Simplicity and Scientific Progress

Konstantin Genin, Kevin Kelly
Carnegie Mellon University

Stanford CSLI Workshop 2018

The Synchronic and Diachronic Schools

Synchronic School: focused on the finished products of science, esp. characterizing which beliefs (or systems of belief) constitute rational responses to evidence.

Diachronic School: characterize which methods are conducive to scientific progress.

Illka Niiniluoto, *Scientific Progress* (2015)

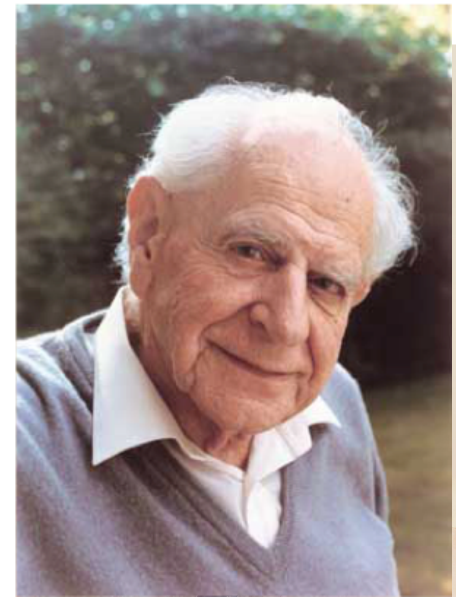
Diachronic School

"… progress necessarily involves the idea of a process through time. Rationality, on the other hand, has tended to be viewed as an atemporal concept … most writers see progress as nothing more than the temporal projection of a series of individual rational choices …. we may be able to learn something by inverting the presumed dependence of progress on rationality."

Laudan, *Progress and its Problems* (1978).

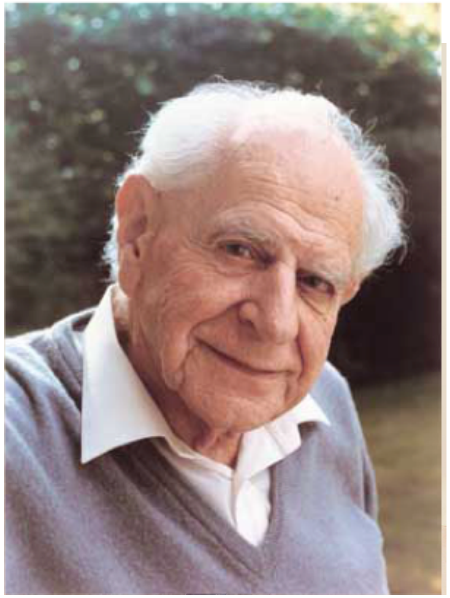
Popper's Critical Rationalism

Popper: Science progresses through a series of highly testable conjectures, followed by dogged attempts at refutation.



Popper's Critical Rationalism

Popper: Science progresses through a series of highly testable conjectures, followed by dogged attempts at refutation.



But why think this is anything more than a series of bold mistakes, yielding to new, and bolder, mistakes?

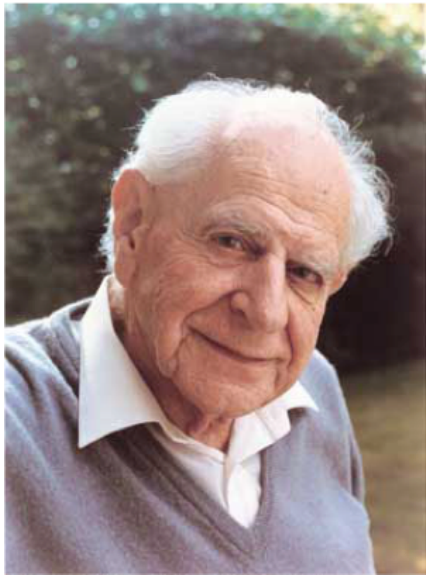
Lakatos Objects

Popper "offers a methodology without an epistemology or a learning theory, and confesses explicitly that his methodology may lead us epistemologically astray, and implicitly, that *ad hoc* stratagems might lead us to Truth."

Imre Lakatos, *The Role of Crucial Experiments in Science* (1971).

Truthlikeness

Popper developed a theory of verisimilitude, hoping to show that the process of conjectures and refutations leads to theories of increasing truthlikeness (1963, 1970).



Popper's idea was famously trivialized (independently) by Pavel Tichy and David Miller (1974). On Popper's account, no false theory is more truthlike than any other!

Truthlikeness Redux

Oddie (1986) and Niiniluoto (1987, 1999) make more sophisticated attempts at a definition of truthlikeness.

Truthlikeness Redux

But there is no demonstration that any method is guaranteed to produce increasingly truthlike theories!

Truthlikeness Redux

"appraisals of the relative distances from the truth presuppose that an epistemic probability distribution . . . is available. In this sense ... the problem of estimating verisimilitude is neither more nor less difficult than the traditional problem of induction."

Illka Niiniluoto, *Truthlikeness* (1987).

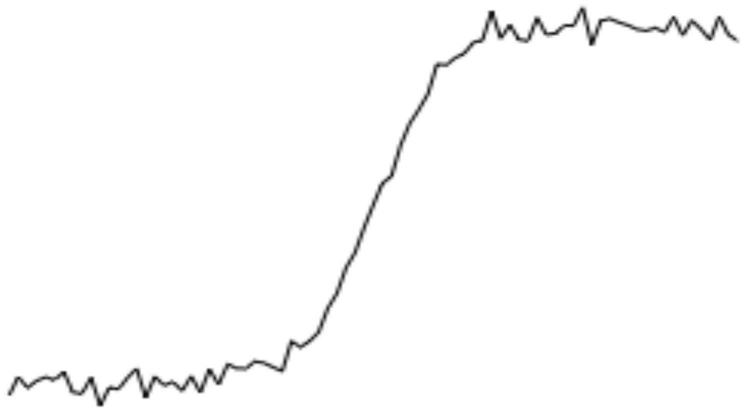
Progressive Methods

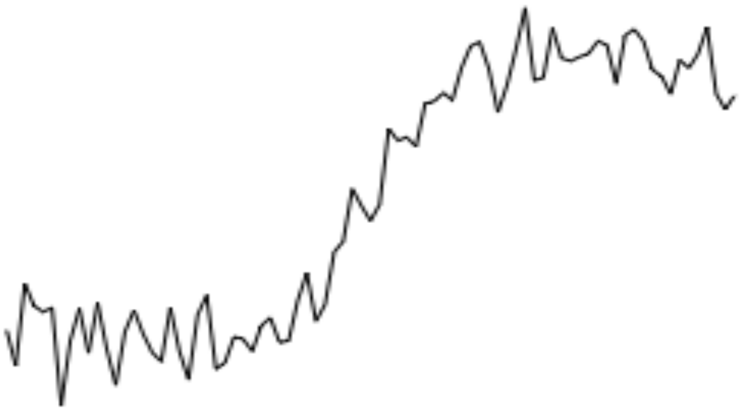
- Say that a method for answering a question is progressive if the chance that it outputs the true answer is strictly increasing with sample size.

- That notion makes sense, even if it does not make sense to ask which of two false theories is closer to the truth!

Progressive Methods

- A method is *α-progressive* if the chance that it outputs the true answer never decreases by more than *α.*





Progressive Methods

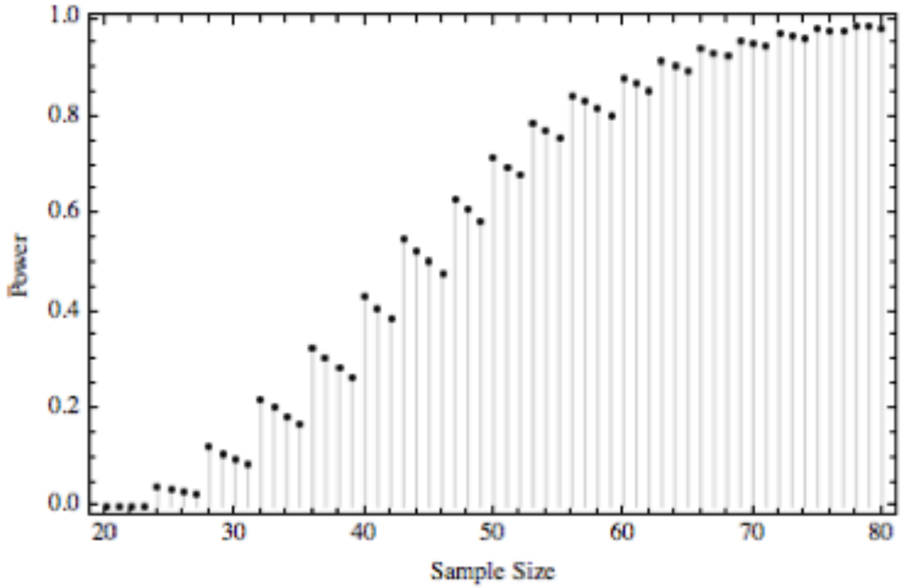
Researchers propose recruiting 100 patients to investigate whether a new drug is better at treating migraine than placebo. In their grant, they analyze their statistical method and conclude the following: if the new drug is significantly better than placebo, the chance that their method detects the improvement is greater than 50%. The funding agency is satisfied. Soon after, the researchers publish a paper claiming to have discovered a promising new treatment!

Progressive Methods

Now, suppose that a replication study is proposed with 150 patients. However, the ex ante analysis reveals that the objective chance of detecting an improvement over placebo, if one exists, has decreased to 40%. The chance of replicating successfully has gone down, even though the first study may well be correct, and yet the investigators propose performing a larger study!

Progressive Methods

Surprisingly, many textbook methods in frequent hypothesis testing exhibit this perverse behavior.



Chernick and Liu, *The Saw-toothed behavior of power vs. sample size and software solutions.* (2012)

Progressive Methods

Theorem (Genin): For typical problems, there exists an α-progressive method for every $\alpha > 0$.

A Vindication of Neo-Popperian Method

Theorem (Genin): All progressive methods must systematically prefer simpler (more falsifiable) theories.

The Plan

1. Prove this result in the simplified setting of propositional information.

2. Port this result to the setting of statistical information.

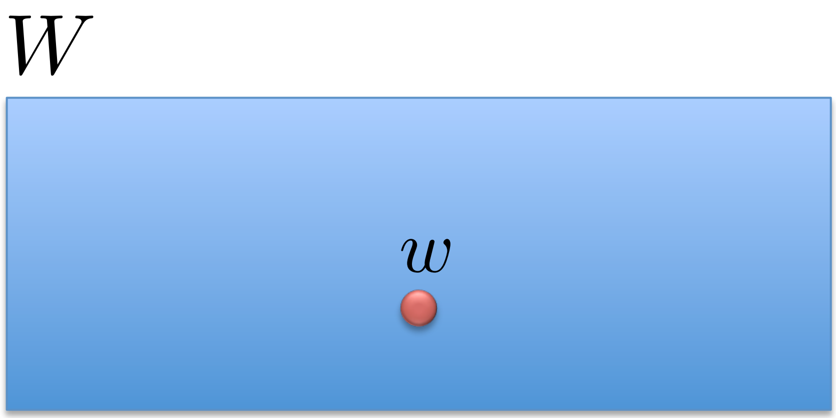
The Topological Bridge

- Start with logical insights.
- Allow methods a small chance α of error.
- Obtain corresponding statistical insights

The Topology of Information

I ● topology

Possible Worlds

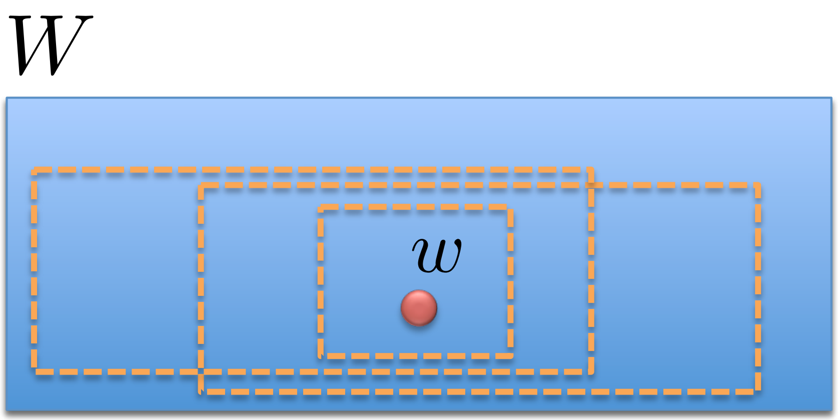


Propositional Information State

The logically strongest proposition you are informed of.

Propositional Information State

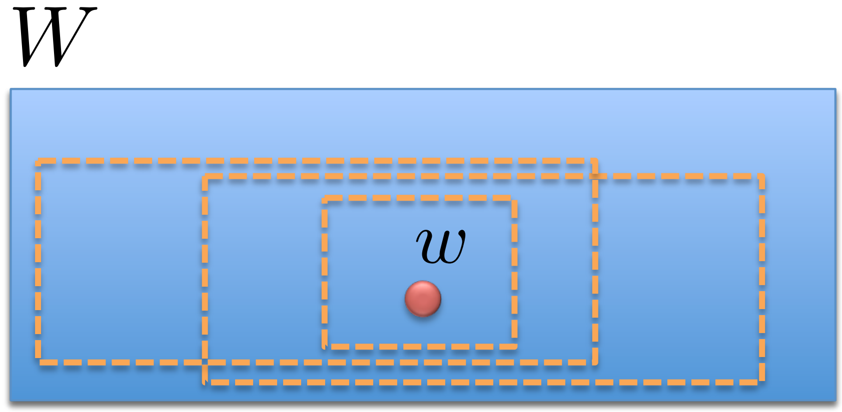
- $\mathcal{I}$ is the set of all possible information states.
- $\mathcal{I}(w)$ is the set of all information states true in w.
- $\mathcal{I}(w \mid E) = \{ F \text{ in } \mathcal{I}(w) : F \subseteq E \}$



Propositional Information State

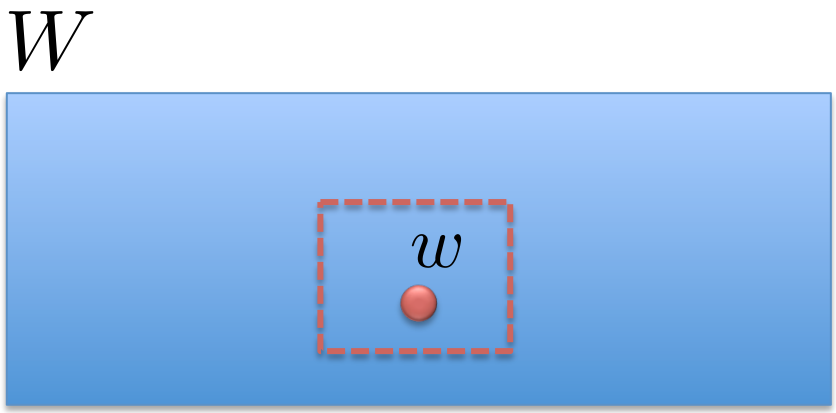
Intended Interpretation: E is in $\mathcal{I}(w)$ iff

a diligent inquirer in w will eventually be afforded information at least as strong as E.



Three Axioms

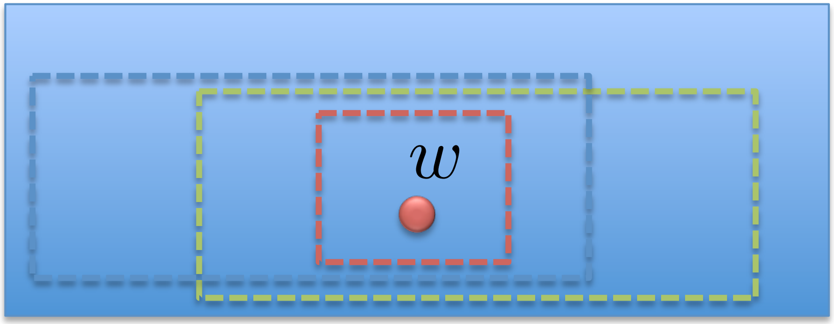
1. Some information state is true in w.



Three Axioms

1. Some information state is true in w.
2. Each pair of information states true in w is entailed by an information state true in w.

W



Three Axioms

1. Some information state is true in w.
2. Each pair of information states true in w is entailed by an information state true in w.
3. There are at most countably many information states.

Hume’s Problem

“The bread, which I formerly ate, nourished me ... but does it follow, that other bread must also nourish me at another time ... ? The consequence seems nowise necessary.”

Hume, *Enquiry*.

Hume's Problem, Topologized.

Hume's Problem, Topologized.

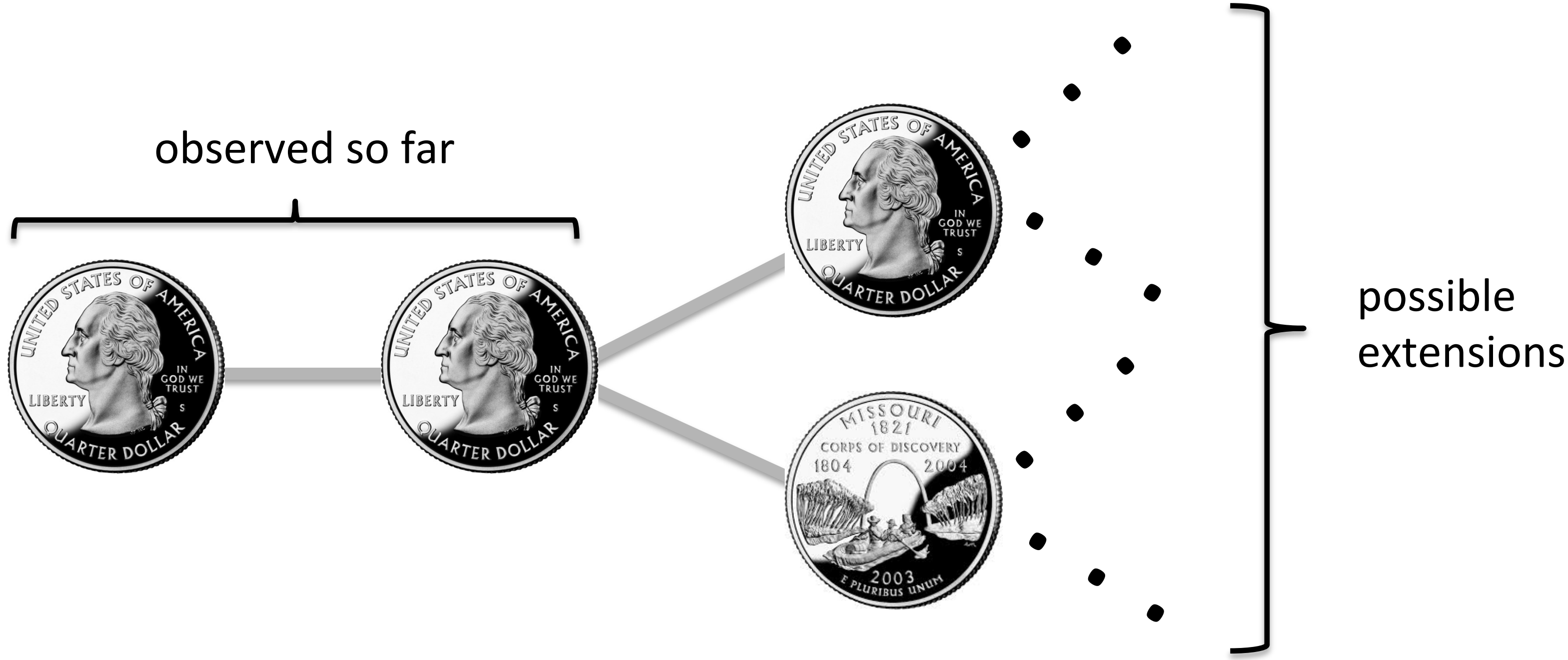
Hume's Problem, Topologized.

Hume's Problem, Topologized.

Example: Sequential Binary Experiment

Worlds = infinite sequences of coin flips.

