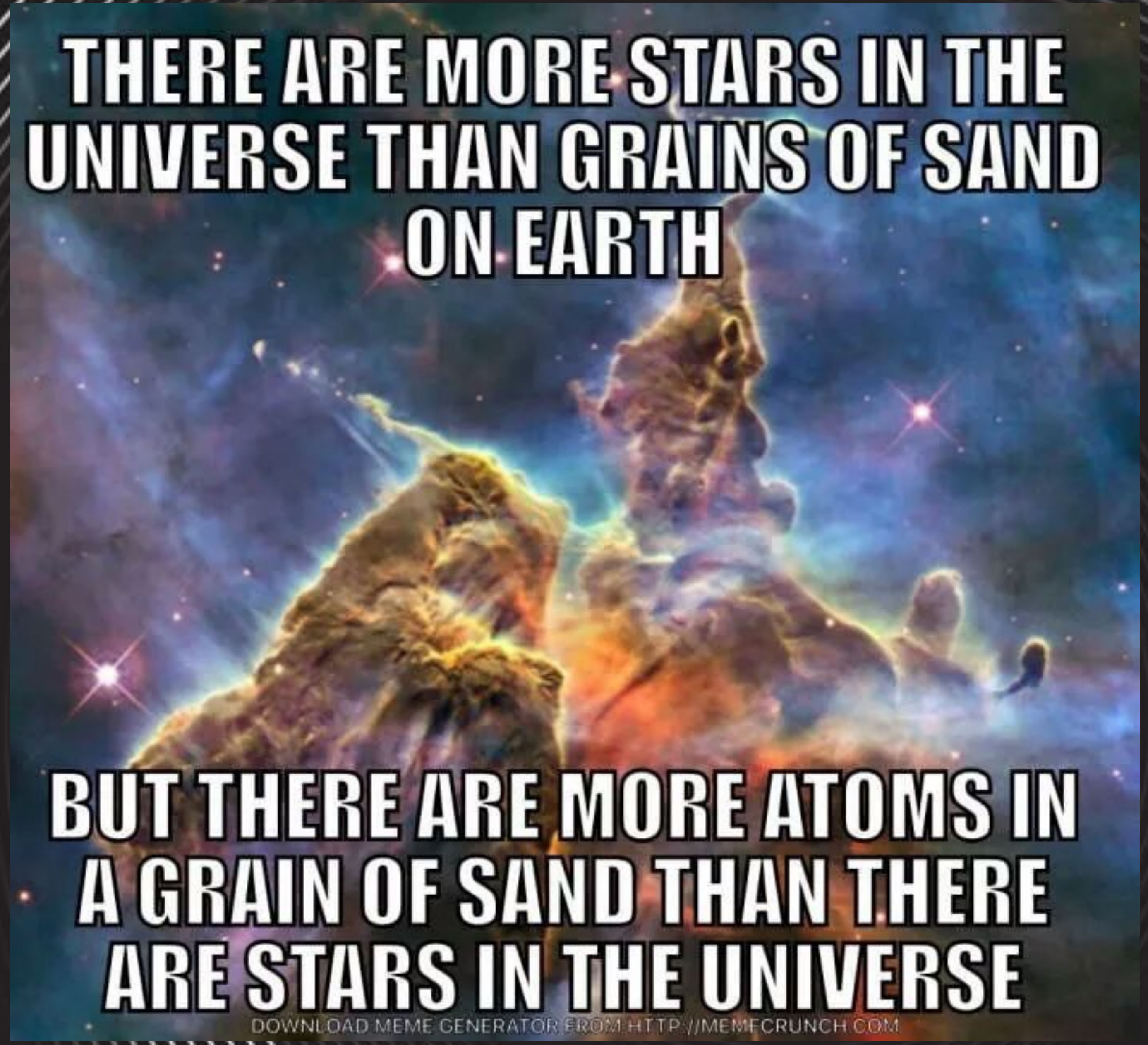
Part I – Scientific Method

Journey across Scales

Geosciences spans wide range of scales

Scales of natural bodies & systems

- Sub-atomic particles, atoms & molecules
- Mineral grains, fluid droplets, gas bubbles
- Rock, magma, soil, water, air
- Mountains, hills, valleys, plains, clouds
- Continents, oceans, plates, ice caps
- Atmosphere, Crust, Mantle, Core
- Stars, Planets, Moons, and Asteroids
- Solar systems, Disks, Galaxies, Clusters
- The Universe



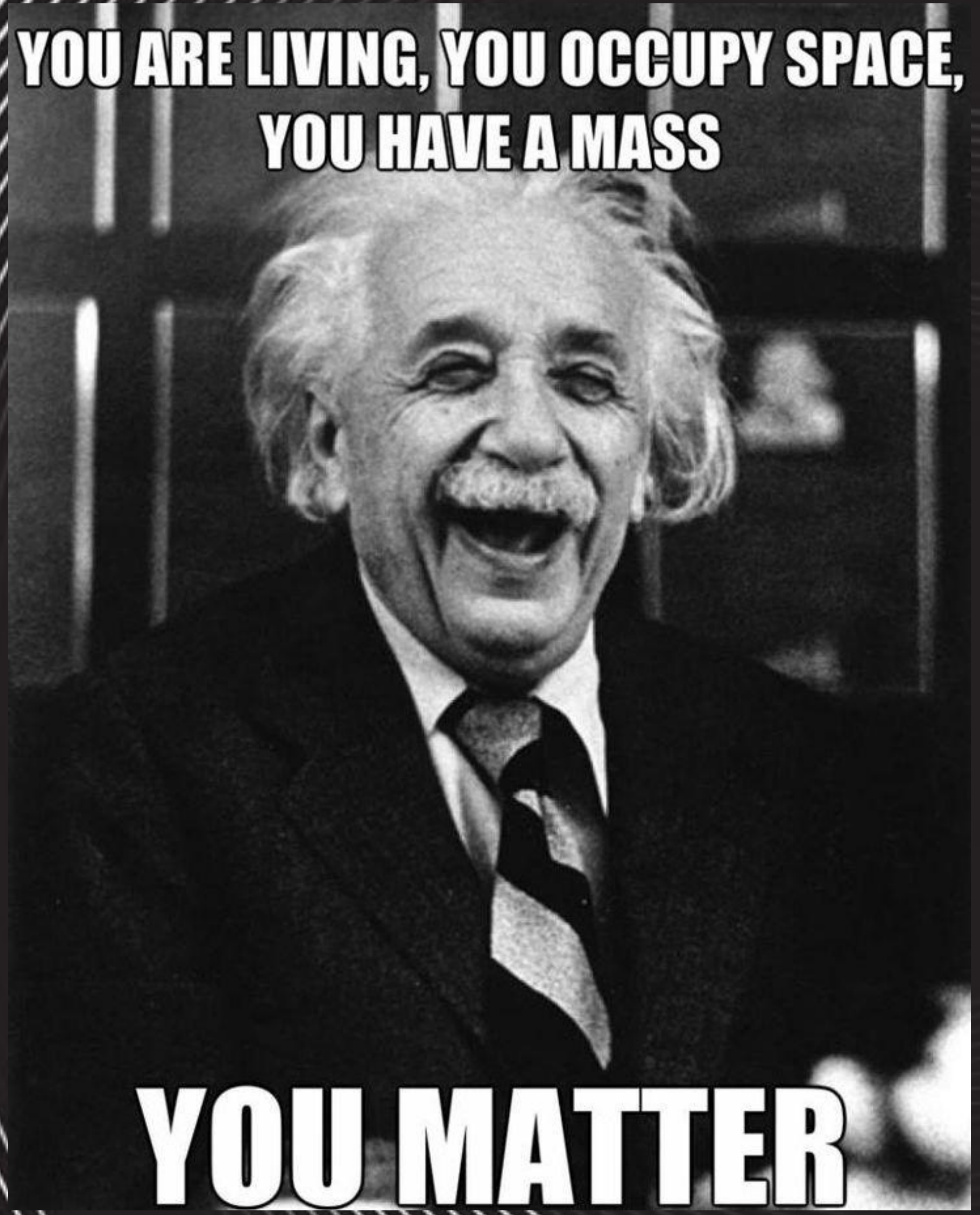
How does it all work?

The long search for answers.

The Big Questions

- Where do we come from?
- What are we doing here?
- Where are we going to?

- can Science provide answers?

