Models as testable hypotheses

Readings for today

- A Survey of Some Fundamental Problems. In Popper, K. (1959). The logic of scientific discovery. Routledge.
- Guest, O., & Martin, A. E. (2021). On logical inference over brains, behaviour, and artificial neural networks. *Psyarxiv*

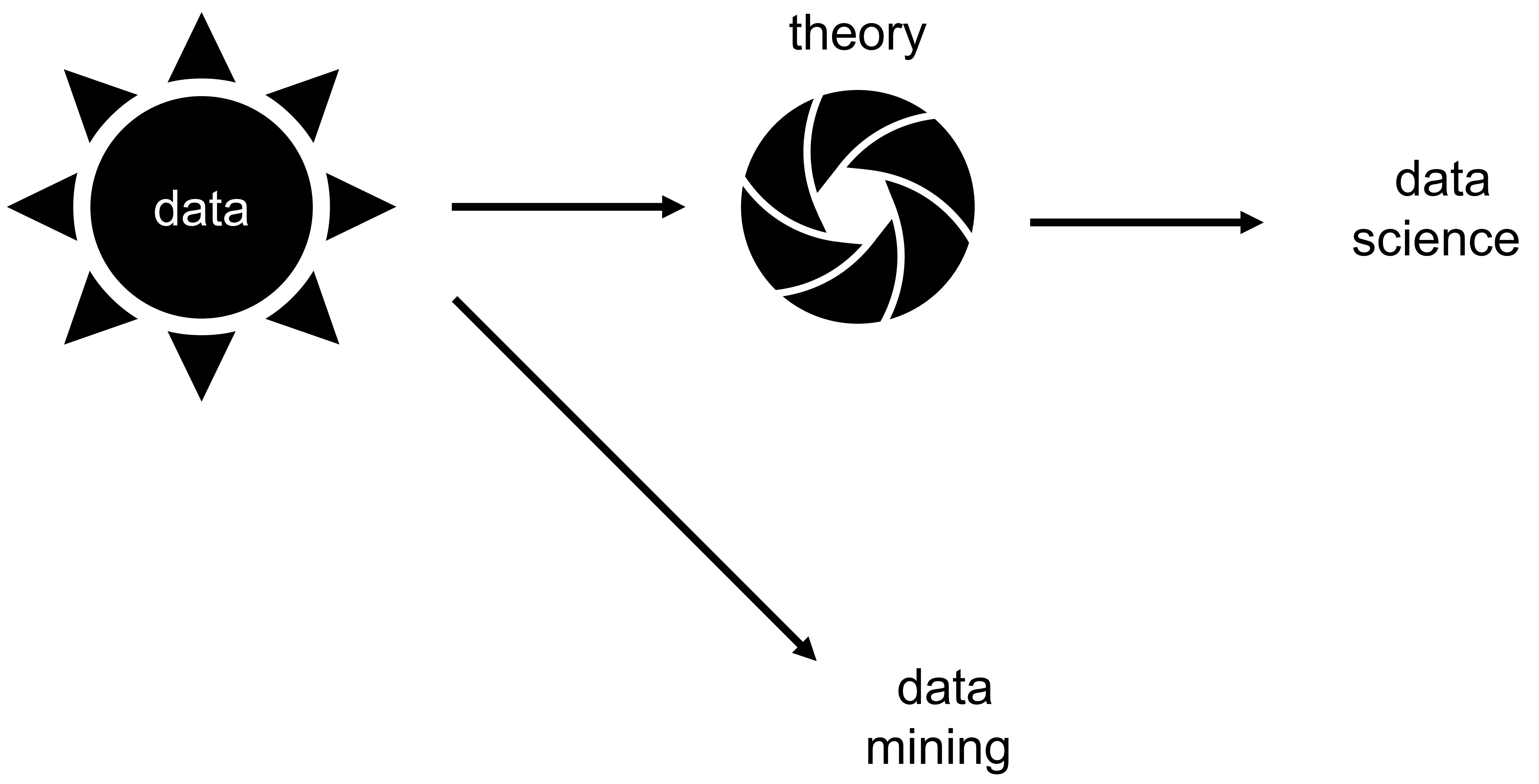
Topics

1. Scientific Inferences
2. Models as mediators
3. Theory vs. hypothesis
4. A naturally testable hypothesis

Science Inferences

Data science is a *science*

<u>Goal</u>: Develop a clear and veridical understanding of the story *behind* your data by evaluating it from a theoretically driven perspective.