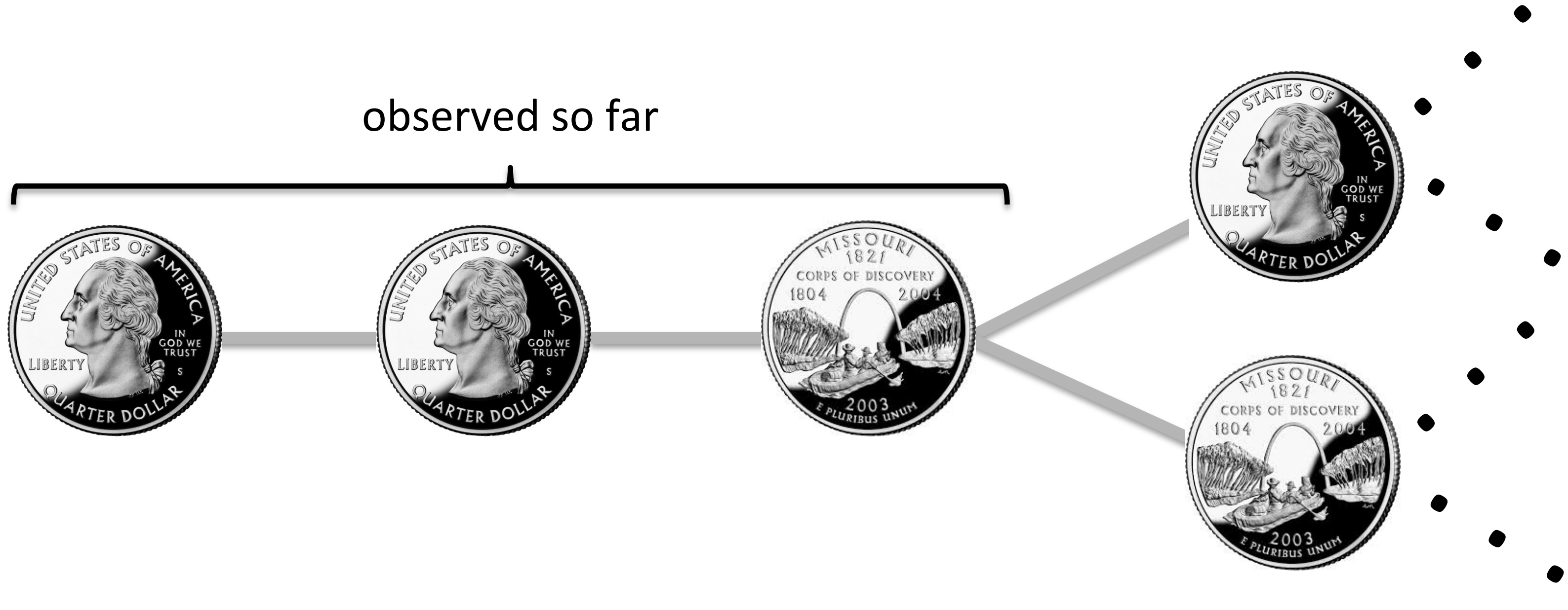
Evidential states = cones of possible extensions of finite sequences:



Example: Sequential Binary Experiment

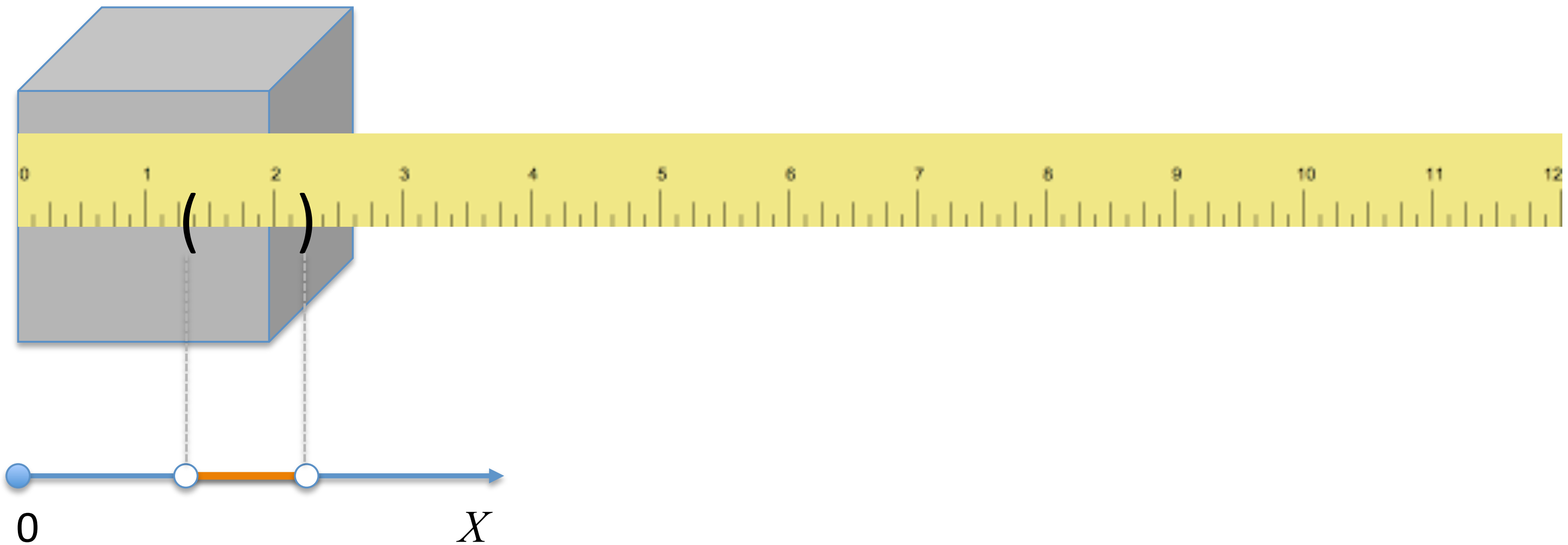
Worlds = infinite sequences of coin flips.

Evidential states = cones of possible extensions of finite sequences:



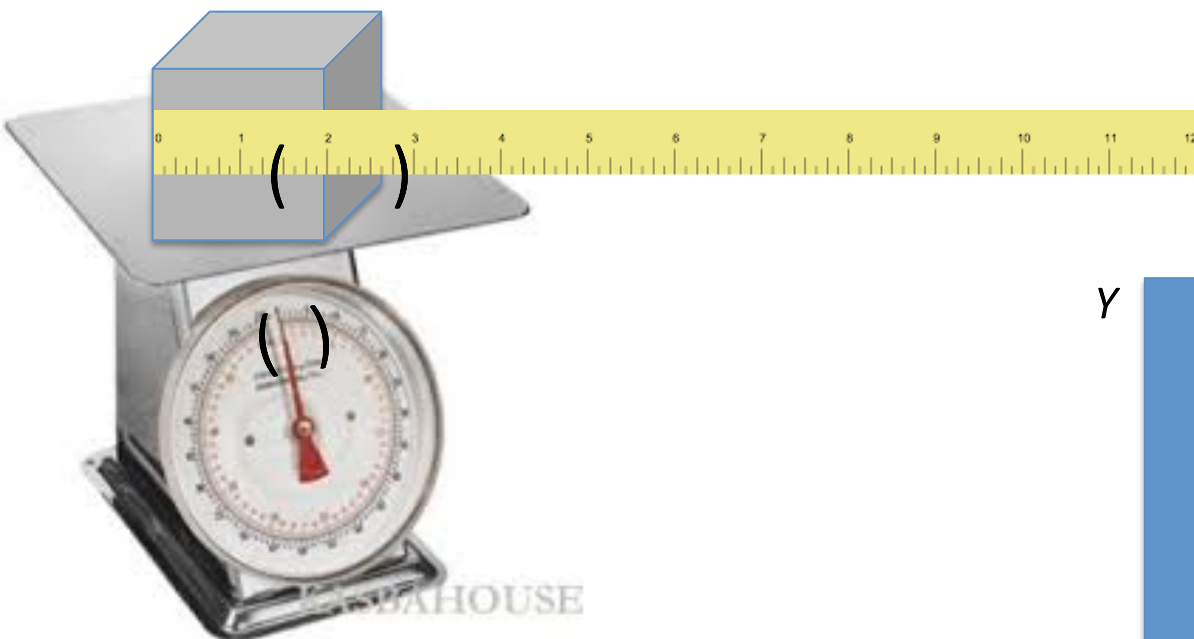
Example: Measurement of X

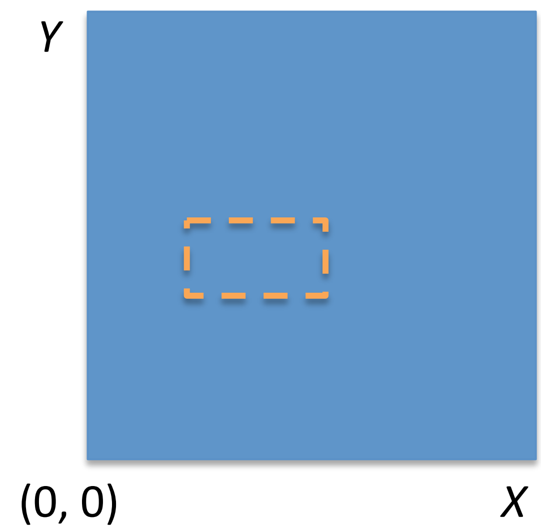
- **Worlds** = real numbers.
- **Information states** = open intervals.



Example: Joint Measurement

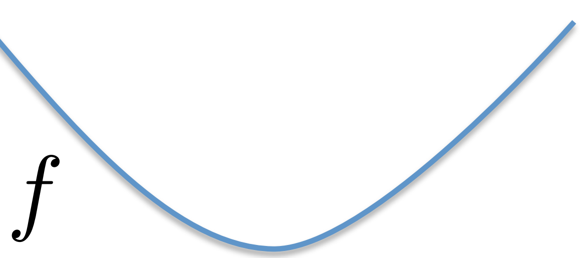
- **Worlds** = points in real plane.
- **Information states** = open rectangles.





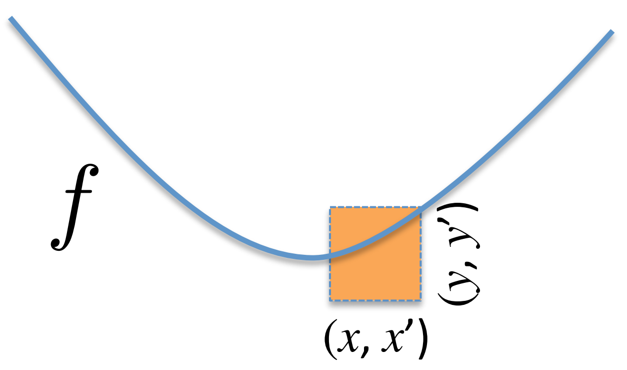
Example: Functions

- **Worlds** = functions $f : \mathbb{R} \to \mathbb{R}.$



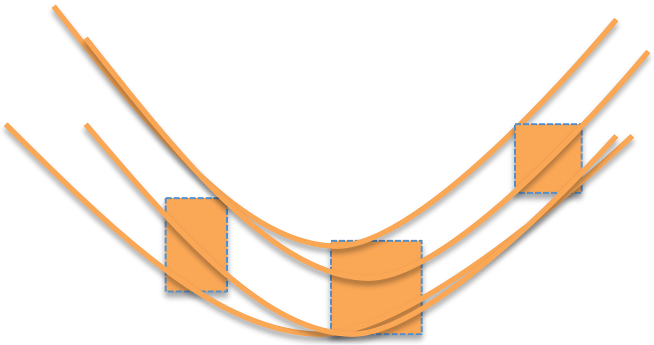
Example: Functions

- An **observation** is a joint measurement.



Example: Functions

- The **information state** is the set of all worlds that touch each observation.

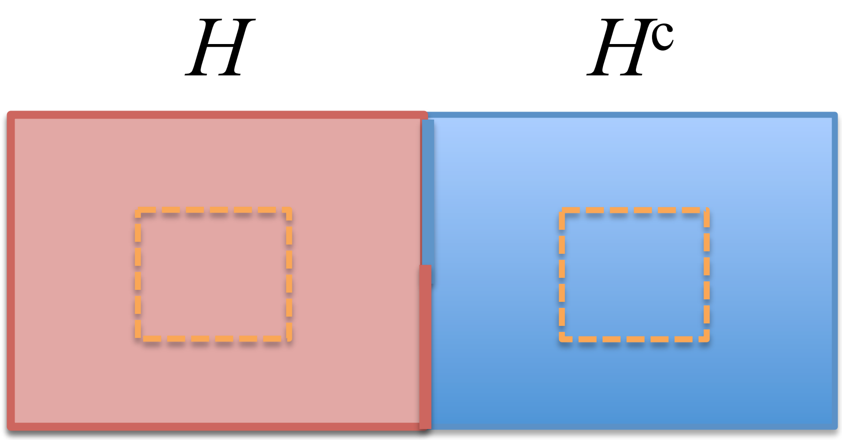


Deductive Verification and Refutation

H is **verified** by E iff $E \subseteq H$.

H is **refuted** by E iff $E \subseteq H^c$.

H is **decided** by E iff H is either verified or refuted by E.

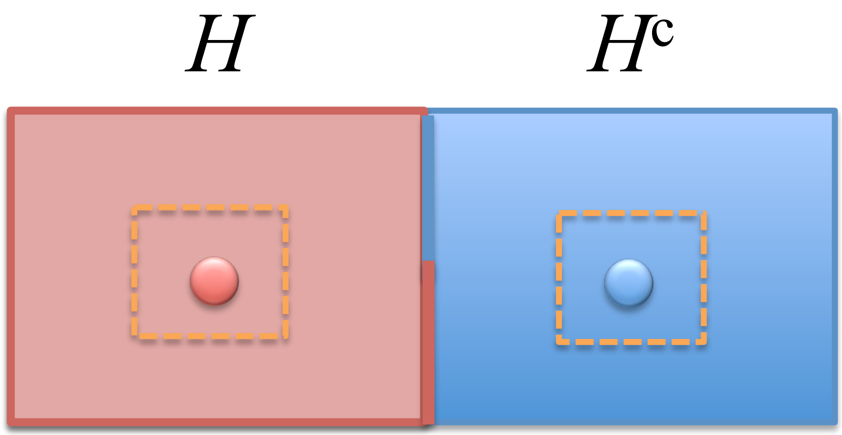


Will be Verified

w is an **interior point** of H iff

iff H **will be** verified in w;

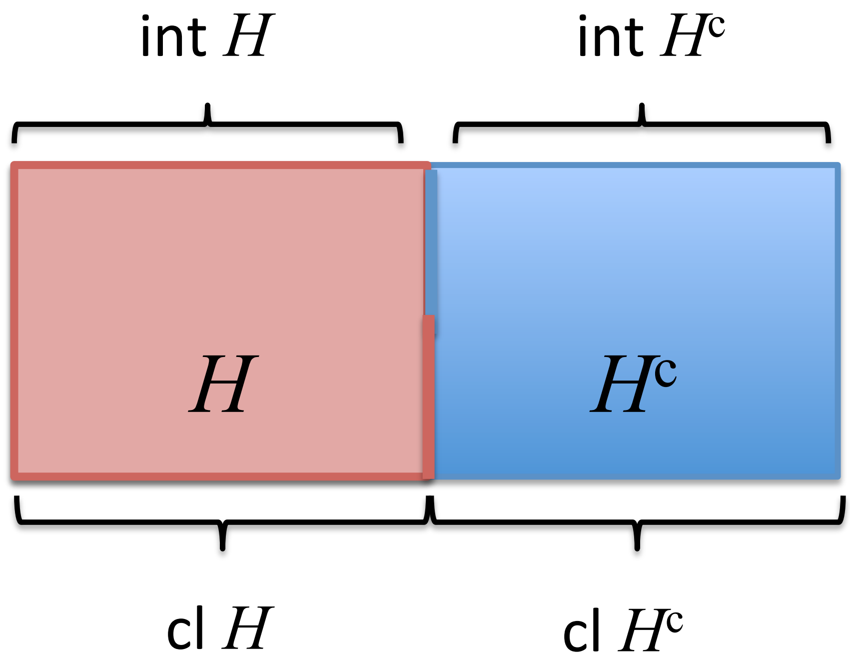
iff there is E in $\mathcal{I}(w)$ s.t. H is verified by E.



Topological Operators as Modal Operators

int H := the proposition that H **will be verified.**

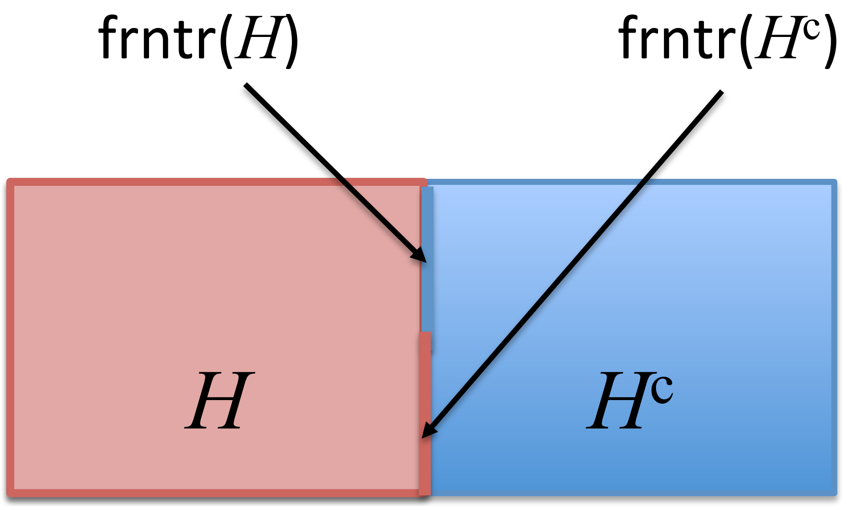
cl H := the proposition that H **will never be refuted.**



Topological Operators

frntr H := the proposition that H is false but will never be refuted.

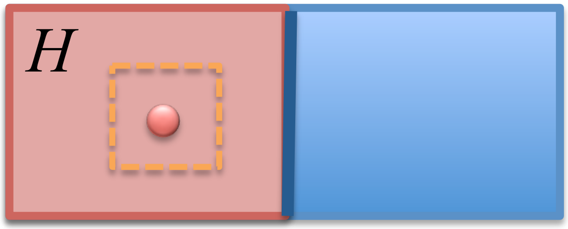
frntr H^c := the proposition that H is true but will never be verified.



Verifiability, Refutability, Decidability

H is **verifiable (open)** iff $H \subseteq \text{int}(H)$.

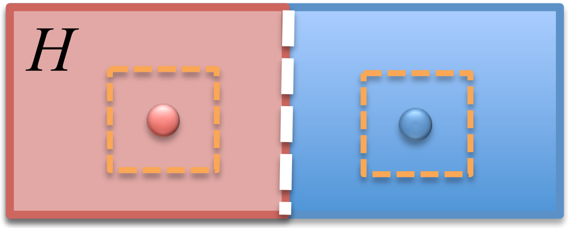
i.e., iff H will be verified however H is true.



H is **refutable (closed)** iff $\text{cl}(H) \subseteq H$.

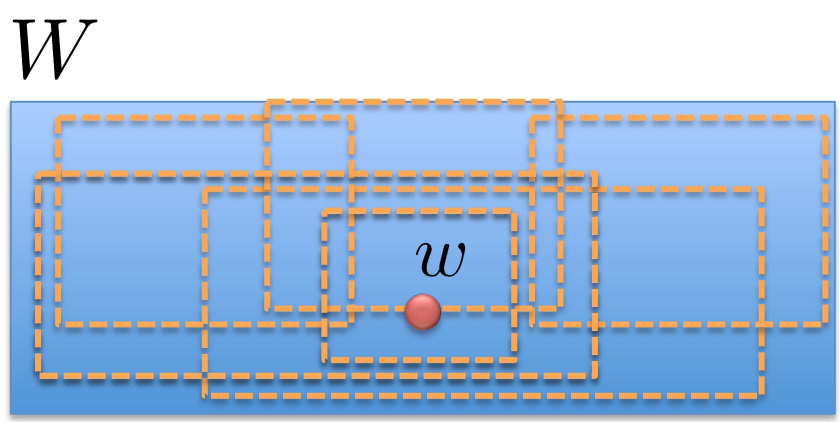
i.e., iff H will be refuted however H is false.