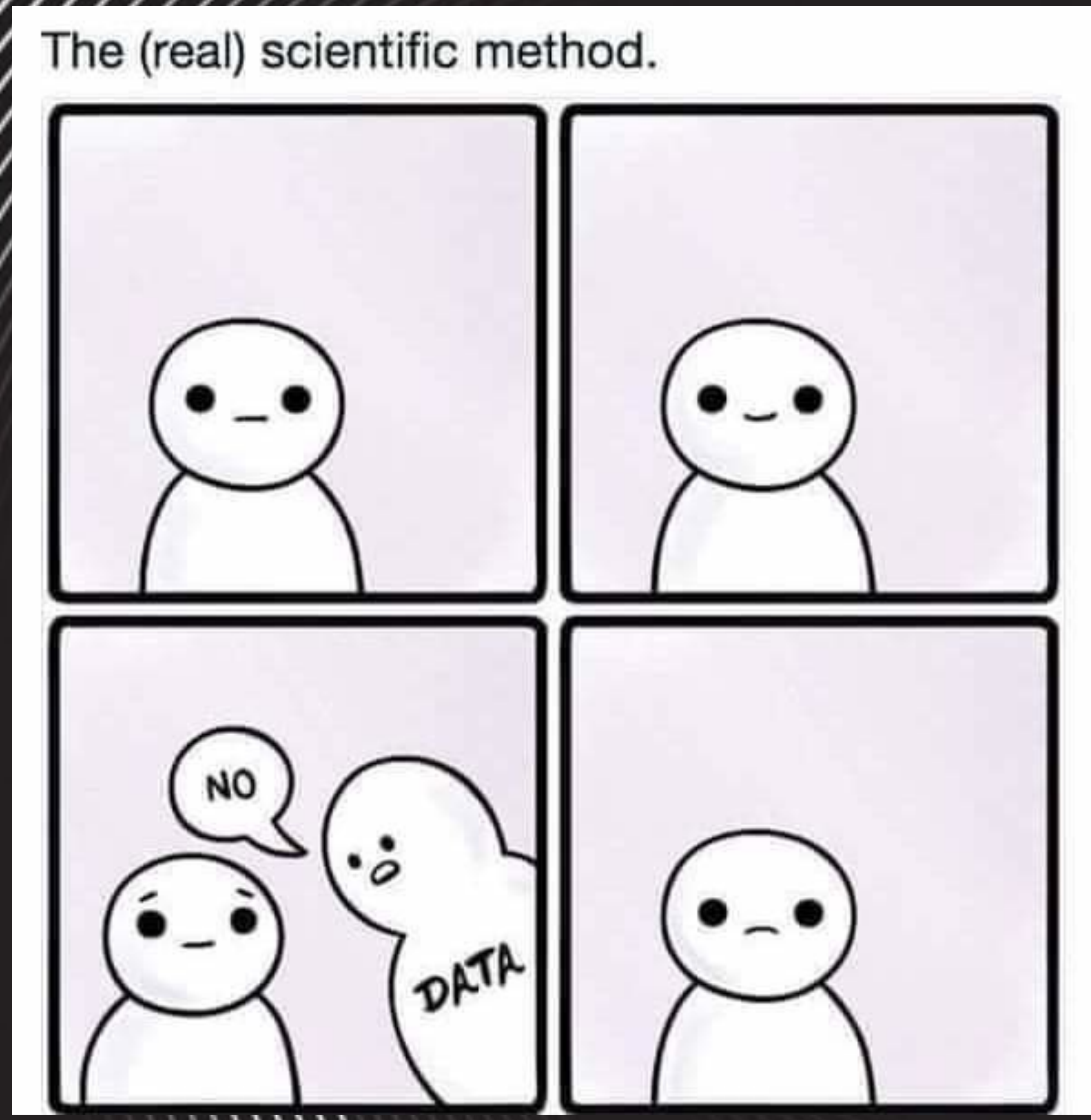


What is Science?

pursuit of understanding by observations, experiments, analysis, models, theory

The Scientific Method

- make observations
- design experiments
- analyse data
- develop models
- formulate theory



Observations

qualitatively or quantitatively record events or processes in natural world

Observations in Geosciences

- collect rock samples
- map geological units
- measure water temperature
- measure topography
- analyse rock composition
- monitor volcanic gas emissions
- …

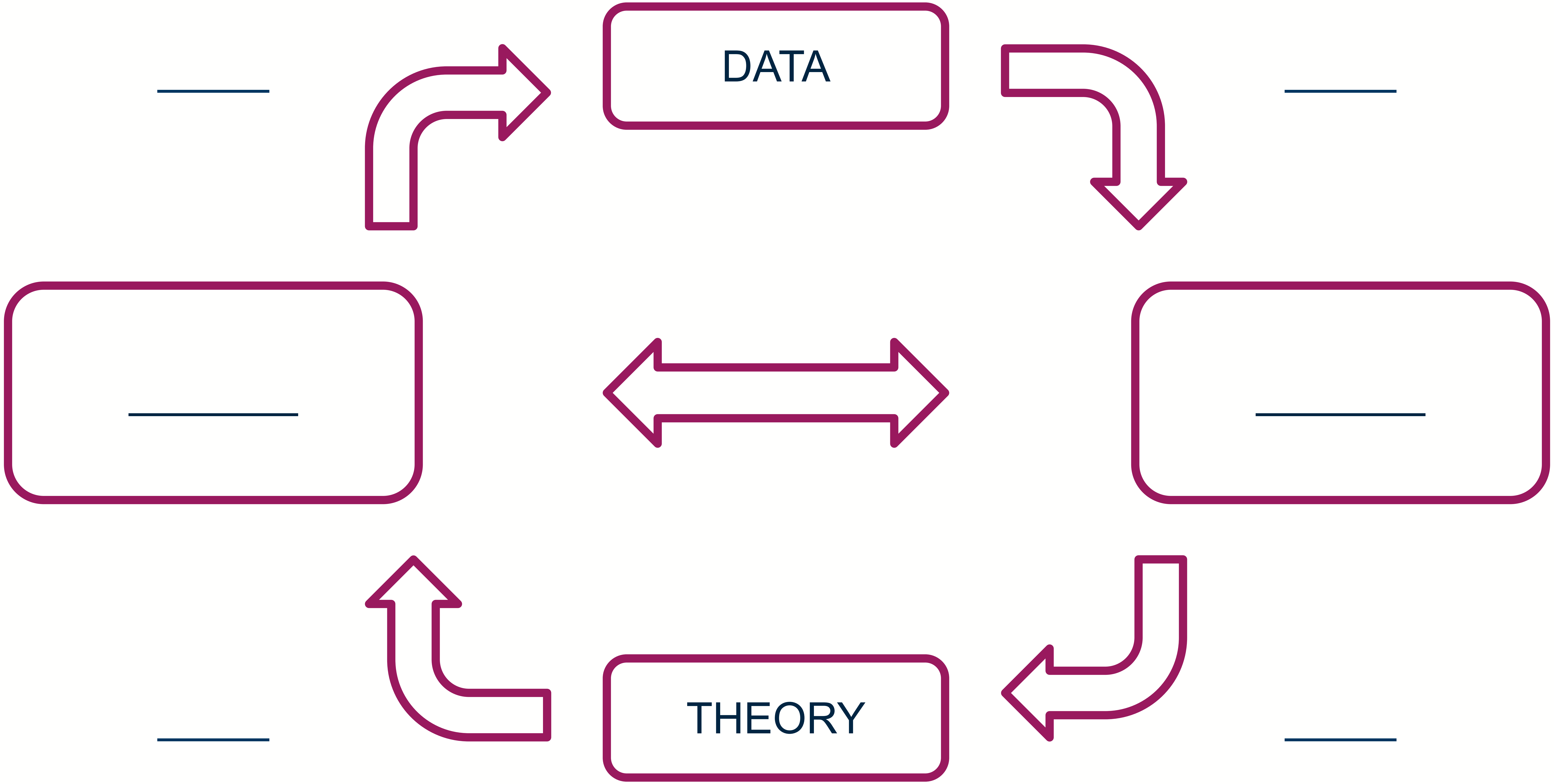
Experiments

repeatedly record event or process under controlled conditions

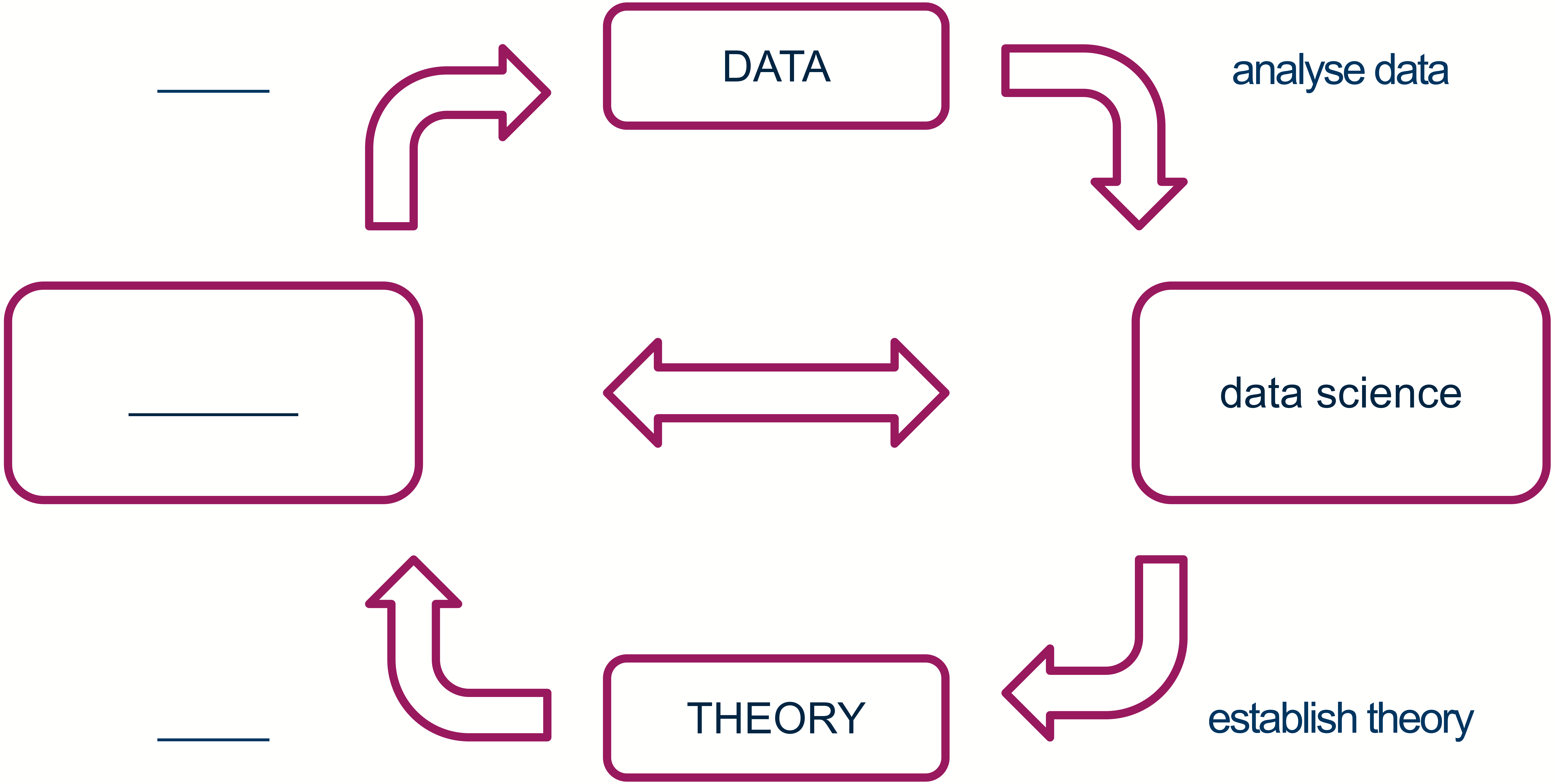
Experiments in Geosciences

- melt rock in furnace
- deform rock in piston cylinder
- make waves in a tank
- create river on a table
- …