The problem of demarcation

<u>Problem:</u> What distinguishes a scientific (aka- empirical) theory from a metaphysical theory (aka- non-empirical)?

Modus ponens (induction / confirmation)

$P \rightarrow Q, P \vdash Q$

If P then Q, thus if P is true Q is also true.

<u>Example:</u> "There are black swans."

Disconfirmation requires exhaustive search

Modus tollens (deduction / falsification)

$P \rightarrow Q, \neg P \vdash \neg Q$

If P then Q, thus if P is false Q is also false.

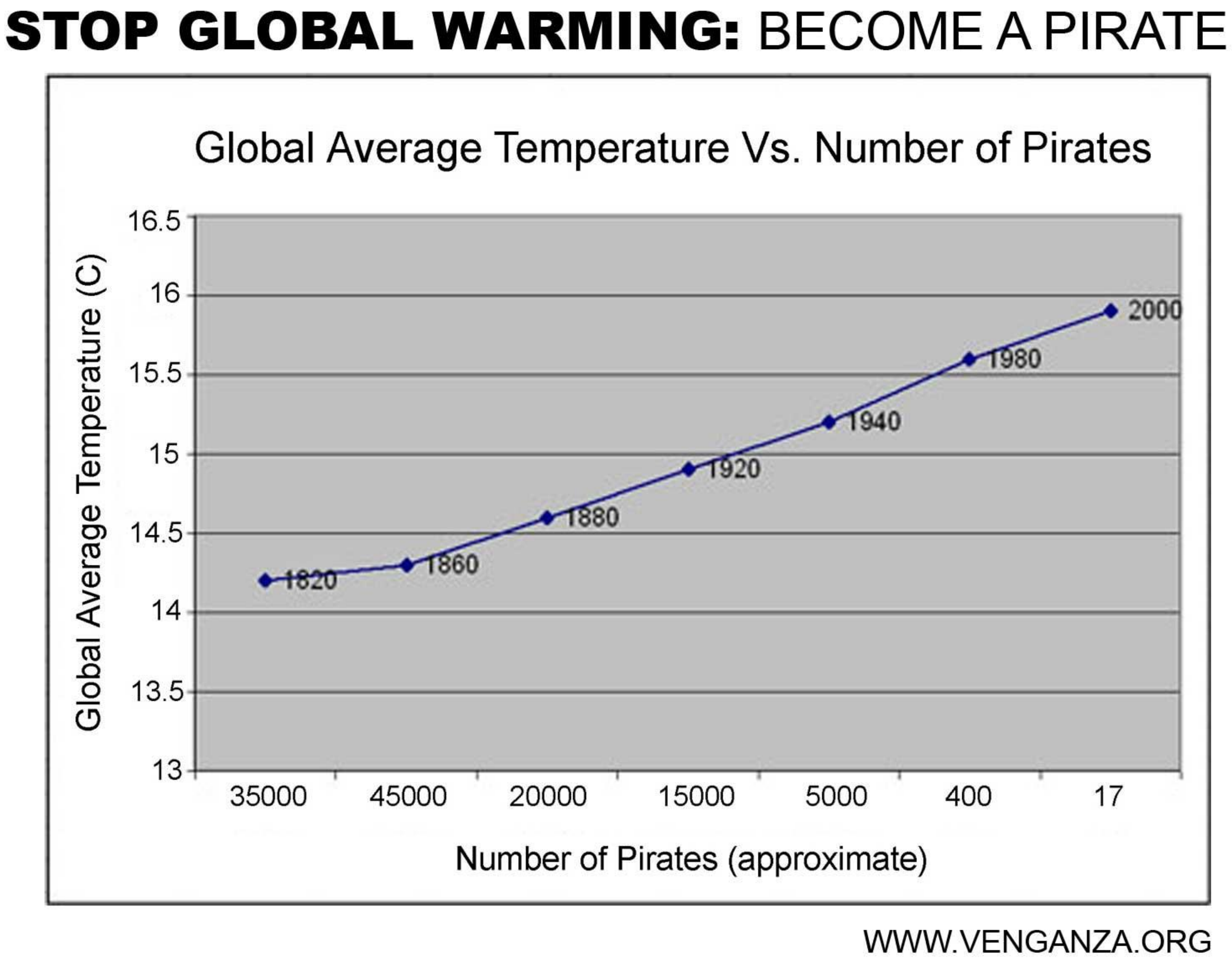
<u>Example:</u> "All swans are white."