H is **decidable (clopen)** iff H is both verifiable and refutable.



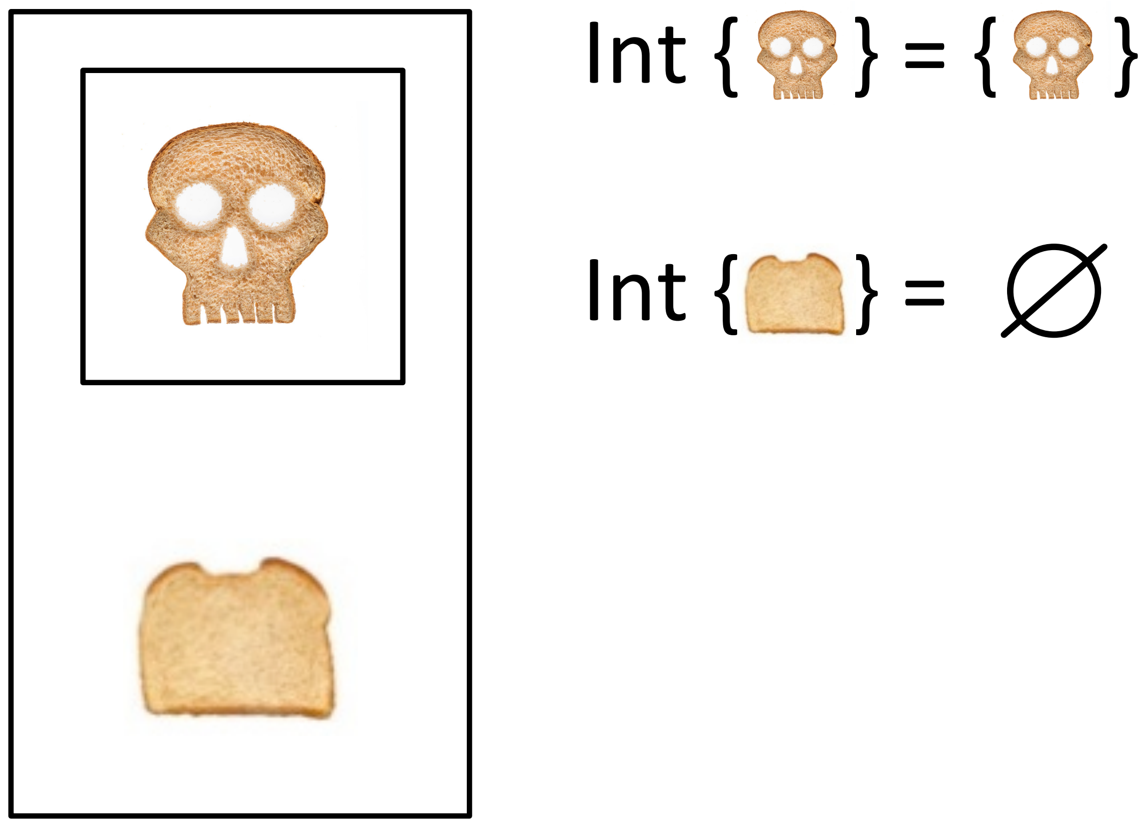
The Topology of Information

- A **topology** on W is determined by its open (verifiable) propositions.
- Every verifiable proposition is a disjunction of information states in $\mathcal{I}$.



Interior

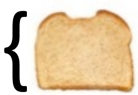
int H = the proposition that H **will be verified**.



Open = Verifiable

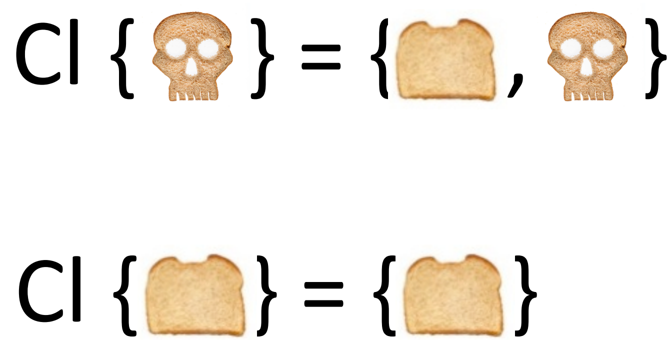
H is open (verifiable) iff H entails **int** H.

Int {} = {}

Int {} = $\varnothing$

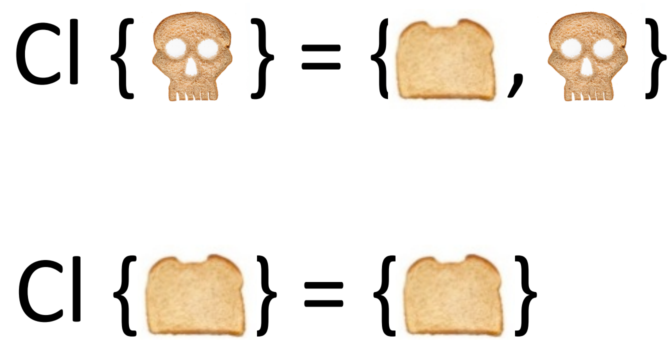
Closure

cl H = the proposition that H **will never be refuted**.



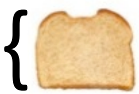
Closed = Refutable

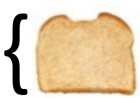
H is closed (refutable) iff **cl** H entails H.



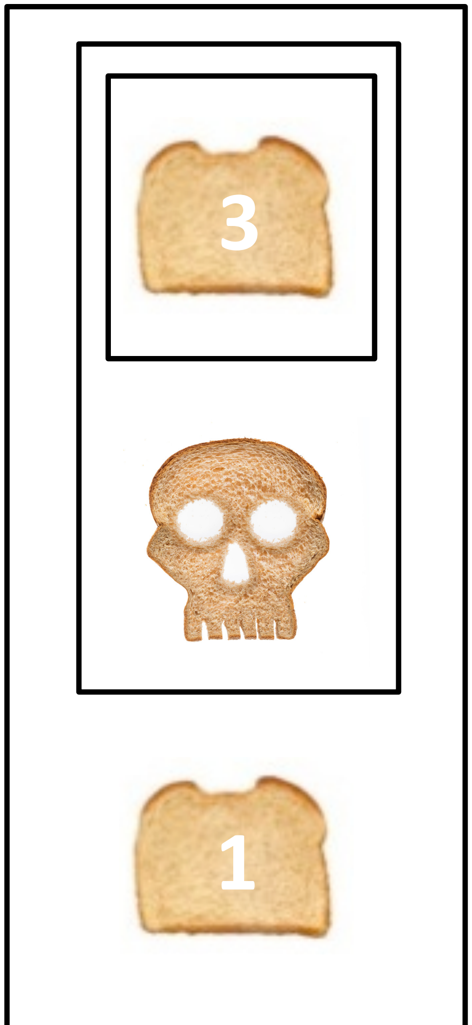
Frontier

frntr H = H is false, but will never be refuted.

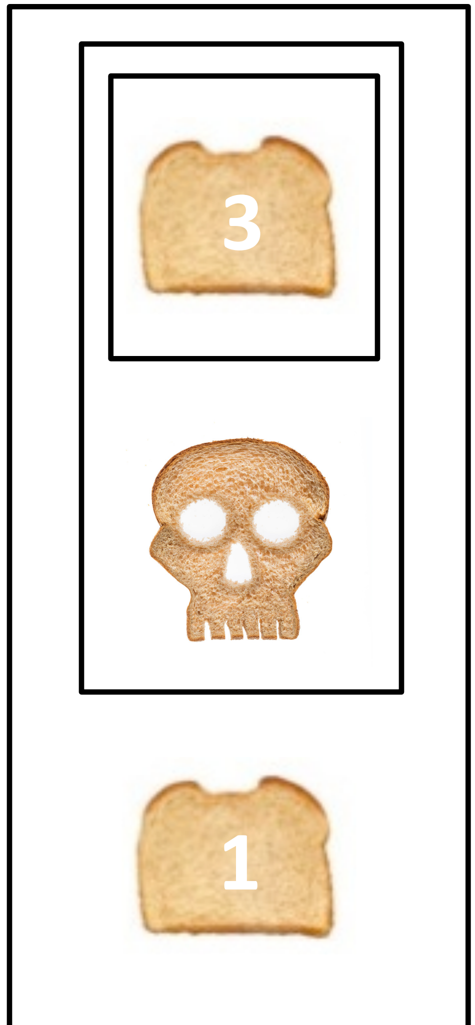
Frntr {  } = {  }

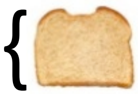
Frntr {  } = $\varnothing$

Hume's Problem, Enhanced.

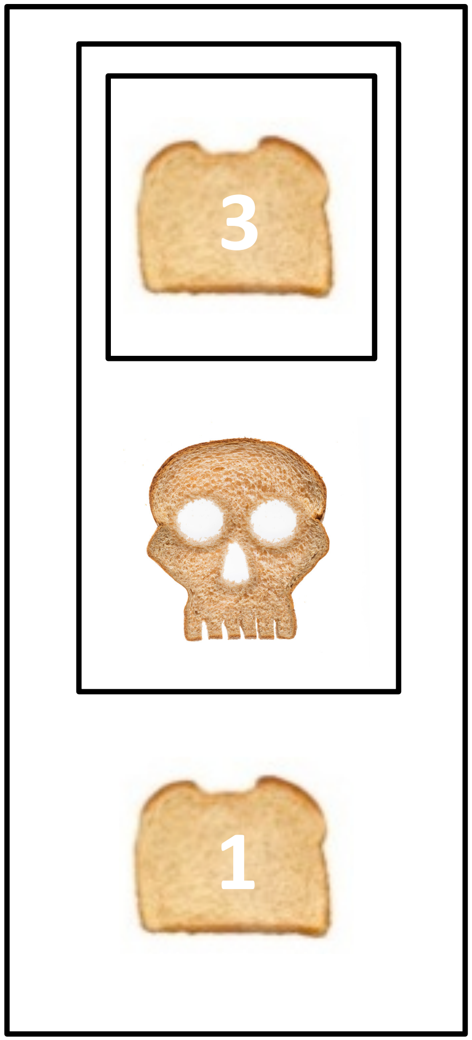


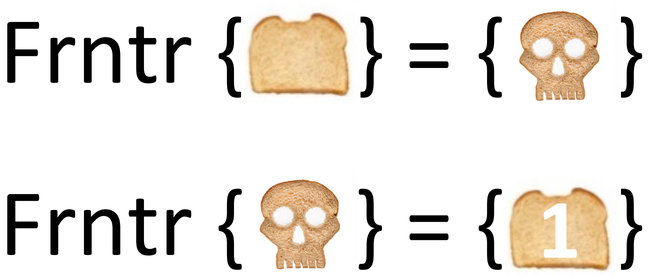
Hume's Problem, Enhanced.



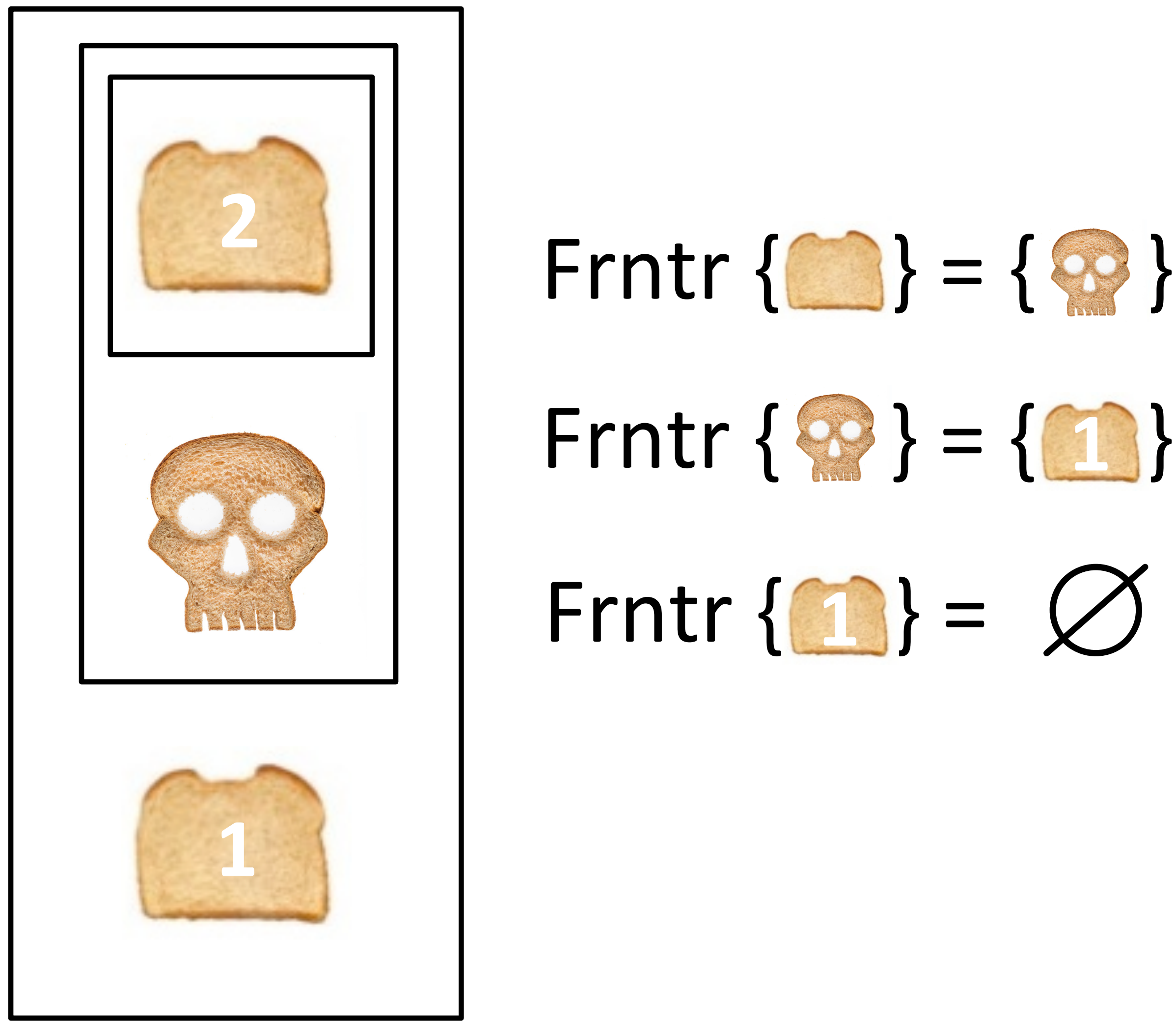
Frntr {  } = {  }

Hume’s Problem, Enhanced.



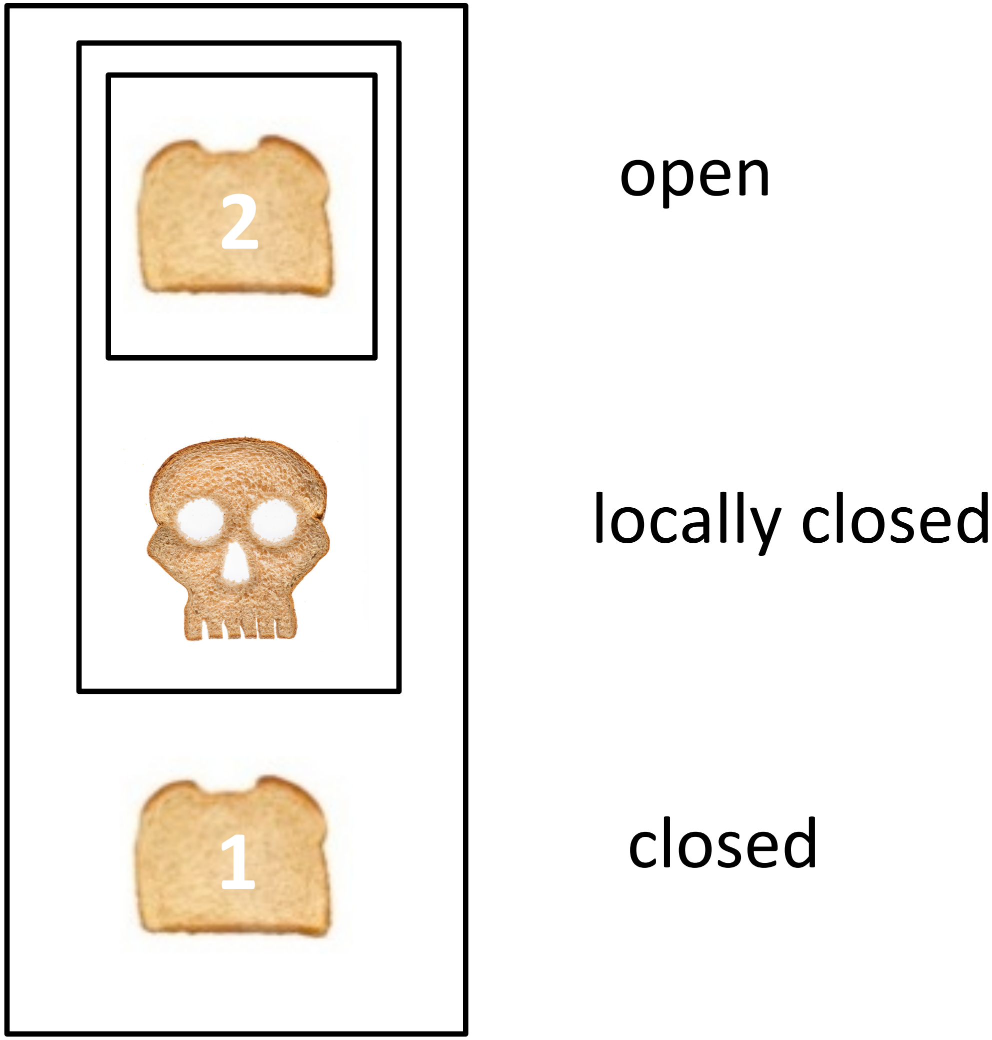


Hume’s Problem, Enhanced.



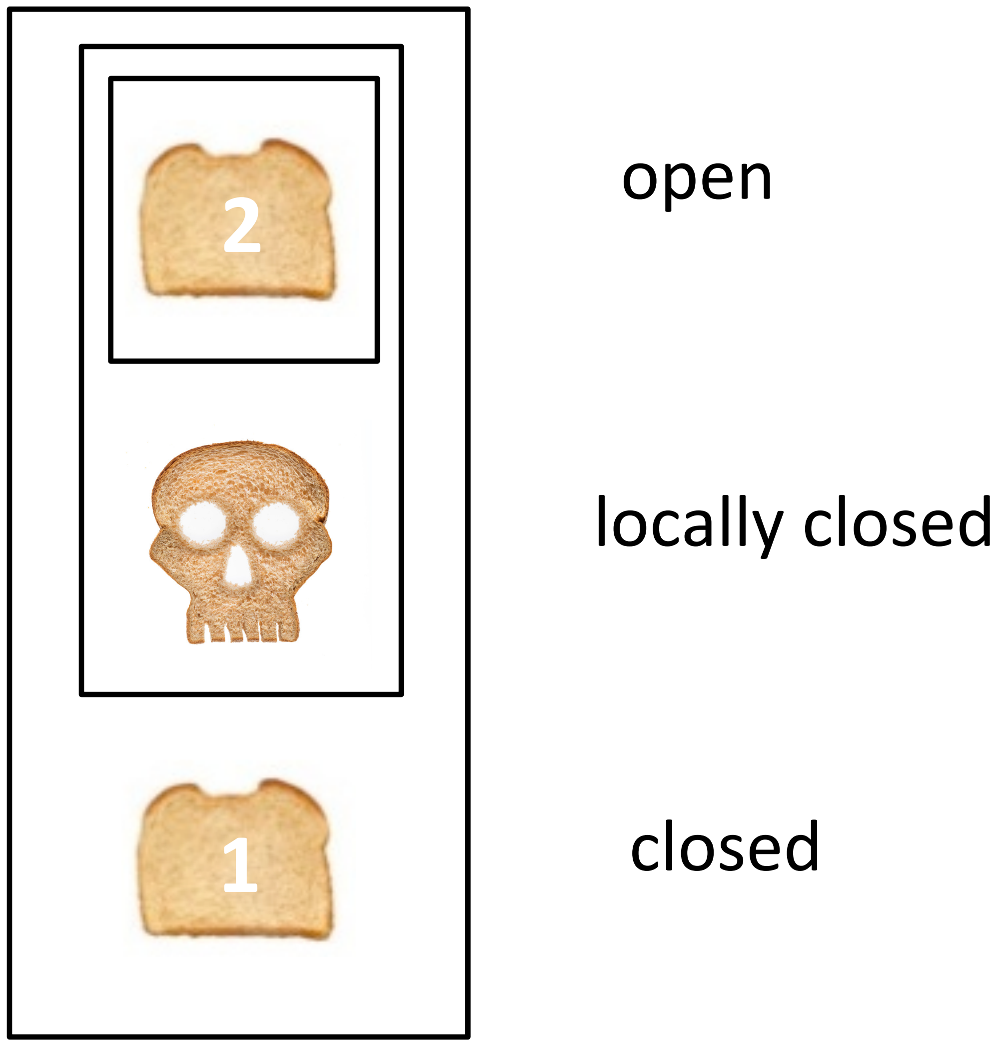
Locally Closed

H is locally closed iff **frntr** H is closed.



