
Lecture 8&9: Computational Cognitive Modeling

Bayesian Modeling

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The problem of induction

A mug?

A mug on a table?

Coffee?

A white mug on a white marble table?

3 pm?

Smell?

Handle?

Marble?

White objects?

A beverage?

“gavagai”

A mug filled with coffee?

Location?

Ceramics?

Original thought experiment due to W. V. Quine (1960).

The problem of induction

now you get more data...

A mug?

A mug on a table?

Coffee?

A white mug on a white marble table?

3 pm?

Handle?

Marble?

Smell?

White objects?

A beverage?

“gavagai”

A mug filled with coffee?

Location?

Ceramics?

Review: an argument for the need for biases

If totally unbiased generalization systems are incapable of making the inductive leap to characterize the new instances, then **the power of a generalization system follows directly from its biases – from decisions based on criteria other than consistency with the training instances**. Therefore, progress toward understanding learning mechanisms depends upon understanding the sources of, and justification for, various biases.

Mitchell (1980)

possible biases



Domain knowledge

Intended use/goal of generalization (e.g., cost of being incorrect... i.e., risk sensitive)

Knowledge about the source of training data
Biases towards simplicity/generality

Analogy with previous generalizations

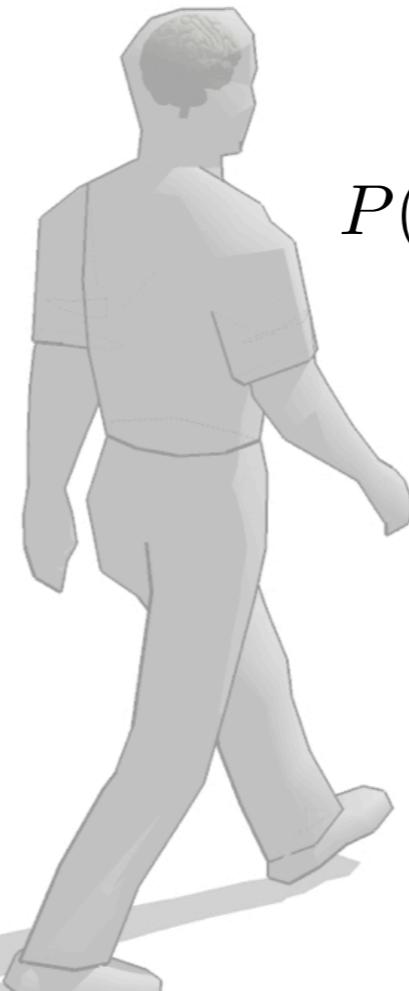
Bayesian modeling is an approach for understanding inductive problems, and it typically takes a strong “top-down” strategy

Three levels of description (*David Marr, 1982*)

Computational

Why do things work the way they do?
What is the goal of the computation?
What are the unifying principles?

$$P(h_i|D) = \frac{P(D|h_i)P(h_i)}{\sum_j P(D|h_j)P(h_j)}$$

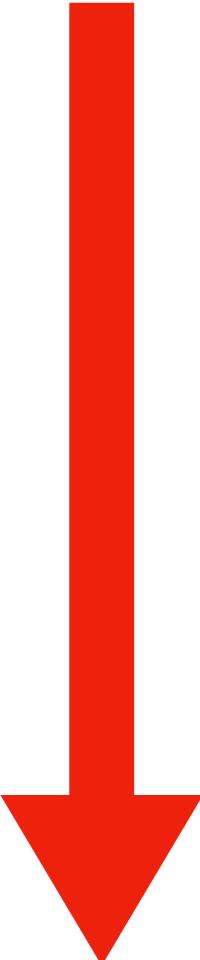


Algorithmic

What representations can implement such computations?
How does the choice of representations determine the algorithm?

Implementational

How can such a system be built in hardware?
How can neurons carry out the computations?



Key principles of Bayesian models of cognition

- Start with analyzing the computational problem that has to be solved, and describe it as a problem of Bayesian inference
- A successful computational level model provides strong constraints when developing an algorithmic and implementational level model
- Bayesian inference provides a flexible framework for testing different hypotheses about representation, without having to worry about how to define special algorithms for inference and learning

Bayesian inference for evaluating hypotheses in light of data

Data (D): John is coughing

“Bayes’ rule”

Hypotheses:

h_1 = John has a cold

h_2 = John has emphysema

h_3 = John has a stomach flu

posterior

likelihood

prior

$$P(h_i|D) = \frac{P(D|h_i)P(h_i)}{\sum_j P(D|h_j)P(h_j)}$$

Which hypotheses should we believe, and with what certainty?

We want to calculate the posterior probabilities: $P(h_1|D)$, $P(h_2|D)$, and $P(h_3|D)$

Bayesian inference

Data (D): John is coughing

$$P(h_i|D) = \frac{P(D|h_i)P(h_i)}{\sum_j P(D|h_j)P(h_j)}$$

posterior likelihood prior
↓ ↓ ↓

Hypotheses:

h_1 = John has a cold

h_2 = John has emphysema

h_3 = John has a stomach flu

$$P(h_1) = .75 \quad P(D|h_1) = 1$$

$$P(h_2) = .05 \quad P(D|h_2) = 1$$

$$P(h_3) = .2 \quad P(D|h_3) = .2$$

Prior favors h_1 and h_3 , over h_2

Likelihood favors h_1 and h_2 , over h_3

Posterior favors h_1 , over h_2 and h_3

$$P(h_1|D) = .89 = \frac{.75(1)}{.75(1) + .05(1) + .2(.2)}$$

$$P(h_2|D) = .06$$

$$P(h_3|D) = .05$$

Where does Bayes' rule come from?

Definition of conditional probability:

$$P(a|b) = \frac{P(a,b)}{P(b)}$$

“product rule”

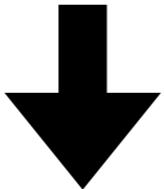
$$P(a,b) = P(a|b)P(b)$$

Derivation

$$P(h,D) = P(h|D)P(D)$$

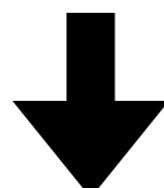
product rule applied
twice

$$P(h,D) = P(D|h)P(h)$$



$$P(h|D)P(D) = P(D|h)P(h)$$

Equating the two right
hand sides



$$P(h|D) = \frac{P(D|h)P(h)}{P(D)} = \frac{P(D|h)P(h)}{\sum_{h'} P(D|h')P(h')}$$

Divide by $P(D)$

Why is this a reasonable way to represent beliefs?

- If your beliefs are inconsistent with axioms of probability, someone can take advantage of you in gambling (see example from Russel and Norvig reading)

Agent 1		Agent 2		Outcome for Agent 1			
Proposition	Belief	Bet	Stakes	$a \wedge b$	$a \wedge \neg b$	$\neg a \wedge b$	$\neg a \wedge \neg b$
a	0.4	a	4 to 6	-6	-6	4	4
b	0.3	b	3 to 7	-7	3	-7	3
$a \vee b$	0.8	$\neg(a \vee b)$	2 to 8	2	2	2	-8
				-11	-1	-1	-1

Figure 13.2 Because Agent 1 has inconsistent beliefs, Agent 2 is able to devise a set of bets that guarantees a loss for Agent 1, no matter what the outcome of a and b .

- Bayes' rule provides a very general account of learning, where prior knowledge can be combined with data to update beliefs

Bayesian concept learning with the number game

Rules and Similarity in Concept Learning

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In *Advances in neural information processing systems* (1999)

Abstract

This paper argues that two apparently distinct modes of generalizing concepts – abstracting rules and computing similarity to exemplars – should both be seen as special cases of a more general Bayesian learning framework. Bayes explains the specific workings of these two modes – which rules are abstracted, how similarity is measured – as well as why generalization should appear rule- or similarity-based in different situations. This analysis also suggests why the rules/similarity distinction, even if not computationally fundamental, may still be useful at the algorithmic level as part of a principled approximation to fully Bayesian learning.

(You will work with this model in homework 4)

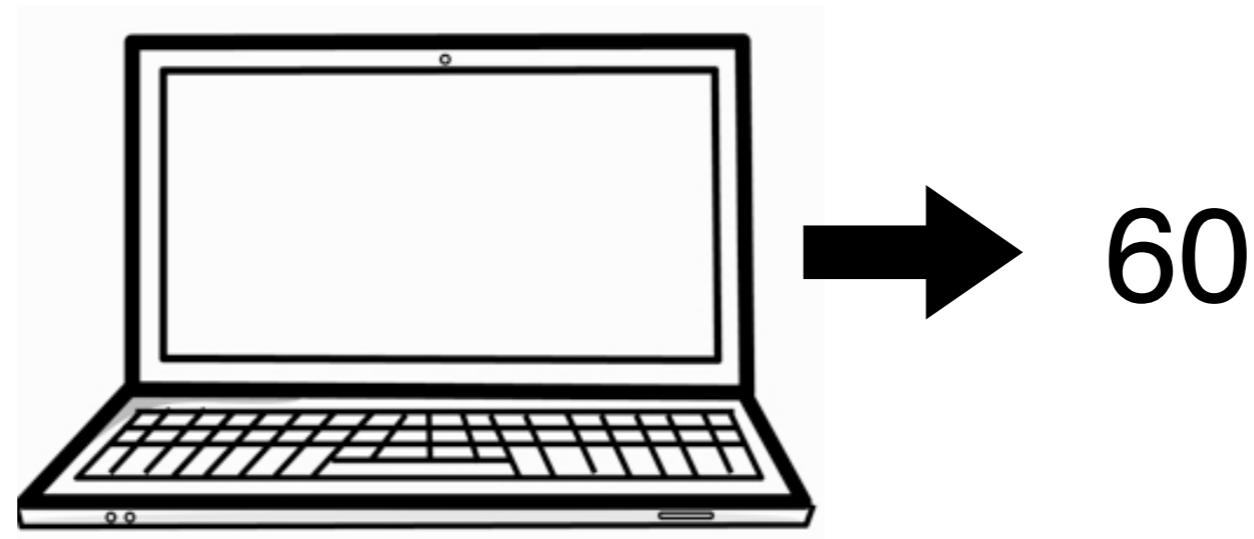
1 Introduction

In domains ranging from reasoning to language acquisition, a broad view is emerging of cognition as a hybrid of two distinct modes of computation, one based on applying abstract rules and the other based on assessing similarity to stored exemplars [7]. Much support for this view comes from the study of concepts and categorization. In generalizing concepts, people's judgments often seem to reflect both rule-based and similarity-based computations [9], and different brain systems are thought to be involved in each case [8]. Recent psychological models of classification typically incorporate some combination of rule-based and similarity-based modules [1,4]. In contrast to this currently popular modularity position, I will argue here that rules and similarity are best seen as two ends of a continuum of possible concept representations. In [11,12], I introduced a general theoretical framework to account

The number game

There is an unknown computer program that generates numbers in the range 1 to 100. You are provided with a small set of random examples from this program.

1 random “yes” example



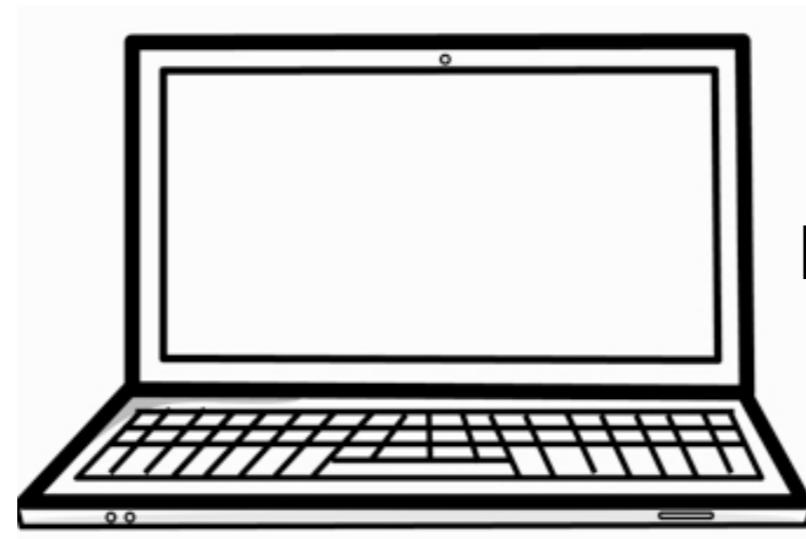
Which numbers will be accepted by the same computer program?

51? 58? 20?

The number game

There is an unknown computer program that generates numbers in the range 1 to 100. You are provided with a small set of random examples from this program.

4 random “yes” examples



60 80 10 30

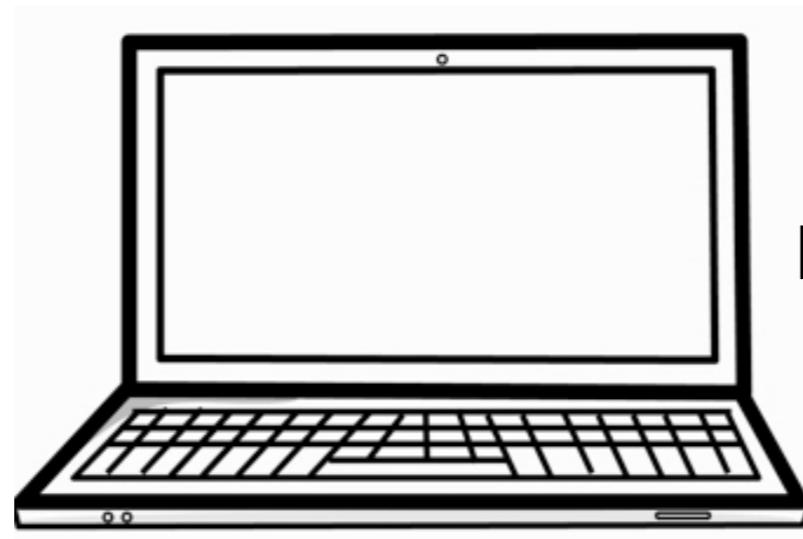
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The number game

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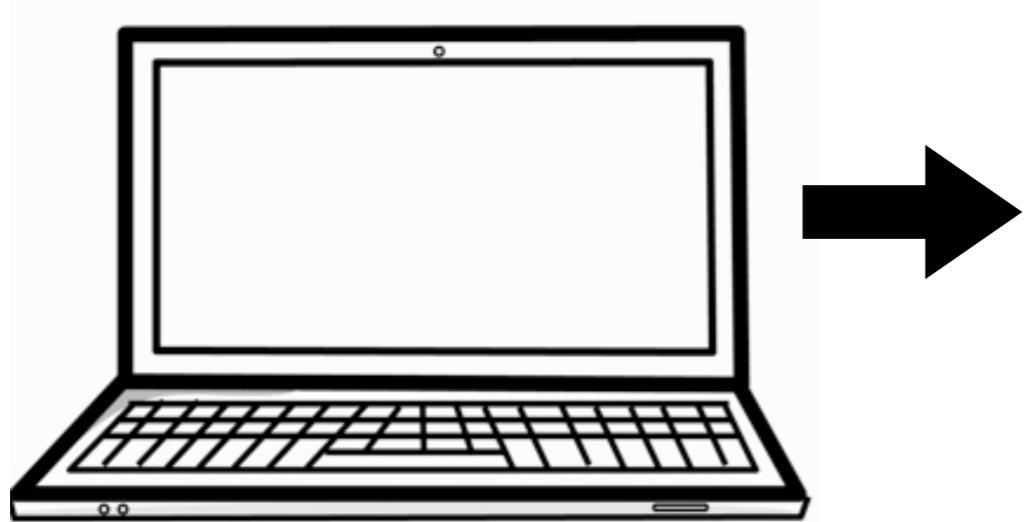
60 52 57 55

Which numbers will be accepted by the same computer program?