Just 1 counter point to disconfirm.

(Popper 1959)

The problem of induction

Example: "Pirates (P) prevent global warming (Q)." $P \to Q, P \vdash Q$



- Supporting evidence (e.g., negative correlation between pirate population and global temperature) confirms.
- Ambiguous evidence is inconclusive.
- Conflicting evidence (e.g., association in the opposite direction) can still used as evidence of the existence of $P \to Q$

(Popper 1959)

Requirements

A deduction-based theoretical system must (paraphrasing):

1. Make **coherent, non-definitional claims** about how the world could be.
2. Generate **empirically testable** consequences.
3. Be distinguishable from alternative theories by what would falsify it.

The only empirical statements are those that can be proven wrong

(Popper 1959)

Requirements

A deduction-based theoretical system must (paraphrasing):

1. **Synthetic:** Make **coherent, non-definitional claims** about how the world could be
2. **Testable:** Generate **empirically testable** consequences.
3. **Distinguishable:** Be distinguishable from alternative theories by what would falsify it.

“Increasing cognitive load reduces working memory accuracy.”

(Popper 1959)

Degrees of falsifiability

1. **More falsifiable than:** Statement *x* is more falsifiable than *y* if everything that could falsify *y* could also falsify *x plus more*: *(Fsb(x) > Fsb(y))*

2. **Equally falsifiable:** Two statements have the same falsifiability if they would be falsified by **exactly the same** observations: *(Fsb(x) = Fsb(y))*

3. **Not comparable:** Two statements are not comparable if **each could be falsified by different kinds of observations**: *(Fsb(x) ∥ Fsb(y))*

↑ Falsifiability ⟶ **↑ Empirical content**

A statement is more falsifiable if more possible observations could prove it wrong.

(Popper 1959)

Models as mediators

Role of models in science

↑ **abstraction** ↓ **abstraction**

Theory → **Model** → **Data**

Models act as mediators between theory and empirical experience (i.e., data)

(Guest & Martin 2021)

Proper inference from models

Modus ponens (induction)

if  “predicts” →  neural readout, behaviour, statistical models thereof

then  $\underline{\underline{\text{is}}}$  neural system, cognitive system

it “predicts”

therefore, it is

Modus tollens (deduction)

if  “predicts” →  neural readout, behaviour, statistical models thereof

then  $\underline{\underline{\text{is}}}$  neural system, cognitive system

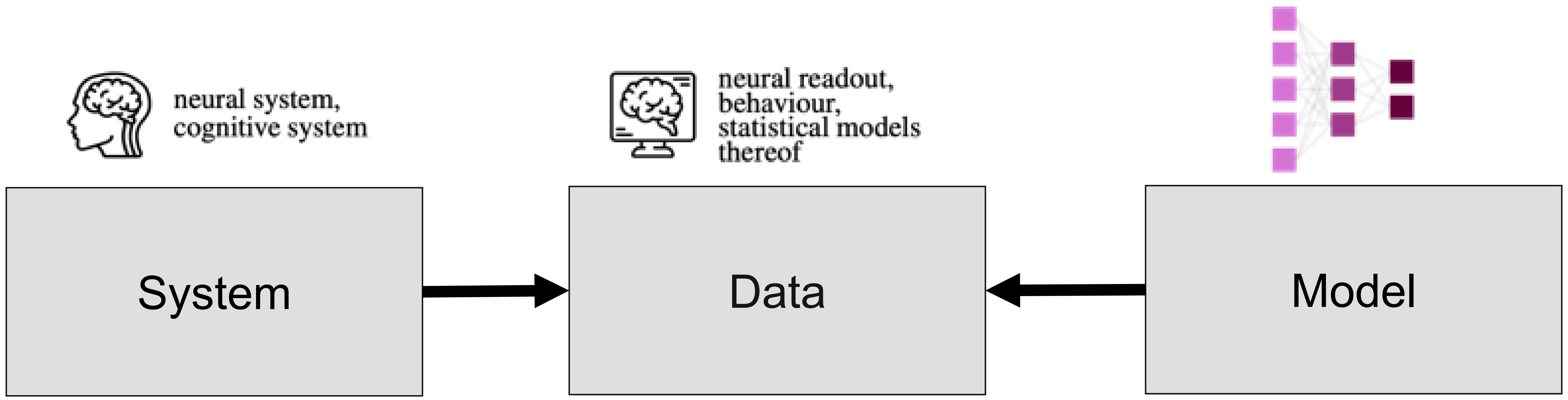
it is not

therefore, it does not “predict”