Locally Closed

H is locally closed iff H entails that H will be refutable (closed).



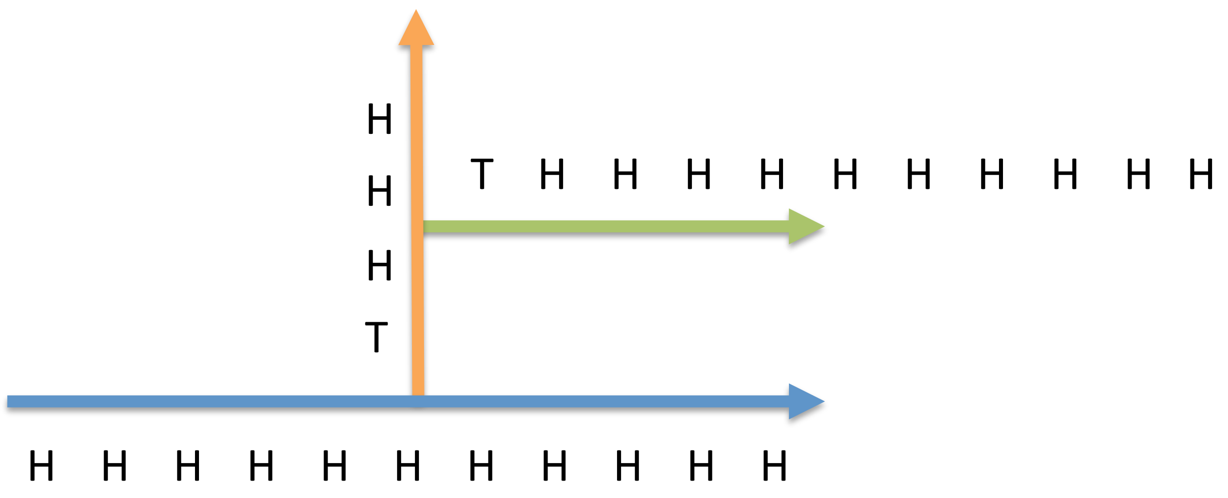
Sequential Example

etc.

H_2 = “You will see T exactly twice” is locally closed.

H_1 = “You will see T exactly once” is locally closed.

H_0 = “You will never see T” is closed.



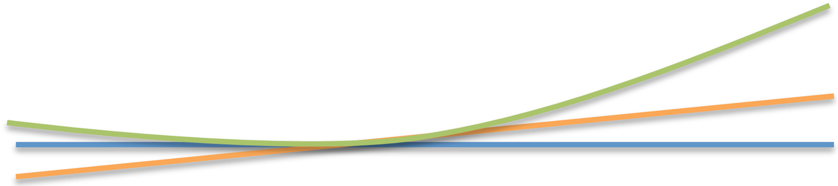
Equation Example

$etc.$

H_2 = "quadratic" is locally closed.

H_1 = "linear" is locally closed.

H_0 = "constant" is closed.

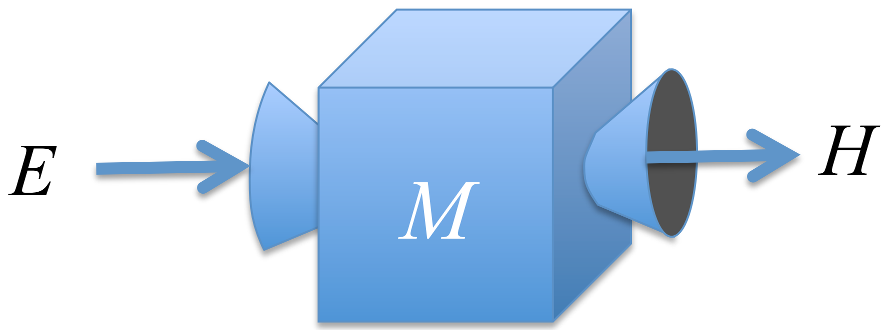


Topology

- H is **limiting open** iff H is a countable union of locally closed sets.
- H is **limiting closed** iff H^c is limiting open.
- H is **limiting clopen** iff H is both limiting open and limiting closed.

Propositional Methods

- **Propositional methods** produce propositional conclusions in response to propositional information.



Propositional Methods

- M is infallible iff $w \in M(E)$, whenever $E \in \mathcal{I}(w)$.
- M is monotonic iff $M(F) \subseteq M(E)$, whenever $F \subseteq E$.

Convergence

M converges to H in w iff

there is E in $\mathcal{I}(w)$ such that

for all F in $\mathcal{I}\,(w \mid E)$,

$M(F) \subseteq H$.

Deductive Methods

- A **verification method** for H is an infallible, monotonic method V such that:
  1. $w \in H^c$ implies $V(E) = W$ for E in $\mathcal{I}(w)$;
  2. $w \in H$ implies V converges to H in w.

Deductive Methods

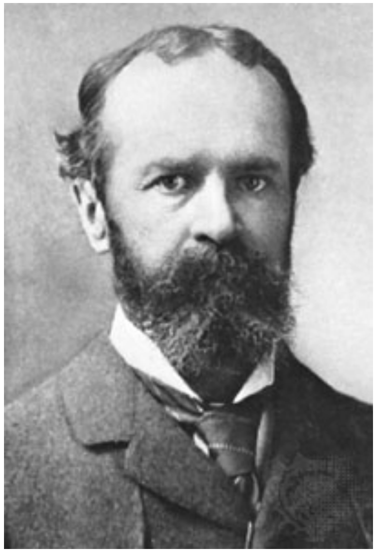
- A **verification method** for H is an infallible, monotonic method V such that:
  1. $w \in H^c$ implies $V(\mathrm{E}) = W$ for E in $\mathcal{I}(w)$;
  2. $w \in H$ implies V converges to H in w.
- A **refutation method** for H is just a verification method for H^c.
- A **decision method** for H converges to H or to H^c without error.

Deductive Methods

- A **verification method** for H is an infallible, monotonic method V such that:
  1. $w \in H^c$ implies $V(E) = W$ for E in $\mathcal{I}(w)$;
  2. $w \in H$ implies V converges to H in w.
- A **refutation method** for H is just a verification method for H^c.
- A **decision method** for H converges to H or to H^c without error.
- H is **methodologically verifiable [refutable, decidable, etc.]** iff H has a method of the corresponding kind.

Inductive Methods

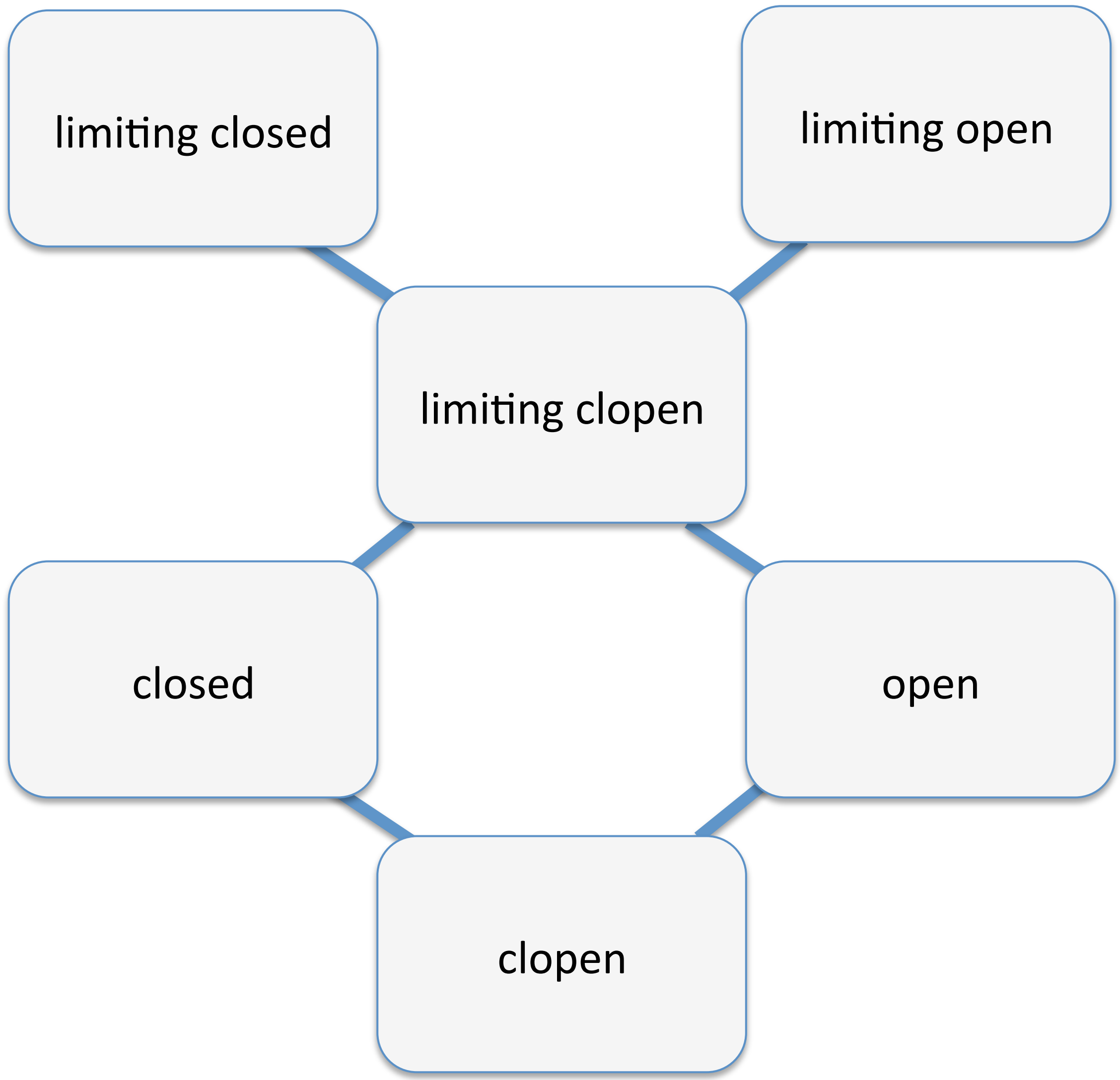
- A **limiting verification method** for H is a method V such that:
  $w \in H$ iff V converges in w to some true H' that entails H.



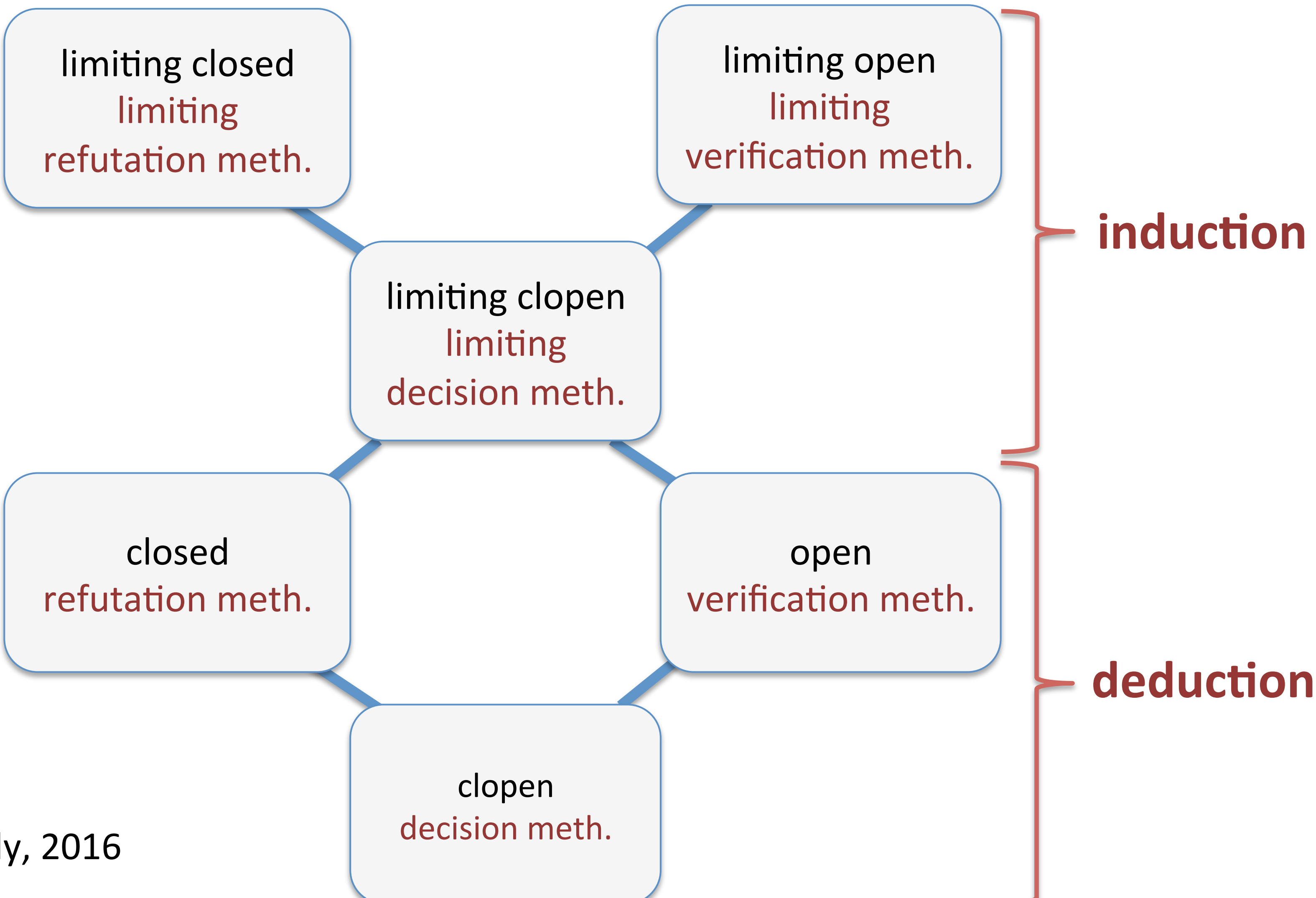
Inductive Methods

- A **limiting verification method** for H is a method V such that:
  $w \in H$ iff V converges in w to some true H' that entails H.
- A **limiting refutation method** for H is a limiting verification method for H^c.
- A **limiting decision method** for H is a limiting verification method and a limiting refutation for H.

Topological Complexity



Characterization Theorem



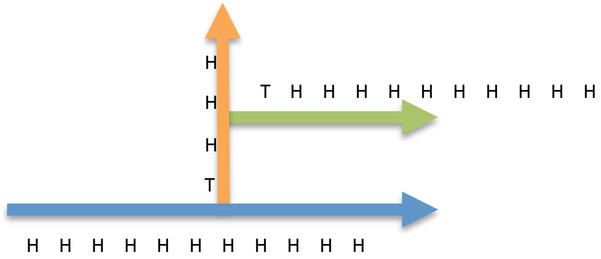
Genin and Kelly, 2016

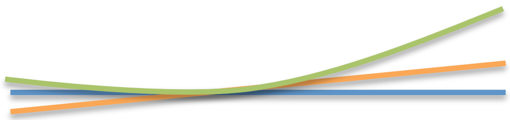
OCKHAM'S TOPOLOGICAL RAZOR

Popper's Simplicity Order

- "More falsifiable hypotheses are simpler".

$$A \preceq B \;\Leftrightarrow\; A \subseteq \mathrm{cl} B.$$





$$H_1 \prec H_2 \prec H_3.$$

A Big Mistake

$$A \preceq B \;\Leftrightarrow\; A \subseteq \text{cl}B.$$

1. Weaker hypotheses are less falsifiable.

$$A \subseteq B \text{ implies } A \preceq B.$$

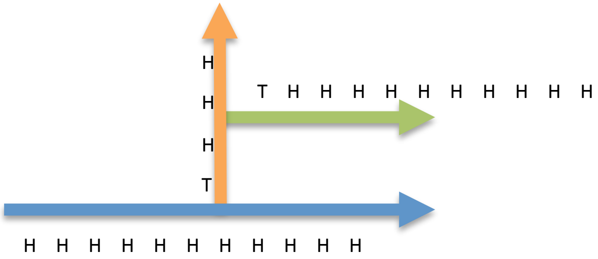
2. So suspending judgment violates Ockham's razor!

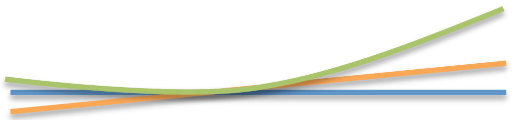
$$A \preceq W.$$

Easy and Natural Fix

Lack of falsifiers is bad only if A is false!

$$A \preceq B \Leftrightarrow A \subseteq \mathsf{frntr} B$$





$$H_1 \prec H_2 \prec H_3.$$

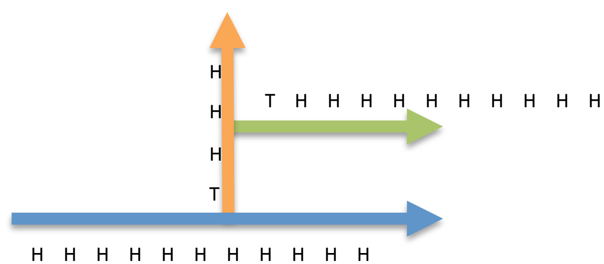
A Smaller Issue

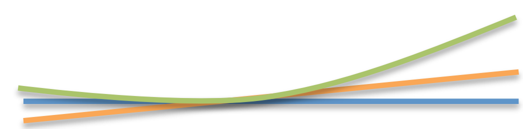
- Gerrymandered hypotheses can obscure simplicity relations.
- E.g., "The true law is linear, or the cat is on the mat" is not simpler than "The true law is quadratic".