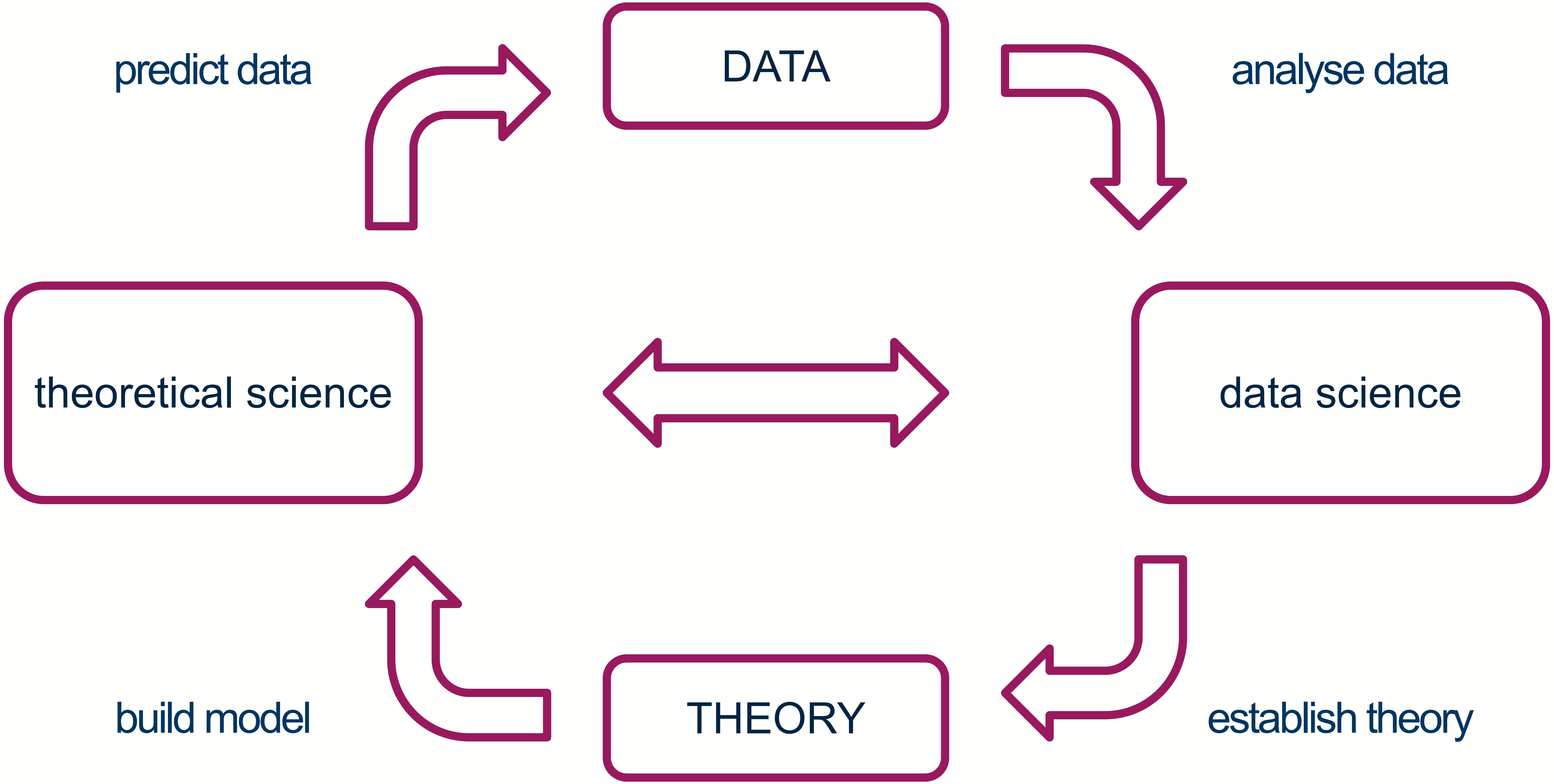
Scientific Method | Data vs. Theory



Scientific Method | Data vs. Theory



Scientific Method | Data vs. Theory



Scientific Method | Data Science

Data-driven

- start with observations, find model to fit data

Empirically-minded

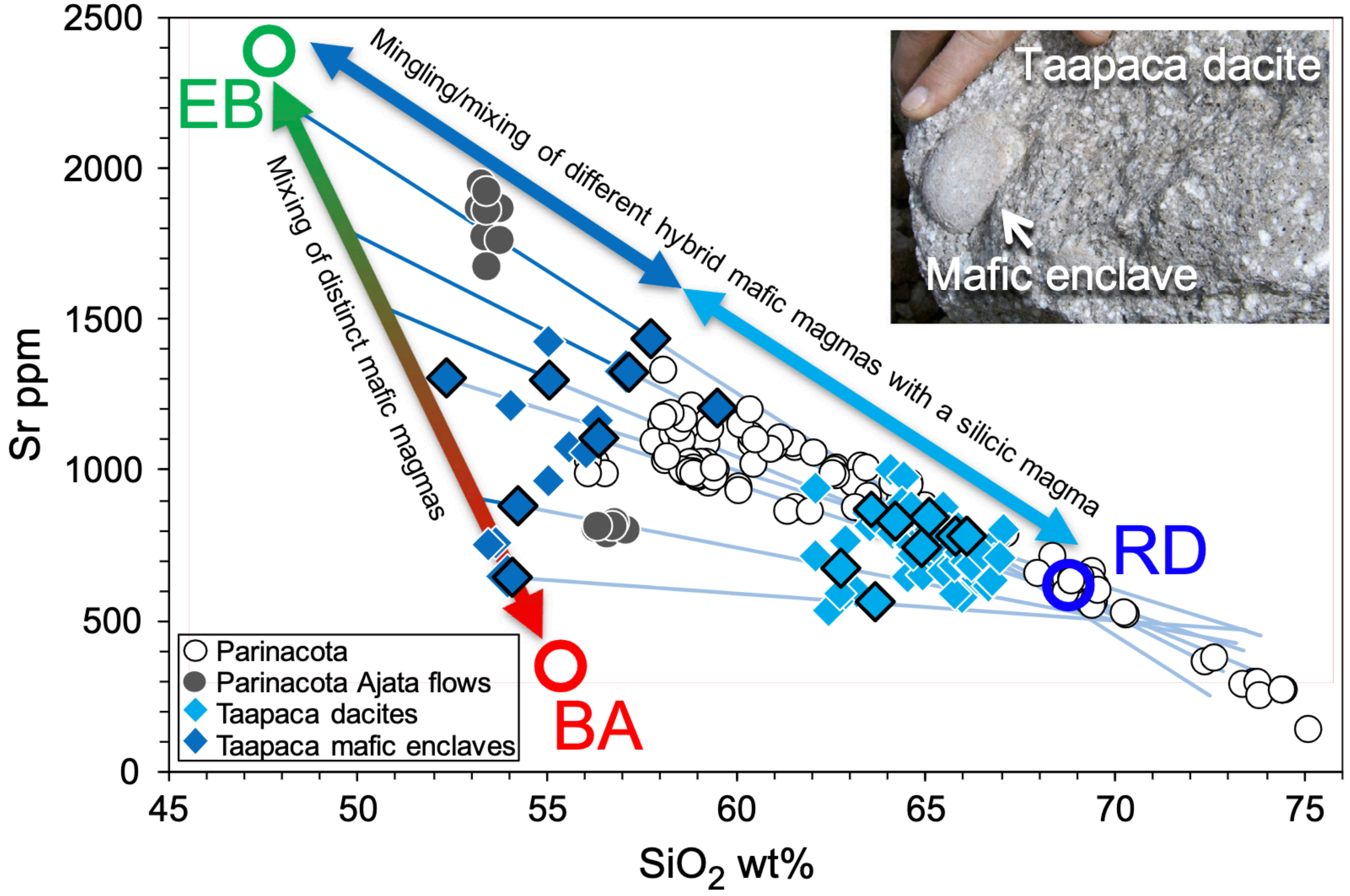
- good fit more important than understanding process

Non-uniqueness

- more than one model fits data, several interpretations reasonable

Examples

- line fitting, clustering analysis, tomographic imaging



End-member extraction for lava compositions (Blum-Oeste & Wörner, Terra Nova, 2016)