(Guest & Martin 2021)

Affirming the consequent

Modus ponens $(P \rightarrow Q)$ with inappropriate causality

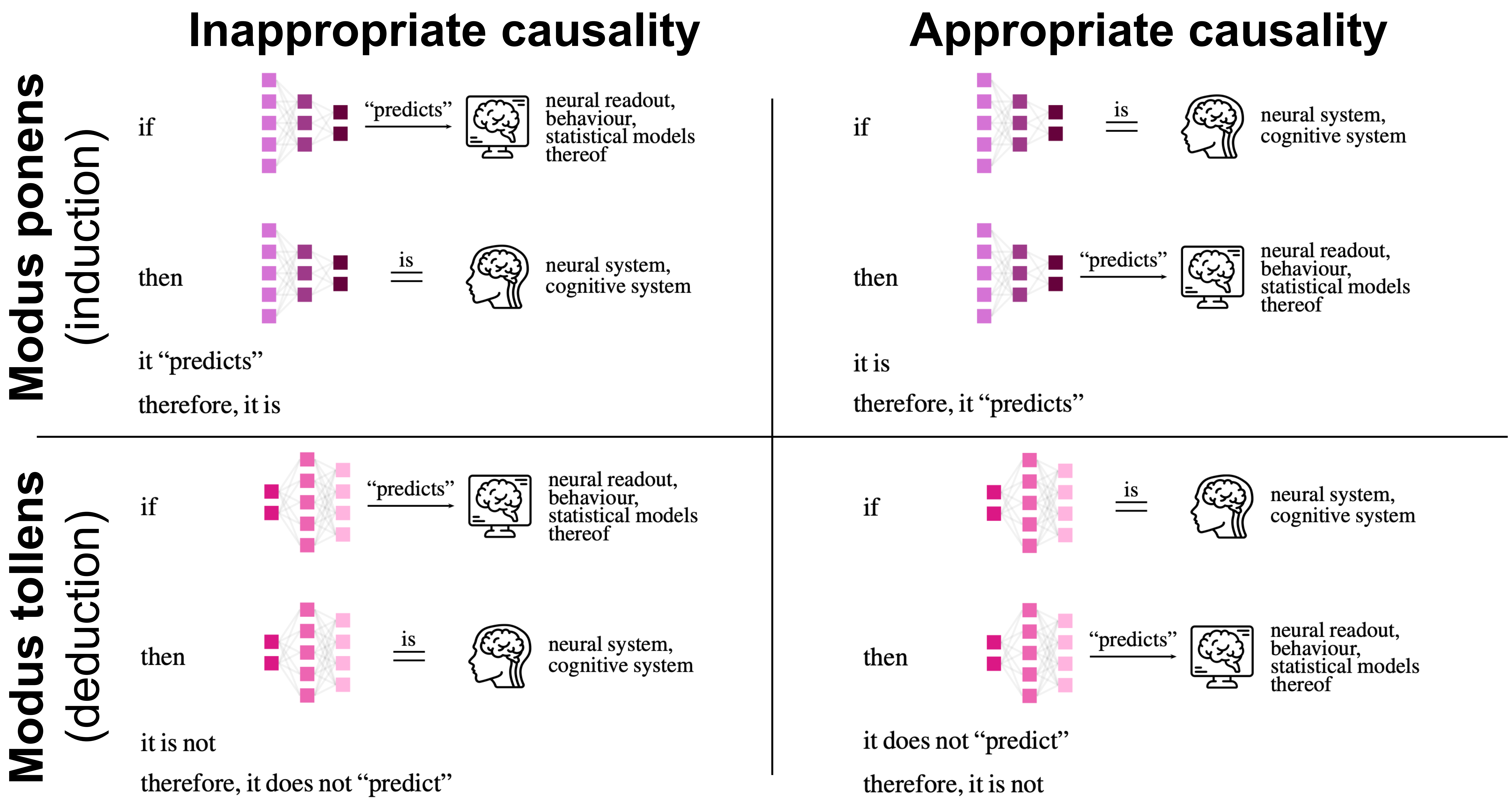


- Correlation does not equal a causal explanation
- Many different processes can produce the same outcome
- Matching outputs does not validate internal explanation

Just because a model reproduces observed behavior **does not mean** it explains how that behavior is produced.