A Response

Simpler theories have simpler ways of being true.

$$A \lhd B \Leftrightarrow A \cap \mathsf{frntr} B \neq \varnothing$$





$$H_1 \lhd H_2 \lhd H_3.$$

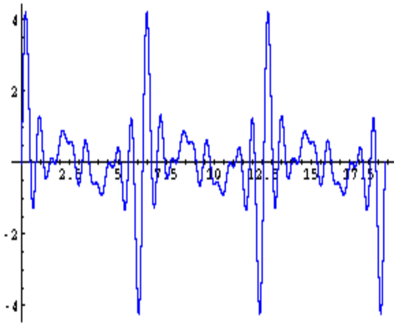
Example: Competing Paradigms

Polynomial paradigm

$Y = \sum_{i=0}^{N} a_i X^i.$

Trigonometric polynomial paradigm

$Y = \sum_{i=0}^{N} a_i \sin(iX) + b_i \cos(iX).$



Example: Competing Paradigms

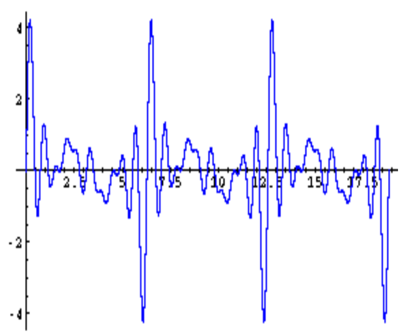
Polynomial paradigm

$$Y = \sum_{i=0}^{N} a_i X^i.$$

degree

Trigonometric polynomial paradigm

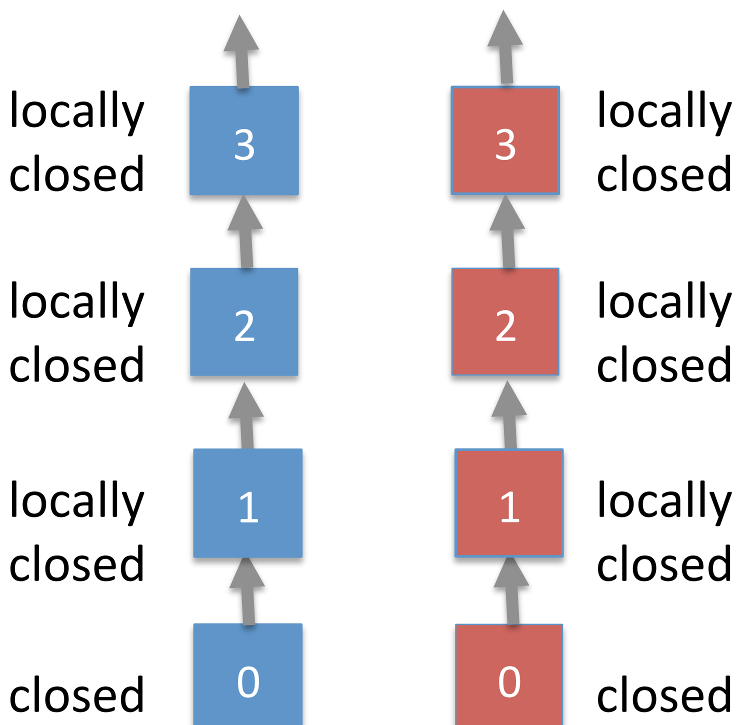
$$Y = \sum_{i=0}^{N} a_i \sin(iX) + b_i \cos(iX).$$

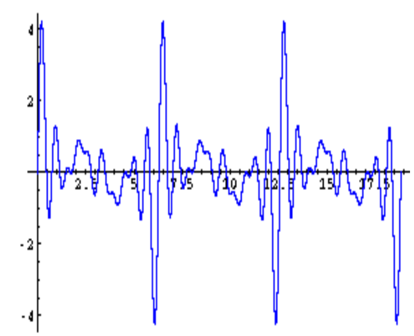


Example: Competing Paradigms

$\mathcal{Q} =$ which degree and which paradigm is true?

$\mathcal{I} =$ finitely many inexact measurements.

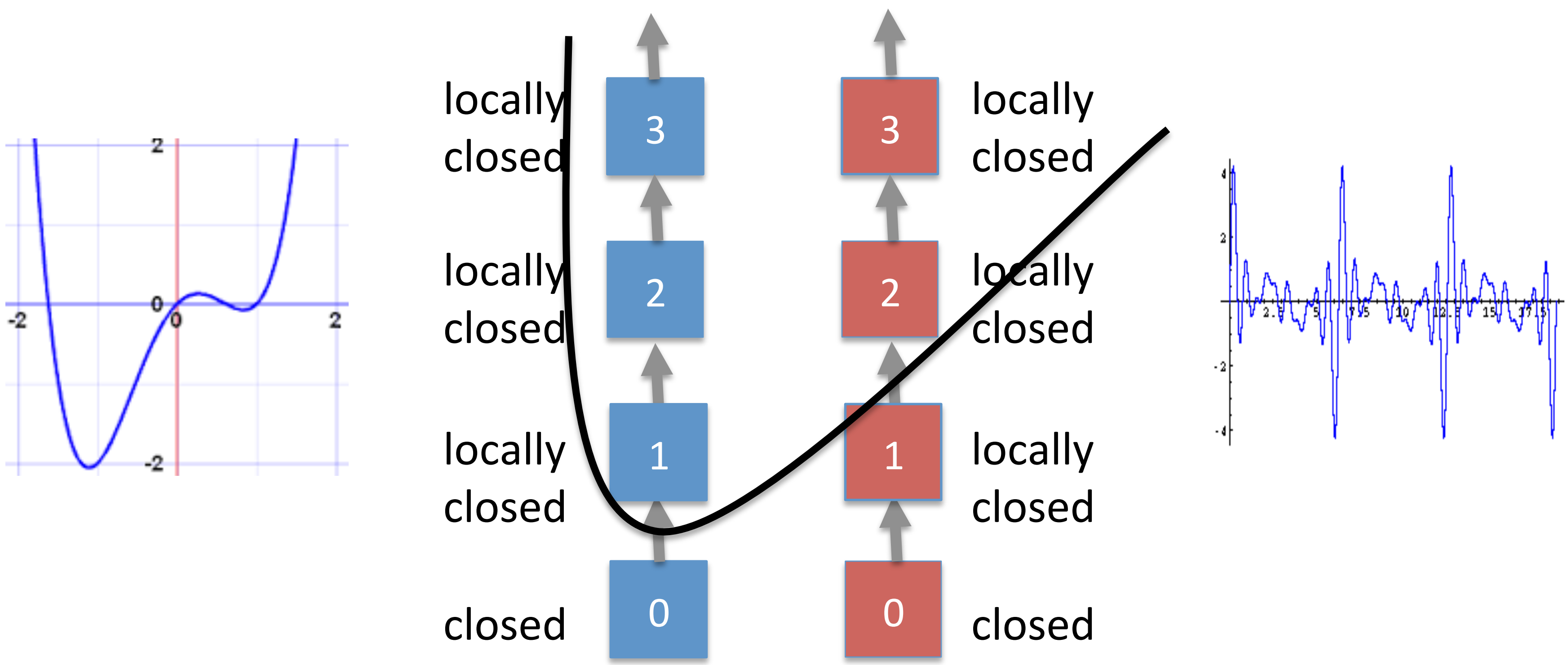




Example: Competing Paradigms

$\mathcal{Q} =$ which degree and which paradigm is true?

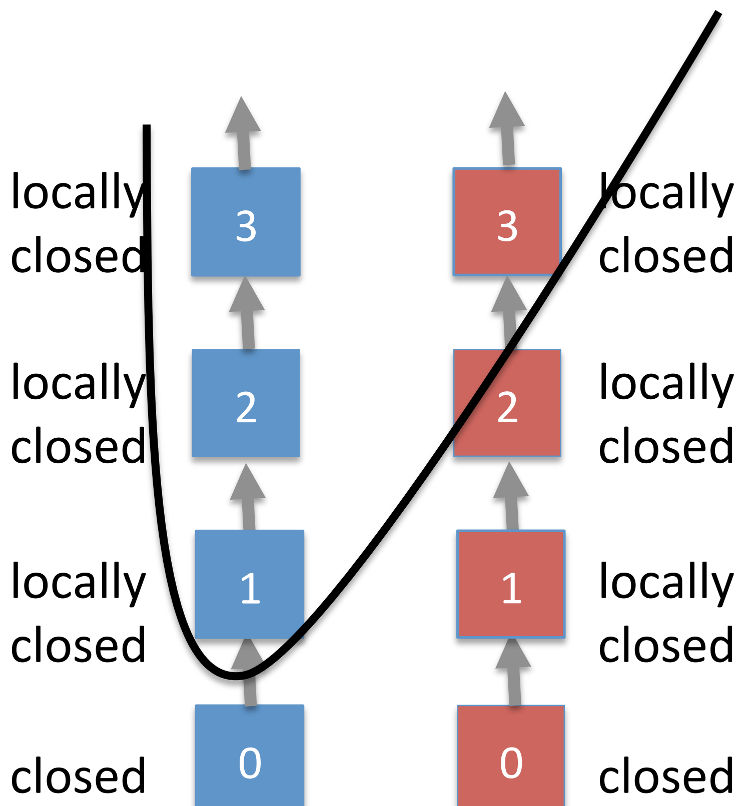
$\mathcal{I} =$ finitely many inexact measurements.

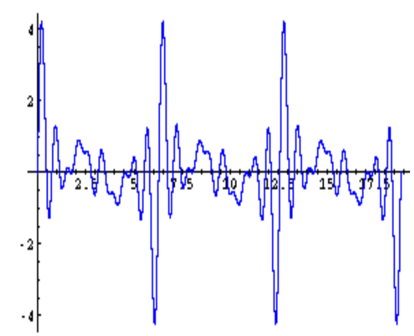


Example: Competing Paradigms

$\mathcal{Q} =$ which degree and which paradigm is true?

$\mathcal{I} =$ finitely many inexact measurements.

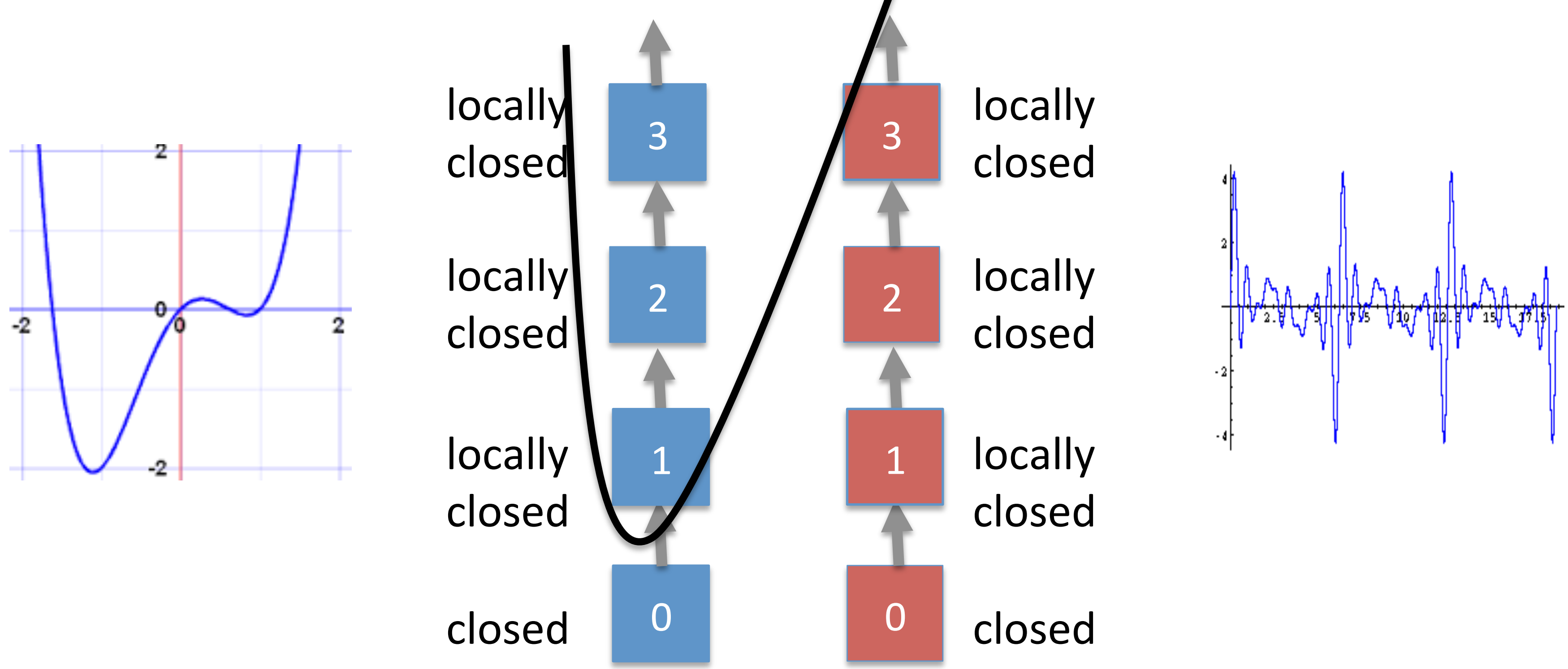




Example: Competing Paradigms

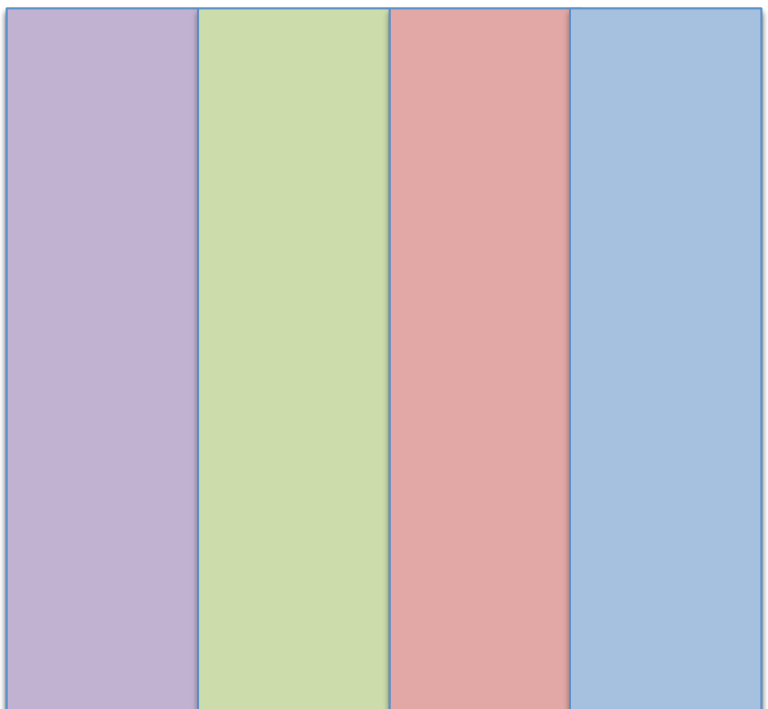
$\mathcal{Q}$ = which degree and which paradigm is true?

$\mathcal{I}$ = finitely many inexact measurements.



Questions

- A question partitions W into countably many possible answers (Hamblin 1958)
- Relevant responses are disjunctions of answers.



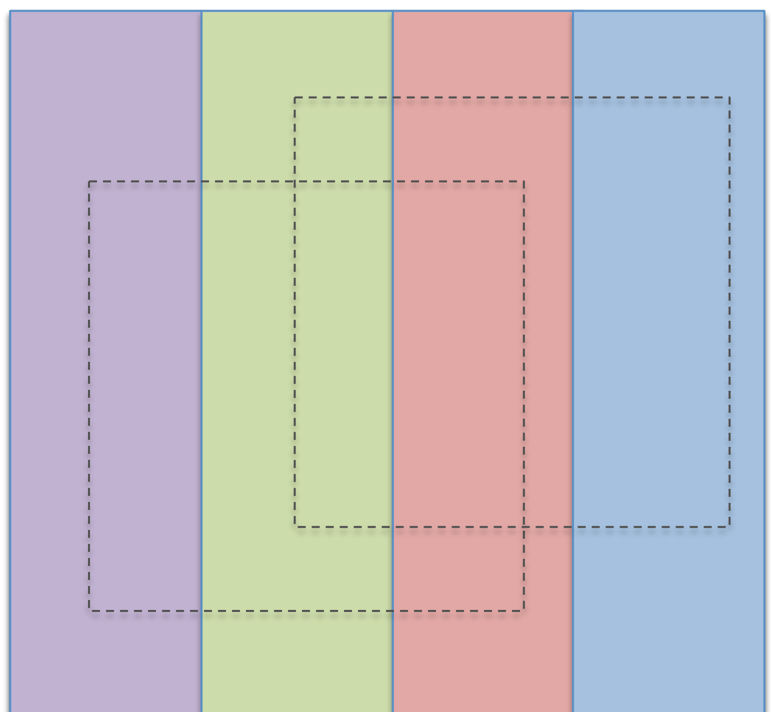
Ockham's Razor

Proposition (Genin and Kelly, 2016). The following principles are **equivalent**.

1. Infer a **simplest** relevant response in light of E.
2. Infer a **refutable** relevant response compatible with E.
3. Infer a relevant response that is **not more complex than the true answer**.

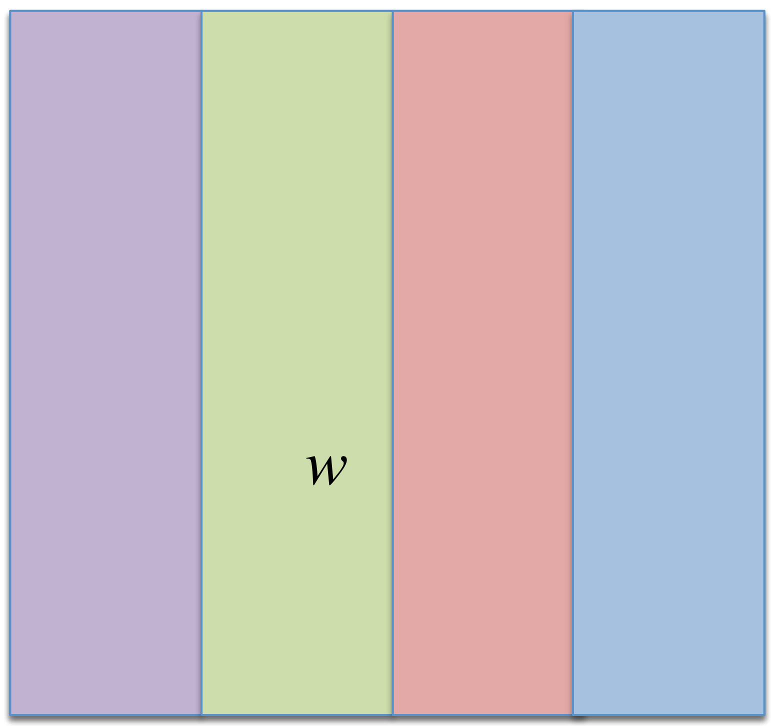
Empirical Problem

$$\mathfrak{P} \; = \; (W, \mathcal{I}, \mathcal{Q}).$$



Empirical Problem

$\mathcal{Q}(w)$ is the answer true in w.



Solutions

A **solution** for $\mathfrak{P} = (W, \mathcal{I}, \mathcal{Q})$ is a propositional method V such that

$w \in H$ iff V converges in w to some true H' that entails $\mathcal{Q}(w)$.

A problem is solvable iff it has a solution.

Solvability, Characterized.

Proposition. A problem $\mathfrak{P} = (W, \mathcal{I}, \mathcal{Q})$ is solvable iff every answer is limiting open.

de Brecht and Yamamoto (2009)

Baltag, Gierasimczuk, and Smets (2015)

Genin and Kelly (2015)

Progressive Solutions

A solution for $\mathfrak{P} = (W, \mathcal{I}, \mathcal{Q})$ is **progressive** iff for all E in $\mathcal{I}(w)$ and F in $\mathcal{I}(w \mid E)$:

if $V(E)$ entails $\mathcal{Q}(w)$, then $V(F)$ entails $\mathcal{Q}(w)$.

That is: the true answer is a fixed point of inquiry.