Scientific Method | Theoretical Science

Process-driven

- start with fundamental laws, build model to predict data

Hypothesis-based

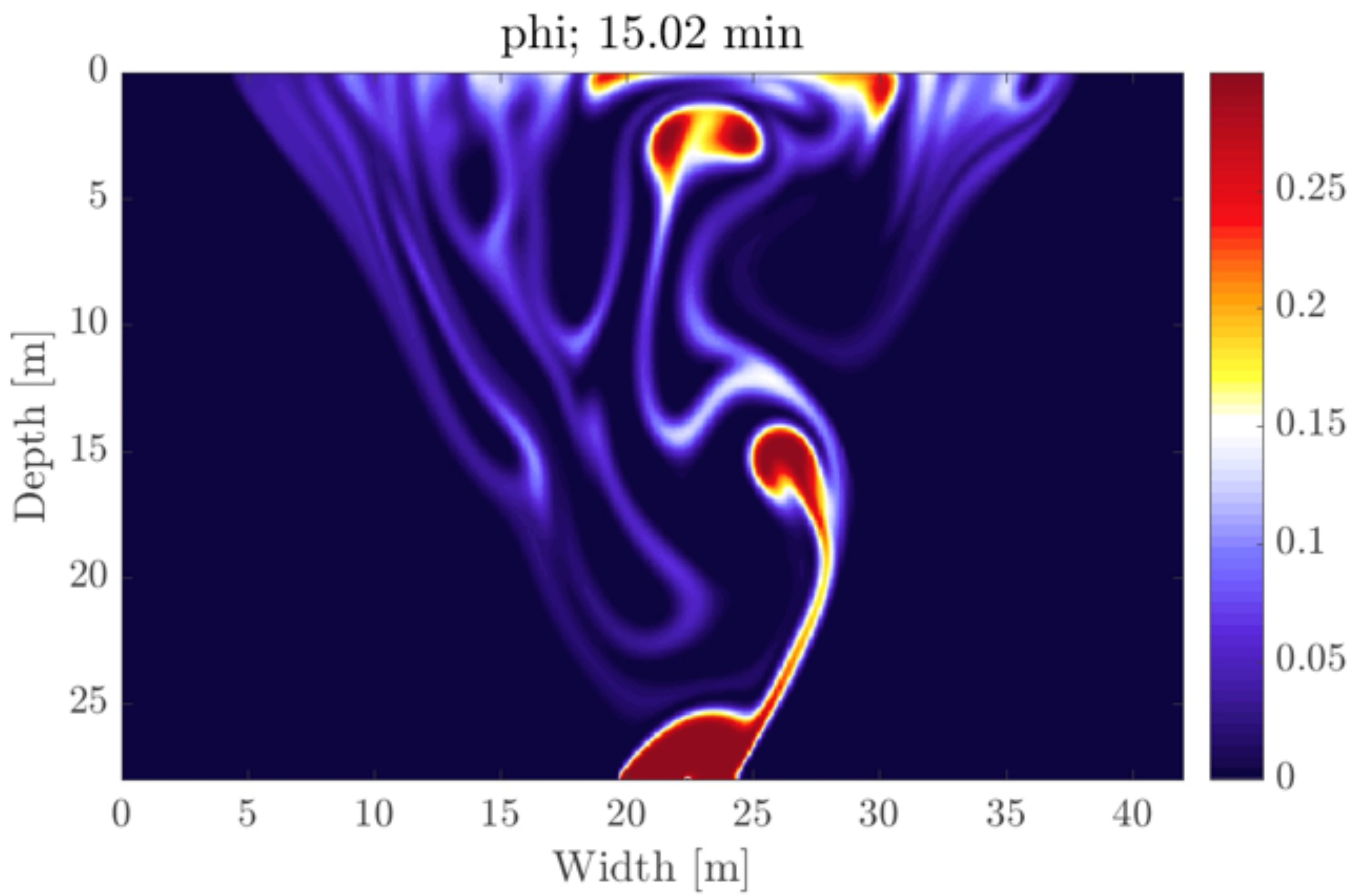
- testing hypothesis more important than fitting data

Uncertainty

- theory incomplete, models idealised, parameters poorly constrained

Examples

- lava flow simulation, rock deformation model, climate model



Lava lake convection at Mt Erebus, Antarctica (Birnbaum et al., EPSL, 2019)

Scientific Method | Modelling

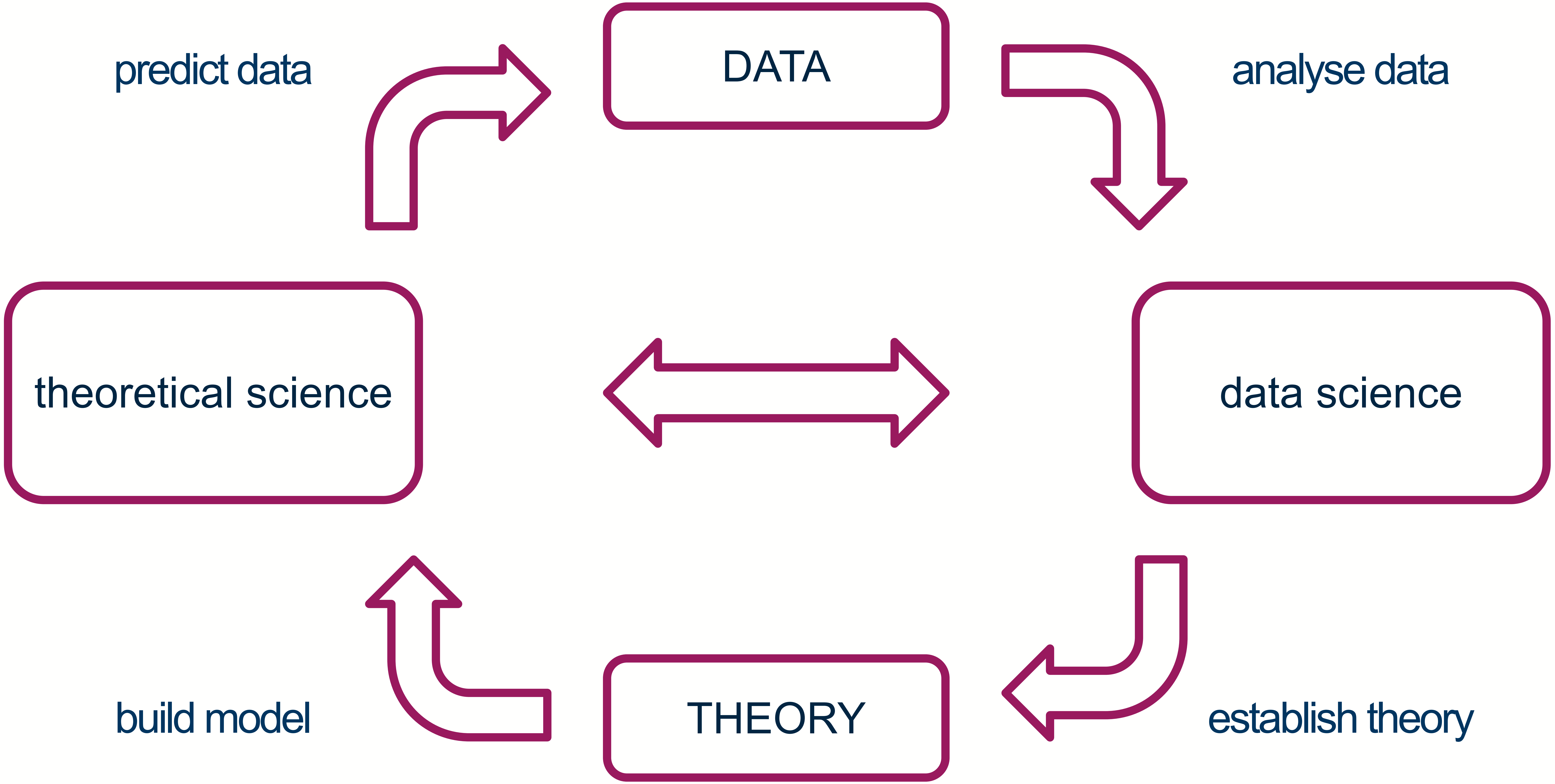
Definition

A simplified representation of a natural process or system aimed at interpreting, understanding, and predicting data.

“Universal Law” of Modelling

All models are wrong,
some models are useful.

Scientific Method | Summary



Global2Local | Intended Learning Outcomes

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Part II – Fundamental Principles