51? 58? 20?

A Bayesian model of the number game

random “yes” examples of an **unknown concept C**



Observations

$$X = \{x^{(1)}, \dots, x^{(n)}\}$$

60 52 57 55

Predictions:

Which numbers y will be accepted by the same computer program C ?

$$P(y \in C \mid X)$$

51? 58? 20?

A Bayesian model of the number game

We have observations:

$$X = \{x^{(1)}, \dots, x^{(n)}\}$$

We have a space of hypotheses, which are sets of numbers $h \in H$

and prior $P(h)$ (more details next slide)

- *mathematical hypotheses*: odd numbers ($h = [1, 3, 5, \dots, 99]$), even numbers ($h = [2, 4, 6, \dots, 100]$), square numbers ($h = [1, 4, 9, 16]$), cube numbers, primes, multiples of n, etc.
- *interval hypotheses*: continuous intervals of the number line

Likelihood $P(X|h)$

$$P(X|h) = \prod_{i=1}^n P(x^{(i)}|h)$$

(assumption that examples are independent)

$$\begin{aligned} P(x^{(i)}|h) &= \frac{1}{|h|} \text{ if } x^{(i)} \in h \\ &= 0 \text{ otherwise} \end{aligned}$$

$|h|$ is the “size” of h

Bayes’ rule for computing posterior beliefs:

$$P(h|X) = \frac{P(X|h)P(h)}{\sum_{h' \in H} P(X|h')P(h')}$$

A Bayesian model of the number game

The hypothesis space and prior

Mathematical hypotheses

- odd numbers
- even numbers
- square numbers
- cube numbers
- primes
- multiples of n, such that $3 \leq n \leq 12$
- powers of n, such that $2 \leq n \leq 10$
- numbers ending in n, such that $0 \leq n \leq 9$

(Mathematical hypotheses are
equally likely in the prior)

$$P(h)$$

Interval hypotheses

- Intervals between n and m, such that $1 \leq n \leq 100$; $n \leq m \leq 100$

(Interval hypotheses reweighted to
favor intermediate sizes) $P(h)$

λ is free parameter that trades off “math” vs. “interval” hypotheses

A Bayesian model of the number game

We have observations:

$$X = \{x^{(1)}, \dots, x^{(n)}\}$$

We want to make predictions for new numbers y :

$$P(y \in C \mid X)$$

Bayes' rule for computing posterior beliefs:

$$P(h|X) = \frac{P(X|h)P(h)}{\sum_{h' \in H} P(X|h')P(h')}$$

Posterior predictions about new example y :

$$P(y \in C \mid X) = \sum_{h \in H} P(y \in C \mid h)P(h|X)$$

first term is 1 or 0 based on membership

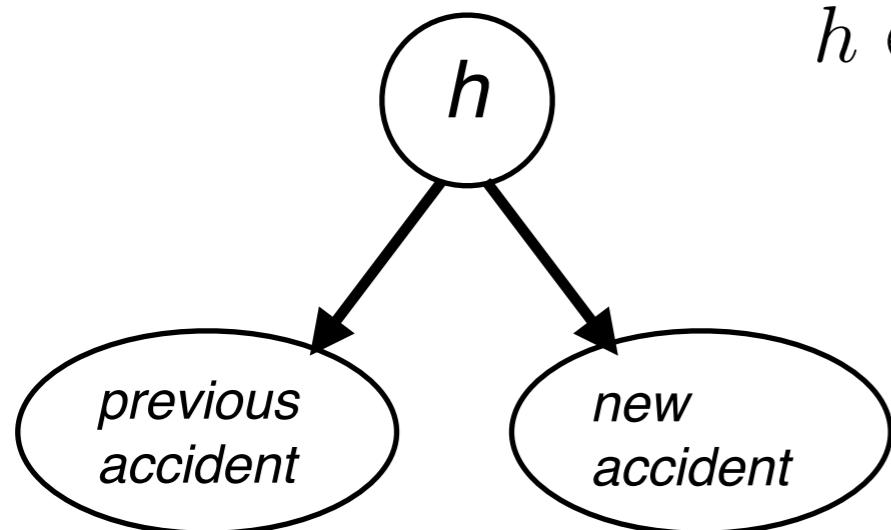
Bayesian hypothesis averaging : when making Bayesian predictions, one must average over all possible hypotheses, weighted by their posterior belief

Examples: Bayesian hypothesis averaging

Say you are an insurance company, and you want to predict which customers are more likely to get into a car accident.

$$P(\text{new accident} | \text{previous accident}) = \sum_h P(\text{new accident}|h)P(h|\text{previous accident})$$

$$h \in \{\text{good driver, bad driver}\}$$



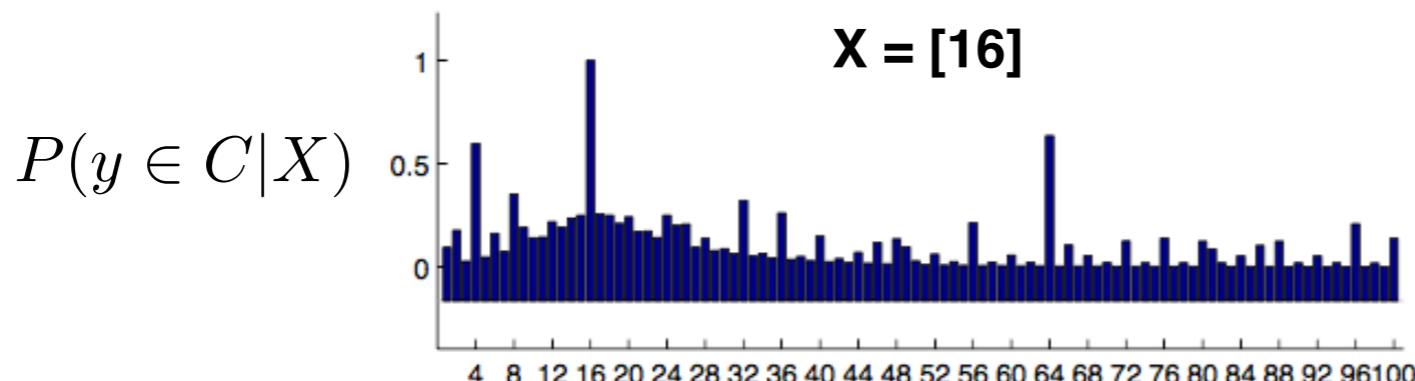
also known as “marginalization” of a variable (h)

Another example (the previous evidence does not necessarily need to be relevant)

$$P(\text{new accident} | \text{born in Feb.}) = \sum_h P(\text{new accident}|h)P(h|\text{born in Feb.})$$

$$h \in \{\text{good driver, bad driver}\}$$

The **size principle**: hypotheses with smaller extensions are more likely than hypotheses with larger extensions



Likelihood

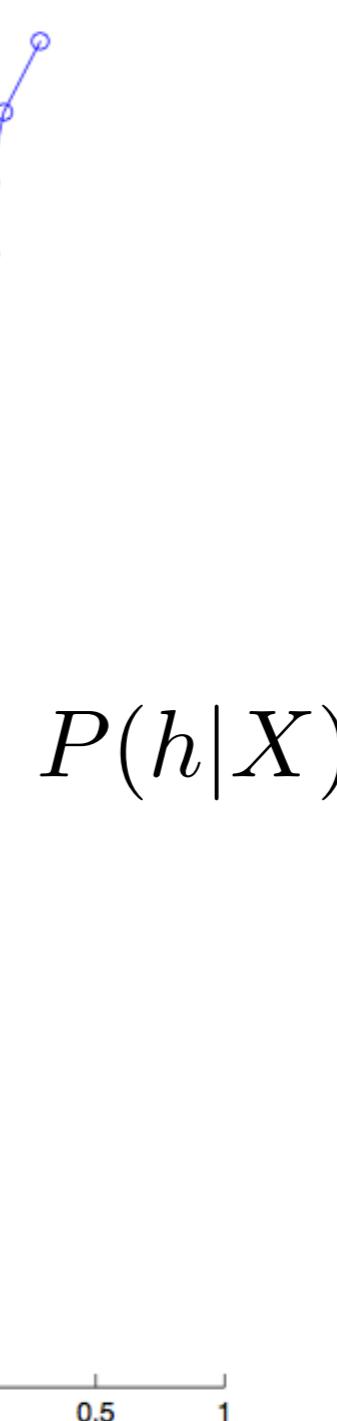
$$P(x^{(i)}|h) = \begin{cases} \frac{1}{|h|} & \text{if } x^{(i)} \in h \\ 0 & \text{otherwise} \end{cases}$$

Most likely hypotheses

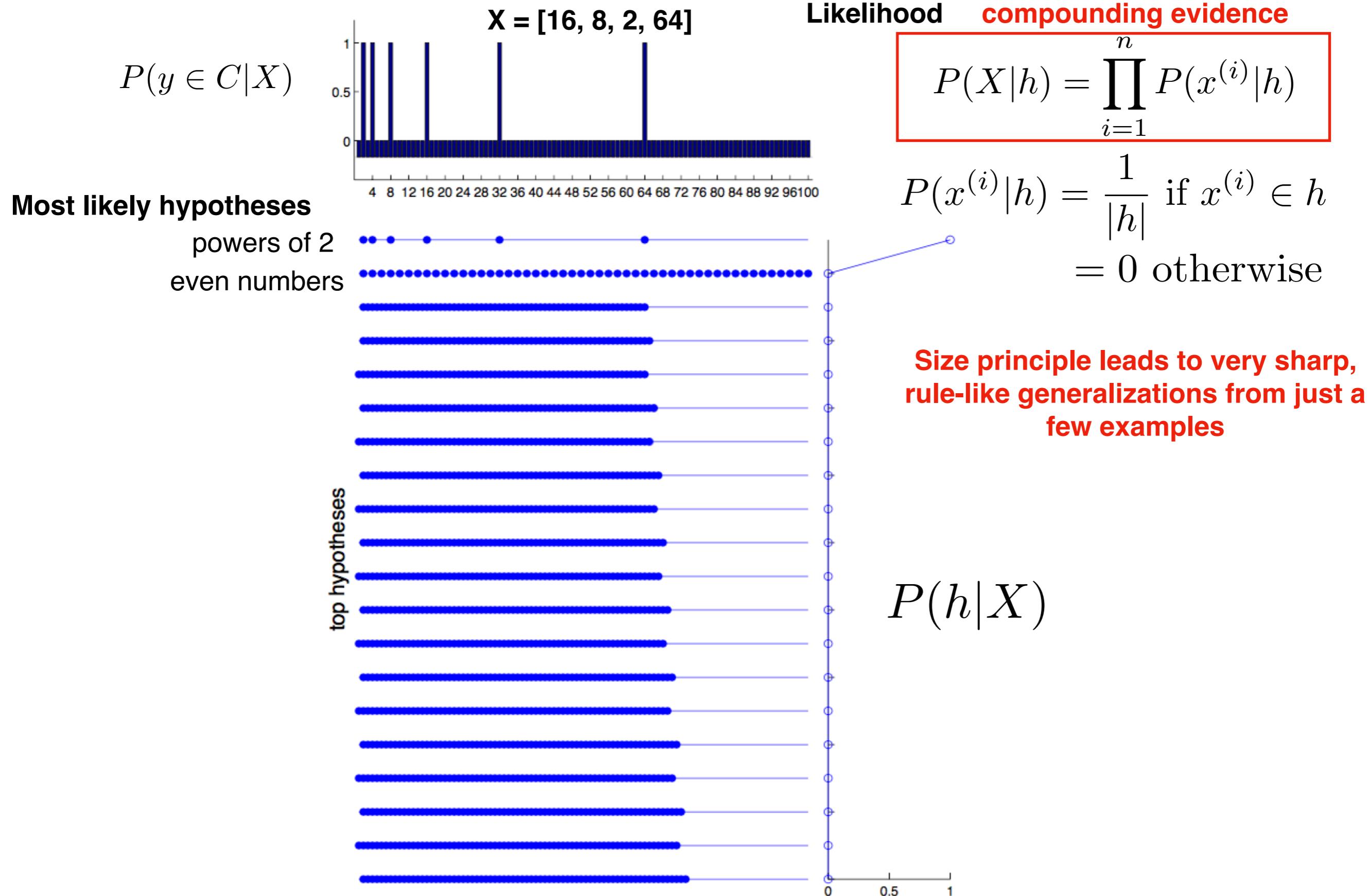
powers of 4
powers of 2
numbers ending in 6
square numbers

even numbers

top hypotheses



The **size principle**: hypotheses with smaller extensions are more likely than hypotheses with larger extensions



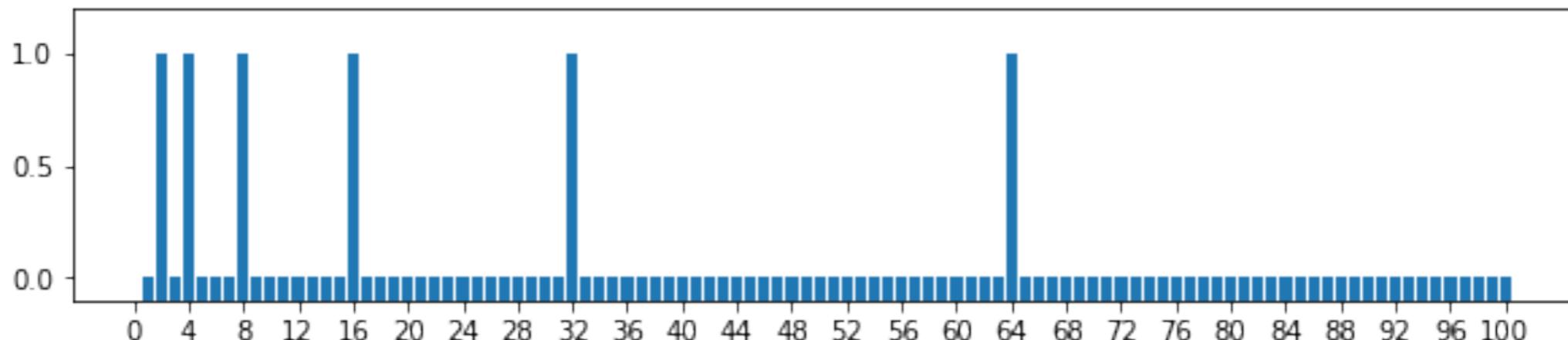
How the size principle influences generalization