(Guest & Martin 2021)

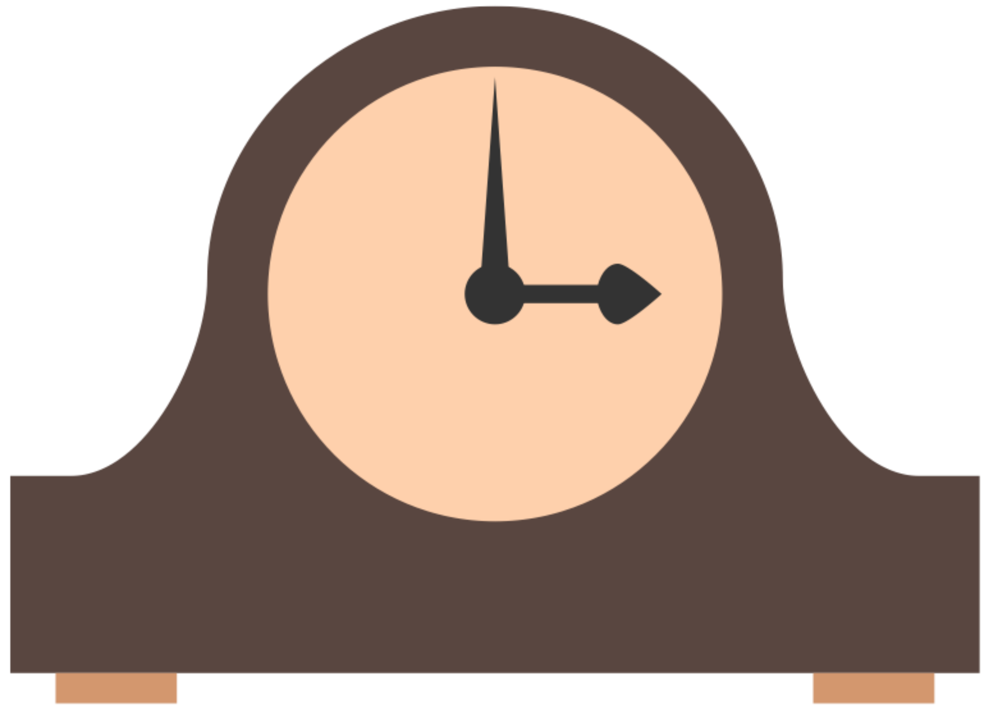
Proper inference from models



(Guest & Martin 2021)

The problem of multiple realizability

Function



Functional role:

The high-level description in terms of how inputs are transformed into outputs.

Mechanistic role:

The way in which a function is implemented in a physical substrate.

(Guest & Martin 2021)

Two types of models

↑ **abstraction** ↓ **abstraction**

Theory → **Generative Model** → **Statistical Model** → **Data**

Mechanistic description of the system / Proposes ***how*** data could be produced.

Functional relationships that I see in my data. ***What*** *patterns* actually appear in the data.

If your generative model is accurate,
it implies certain statistical regularities you should see in the data.

(Guest & Martin 2021)

Two types of models

↑ **abstraction**

On each moment in time, noisy evidence is sampled and added to an accumulator. When the accumulated evidence crosses a boundary, a decision is made.

↓ **abstraction**

Theory → **Generative Model** → **Statistical Model** → **Data**

Humans make decisions by accumulating evidence over time until they reach a threshold.

Do those predicted patterns actually show up?