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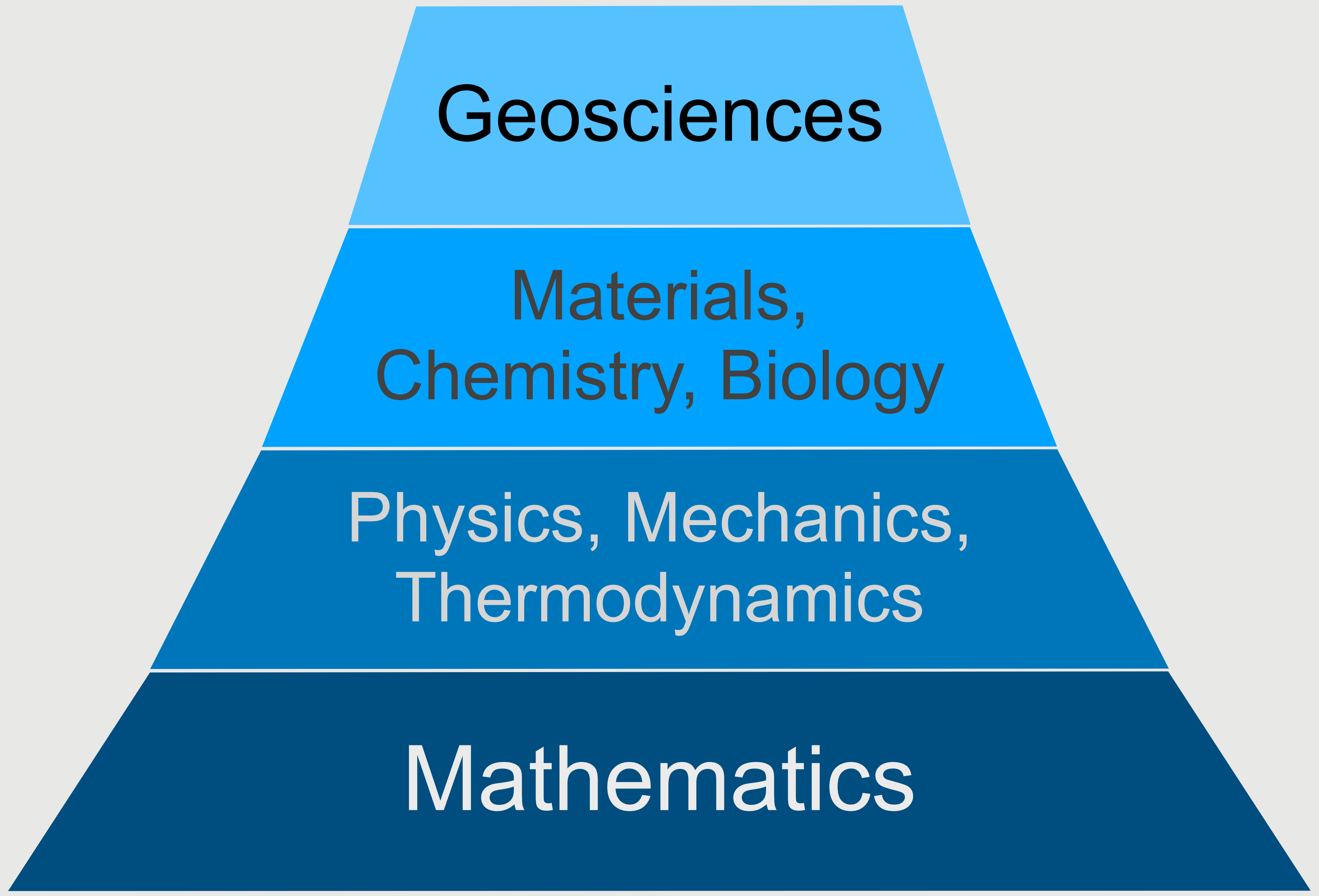
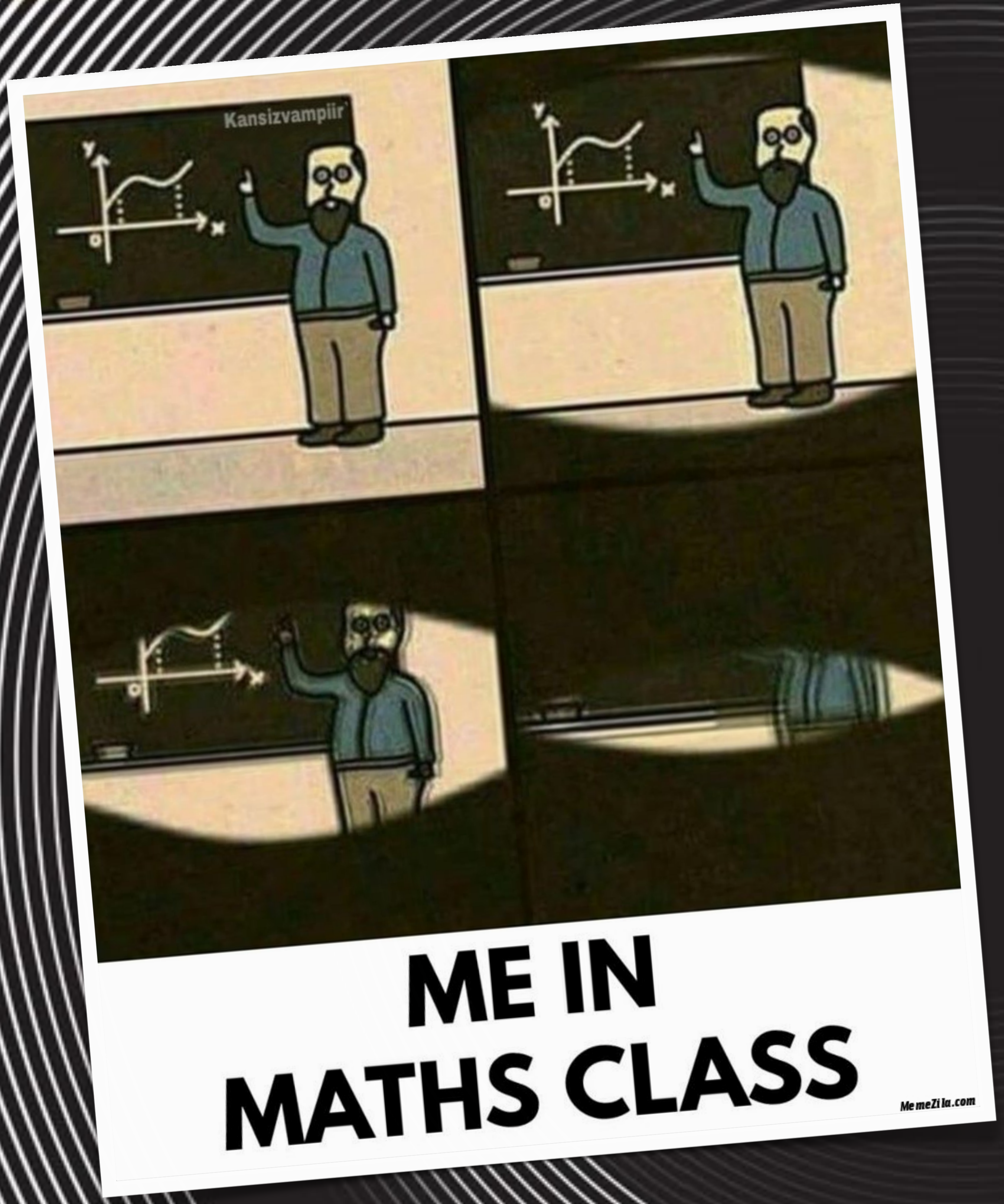
Pyramid of Sciences

basically, we're all doing applied maths
(sorry 🤷‍♂️)!

Natural Science Disciplines



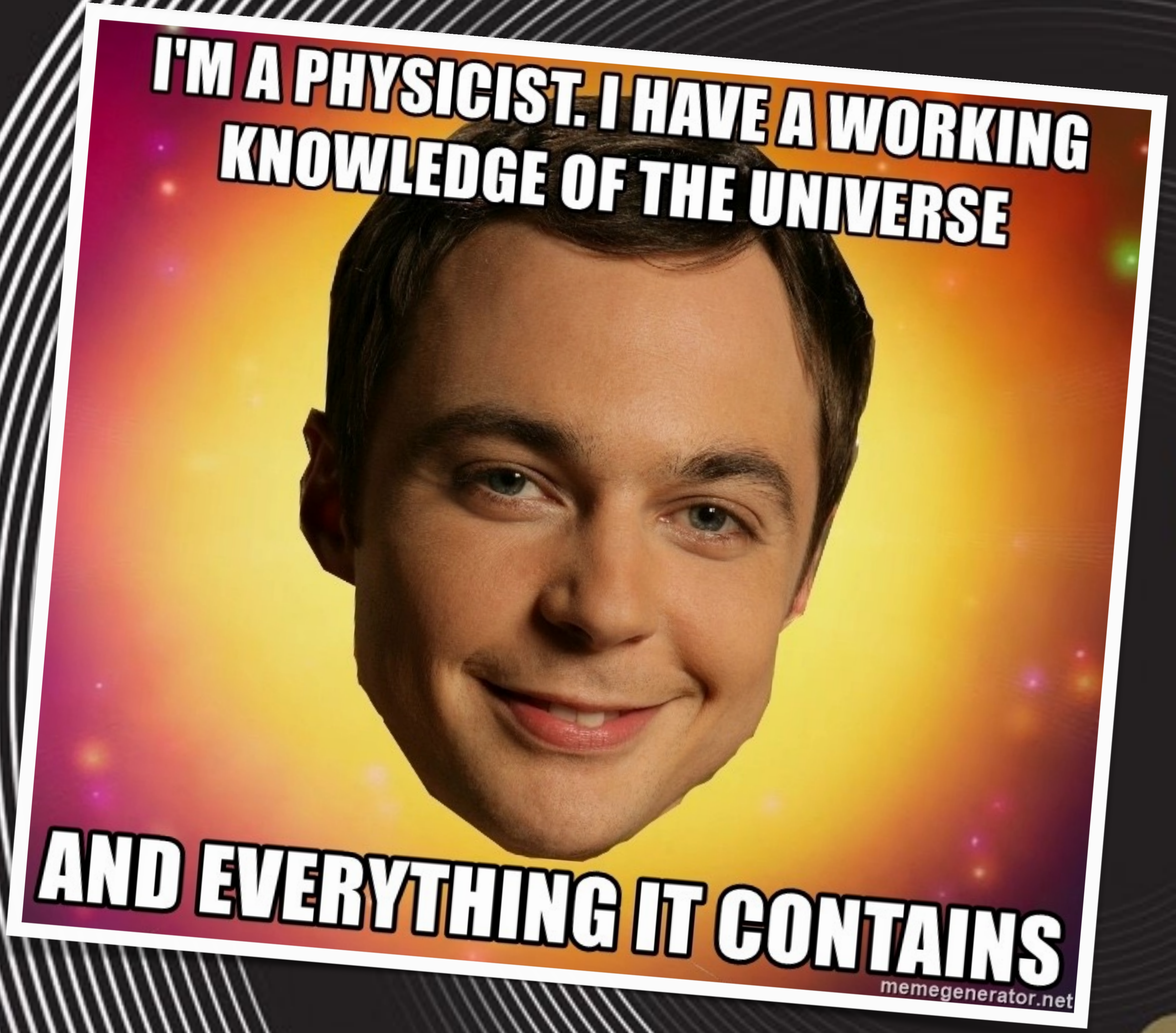


Physics

- study of natural processes, properties of matter and energy
- describes natural world by mathematical expressions

Sub-disciplines of Physics

- Mechanics: forces, motion
- Thermodynamics: heat, energy
- Chemistry: matter, reactions
- Biology: living organisms
- Geosciences: geomaterials, processes, systems