With size principle (strong sampling):

$$P(x^{(i)}|h) = \begin{cases} \frac{1}{|h|} & \text{if } x^{(i)} \in h \\ 0 & \text{otherwise} \end{cases}$$

$P(y \in C|X)$

$X=[16, 8, 2, 64]$

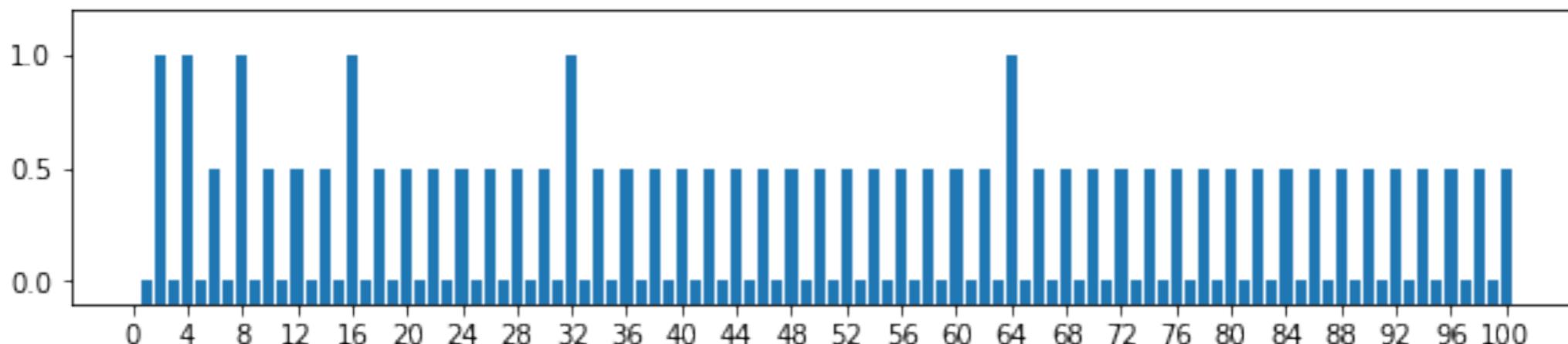


Without size principle (weak sampling):

$$P(X|h) = \begin{cases} 1 & \text{if } x^{(i)} \in h \text{ for all } i \\ 0 & \text{otherwise} \end{cases}$$

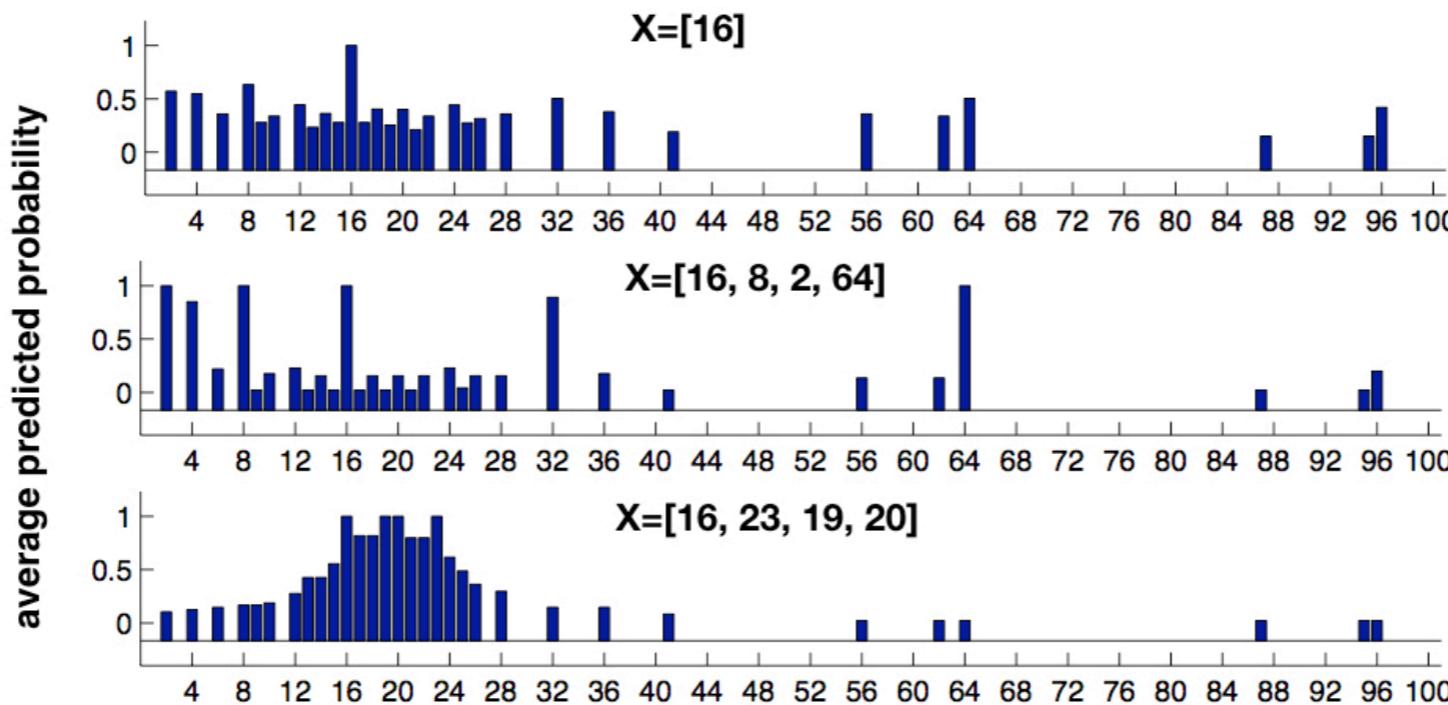
$P(y \in C|X)$

$X=[16, 8, 2, 64]$



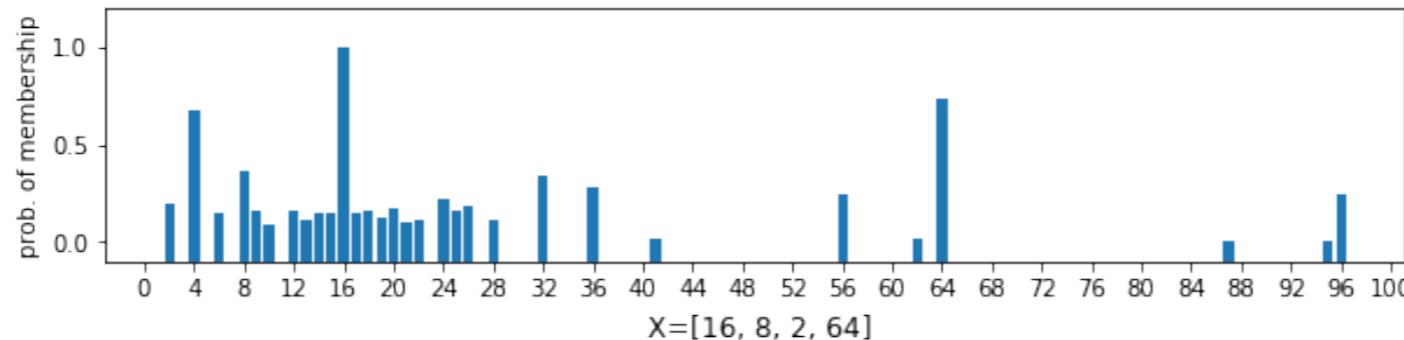
Human vs. model predictions in the number game

Human judgments in number game

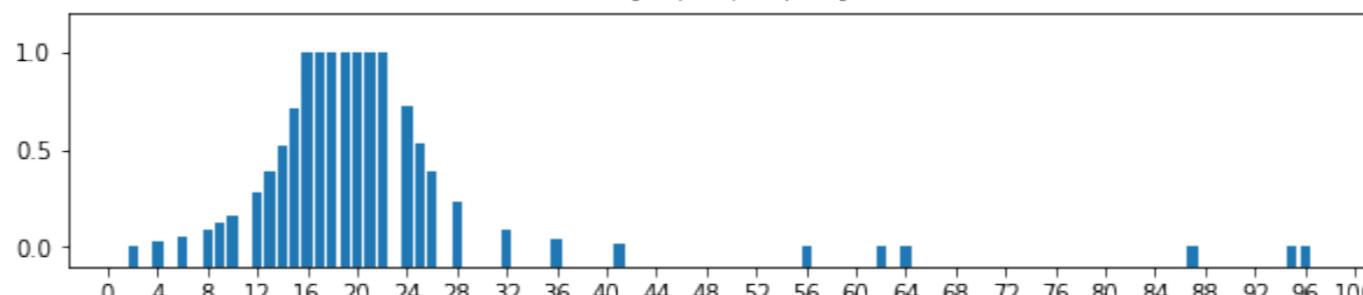
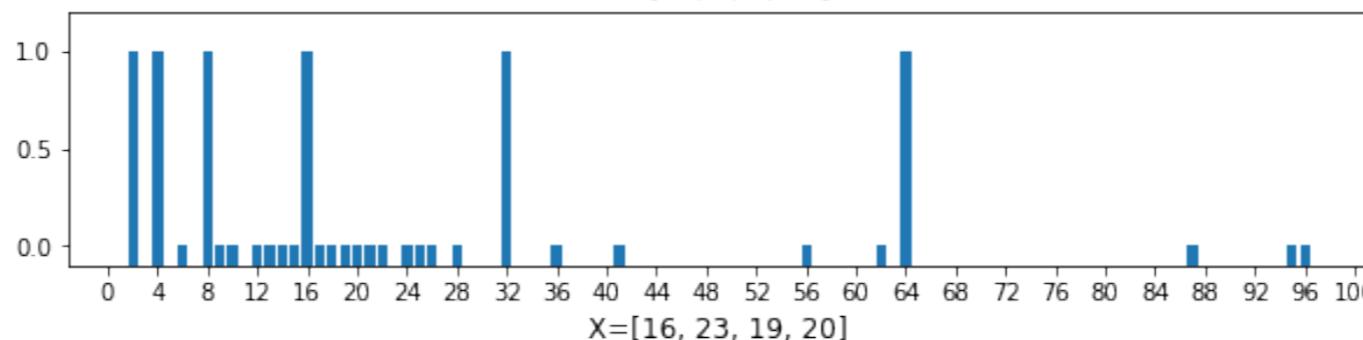


Predictions of Bayesian model (strong sampling)

X=[16]

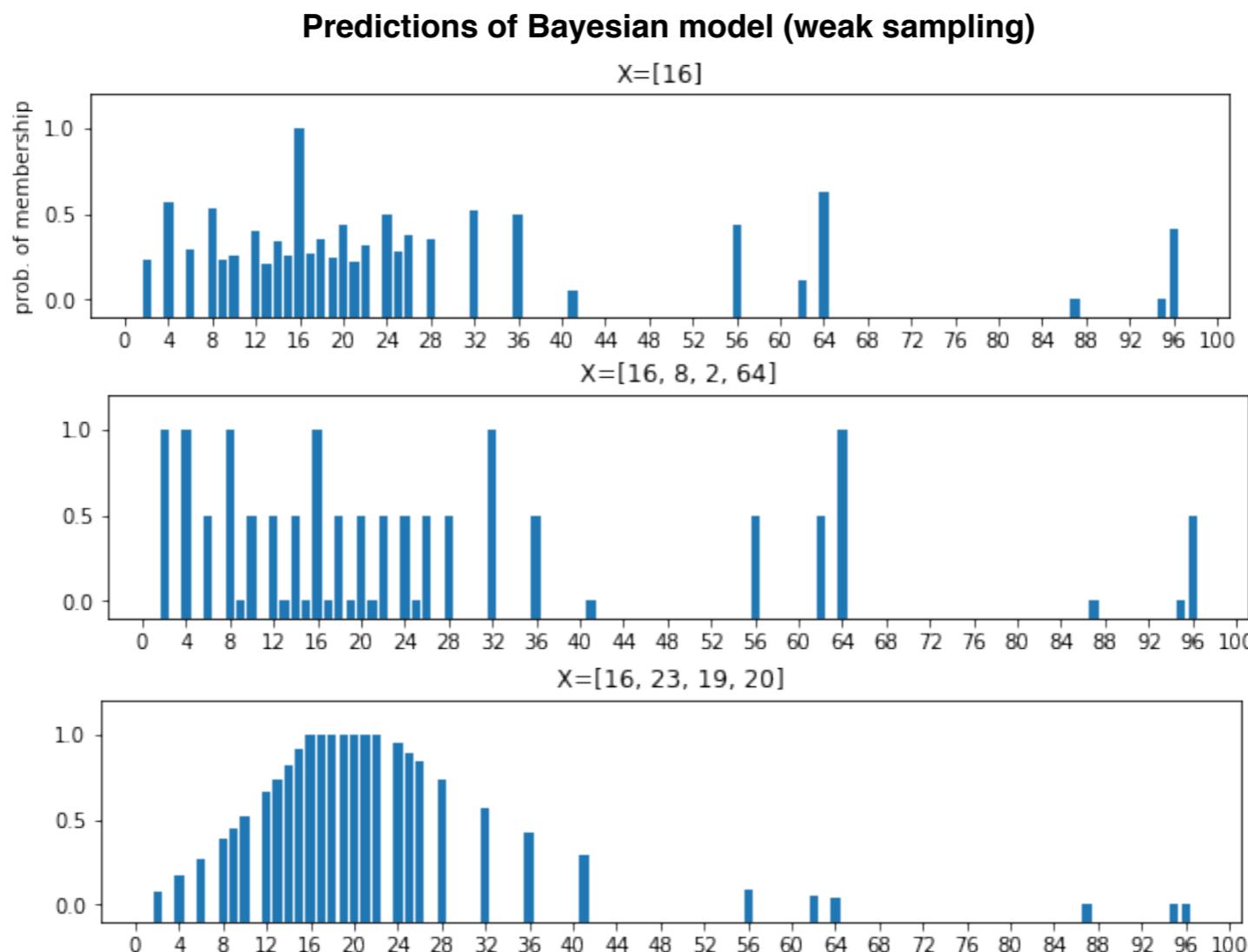
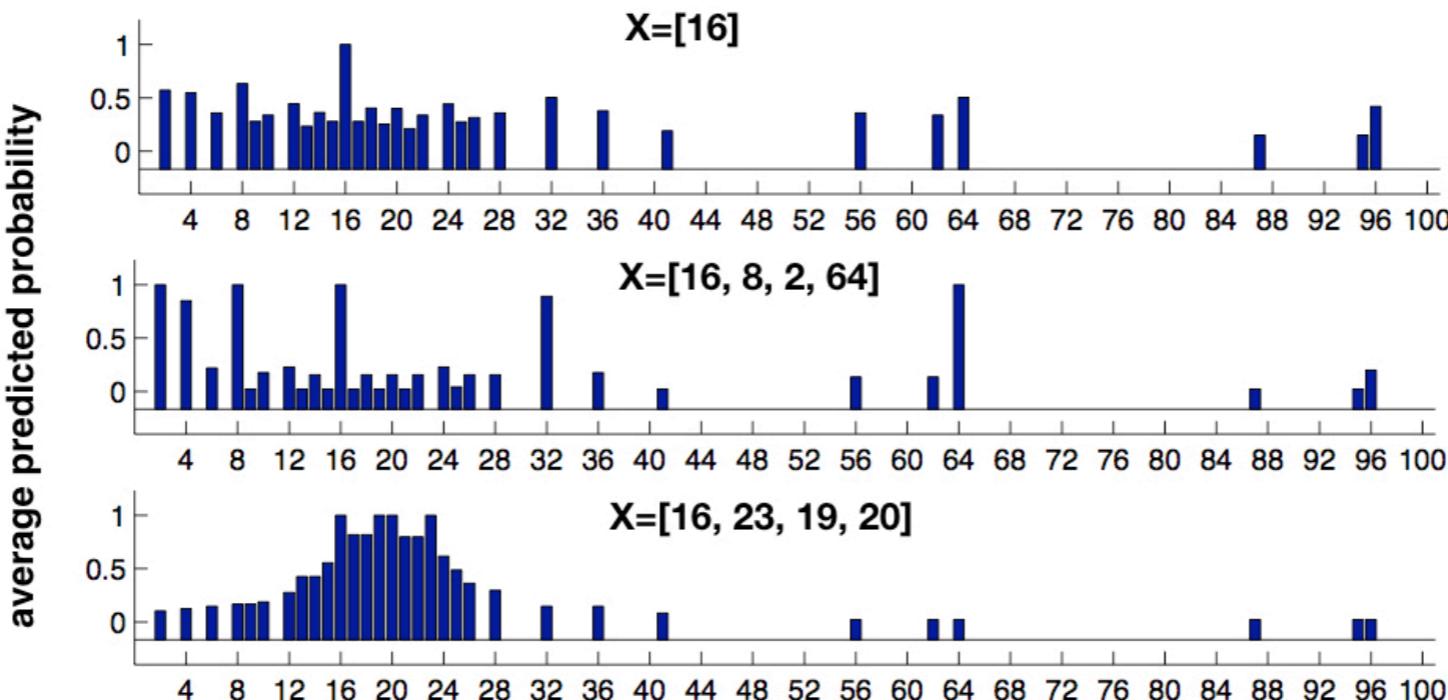