Progressive Solutions

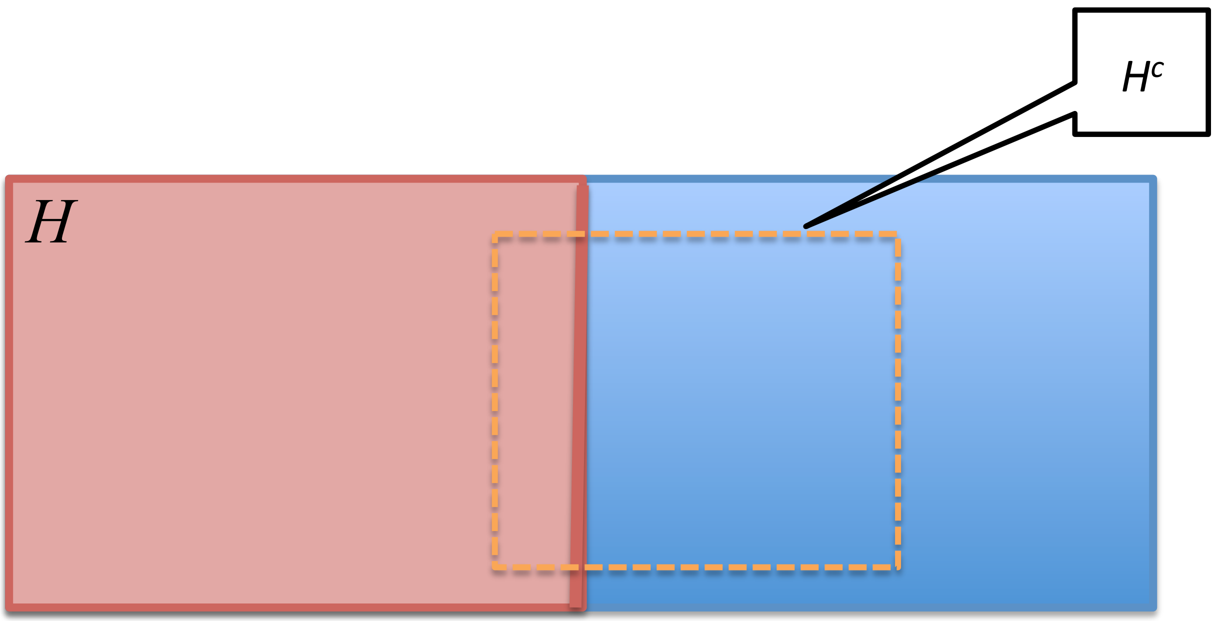
Proposition. If there exists an enumeration $A_1, A_2, \ldots$ of the answers to Q agreeing with the simplicity order, then Q is progressively solvable.

Epistemic Mandate for Ockham's Razor

Proposition (Genin and Kelly, 2016)**.** Every progressive solution obeys Ockham's razor.

Epistemic Mandate for Ockham's Razor

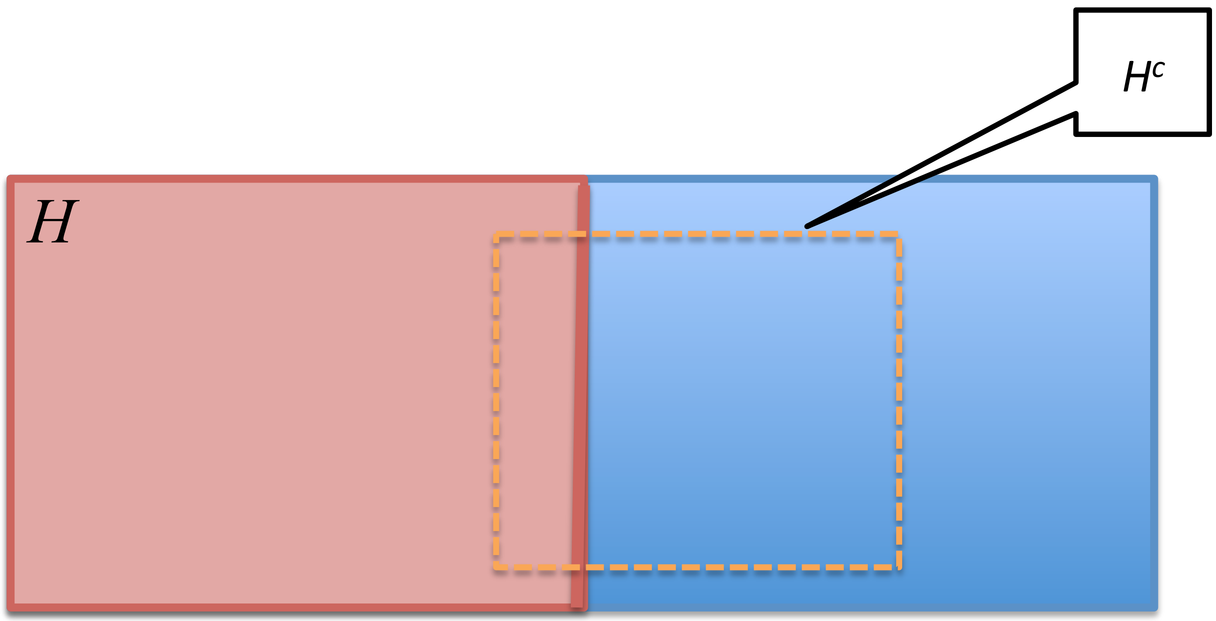
Proposition (Genin and Kelly, 2016)**.** Every progressive solution obeys Ockham's razor.



$$H \lhd H^c$$

Epistemic Mandate for Ockham's Razor

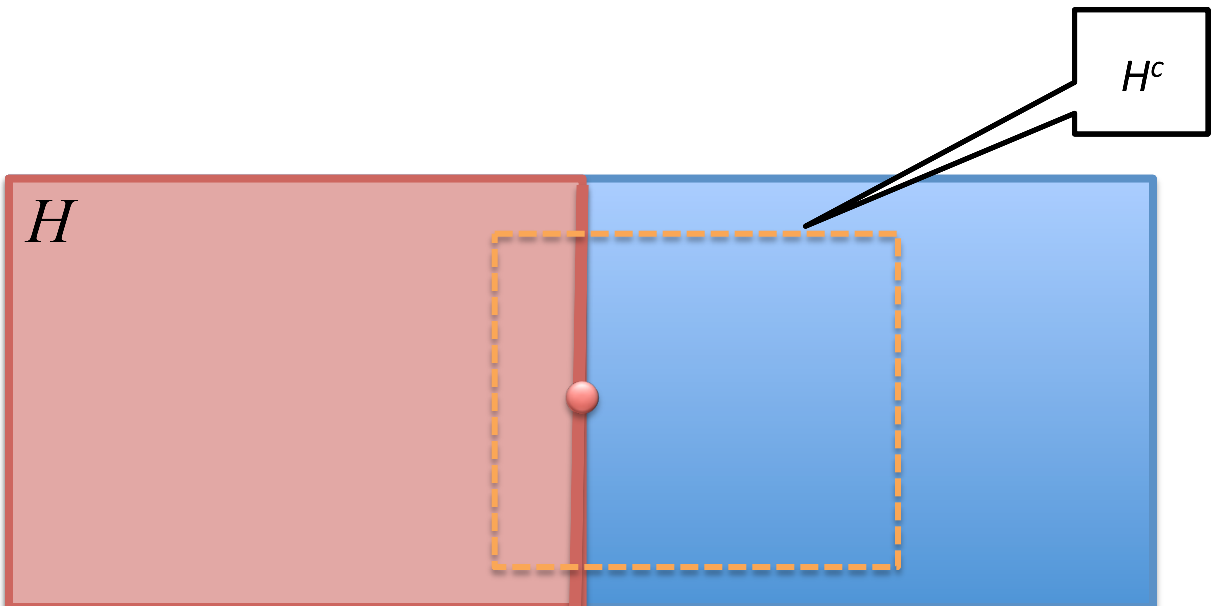
Proposition (Genin and Kelly, 2016)**.** Every progressive solution obeys Ockham's razor.



$$H \lhd H^c$$

Epistemic Mandate for Ockham's Razor

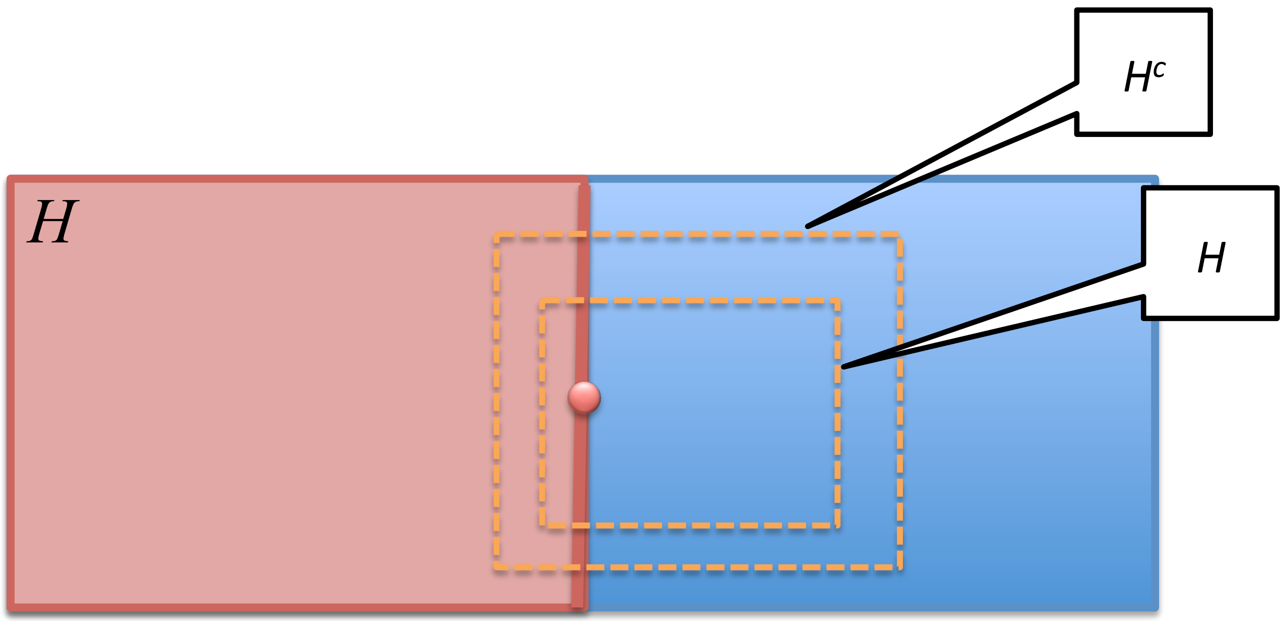
Proposition (Genin and Kelly, 2016)**.** Every progressive solution obeys Ockham's razor.



$$H \lhd H^c$$

Epistemic Mandate for Ockham's Razor

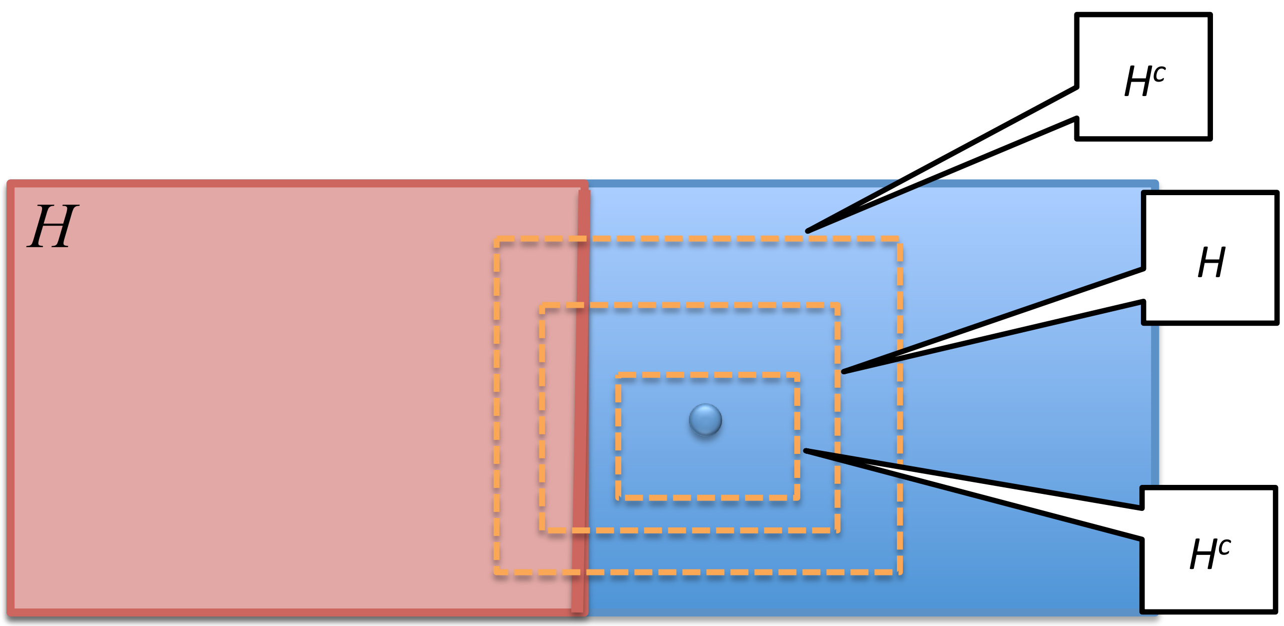
Proposition (Genin and Kelly, 2016)**.** Every progressive solution obeys Ockham's razor.



$$H \lhd H^c$$

Epistemic Mandate for Ockham's Razor

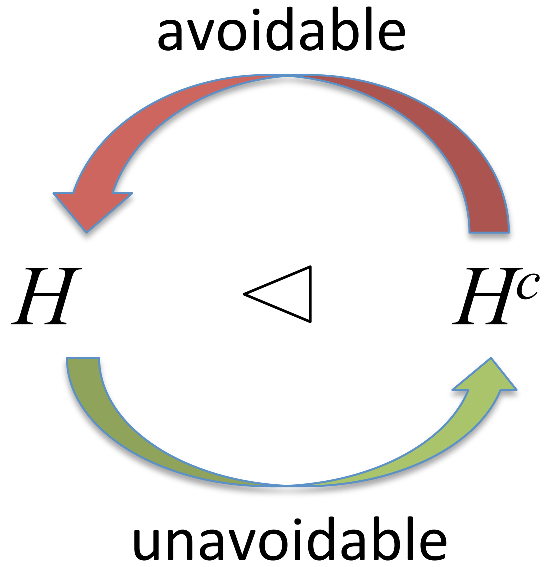
Proposition (Genin and Kelly, 2016)**.** Every progressive solution obeys Ockham's razor.



$$H \lhd H^c$$

Non-Circular

By **favoring** a **complex** hypothesis, you lose in a **complex** world!



Skepticism

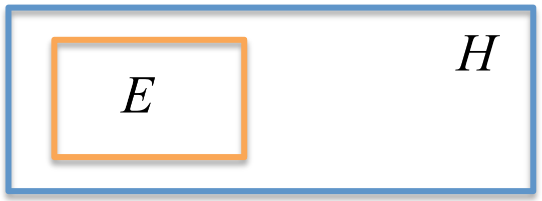
That story

"… may be okay if the candidate theories are deductively related to observations, but when the relationship is probabilistic, I am skeptical …"

Elliot Sober (2015).

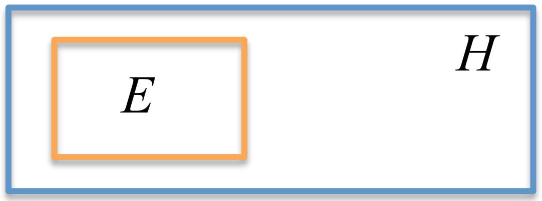
A Worry

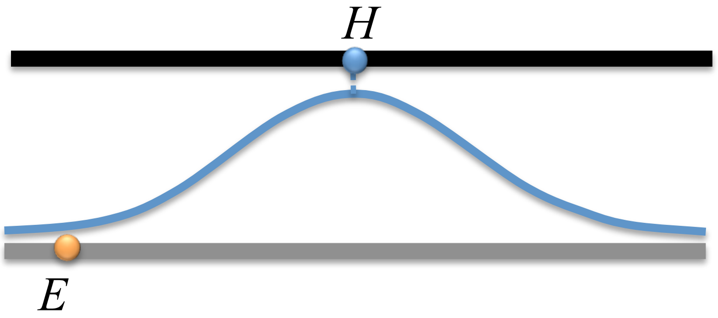
- Propositional information refutes logically incompatible possibilities.



A Worry

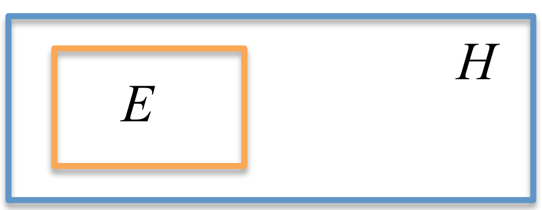
- Propositional information refutes logically incompatible possibilities.
- Typically, statistical samples are logically compatible with every possibility.

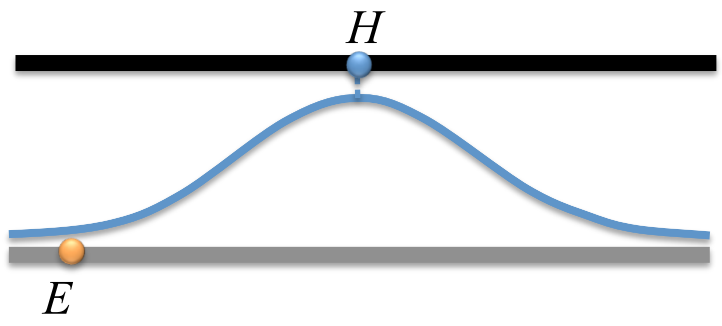




Response

Don’t worry!

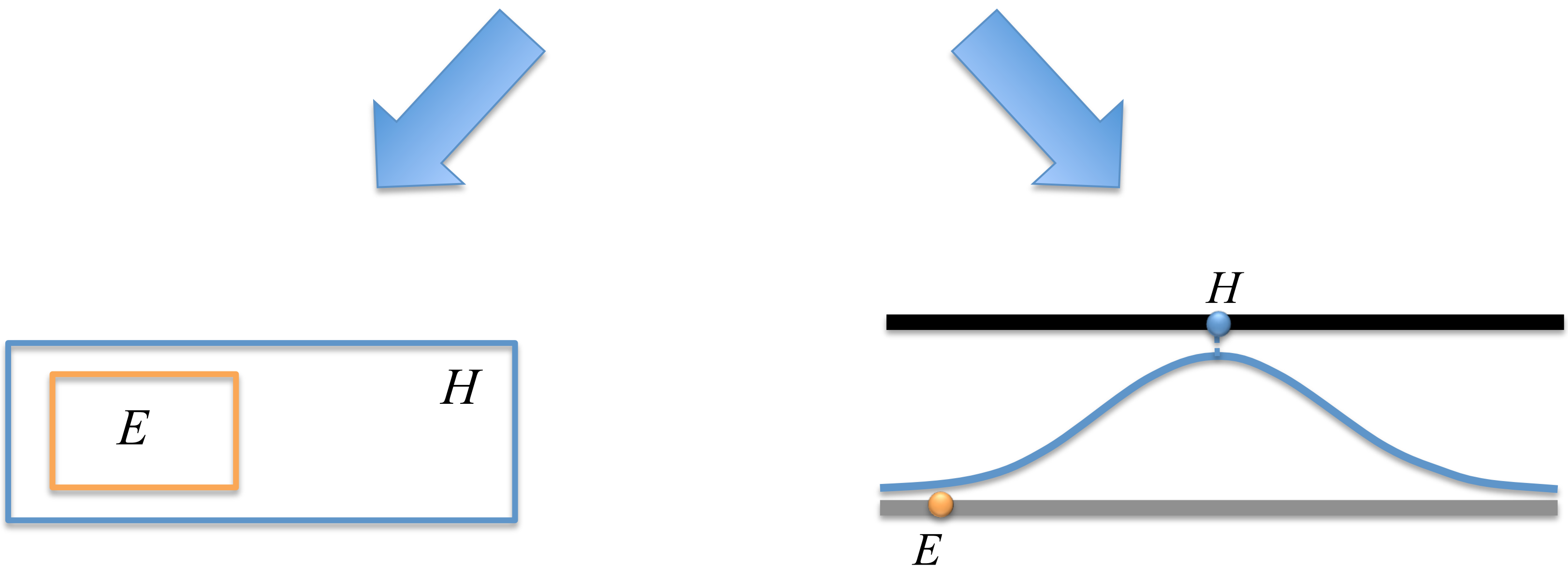




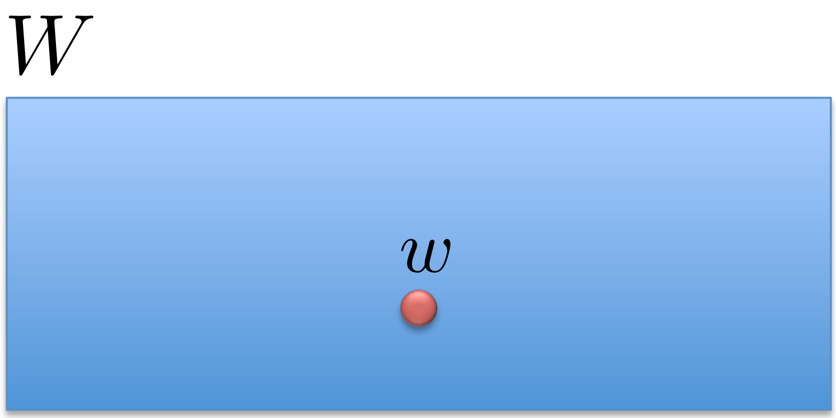
Response

Don't worry!