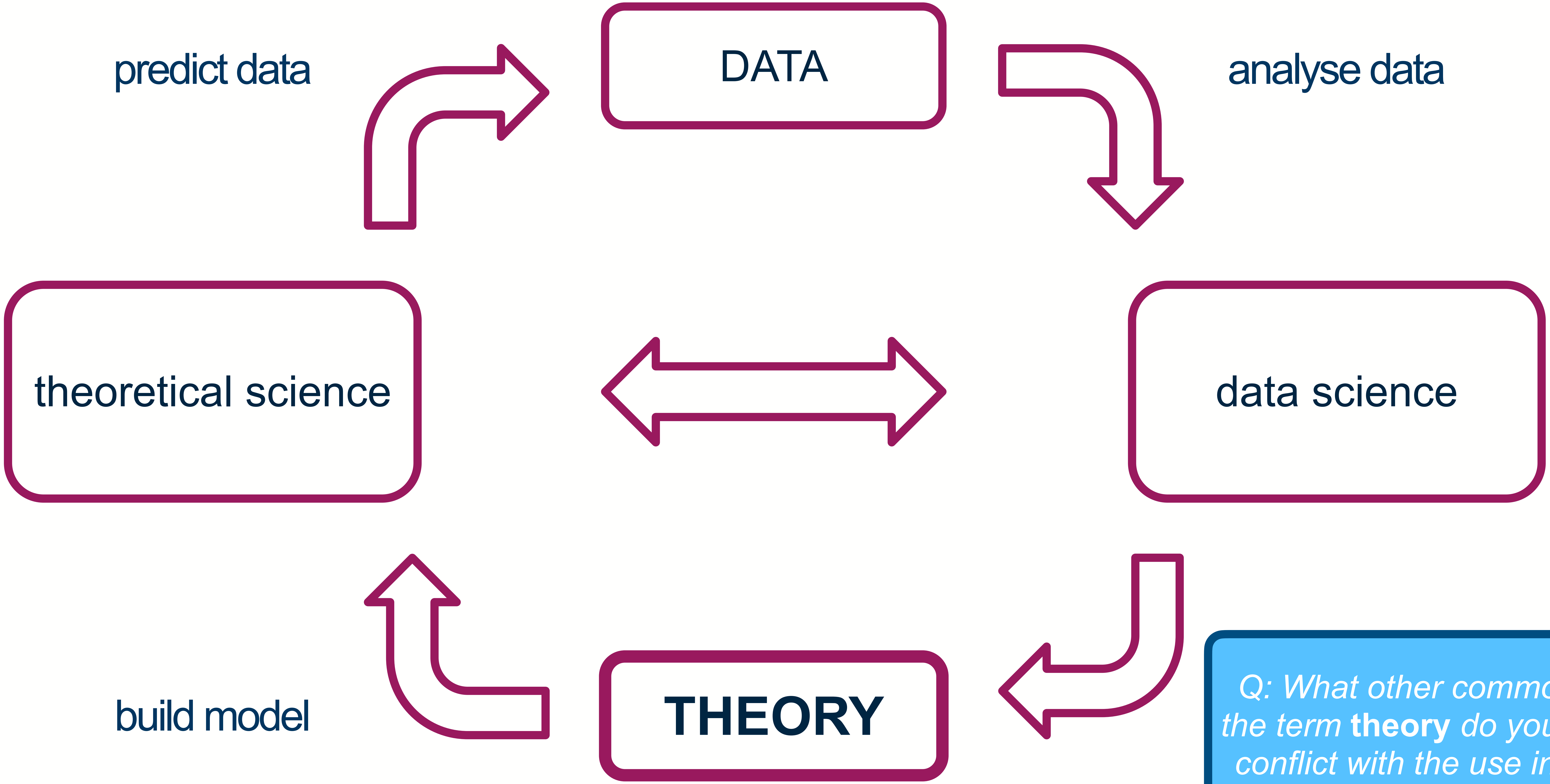
Fundamental Principles

- fundamental theory
- forms framework of analysis
- widely held to be “true nature”
- also called “first principles”

Different theories at different scales

- Quantum Physics: < atoms
- *Classical Physics: atoms – planets*
- Relativity Physics: > planets

Fundamental Principles | Data vs. Theory



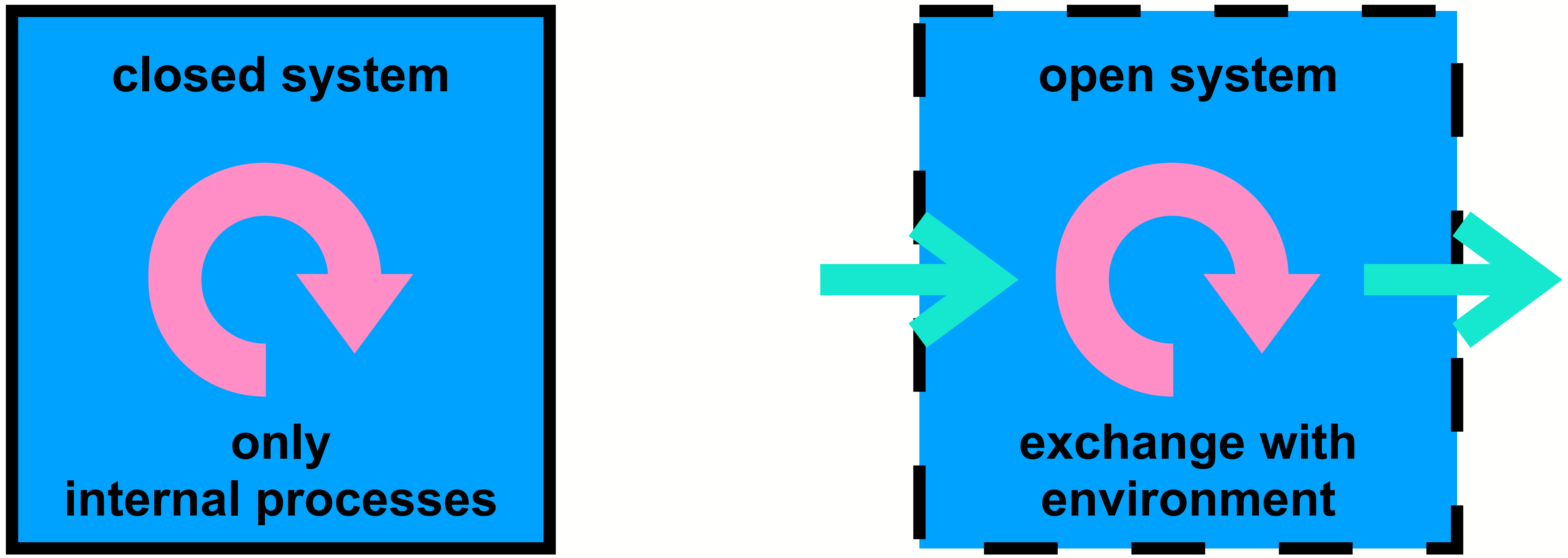
Q: *What other common uses of the term **theory** do you know that conflict with the use in science?*

Fundamental Principles | Conservation Laws

Conservation Laws

A conservation law states that a particular ***measurable property*** *in a* ***closed system*** *does* ***not increase or decrease*** *as the system evolves* ***over time****.*

In physics, conserved properties include ***mass, momentum, and energy****.*



Physical Systems: Bodies vs. Aggregates

*A **body** is a unit of matter and energy distinct from its environment and enclosed by a material interface. In geosciences: mineral grains, melt films, fluid droplets, gas bubbles*

Wikimedia Commons

*An **aggregate** is a continuous, macroscopic (> 1 m) material comprising a large number of microscopic (< 1 cm) bodies which collectively give rise to the properties of aggregate.*

Q: How many olivine grains of 1 mm size fit into 1 m3 of dunite rock?

Fundamental Principles | Mass Conservation

Conservation of Mass or Mass Balance

- mass of single body: M [kg]
- mass density of aggregate: ρ [kg/m^3] (*density: per unit volume*)
- specific volume of aggregate: $v = 1/\rho$ [m^3/kg] (*specific: per unit mass*)
- mass cannot be spontaneously created or destroyed
- total mass of system does not change, unless by exchange with environment

Mass Conservation pops up everywhere!

- places constraint on how much material is available for processes
- places constraints on how materials can be deformed and transported
- places constraints on how materials can react with each other
- ingredient in planetary evolution, rock deformation, magma and water transport models

Fundamental Principles | Momentum Conservation

Conservation of Momentum or Force Balance

- momentum (mass x velocity) of single body: $\mathbf{M} = M\mathbf{v}$ [kg m/s]
- specific momentum of aggregate is its velocity: $\mathbf{v}$ [m/s]
- momentum density of aggregate: $\mathbf{m} = \rho\mathbf{v}$ [kg/(m^2 s)]
- momentum of system does not change, unless by exchange with environment

Recall Newton's Laws of Motion

1. Unless acted upon by a force, objects remains at rest or move at constant velocity.
2. Force = mass x acceleration = rate of momentum change: $\mathbf{f} = M\mathbf{a} = \dfrac{d\mathbf{m}}{dt}$ [kg m/s^2]
3. Action = Reaction: when a body exerts a force on a second body, the second body also exerts a force of equal magnitude and opposite direction on the first body.

Fundamental Principles | Energy Conservation

Conservation of Energy or Energy Balance

- energy (force x distance) of single body: $E = \mathbf{f}d$ [J = kg m²/s²]
- specific energy of aggregate: e [J/kg = m²/s²]
- energy density of aggregate: ρe [J/m³ = kg/(m s²)]
- energy cannot be spontaneously created or destroyed
- total energy of system does not change, unless by exchange with environment
- forms of energy: kinetic, heat, chemical, mechanical, electromagnetic

Applications of Energy Conservation

- places constraints on how much energy is available for processes
- ingredient in heating/cooling, heat transport models
- used to calculate internal temperature evolution of Earth, planets
- account for energy consumed or generated during reactions

Q: What famous equation tells us that this ⬆ is indeed true?