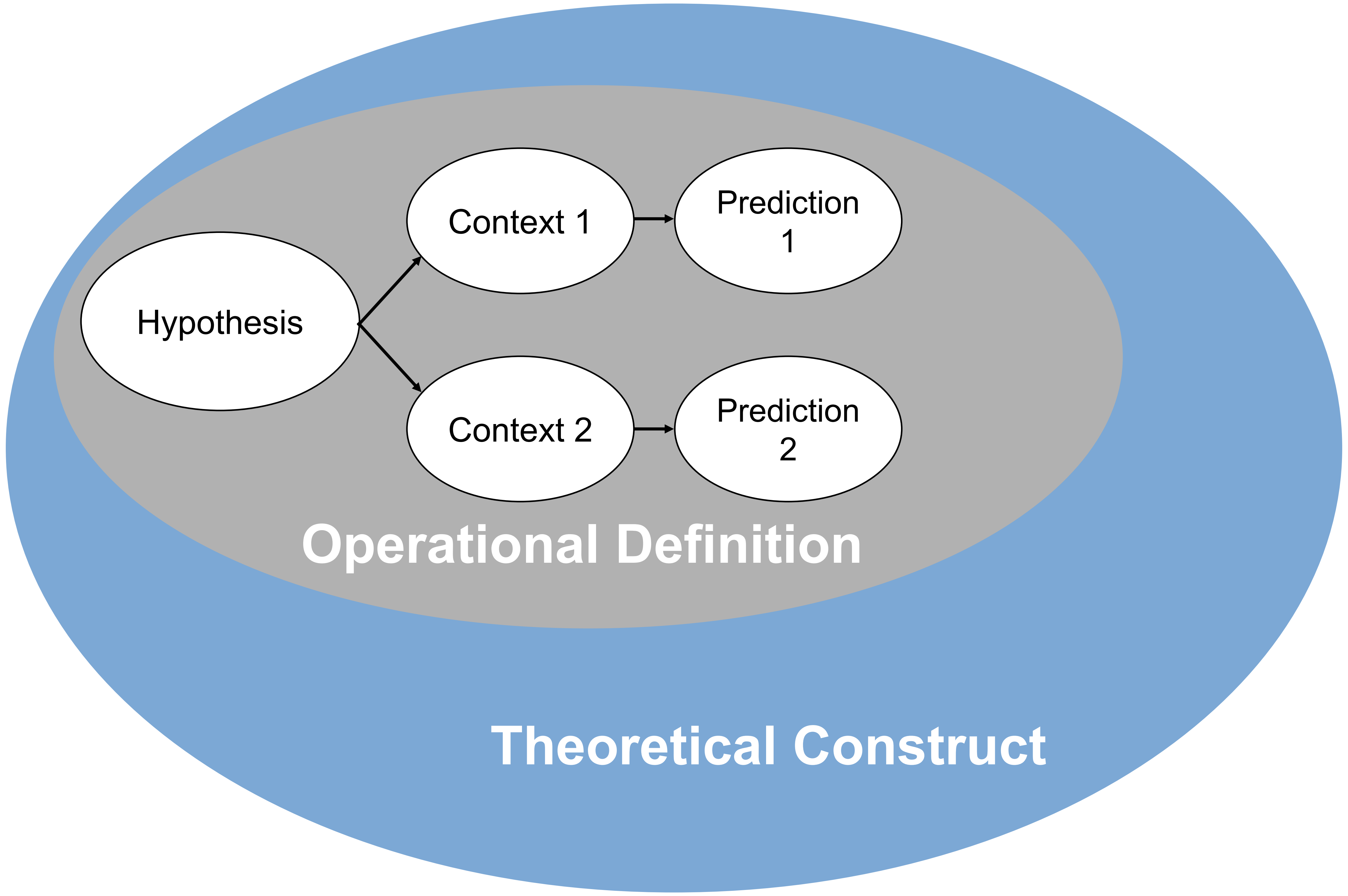
Implies:

- RT should be right-skewed
- Easier stim means faster RTs
- Accuracy and RT should be related

(Guest & Martin 2021)

Theory vs. hypothesis

Refining focus from theory to tests



Theoretical Construct: A general description of a process or capacity (e.g., working memory)

Operational Definition: Reformulation of the theory in terms of a process that can be tested (e.g. number of items that can be recalled after a short delay).

Hypothesis: A testable statement about the operational definition as a set of relations (e.g., humans have an upper limit to the number of items they can recall after a 1min delay).

Context: Specific environment that the hypothesis is evaluated in (e.g., digit span task).

Prediction: Specific formulation of the hypothesis in a specific context (e.g., recall errors will increase as digit span increases).

Predictions as projections of theory

Theory → Hypothesis → Statistical Model

Fundamental form of a theory

theory

$$c \leftarrow f(I) = O$$

capacity input output

(van Rooij & Baggio 2020)

Fundamental form of a statistic

relational function

$$Y = f(X)$$

output input

$$f$$

The form of a statistical test, f, is a ***quantitative*** description of a specific hypothesis being evaluated (whether or not a p-value is calculated)

quantitative = testable = falsifiable

A naturally *testable* hypothesis

Types of hypotheses

Null (H_0) Hypothesis: The hypothesis that needs to be rejected based on your theoretical premise.

- The status quo if your theory is wrong.

Research (H_i) Hypothesis: An alternative to the H_0 that is consistent in form to your theoretical premise

- One of many.

Identification of a null hypothesis (or space of null hypotheses) to be rejected immediately frames your hypothesis as falsifiable and, thus, testable.