Common **topological** structure

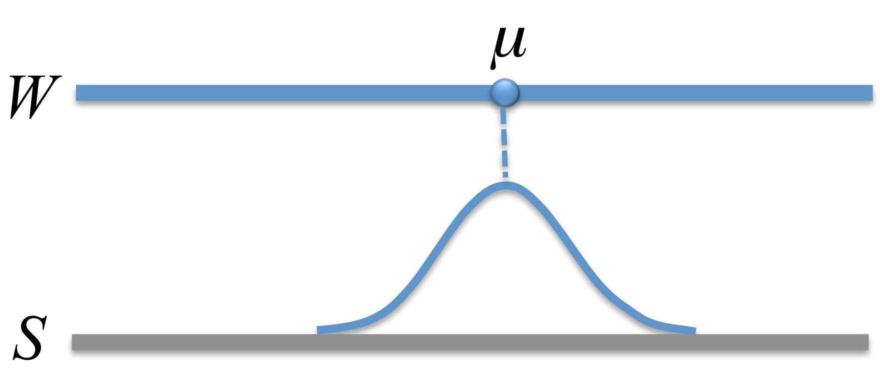


Recall: Possible Worlds



Statistical Worlds

- Probability measures over a sample space.

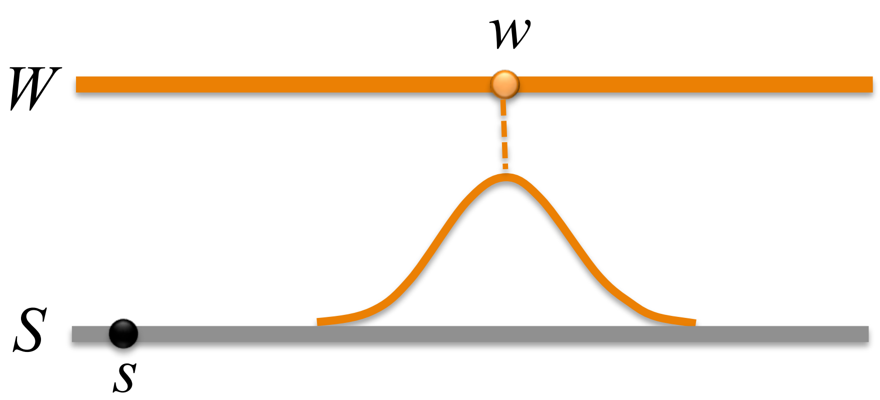


Recall: Information States

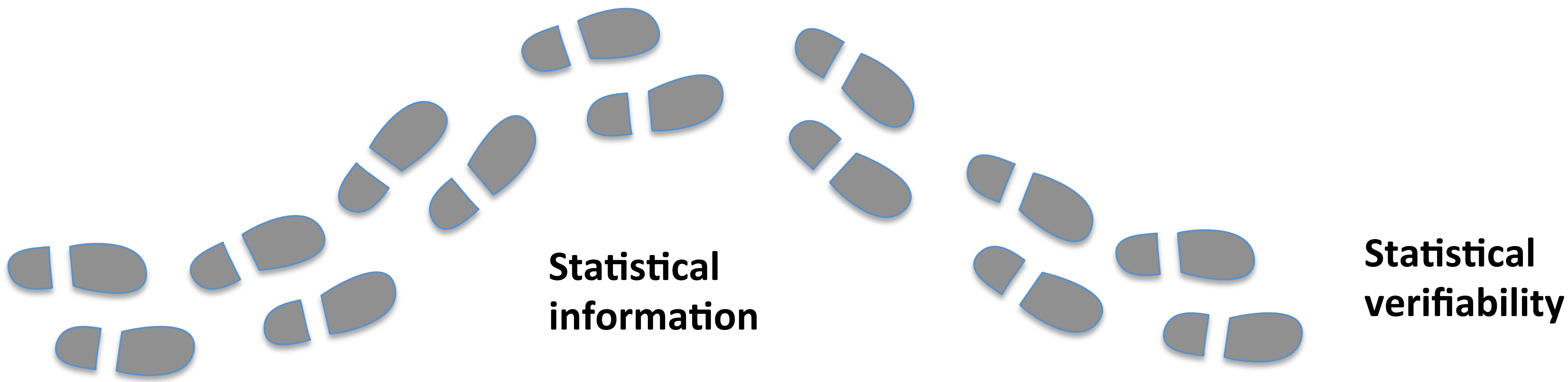
The logically strongest proposition you are informed of.

Statistical Information?

- It seems that the only statistical information state is W.

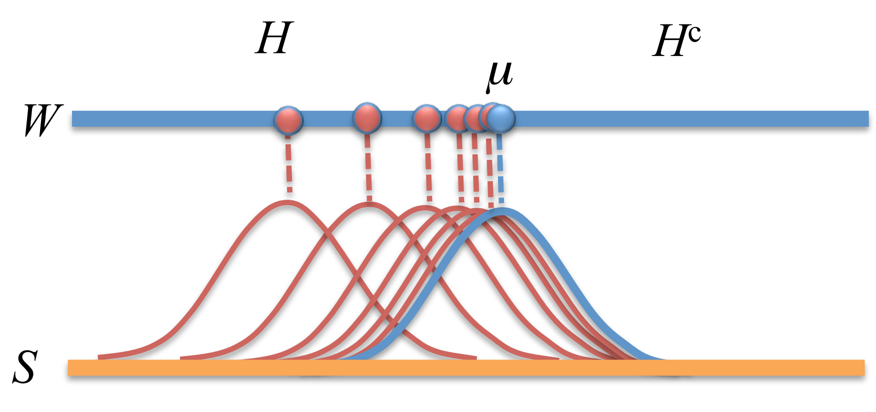


Side-step the Worry



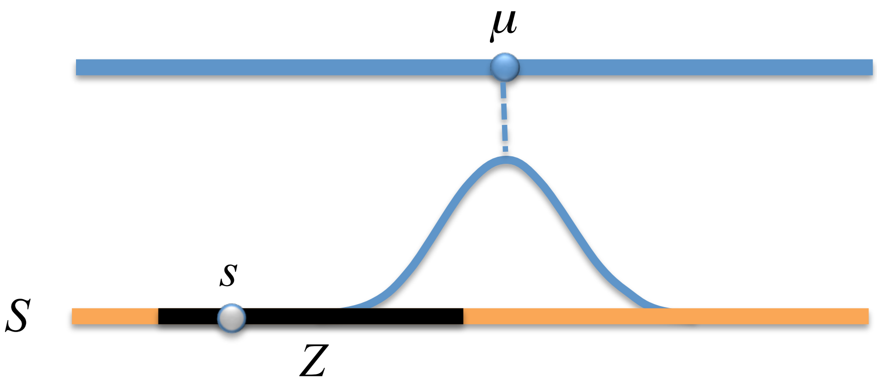
Statistical Information Topology

Possibilities nearer to the truth should be harder to rule out by statistical methods.



Gathering Statistical Information

1. The sample space S has its own topology.
2. Choose a sample event Z over S.
3. Obtain sample s.
4. Observe whether Z occurs.

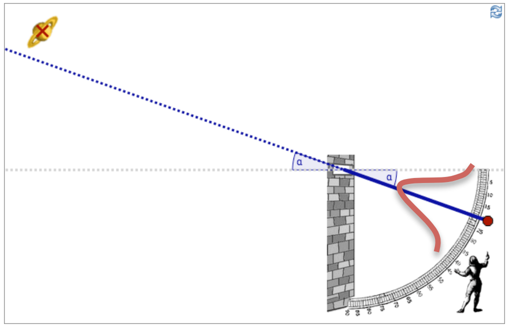


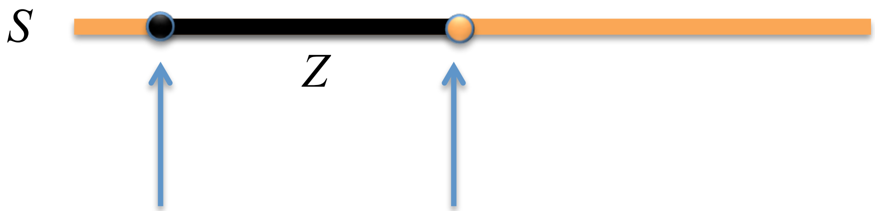
Feasible Sample Events

- You can't decide whether a sample is rational-valued.

Feasible Sample Events

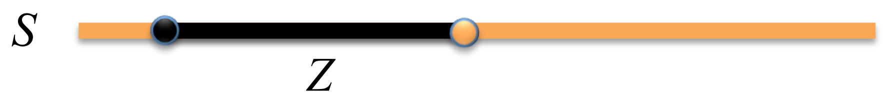
- You can't determine whether a sample hits exactly on the boundary of an open interval.





Feasible Sample Events

- But every non-trivial Z on the real line has boundary points.

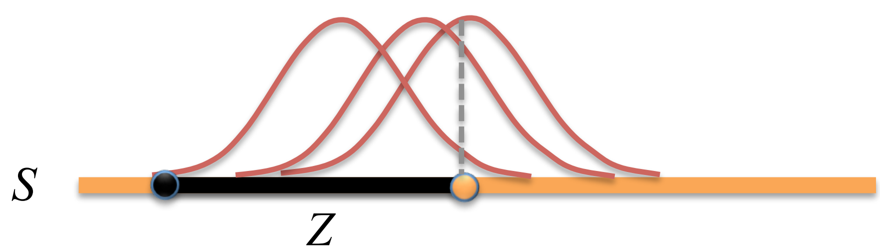


Feasible Sample Events

- That doesn't matter statistically as long as the boundary carries 0 probability.
- So Z is a **feasible** sample event iff

$$p(\text{bdry } Z) = 0, \text{ for each } p \text{ in } W.$$

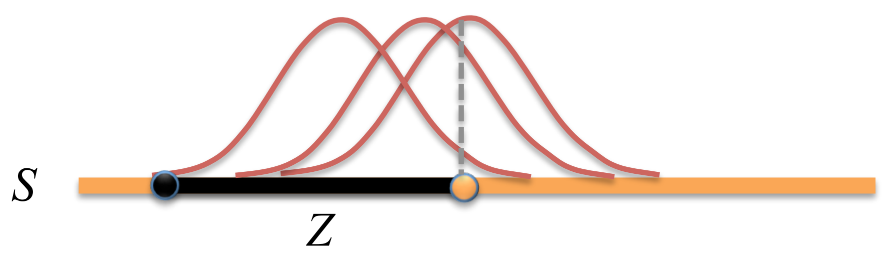
- I.e, feasible Z is **almost surely clopen** (decidable) in S.



Feasible Statistical Models

- S is **feasible** for W iff

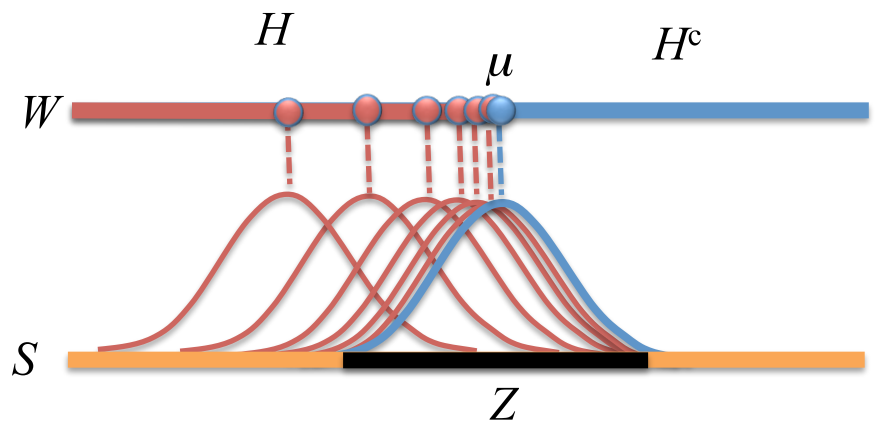
  S has a countable topological basis of feasible zones.



Statistical Information Topology

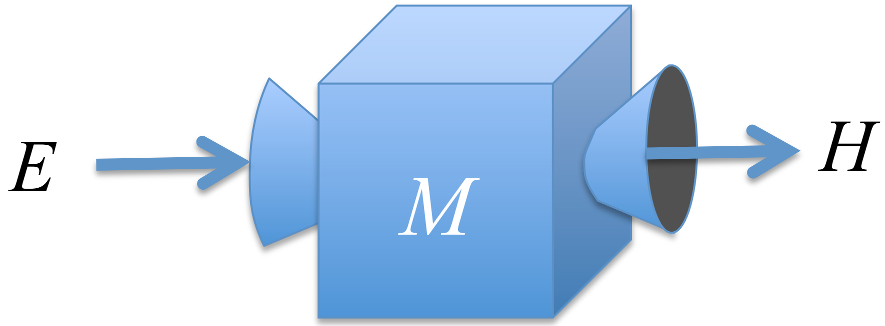
$w \in \mathrm{cl}(H)$ iff H contains a sequence of worlds $\mu_1, \ldots,$ $\mu_n, \ldots$ such that for every feasible sample event $Z \subseteq S$:

$$\lim_{n \to \infty} \mu_n(Z) \to \mu(Z).$$



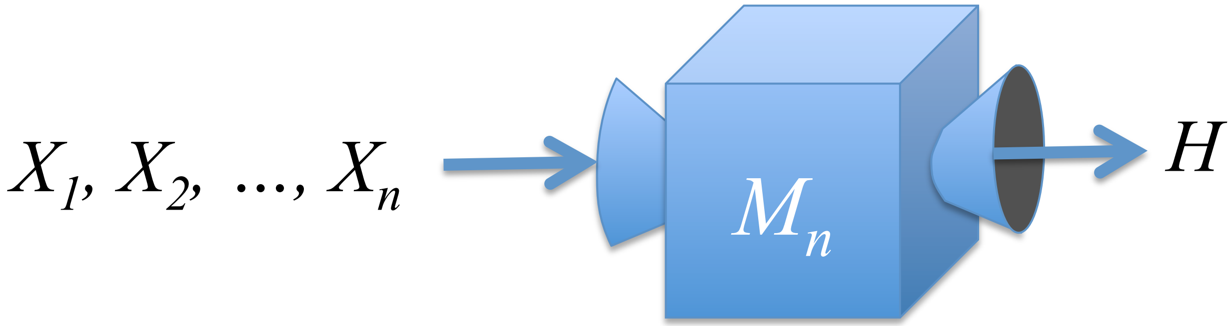
Recall: Propositional Methods

- **Propositional methods** produce propositional conclusions in response to propositional information.



Statistical Methods

- **Statistical methods** produce propositional conclusions in response to statistical samples.



Feasible Statistical Methods

A **feasible statistical method** at sample size n is a function M_n from sample events in S^n to propositions over W such that:

$$(M_n)^{-1}(H) \text{ is } \textbf{feasible}.$$

A **feasible statistical method** is a collection

$$(M_n : n \in \mathbf{N})$$

of feasible statistical methods at each sample size.

Recall: Verification Methods

- A **verification method** for H is an infallible, monotonic method V such that:
  1. $w \in H^c$ implies V always concludes W.
  2. $w \in H$ implies V converges to H.

Statistical Verification

- A **statistical verification method** for H at **significance level** $\alpha > 0$ is a feasible method $(V_n : n \geq 1)$, such that:
  1. at each sample size, outputs W with probability at least $1\text{-}\alpha$, if H is false.
  2. converges in probability to H, if H is true.

- H is **statistically verifiable** iff H has a statistical verification method at each $\alpha > 0$.

Statistical Verification

- A **statistical verification method** for H at **significance level** $\alpha > 0$ is a feasible method $(V_n : n \geq 1)$, such that:
  1. $\mu^n [V_n^{-1}(W)] \geq 1 - \alpha$, if H is false in μ;
  2. $\mu^n [V_n^{-1}(H)] \to 1$, if H is true in μ.

- H is **statistically verifiable** iff H has a statistical verification method at each $\alpha > 0$.

Recall: Verification in the Limit

- A **limiting verification method** for H is a method M such that in every world w:

  H is true in w iff M converges to some true H' that entails H.

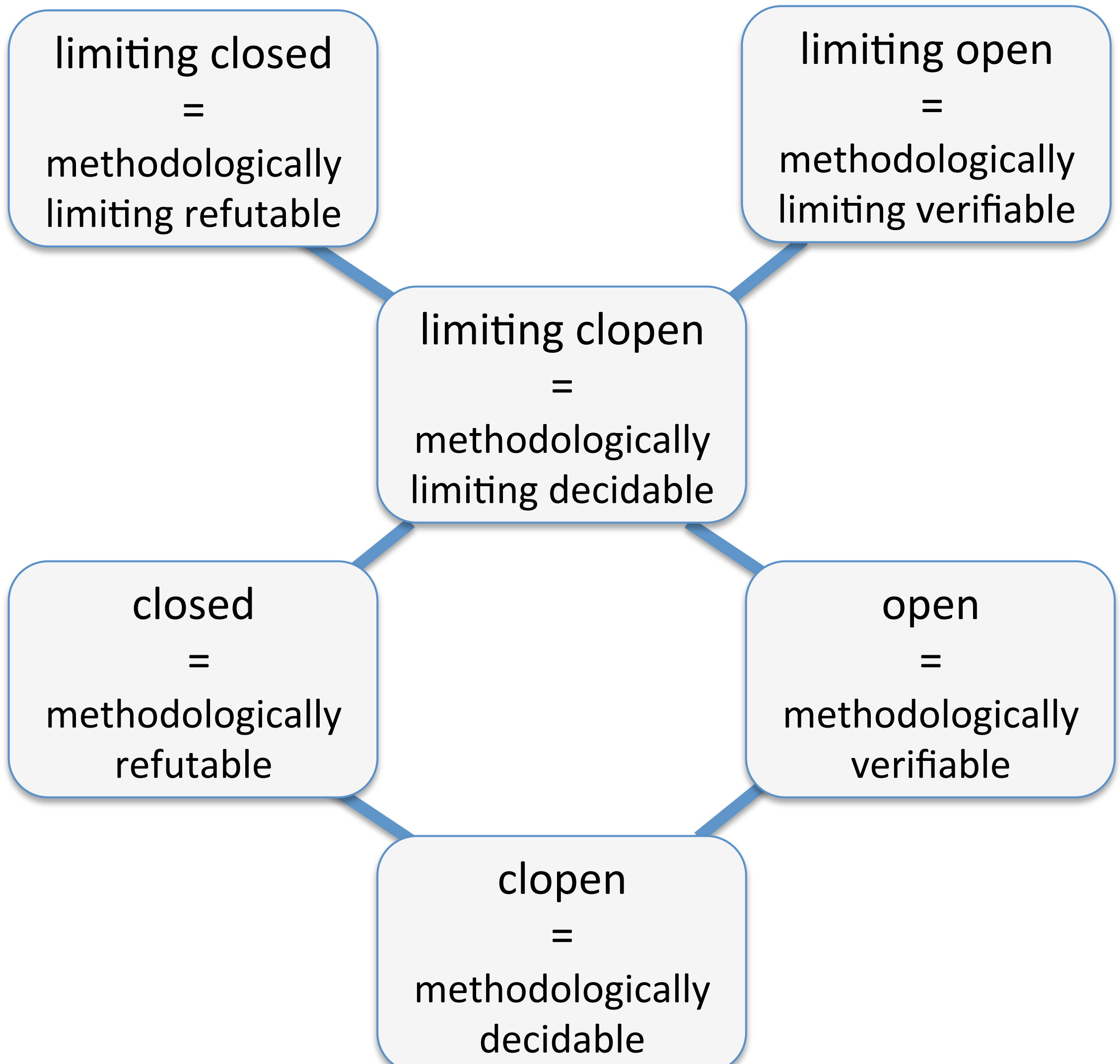
- H is **verifiable in the limit** iff H has a limiting verifier.