Fundamental Principles | Entropy Production

Laws of Thermodynamics

First Law: *The total internal energy in a closed system does not change over time.*

Second Law: *The total entropy in a closed system cannot decrease over time.*

total ***energy***	total ***entropy***
=	+
in closed system	**in closed system**

Fundamental Principles | Entropy Production

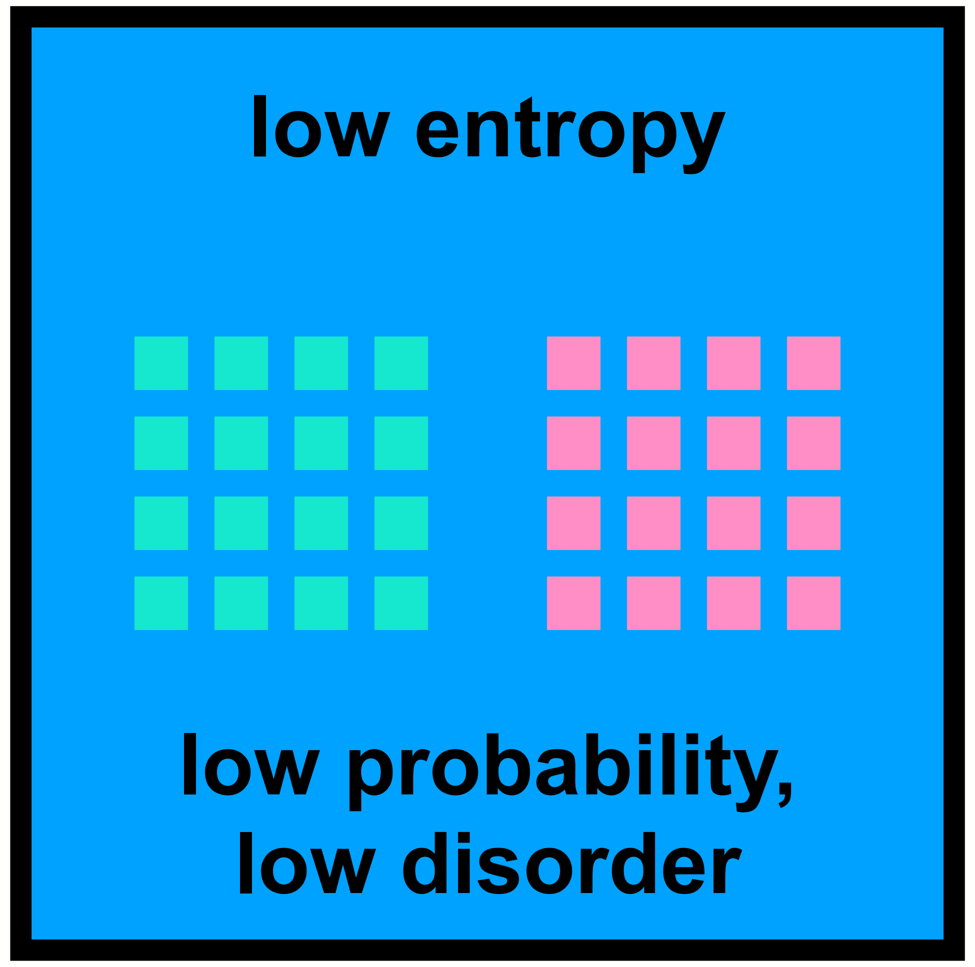
What is Entropy?

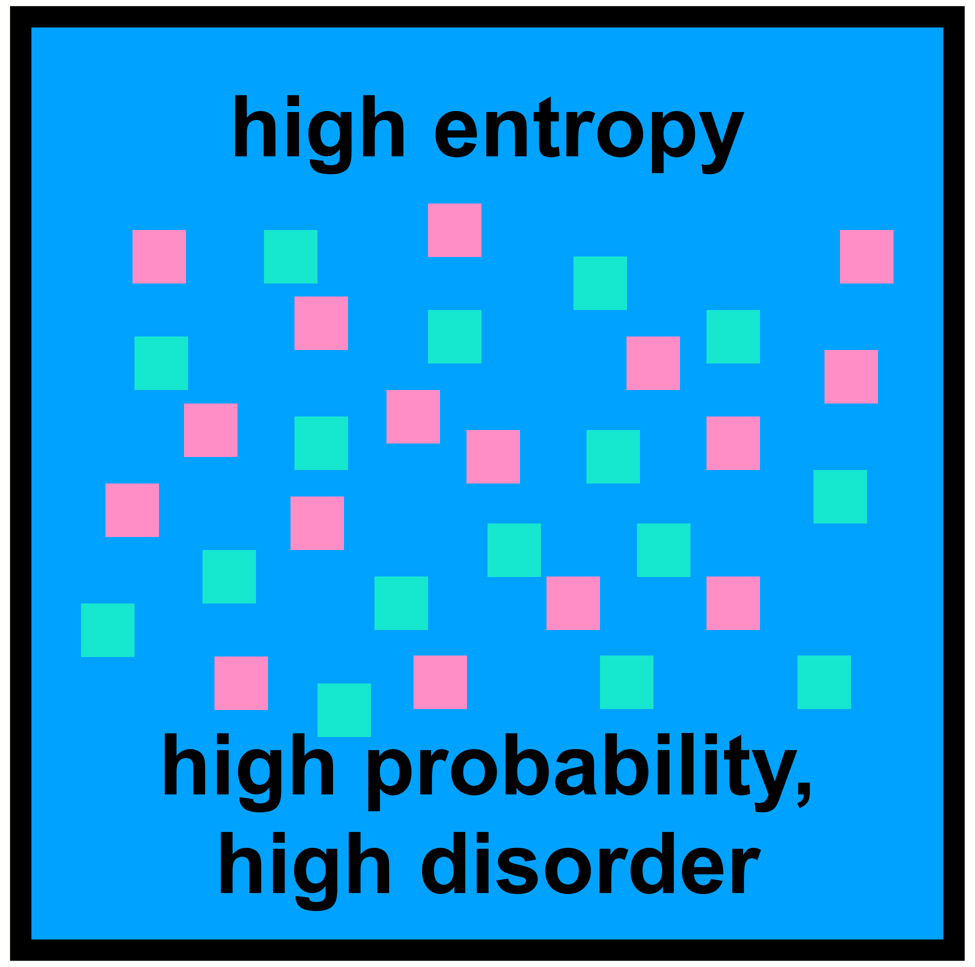
Probability of arrangement of microscopic bodies to produce macroscopic state

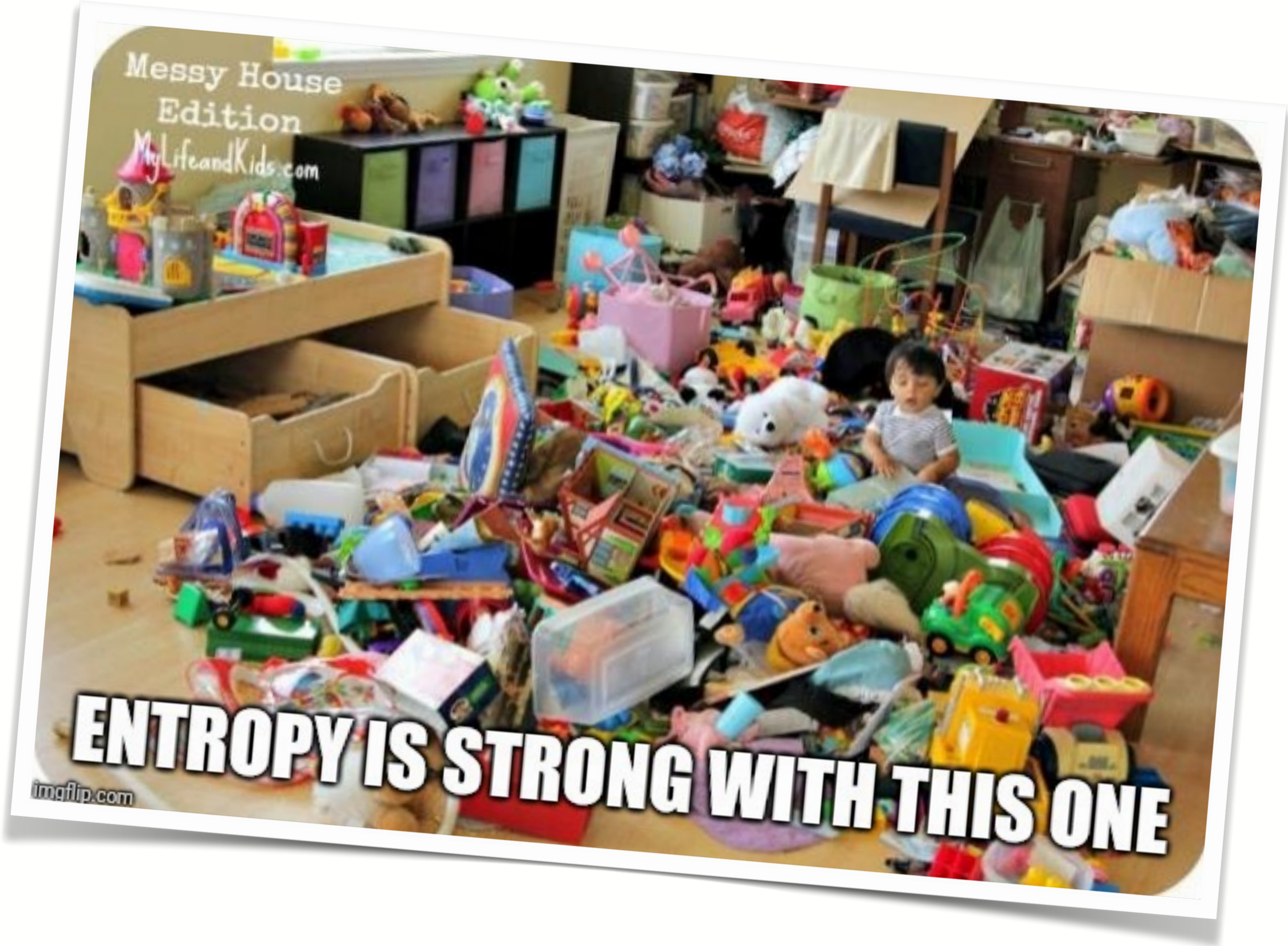
Measure of disorder, of how ‘spread out’ system’s matter and energy are.

Reversible processes conserve entropy, irreversible processes produce entropy.

Entropy in an open system can decrease only at cost of increased entropy around it.