X=[16, 23, 19, 20]



Human vs. model predictions in the number game (weak sampling)

Human judgments in number game



(weak sampling does not capture the sharpness of people's generalization curves)

Conclusions from Bayesian concept learning and the number game

- People can make meaningful predictions from very sparse evidence, aided by strong assumptions for how the data is generated (strong sampling)
- People display a mixture of both “rule-like” and “similarity-like” generalizations, depending on what the data entails
- A Bayesian account of concept learning displays both of these characteristics, and can make quantitative predictions regarding how people generalize to new examples.
- Discussion point: Where does the hypothesis space come from?

Word learning as Bayesian inference

(Xu and Tenenbaum, 2007, *Psychological Review*)

Prompt: “This is a dax”



**Training
examples:**

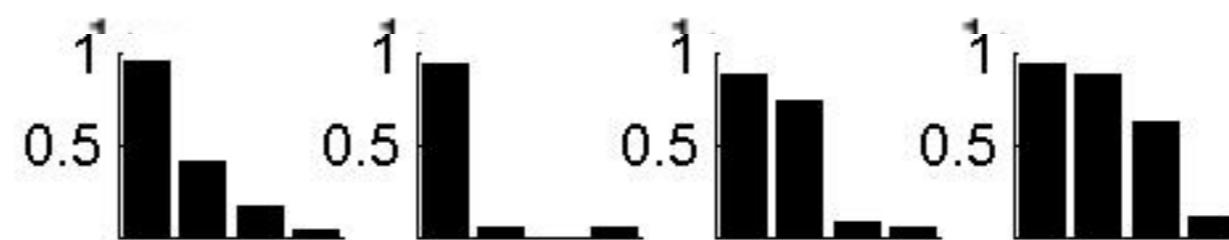
1

3 subordinate

3 basic

3 superordinate

Children's
generalizations



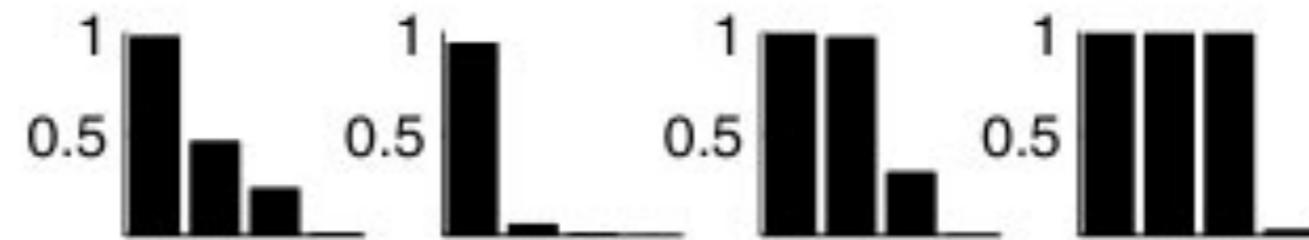
**Test object
match level:**
subord.
basic
superord.
nonmatch

...

...

...

Bayesian
concept learning with
tree-structured
hypothesis space

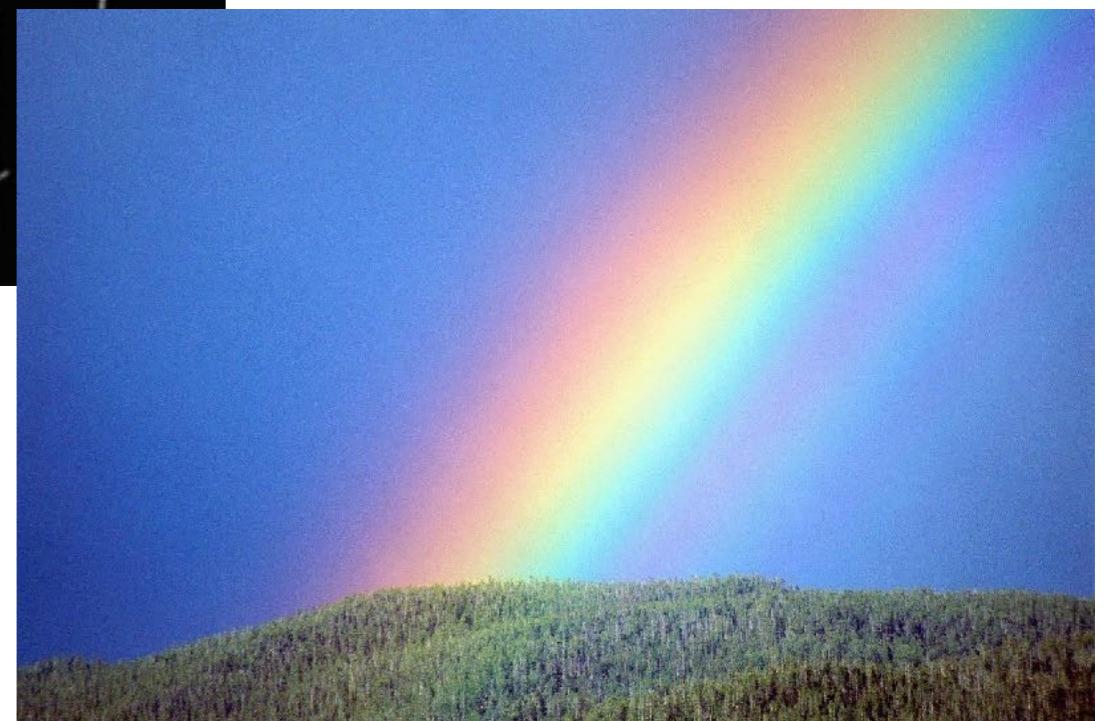


Slide credit: Josh Tenenbaum

Categorical perception: A link between categorization and perception/discrimination



From Goldstone and Hendrickson (2009)

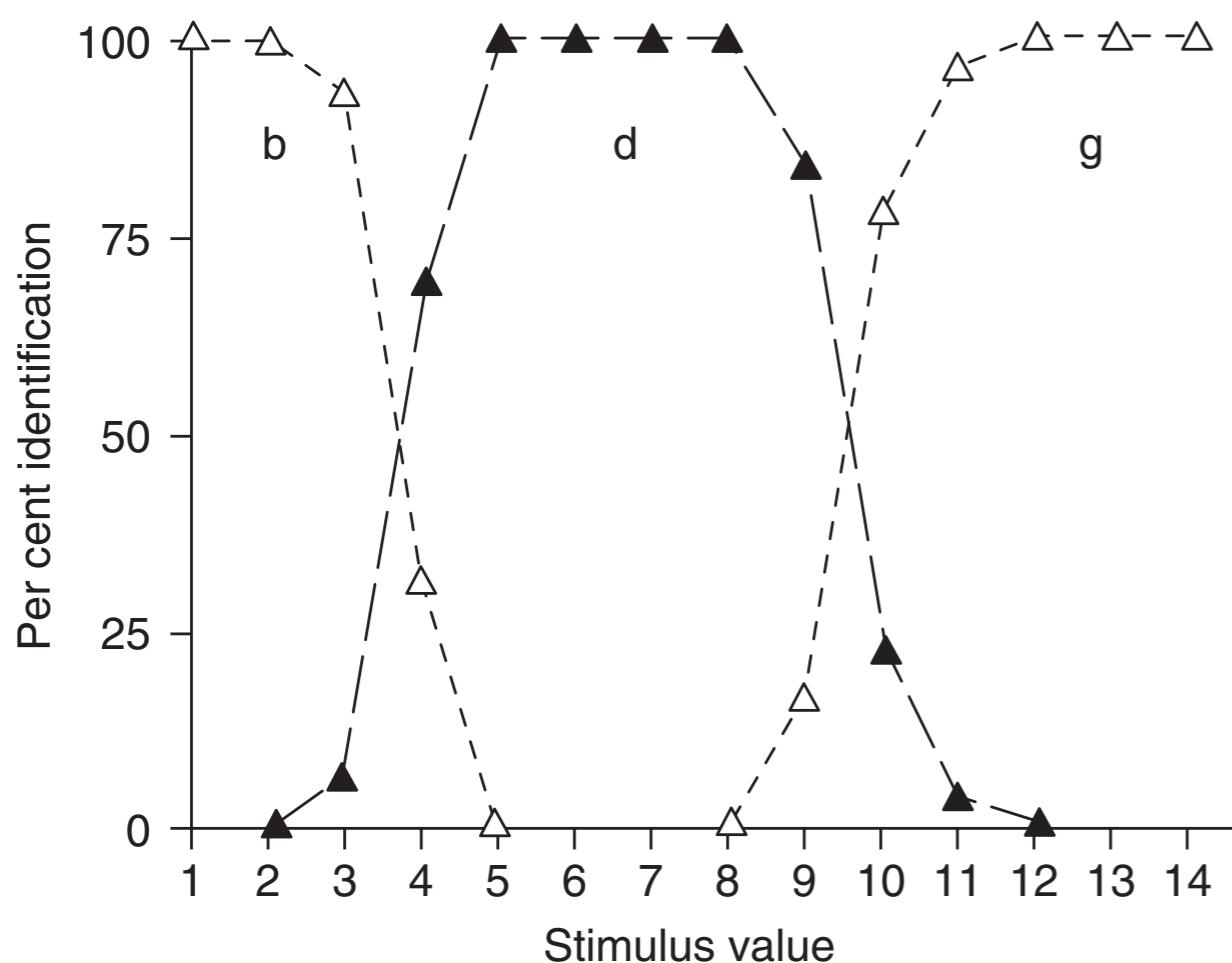


Categorical perception in speech

A link between categorization and discrimination

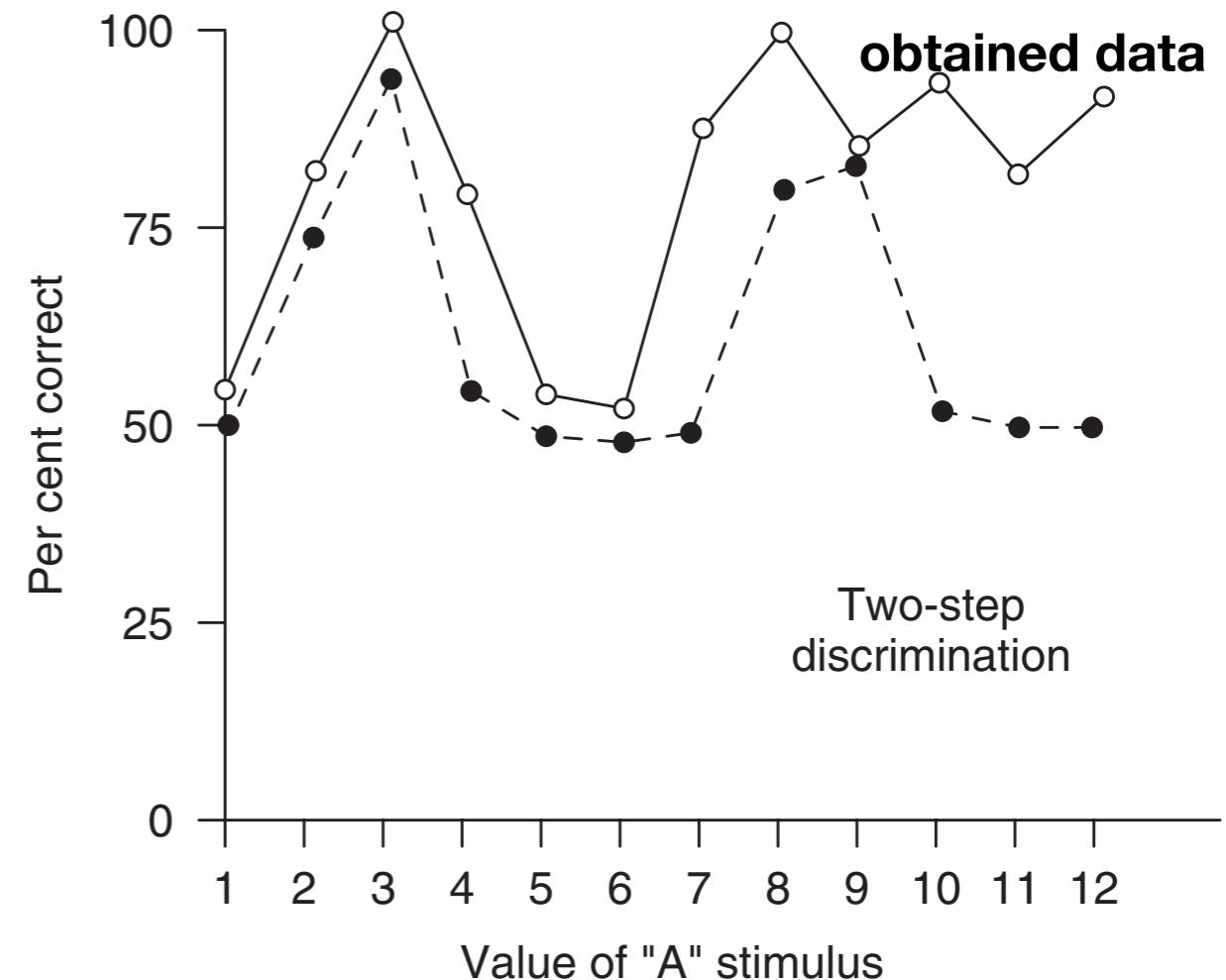
Identification (labeling) task

("ba" vs. "da" vs. "ga")