Statistical Verification in the Limit

- A **limiting statistical verification method** for H
  - converges in probability to some H' entailing H iff H is true.

- H is **statistically verifiable in the limit** iff H has a limiting statistical verifier.

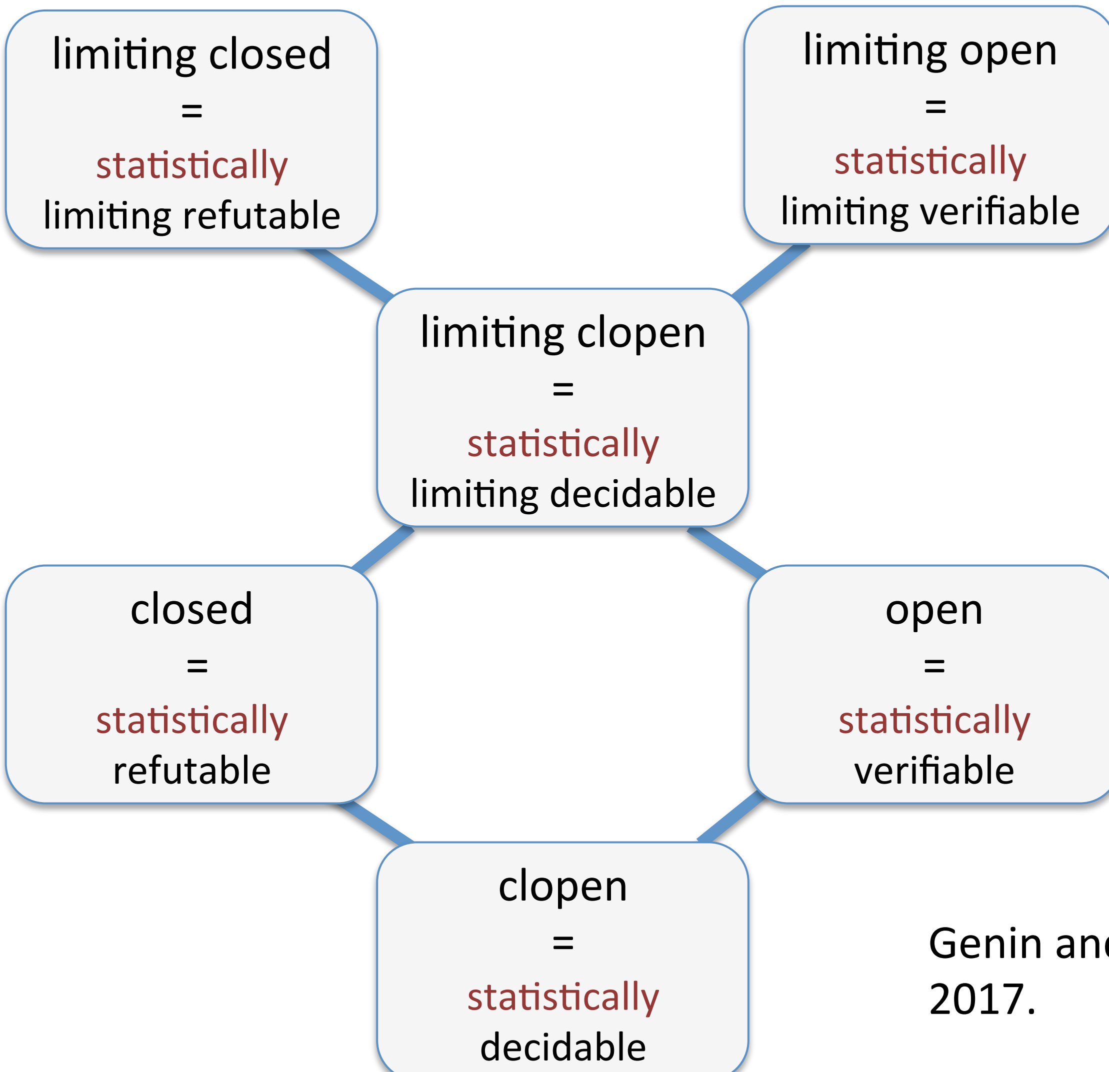
The Propositional Hierarchy



The Main Result

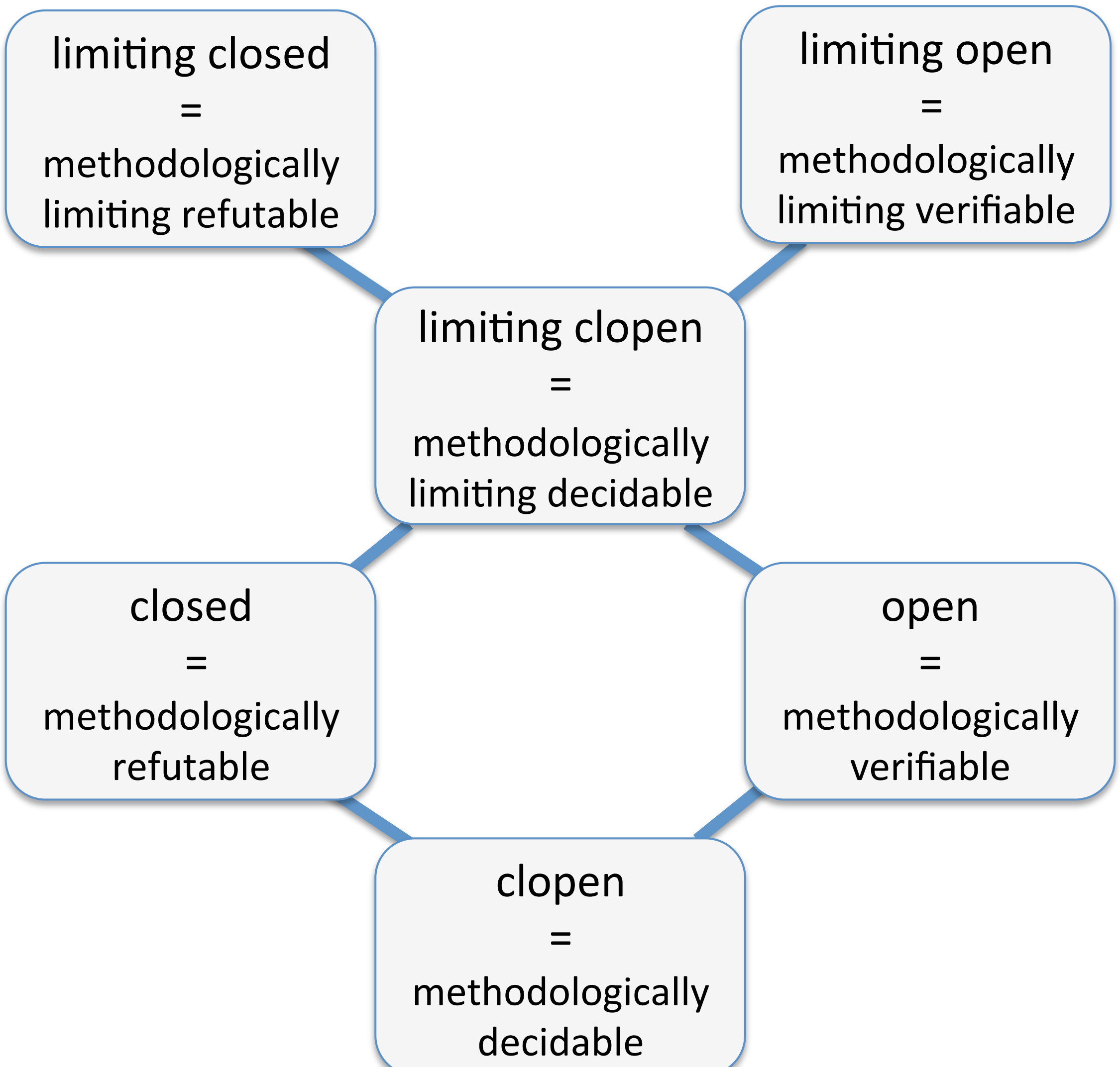
Proposition. (Genin, Kelly 2017) Suppose that S is feasible for W. Then, the open sets in the weak topology are exactly the statistically verifiable hypotheses.

The Statistical Hierarchy



Genin and Kelly, 2017.

So in Both Logic and Statistics:



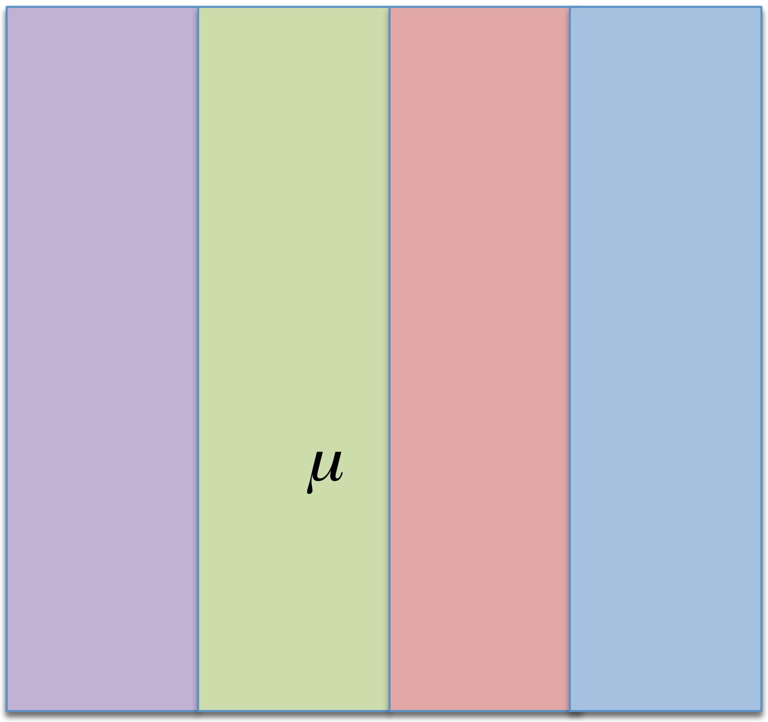
The Topological Bridge

The Topological Bridge

- Start with logical insights.
- Allow methods a small chance α of error.
- Obtain corresponding statistical insights

Statistical Problem

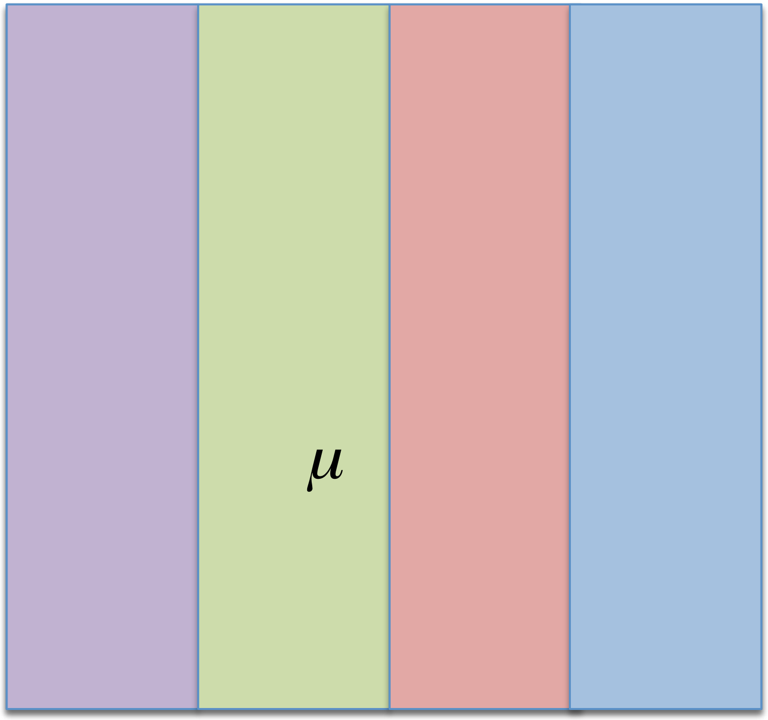
A statistical question partitions a set of probability measures into countably many answers.



Statistical Solutions

A statistical method (M_n) is a solution to Q iff for all μ

$$\mu^n[M_n^{-1}(\mathcal{Q}(\mu))] \overset{n}{\to} 1.$$



Recall: Ockham's Razor

Proposition (Genin and Kelly, 2016). The following principles are **equivalent**.

1. Infer a **simplest** relevant response in light of E.
2. Infer a **refutable** relevant response compatible with E.
3. Infer a relevant response that is **not more complex than the true answer**.

Ockham's Statistical Razor

Concern: "consistency with E" is trivial in statistics.

Response: the "err on the side of simplicity" version of Ockham's razor does not mention consistency with E.

3. Infer a relevant response that is more complex than the true answer **with chance < α**.

Ockham's Statistical Razor

A solution (M_n) to $\mathcal{Q}$ satisfies **Ockham's α-razor** iff

$$\text{if } A \in \mathcal{Q} \text{ and } \mathcal{Q}(\mu) \lhd A, \text{ then } \mu^n[M_n^{-1}(A)] < \alpha.$$

Progressive Methods

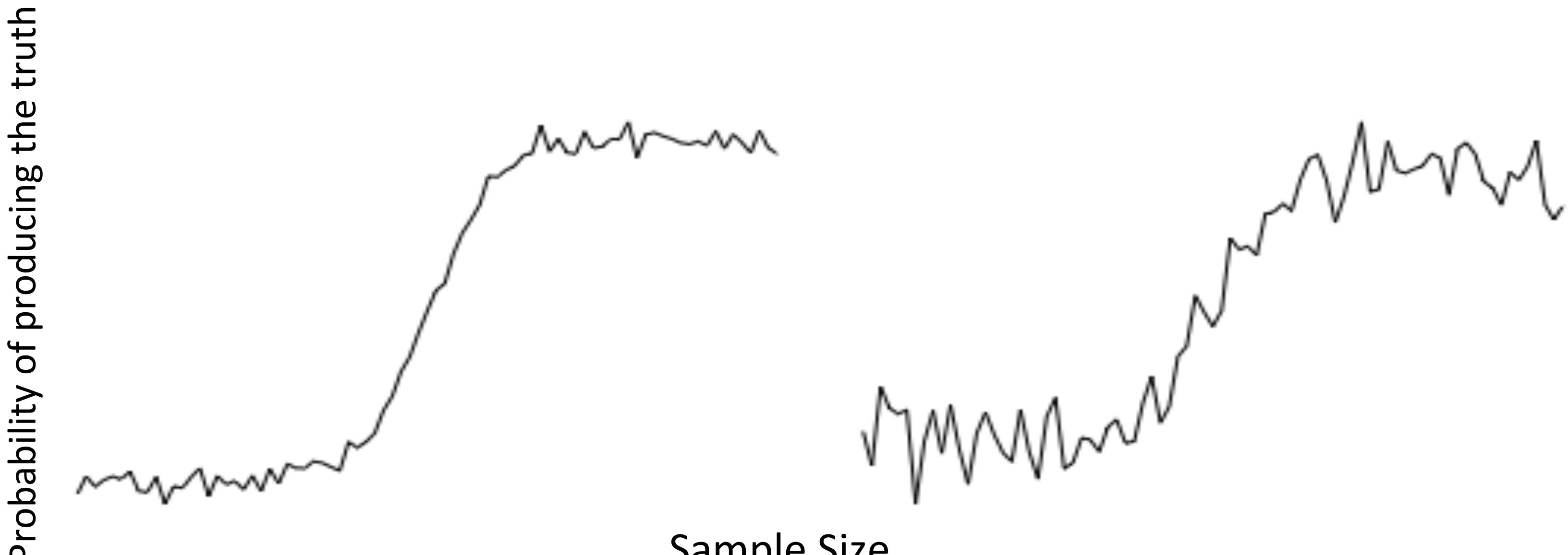
A solution (M_n) to question Q is progressive if the chance that it outputs the true answer is strictly increasing with sample size, i.e. for all $n_1 < n_2$:

$$\mu^{n_2}[M_{n_2}^{-1}(\mathcal{Q}(\mu))] > \mu^{n_1}[M_{n_1}^{-1}(\mathcal{Q}(\mu))].$$

α-Progressive Methods

- (M_n) is α-progressive if the chance that it outputs the true answer never decreases by more than α, i.e. for $n_1 < n_2$:

$$\mu^{n_2}[M_{n_2}^{-1}(\mathcal{Q}(\mu))] + \alpha > \mu^{n_1}[M_{n_1}^{-1}(\mathcal{Q}(\mu))].$$



Progressive Methods

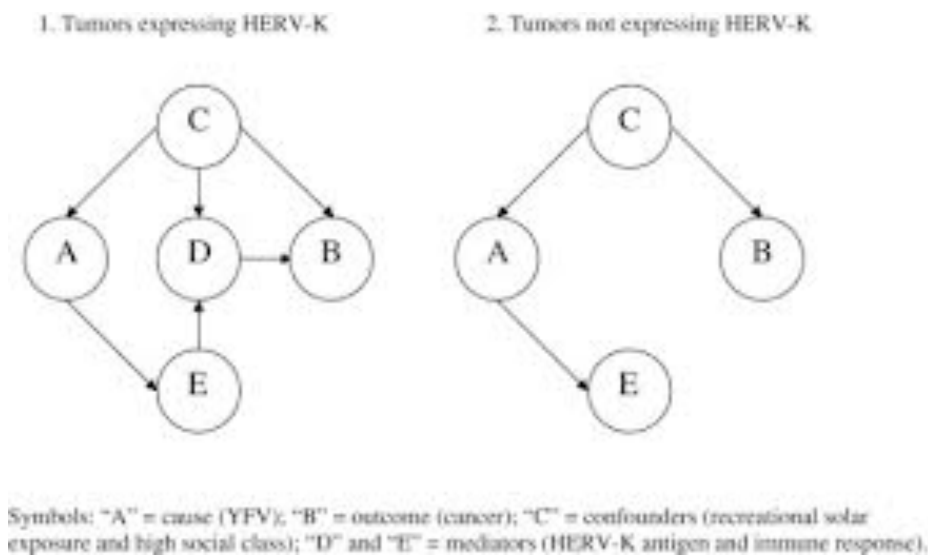
Theorem (Genin, 2017)**:** If there exists an enumeration $A_1, A_2, \ldots$ of the answers to Q that agrees with the simplicity order, then there exists an α-progressive method for every $\alpha > 0$.

Ockham and Progress

Theorem (Genin, 2017)**:** Every α-progressive solution satisfies Ockham's α-razor.

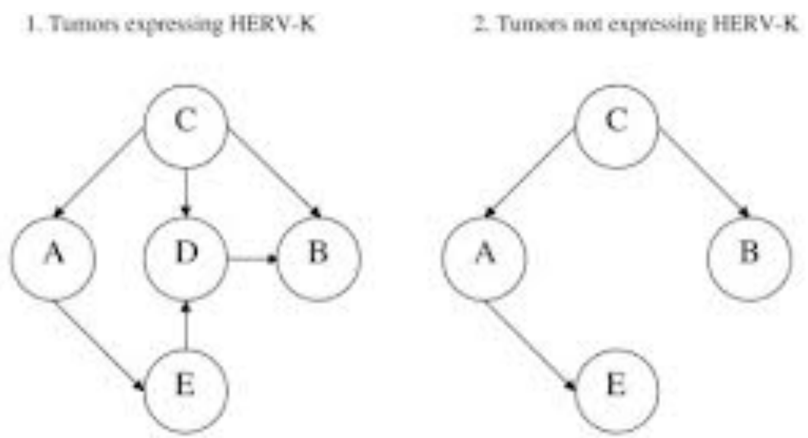
Application: Causal Inference from Non-experimental Data

- **Causal** inference from **observational** data.
- The search is strongly guided by **Ockham's razor**.
- Previously, methods were only proven to be point-wise-consistent.



Application: Causal Inference from Non-experimental Data

Proposition (Genin, 2018)**.** For the problem of inferring Markov equivalence classes, there exist α-progressive solution for every $\alpha > 0$.



Symbols: "A" = cause (YFV); "B" = outcome (cancer); "C" = confounders (recreational solar exposure and high social class); "D" and "E" = mediators (HERV-K antigen and immune response).

Thank you!