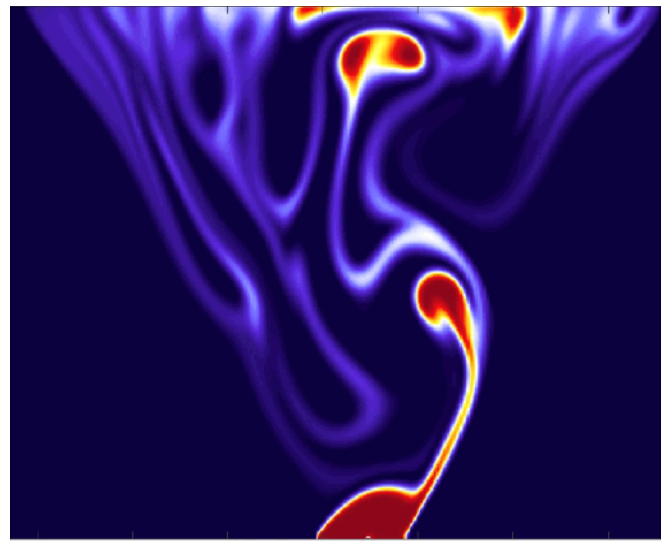
Fundamental Principles | Transport Processes

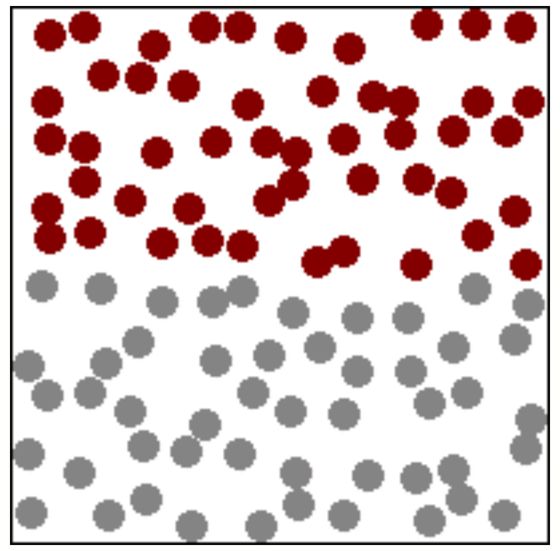
Dynamic Systems

- macroscopic transports of mass, momentum, energy are active (*moving stuff about*)
- work is being done and energy gets dissipated into heat (*no such thing as free lunch*)
- entropy is being produced (*things tend to get messy*)
- Flux: generic term for transport rate $\mathbf{q}_a$ of any macroscopic property a.

Two basic types of transport processes

- Advection: transport by macroscopic transport of mass.
- Diffusion: transport by microscopic fluctuating motion.





Fundamental Principles | Transport Processes

"General Law of Dynamic Transport"

Flux = *Driving Force* x *Material Resistance*

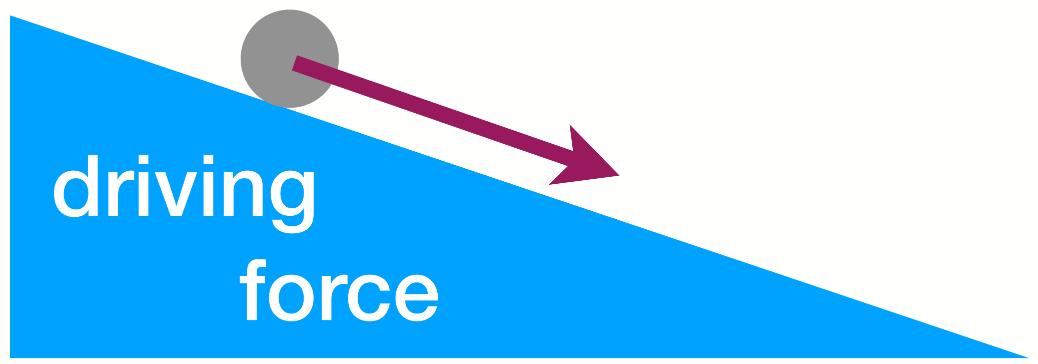
Disequilibrium and Relaxation

Disequilibrium => Driving Force => Dynamic Transport => Relaxation

- State of disequilibrium produces driving forces, drives transport (*stuff is bunched up*)
- Transport relaxes driving force and equilibrates system (*stuff gets spread out*)

Fundamental Principles | Transport Processes

Driving Force

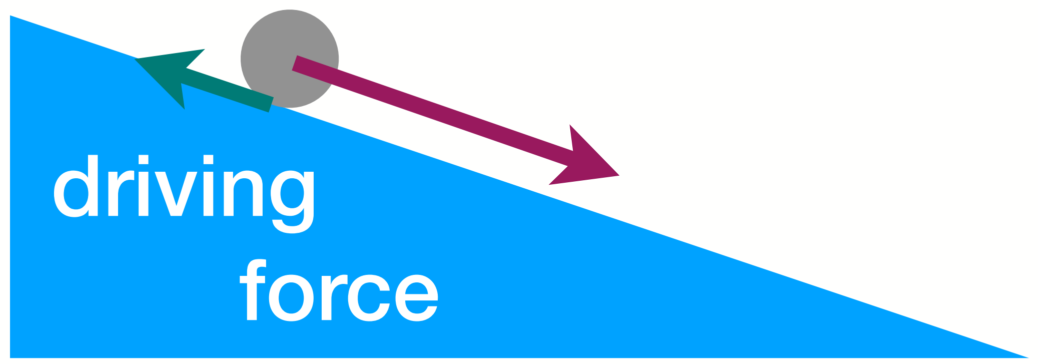


- All transports go *downhill* on gradients in system properties

Conjugate force-flux couples

- pressure gradients => advective flux of mass (moving stuff about)
- chemical potential gradients => diffusive flux of chemical concentrations
- velocity gradients => diffusive flux of momentum
- temperature gradients => diffusive flux of heat (entropy)

Fundamental Principles | Transport Processes



Material Resistance

- Rate of transport limited by material resistance
  - advection of mass => resisted by material stiffness (viscosity, elasticity, plasticity)
  - diffusion of chemistry => resisted by chemical diffusivity
  - diffusion of momentum => resisted by momentum diffusivity (viscosity)
  - diffusion of heat => resisted by thermal diffusivity (conductivity)

Entropy Production / Heat Dissipation

- irreversible loss of energy available for doing work

Entropy Production = Flux x *Driving Force*

= (*Driving Force*)^2 x *Material Resistance* ≥ *0!*

Fundamental Principles | Equilibrium

Thermodynamic or Static Equilibrium

The state of maximum entropy or minimum free energy where macroscopic transports of matter and energy have ceased, driving forces are fully relaxed, and all processes are at rest.

Dynamic Equilibrium or Steady State

A state where simultaneous processes are balanced such that their rates of change cancel each other out and no net change of macroscopic properties occurs, despite transports of matter and energy remaining active.

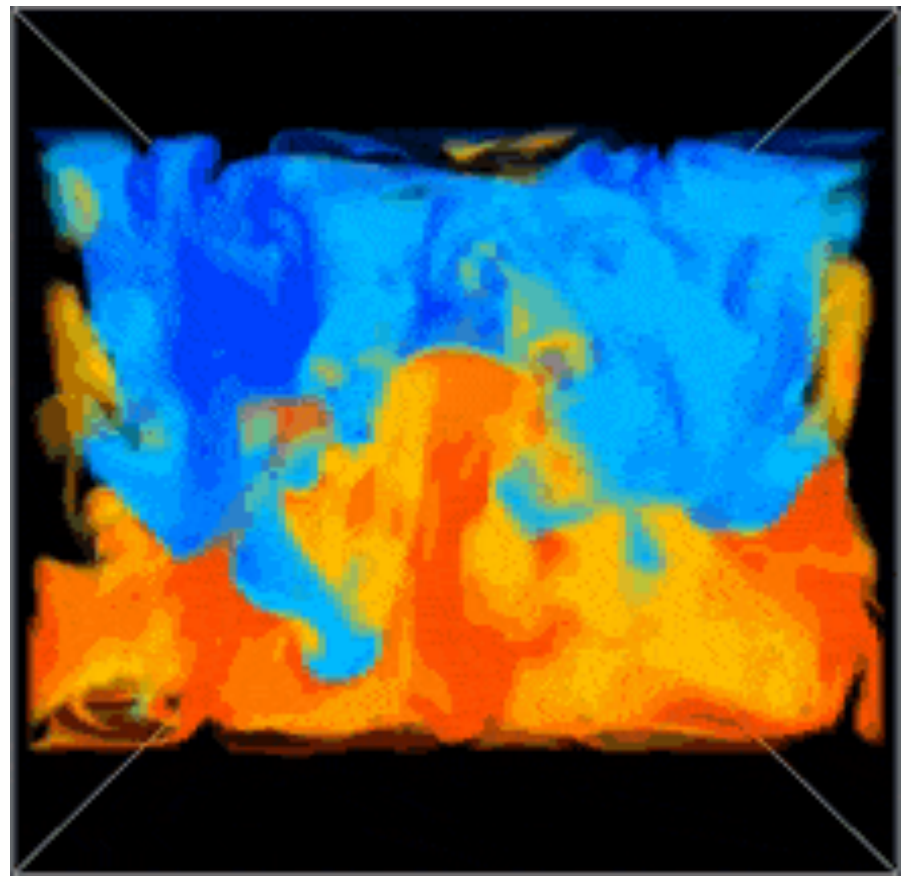
Fundamental Principles | Equilibrium

Scale Matters

Equilibration time depends on distance and vice versa!

- Equilibration by advection: time ~ distance / advection speed
- Equilibration by diffusion: time ~ (distance)^2 / diffusivity

- Example: hot mantle rising up by advection competing with heat loss at surface by diffusion
  - mantle flow speed ~ 10 cm/yr, heat diffusivity ~ 10^{-6} m^2/s
  - eq. time for 10 km: 0.1 Myr advection, 30 Myr diffusion
  - eq. distance in 1 Myr: 100 km advection, 6 km diffusion



INTRO | Firm Foundations

Summary

- make observations, design experiments, analyse data, establish theory, predict data
- fit models to interpret data, establish data-based theory
- build models to predict data, test theory-based hypotheses
- Fundamental Laws: Conservation of mass, momentum, energy, production of entropy
- All processes driven by gradients in properties, limited by material resistance
- Equilibrium reached if all fluxes are balanced or all driving forces fully relaxed

Interactive Task on Padlet

- head over to Padlet (add Padlet link) and share your thoughts on…
- Name any scientific theory relating to how the Earth works on a global scale, and what type observations it is based on.

Any Questions?

- ask your questions or upvote existing ones on Slido (add Slido link)
- FAQs will be answered during Online Live Labs, GTA drop-in sessions on MS Teams