Theory → Hypothesis → Statistical Model

Theory: Hunger impairs working memory.

Operational Definitions:

1. Hunger is the bodily state that occurs when no food is consumed for 4 or more hours.
2. Working memory is how many items that can be recalled after a short period of time in the Digit Span task.

Hypotheses:

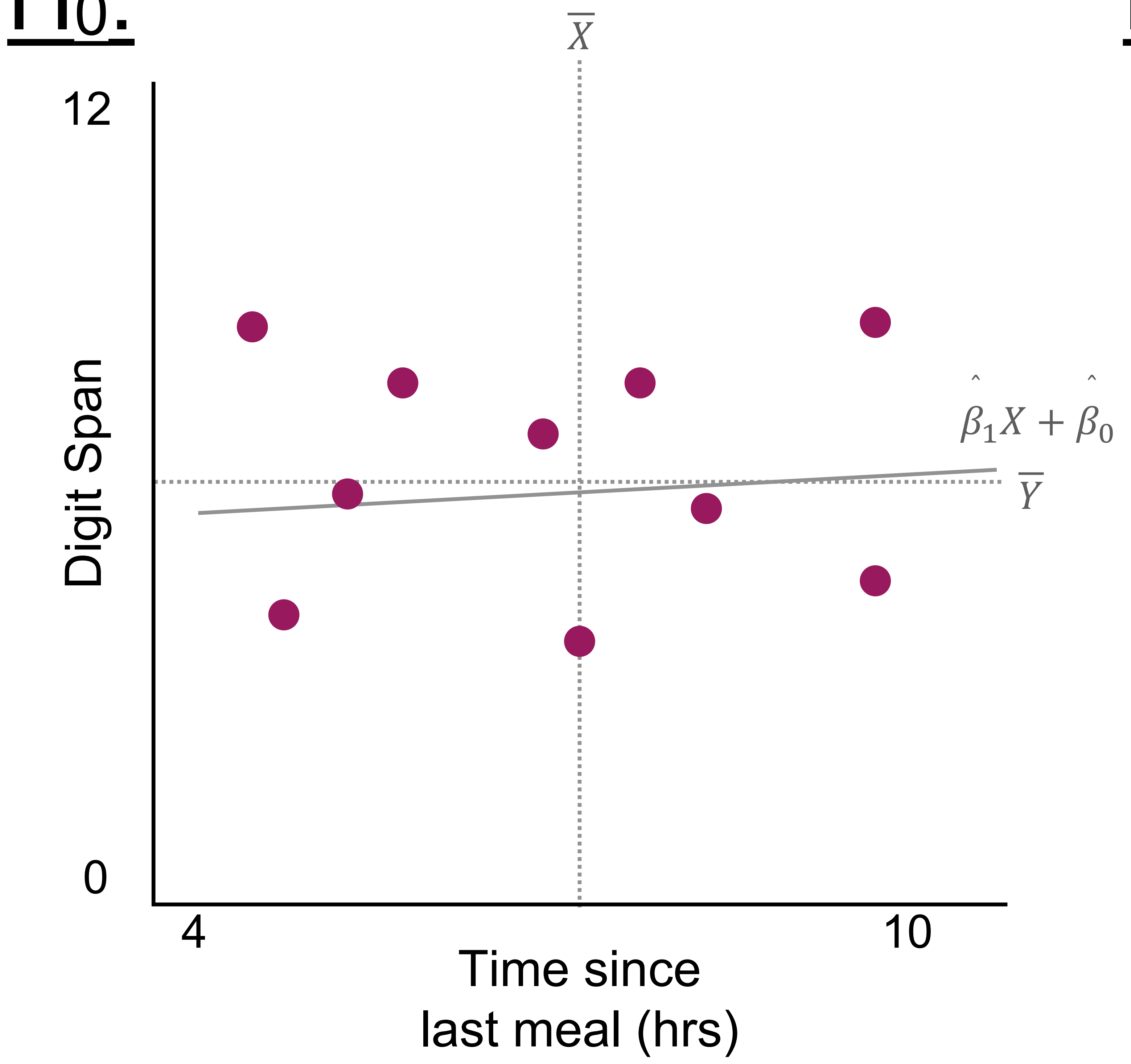
H_0: Digit recall does not change with hours since last meal.

H_A: Digit recall reduces with time since last meal.