Discrimination task

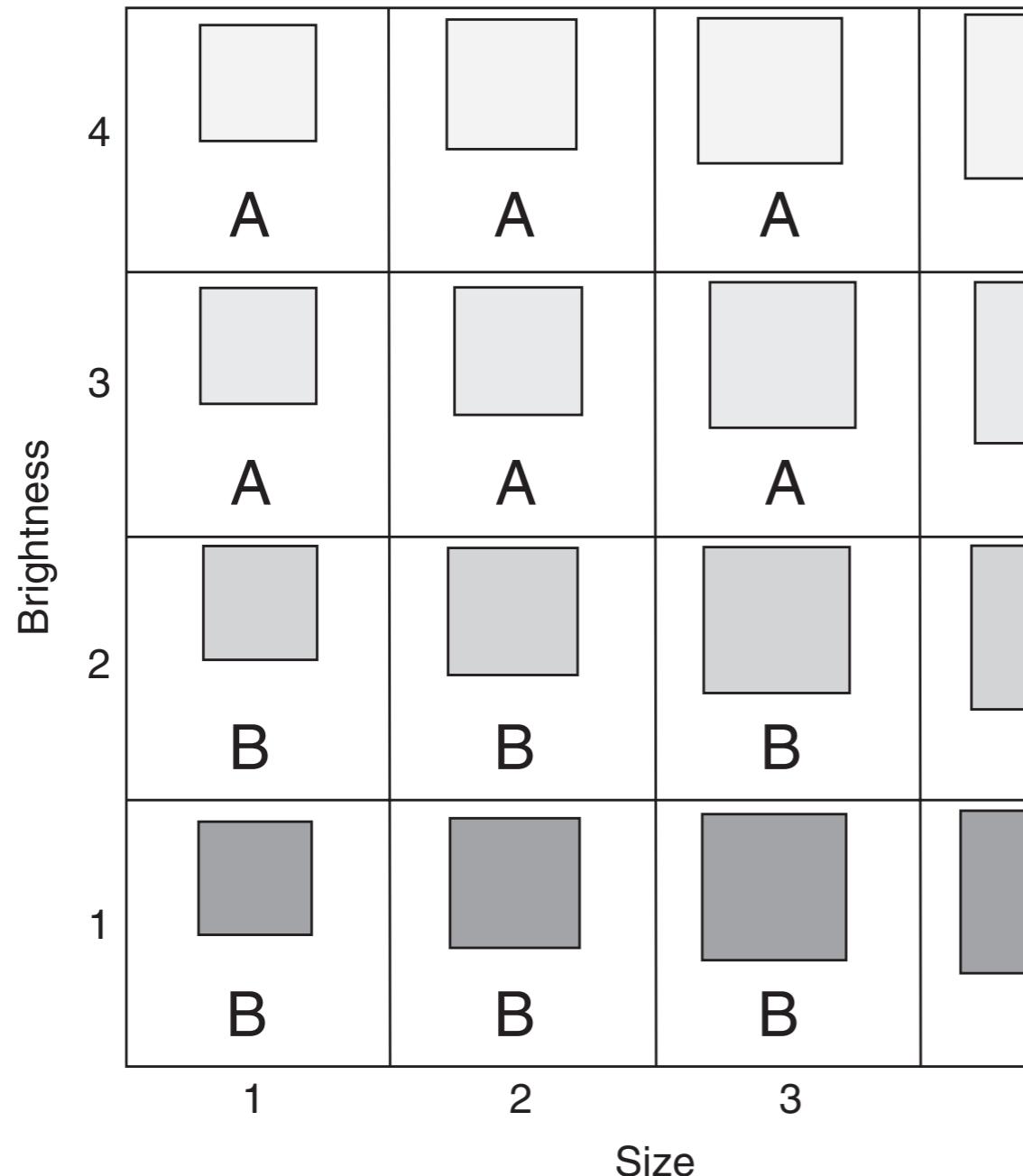
(ABX; which is X identical to, A or B?)



From Liberman, A. M., Harris, K. S., Hoffman, H. S., & Griffith, B. C. (1957)

Categorical perception for artificial visual categories

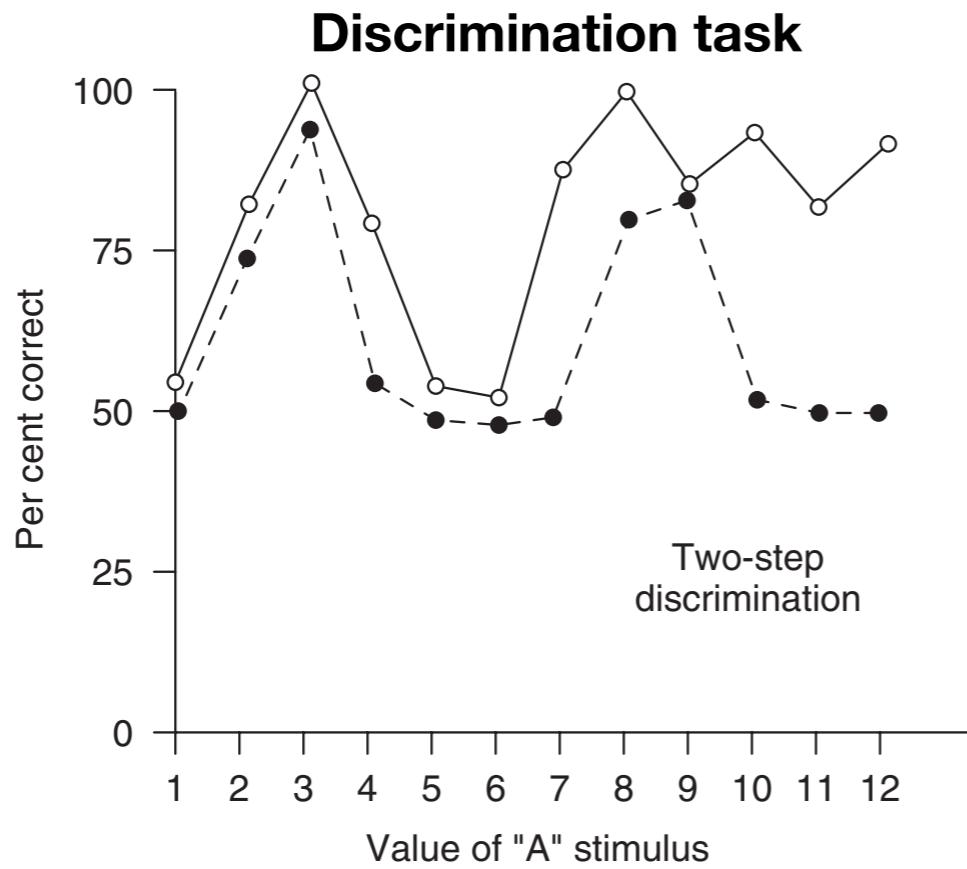
A link between categorization and discrimination



enhanced discrimination
along this dimension,
especially at the “A” vs.
“B” boundary

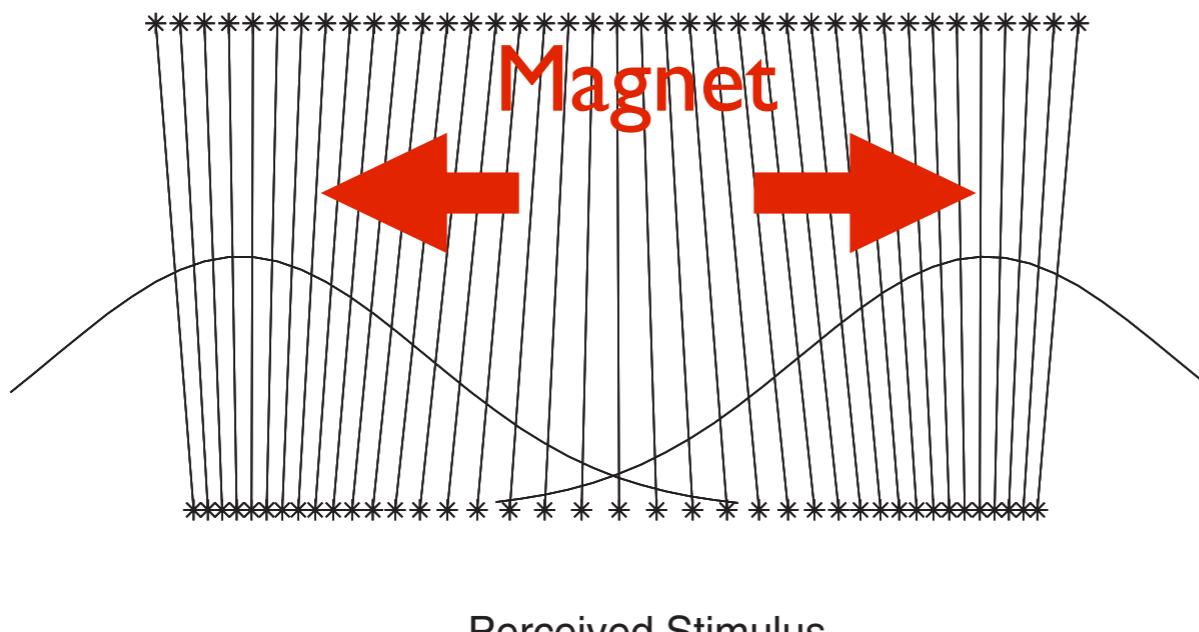
From Rob Goldstone (1994)

Categorical perception: A link between categorization and discrimination



(b)

Actual Stimulus



Categorical perception is very closely related to the “perceptual magnet effect” in speech studied by Pat Kuhl et al.

Let's try to understand the perceptual magnet effect through a Bayesian model

The Influence of Categories on Perception: Explaining the Perceptual Magnet Effect as Optimal Statistical Inference

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Brown University

Thomas L. Griffiths
University of California, Berkeley

James L. Morgan
Brown University

A variety of studies have demonstrated that organizing stimuli into categories can affect the way the stimuli are perceived. We explore the influence of categories on perception through one such phenomenon, the perceptual magnet effect, in which discriminability between vowels is reduced near prototypical vowel sounds. We present a Bayesian model to explain why this reduced discriminability might occur: It arises as a consequence of optimally solving the statistical problem of perception in noise. In the optimal solution to this problem, listeners' perception is biased toward phonetic category means because they use knowledge of these categories to guide their inferences about speakers' target productions. Simulations show that model predictions closely correspond to previously published human data, and novel experimental results provide evidence for the predicted link between perceptual warping and noise. The model unifies several previous accounts of the perceptual magnet effect and provides a framework for exploring categorical effects in other domains.

Keywords: perceptual magnet effect, categorical perception, speech perception, Bayesian inference, rational analysis

The influence of categories on perception is well known in domains ranging from speech sounds to artificial categories of objects. Liberman, Harris, Hoffman, and Griffith (1957) first described categorical perception of speech sounds, noting that listeners' perception conforms to relatively sharp identification boundaries between categories of stop consonants and that whereas between-category discrimination of these sounds is nearly perfect, within-category discrimination is little better than chance. Similar patterns have been observed in the perception of colors (Davidoff, Davies, & Roberson, 1999), facial expressions (Etcoff & Magee, 1992), and familiar faces (Beale & Keil, 1995), as well

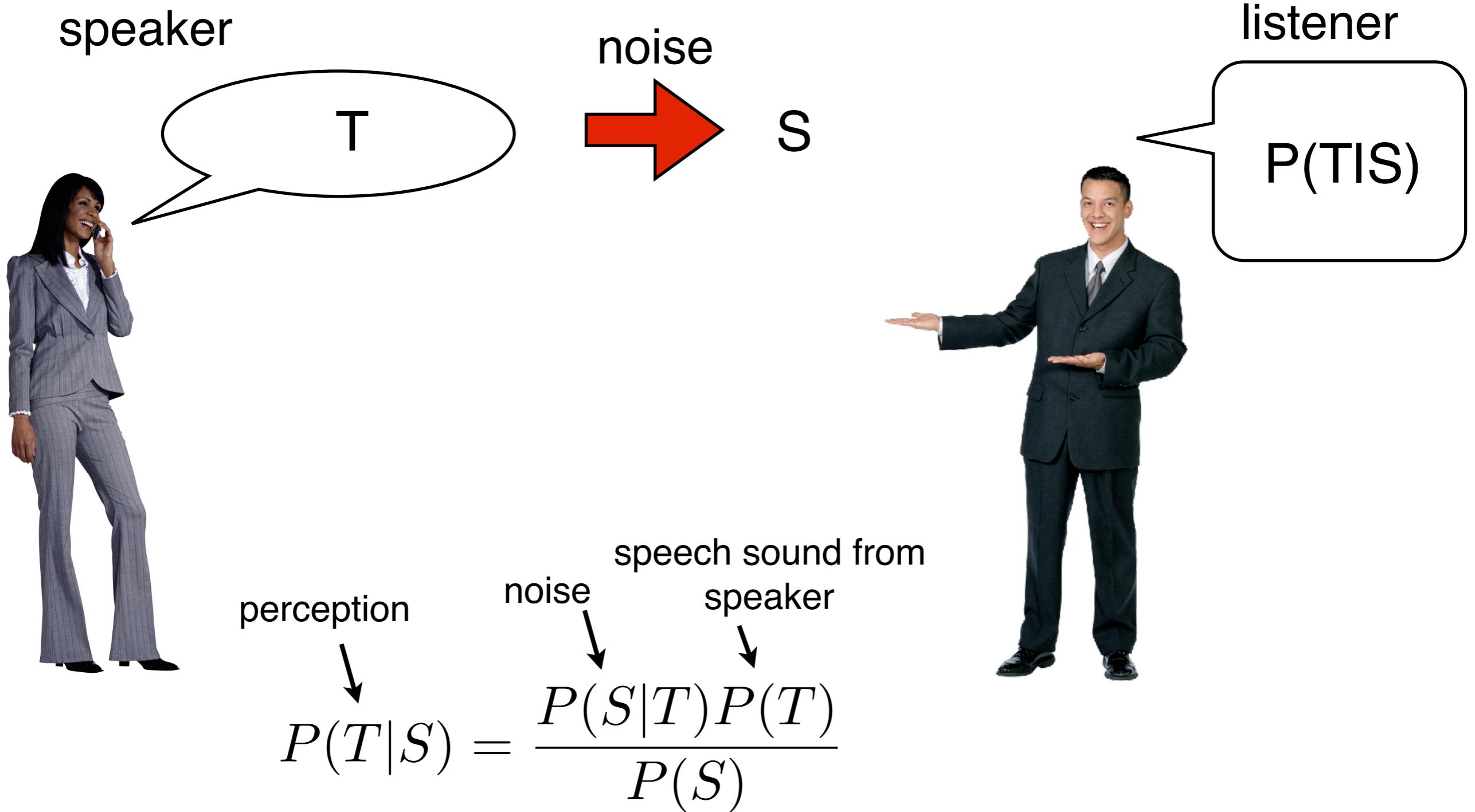
as the representation of objects belonging to artificial categories that are learned over the course of an experiment (Goldstone, 1994; Goldstone, Lippa, & Shiffrin, 2001). All of these categorical effects are characterized by better discrimination of between-category contrasts than within-category contrasts, although the magnitude of the effect varies between domains.