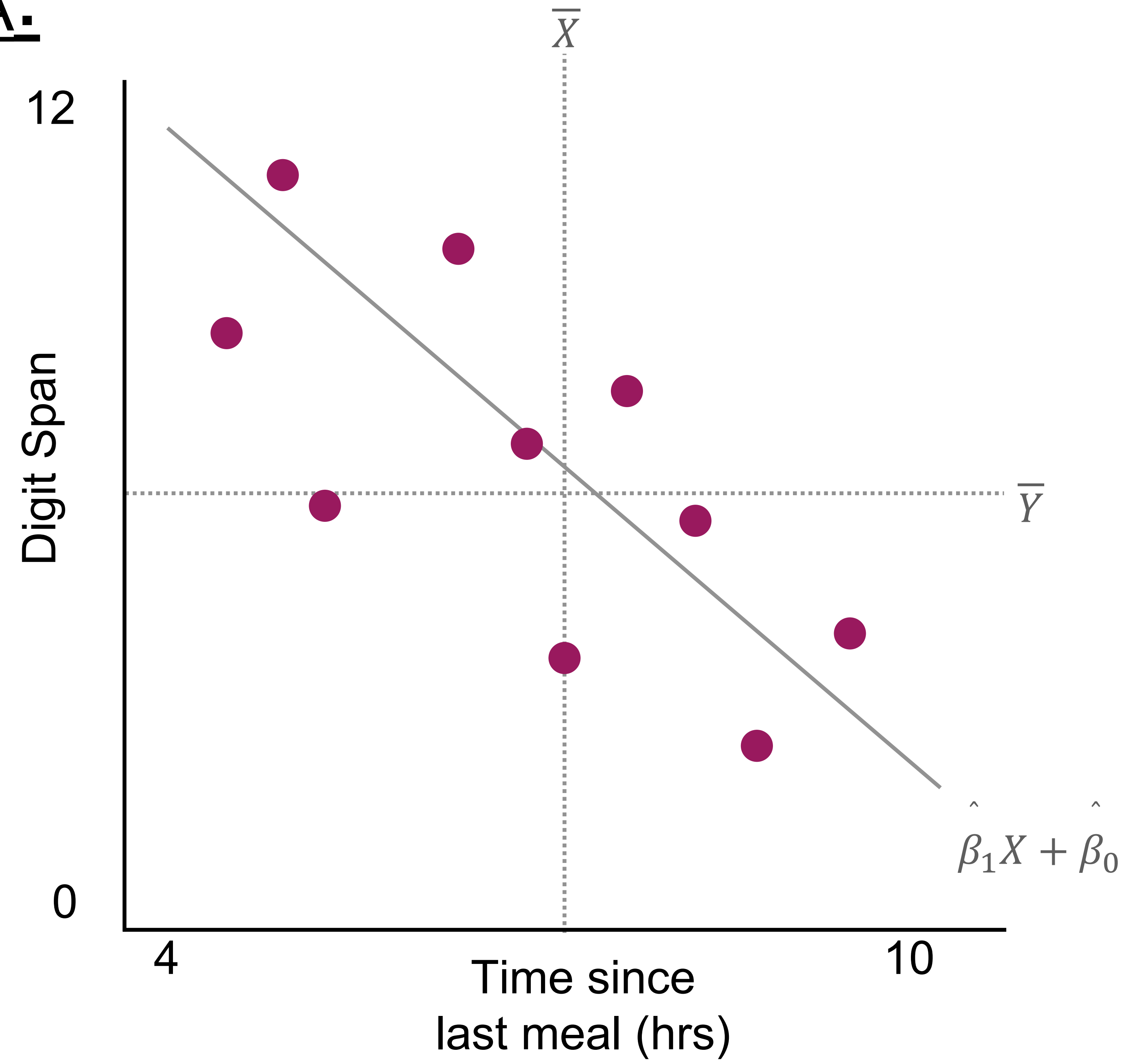
H_B: Digit recall increases with time since last meal.

Theory → Hypothesis → Statistical Model

H0:



HA:



Functional form:

$$\hat{Y}_{ds} = \beta_1 X_{time} + \beta_0$$

Hypotheses:

H0: $\beta_1 = 0$

HA: $\beta_1 < 0$

HB: $\beta_1 > 0$

Take home message

- Falsifiablity is the main demarcation distinguishing science from non-scientific inquiry.
- Models act as mediators linking high level theory to empirical data (aka-experience).
- Statistical models function as inherently falsifiable hypotheses generated from high-level theories.