In this article, we develop a computational model of the influence of categories on perception through a detailed investigation of one such phenomenon, the *perceptual magnet effect* (Kuhl, 1991), which has been described primarily in vowels. The perceptual magnet effect involves reduced discriminability of speech sounds near phonetic category prototypes. For several reasons, speech sounds, particularly vowels, provide an excellent starting point for assessing a model of the influence of categories on perception. Vowels are naturally occurring, highly familiar stimuli that all listeners have categorized. As discussed later, a precise two-

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This research was supported by National Science Foundation grants to N.H.F.

Bayesian model of speech perception



The speaker makes an intended sound production T.
Noise in the air perturbs T into S.
The listener calculates the posterior P(T|S)

Bayesian model of speech perception

The speaker makes a sound production T.
Noise in the air perturbs T into S.

Prior

$$T|c \sim N(\mu_c, \sigma_c^2)$$

If the stimulus is noisy, pull your perception towards the category you think it comes from.

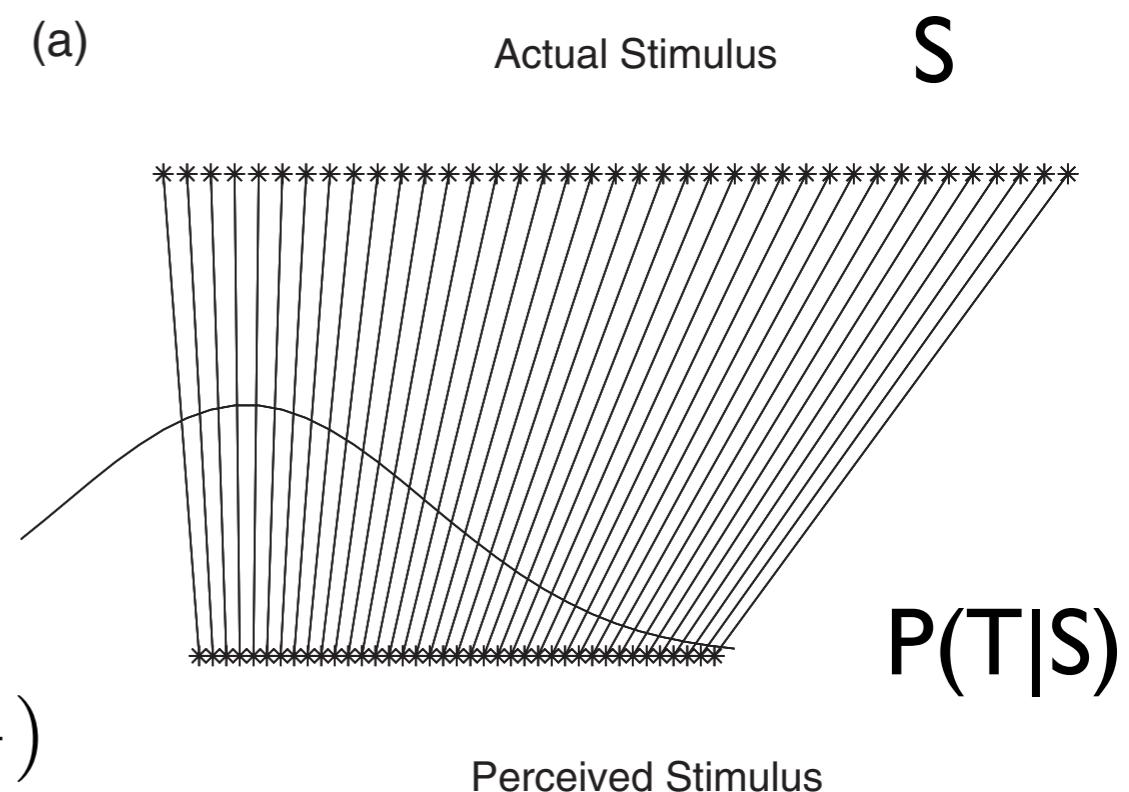
Likelihood (normal distribution)

$$S|T \sim N(T, \sigma_S^2)$$

Posterior

$$P(T|S, c) = \frac{P(S|T)P(T|c)}{P(S|c)}$$

$$P(T|S, c) = N\left(\frac{\sigma_c^2 S + \sigma_S^2 \mu_c}{\sigma_c^2 + \sigma_S^2}, \frac{\sigma_c^2 \sigma_S^2}{\sigma_c^2 + \sigma_S^2}\right)$$



Posterior is Gaussian, where the mean is a **weighted average** between the **actual stimulus S** and the **prior mean μ_c** .

- If the noise is high (high σ_S), rely more on the prior category mean
- If the category is highly variable (high σ_c), rely more on the actual stimulus S

Key technical concept: Conjugate priors

When prior and posterior are in the same family, then we have a **conjugate prior** for the likelihood function.

prior	likelihood	posterior	common use case
Normal	Normal (unknown mean, known variance)	Normal	estimating mean of a continuous sample
Beta	Binomial	Beta	estimating fairness of a coin based on counts
Dirichelt	Multinomial	Dirichelt	estimating weights on k-sided dice based on counts
...			

This makes it **very easy to compute posterior distributions**, as it can be done in closed form with standard formulas.

https://en.wikipedia.org/wiki/Conjugate_prior

Bayesian model of speech perception: Multiple categories

The speaker makes a sound production T.
Noise in the air perturbs T into S.

Step 1) Bayesian classification of the speech sound in category c

$$p(c|S) = \frac{p(S|c)p(c)}{\sum_c p(S|c)p(c)}$$

$$p(S|c) = \int p(S|T)p(T|c) dT$$

(this term is another Gaussian distribution)

Step 2) Compute reconstruction of T as weighted mixture of posteriors

$$p(T|S) = \sum_c p(T|S, c)p(c|S)$$

(mixture of Gaussians)

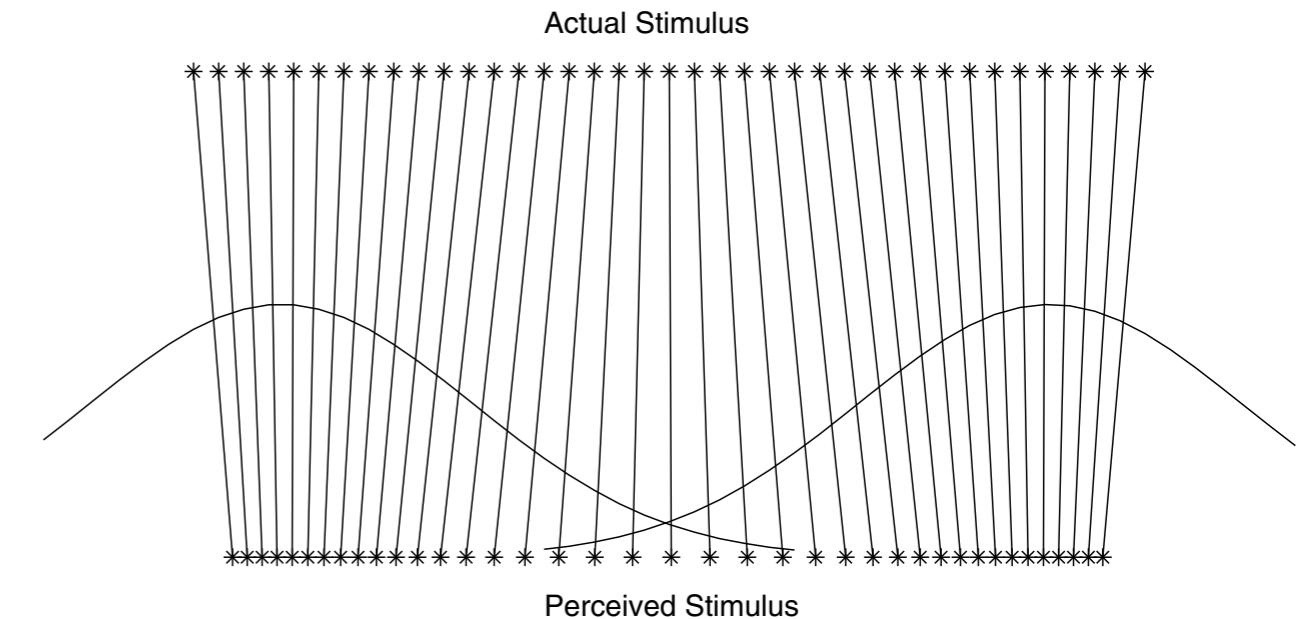
$$P(T|S, c) = N\left(\frac{\sigma_c^2 S + \sigma_S^2 \mu_c}{\sigma_c^2 + \sigma_S^2}, \frac{\sigma_c^2 \sigma_S^2}{\sigma_c^2 + \sigma_S^2}\right)$$

(term is posterior from previous slide with known category)

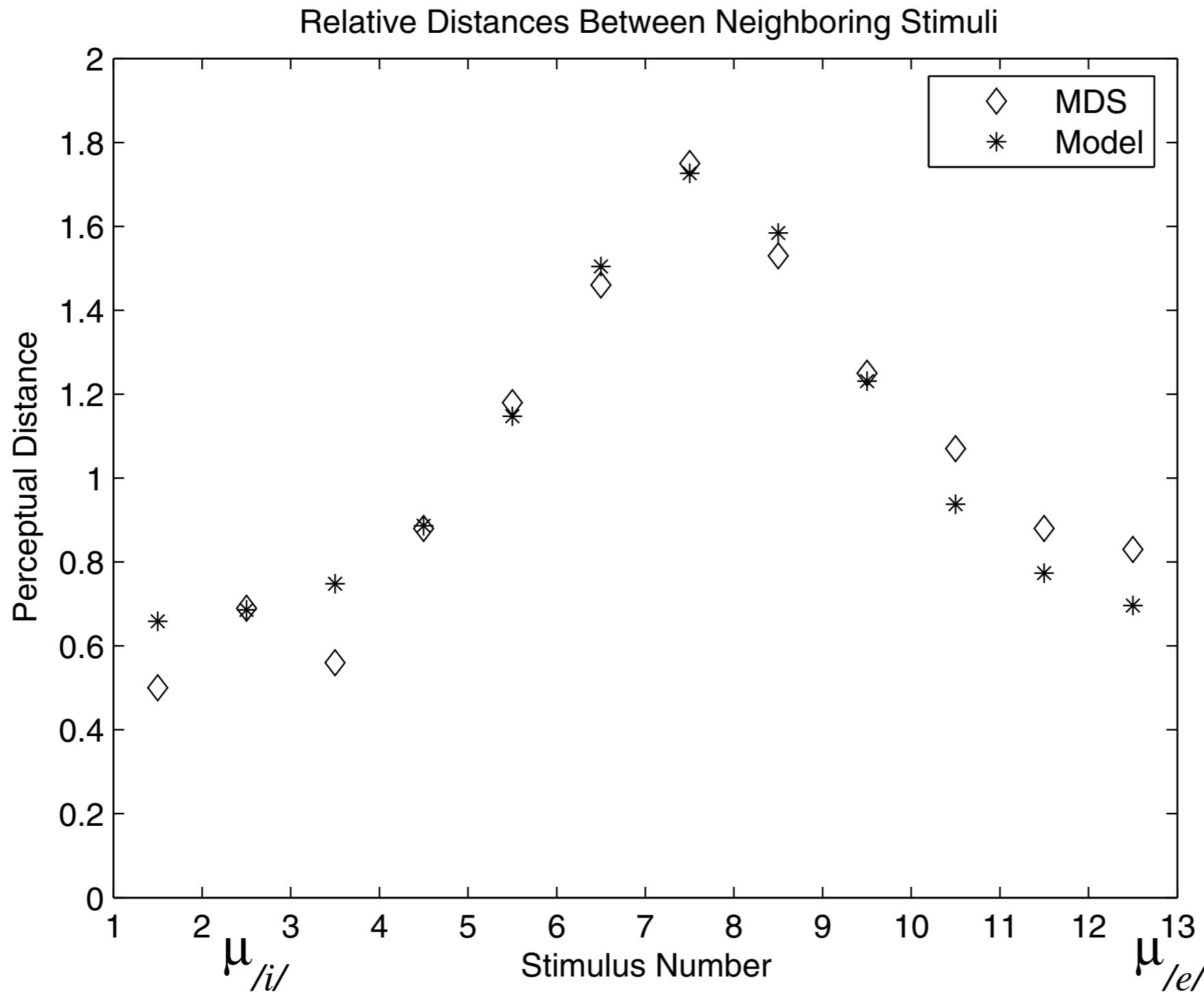
Posterior mean (expected value) $E[x] = \sum_x xp(x)$

$$E[T|S] = \frac{\sigma_c^2}{\sigma_c^2 + \sigma_S^2} S + \frac{\sigma_S^2}{\sigma_c^2 + \sigma_S^2} \sum_c p(c|S) \mu_c$$

- If the noise is high (high σ_S), rely more on the category means
- If the category is highly variable (high σ_c), rely more on the actual stimulus S



Comparing the Bayesian model to perceptual data



participant data
Bayesian model

Computing perceptual
distance

- Participant discrimination judgments converted to perceptual distance using multi-dimensional scaling (MDS)
- Bayesian model predictions computed as $E[TIS]$

Conclusions from the Bayesian models of the perceptual magnet effect

- Categories influence perception in a range of domains: speech, color, faces, etc...

Although it's clear that categories influence perception, it's not clear WHY they should

- There are many other models of categorical perception and perceptual magnet effect, but they don't really answer the “why” question.

The Bayesian model suggests why perception should have this characteristic: It's a rational adaption for perceiving/reconstructing stimuli under noise.

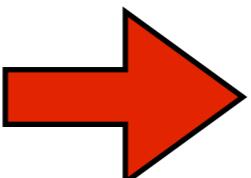
Implications for understanding behavioral data: User ratings

Actual object



T

noise
(in perception,
memory, etc.)



S



$P(TIS, c)$

Perceived experience may
warped by the category c

Kiin Thai Eatery Claimed

228 reviews [View Details](#)

\$\$ - Thai [Edit](#)

Map data ©2018 Google

36 E 8th St
New York, NY 10003
b/t Greene St & University Pl
Greenwich Village
[Get Directions](#)
 N R 8 St. - Nyu and 2 more stations
 (212) 529-2363
 kiinthaieatery.com
 [Send to your Phone](#)

"We ordered thai iced tea, spring rolls, papaya salad, chicken wings, green curry, beef pad thai, and a brownie with ice-cream for dessert." in 50 reviews
\$13 Classic Pad Thai

"'Nham Prik Ong' relish Set (\$12): a very typical Thai dish (that I had and saw often in Bangkok) done very well." in 9 reviews

"The sai oua sausage is really authentic, and the seafood som tum is actually very spicy and delicious." in 31 reviews

More business info

Takes Reservations Yes
Delivery Yes
Take-out Yes
Accepts Credit Cards Yes
Accepts Apple Pay No
Good For Lunch, Dinner
Parking Street
Bike Parking Yes
Good for Kids Yes
Good for Groups Yes
Attire Casual
Ambience Casual
Noise Level Average
Alcohol Full Bar
Outdoor Seating No
Wi-Fi Free
Has TV No
Waiter Service Yes
Caters No
Gender Neutral Restrooms Yes

Predicting the future with Bayesian inference

PSYCHOLOGICAL SCIENCE

Research Article

Optimal Predictions in Everyday Cognition

Thomas L. Griffiths¹ and Joshua B. Tenenbaum²

¹Department of Cognitive and Linguistic Sciences, Brown University, and ²Department of Brain and Cognitive Sciences, Massachusetts Institute of Technology

ABSTRACT—*Human perception and memory are often explained as optimal statistical inferences that are informed by accurate prior probabilities. In contrast, cognitive judgments are usually viewed as following error-prone heuristics that are insensitive to priors. We examined the optimality of human cognition in a more realistic context than typical laboratory studies, asking people to make predictions about the duration or extent of everyday phenomena such as human life spans and the box-office take of movies. Our results suggest that everyday cognitive judgments follow the same optimal statistical principles as perception and memory, and reveal a close correspondence between people's implicit probabilistic models and the statistics of the world.*

If you were assessing the prospects of a 60-year-old man, how

Perry, Super, & Gallogly, 2001; Huber, Shiffrin, Lyle, & Ruys, 2001; Knill & Richards, 1996; Kording & Wolpert, 2004; Shiffrin & Steyvers, 1997; Simoncelli & Olshausen, 2001; Weiss, Simoncelli, & Adelson, 2002). In contrast—perhaps as a result of the great attention garnered by the work of Kahneman, Tversky, and their colleagues (e.g., Kahneman, Slovic, & Tversky, 1982; Tversky & Kahneman, 1974)—cognitive judgments under uncertainty are often characterized as the result of error-prone heuristics that are insensitive to prior probabilities. This view of cognition, based on laboratory studies, appears starkly at odds with the near-optimality of other human capacities, and with people's ability to make smart predictions from sparse data in the real world.

To evaluate how cognitive judgments compare with optimal statistical inferences in real-world settings, we asked people to predict the duration or extent of everyday phenomena such as human life spans and the gross of movies. We varied the phe-

Let's make some predictions

You stopped by a friend's apartment, and she has been watching a movie for 15 minutes. What would you predict for the length of the movie in total?

You stopped by a friend's apartment, and she has been watching a movie for 75 minutes. What would you predict for the length of the movie in total?

Let's make some predictions

You stopped by a friend's apartment, and she has been watching a movie for 15 minutes. What would you predict for the length of the movie in total?

You stopped by a friend's apartment, and she has been watching a movie for 75 minutes. What would you predict for the length of the movie in total?

A movie has grossed 15 million dollars at the box office, but you don't know how long it's been running. How much will it gross in total?

A movie has grossed 75 million dollars at the box office, but you don't know how long it's been running. How much will it gross in total?

Let's make some predictions

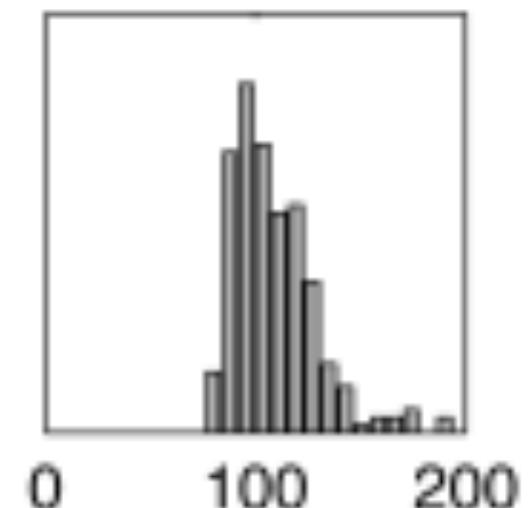
You stopped by a friend's apartment, and she has been watching a movie for 15 minutes. What would you predict for the length of the movie in total?

You stopped by a friend's apartment, and she has been watching a movie for 75 minutes. What would you predict for the length of the movie in total?

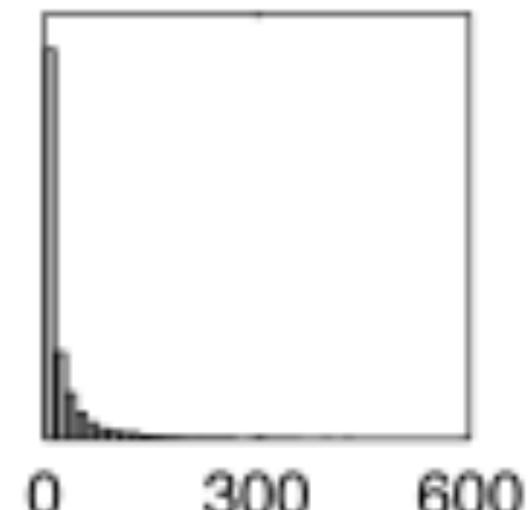
A movie has grossed 15 million dollars at the box office, but you don't know how long it's been running. How much will it gross in total?

A movie has grossed 75 million dollars at the box office, but you don't know how long it's been running. How much will it gross in total?

Movie runtimes



Movie grosses



Simple Bayesian model of predicting the future

A movie has grossed 15 million dollars at the box office, but you don't know how long it's been running. How much will it gross total?

Movie runtimes

t_{total} : the total quantity you are estimating

t : the current quantity you are given (current runtime of movie, current gross, etc.)

Bayesian estimation problem

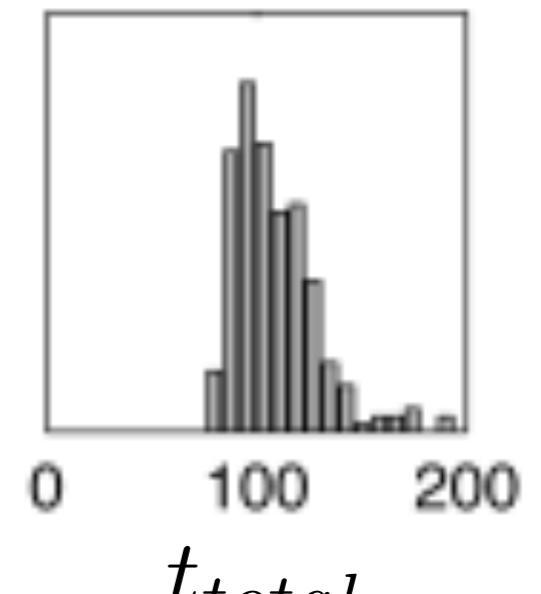
$$P(t_{total}|t) = \frac{P(t|t_{total})P(t_{total})}{P(t)}$$

posterior likelihood prior

Likelihood

$$P(t|t_{total}) = 1/t_{total}$$

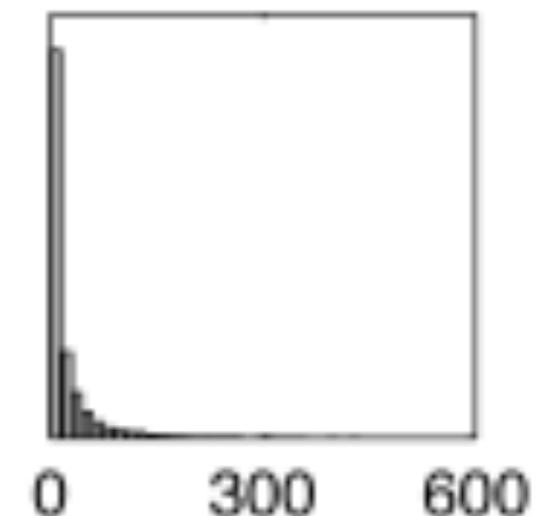
Assumption: you are equally likely to encounter a quantity at any point across its lifespan (movie / person / etc.)



Movie grosses

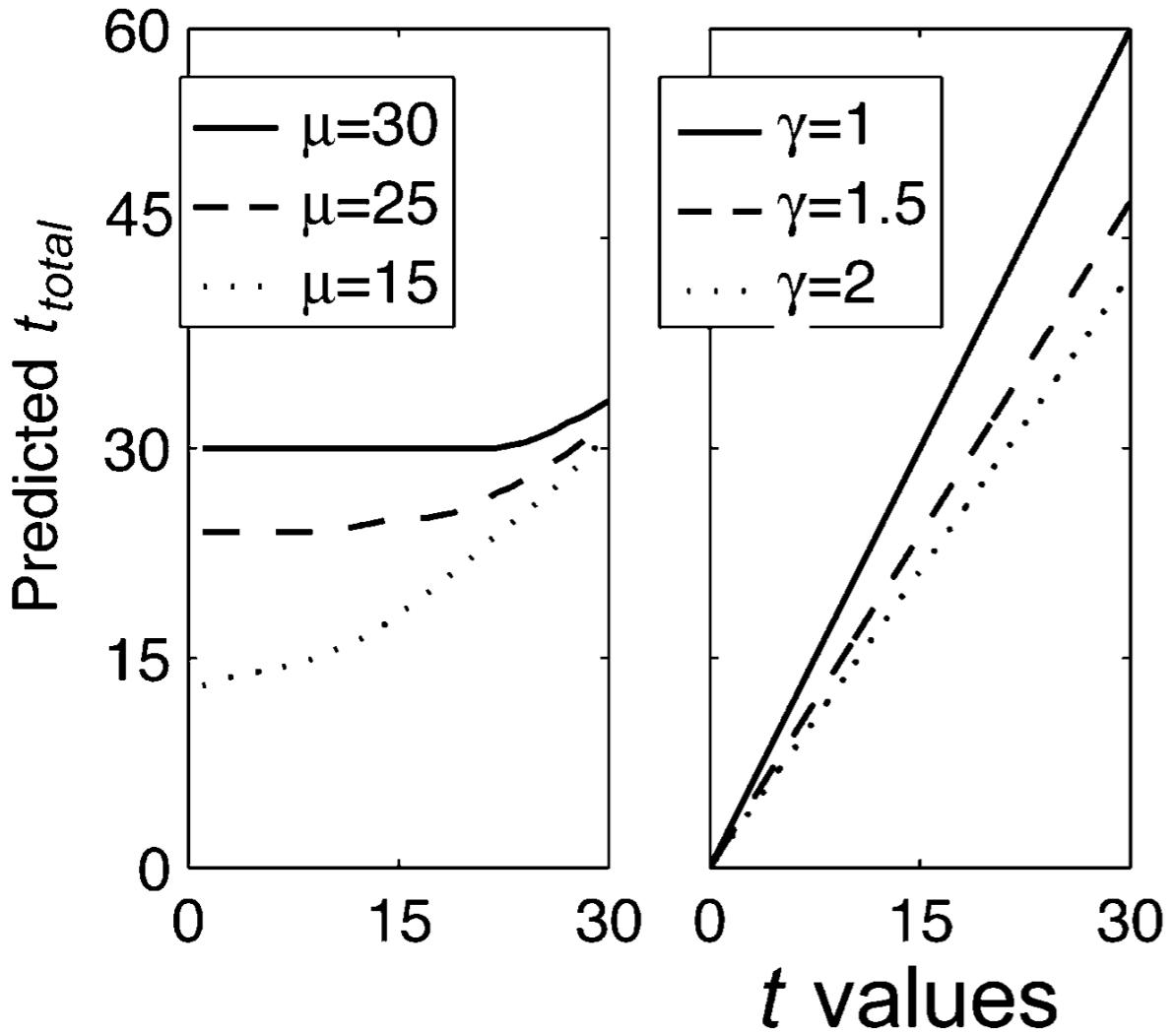
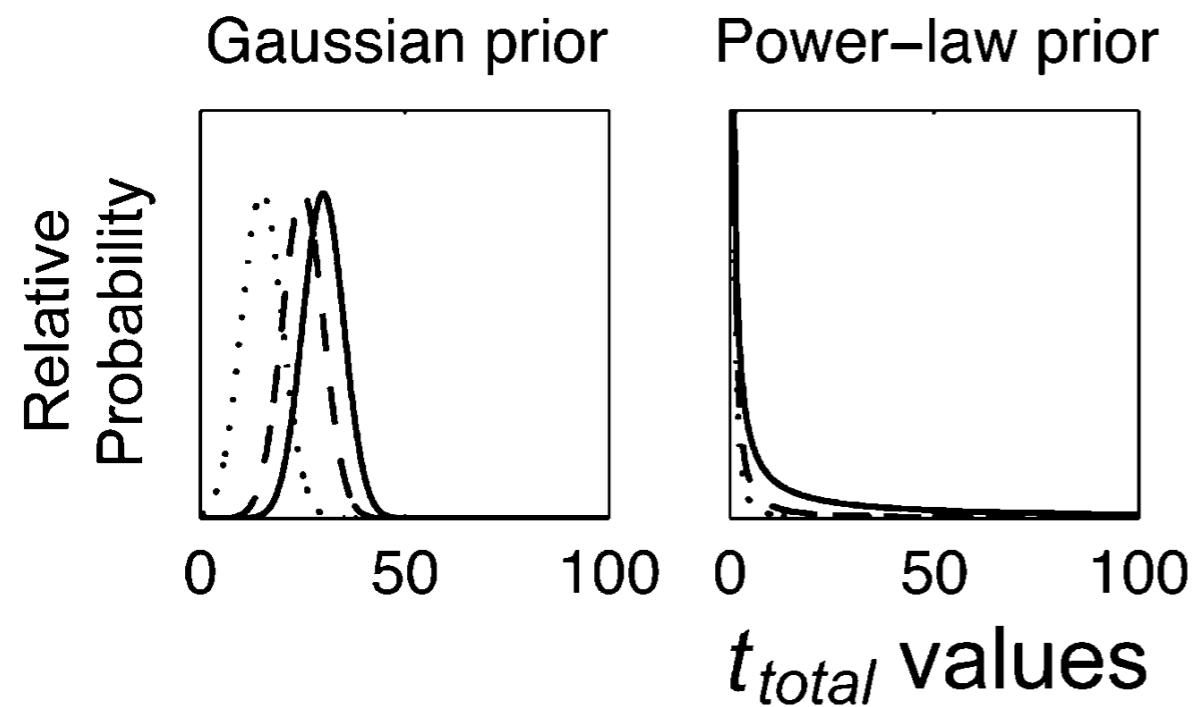
Prior

$P(t_{total})$ is estimated from real world statistics

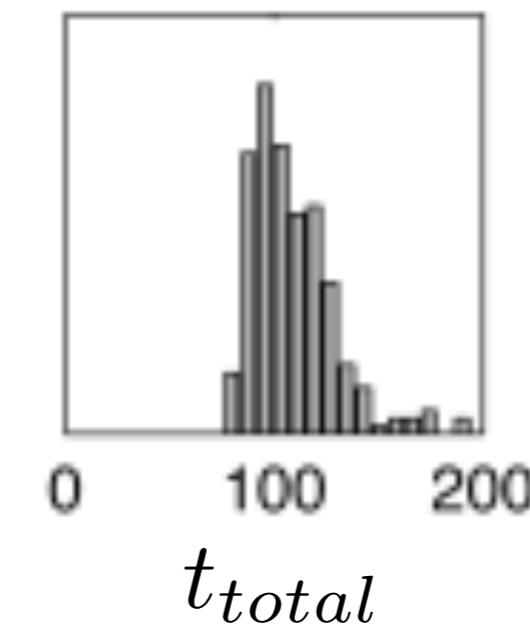


t_{total}

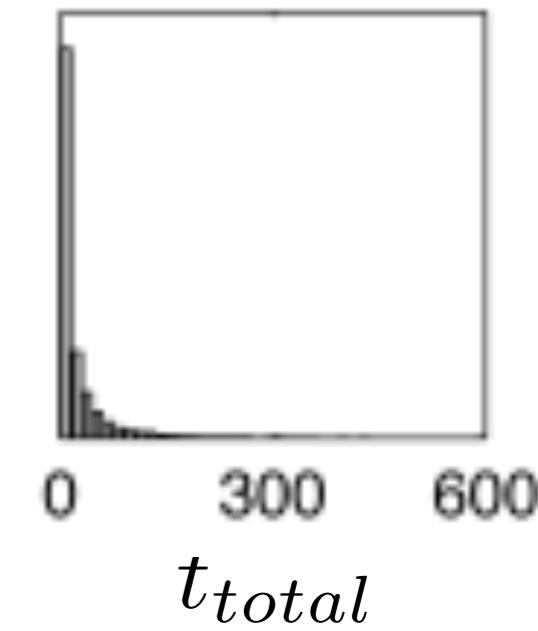
Different priors have qualitatively different predictions



Movie runtimes
(Gaussian)



Movie grosses
(Power-law)



Gaussian prior

$$P(t_{total}) \propto \exp\left(-\frac{1}{2\sigma^2}(t_{total} - \mu)^2\right)$$

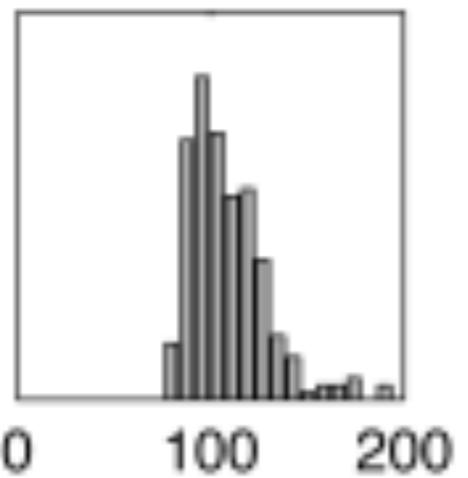
Power-law prior

$$P(t_{total}) \propto t_{total}^{-\gamma}$$

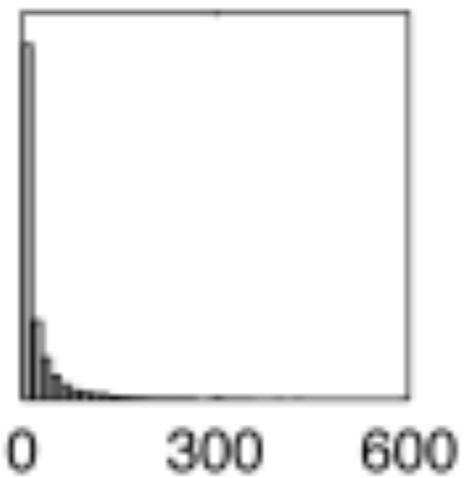
Posterior

$$P(t_{total}|t) = \frac{P(t|t_{total})P(t_{total})}{P(t)}$$

**Movie runtimes
(Gaussian)**



**Movie grosses
(Power-law)**



Different priors have qualitatively different predictions: Comparison with human data

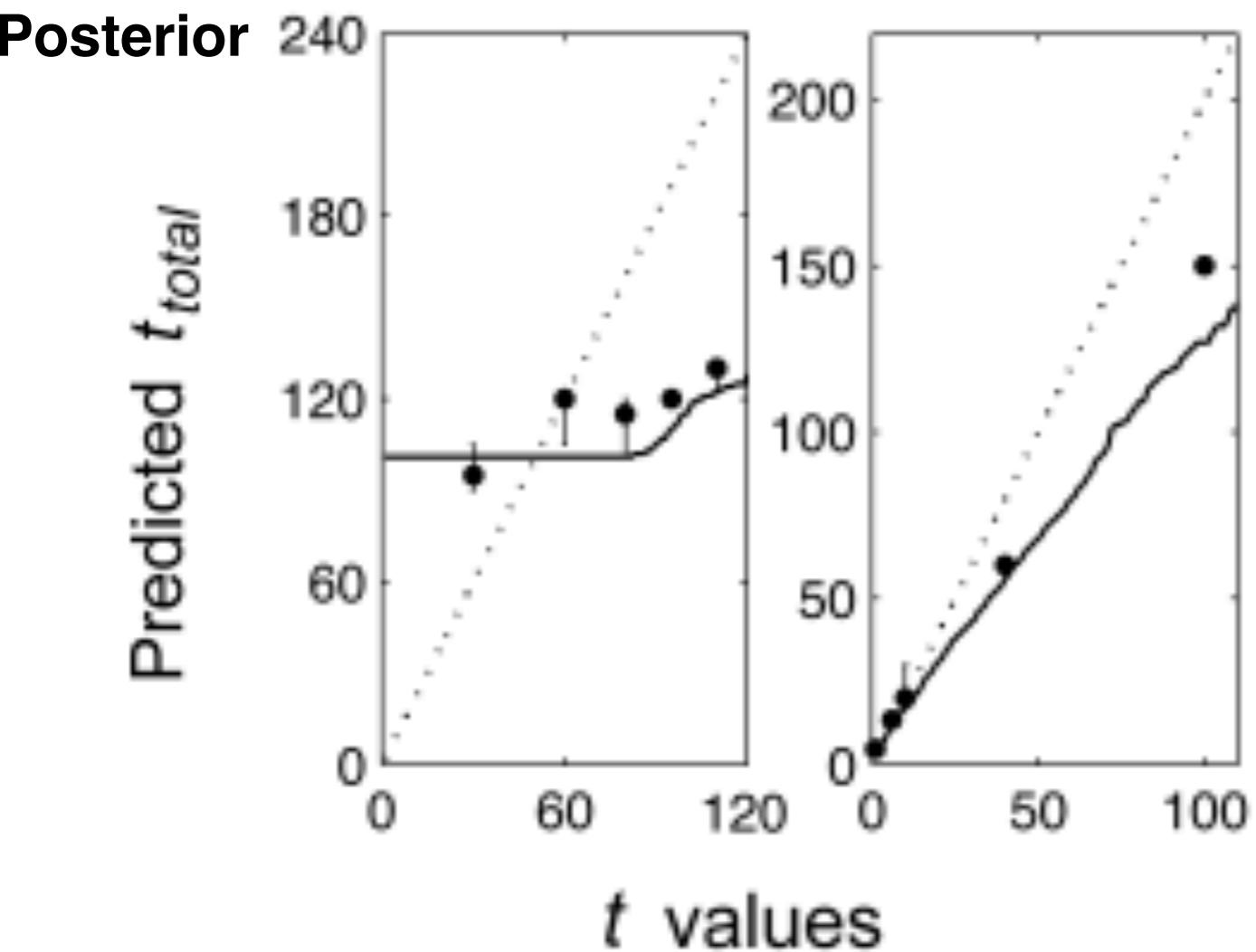
Prior

Posterior

Black dots are median prediction of human participants

Solid lines are optimal Bayesian posterior predictions

$$P(t_{total}|t) = \frac{P(t|t_{total})P(t_{total})}{P(t)}$$



Optimal Bayesian predictions

For movie runtimes, predict the mean unless the runtime has already exceeded it.

For movie grosses, multiply the current gross by roughly 1.5

Patterns of prediction across a range of domains

Poem lengths: If your friend read you her favorite line of poetry, and told you it was line 5 of a poem, what would you predict for the total length of the poem?

Life spans: Insurance agencies employ actuaries to make predictions about people's life spans—the age at which they will die—based upon demographic information. If you were assessing an insurance case for an 18-year-old man, what would you predict for his life span?

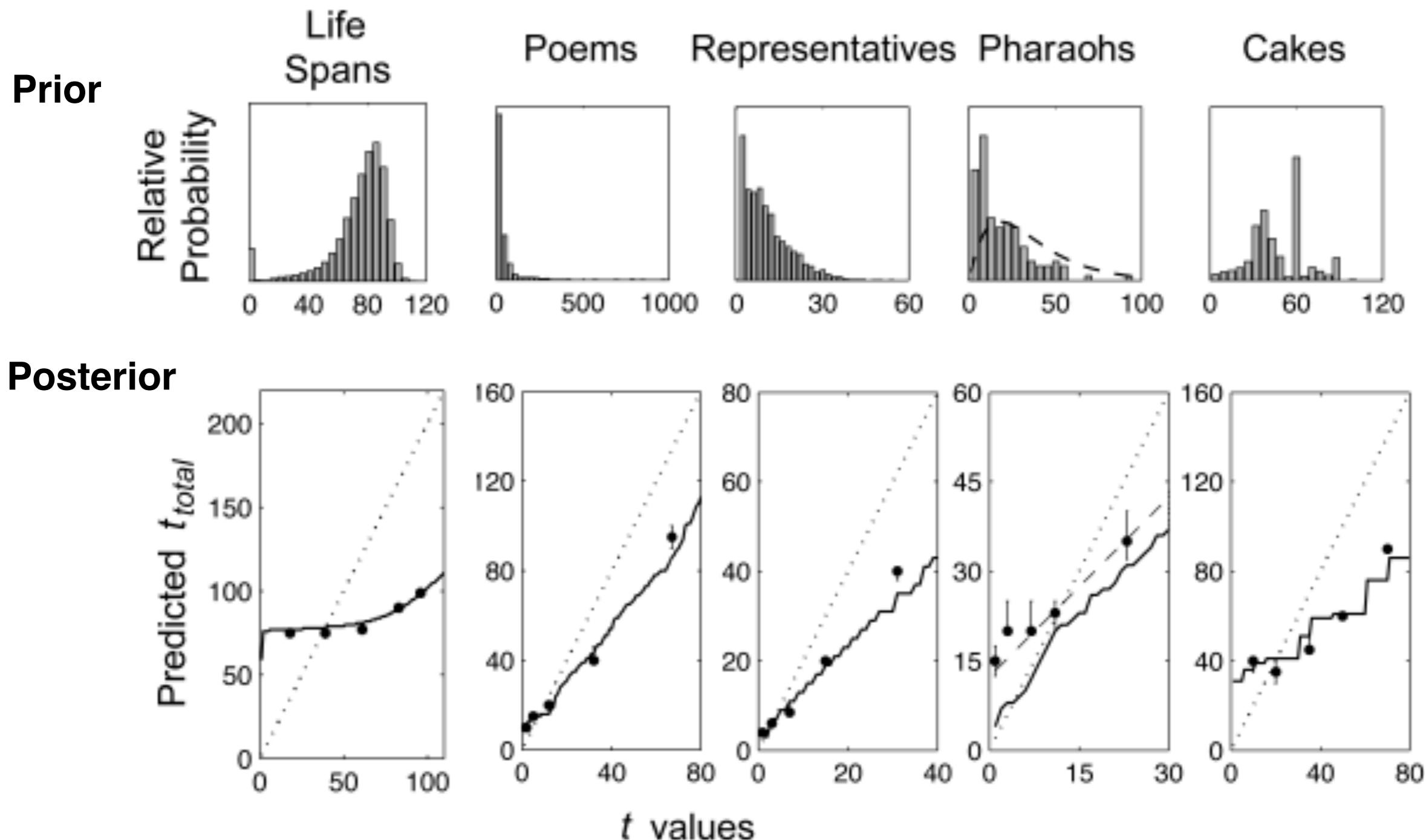
Baking times for cakes: Imagine you are in somebody's kitchen and notice that a cake is in the oven. The timer shows that it has been baking for 35 minutes. What would you predict for the total amount of time the cake needs to bake?

Waiting times: If you were calling a telephone box office to book tickets and had been on hold for 3 minutes, what would you predict for the total time you would be on hold?

Reigns of pharaohs: If you opened a book about the history of ancient Egypt to a page listing the reigns of the pharaohs, and noticed that at 4000 BC a particular pharaoh had been ruling for 11 years, what would you predict for the total duration of his reign?

Terms of U.S. representatives: If you heard a member of the House of Representatives had served for 15 years, what would you predict his total term in the House would be?

Patterns of prediction across a range of domains



Black dots are median prediction of participants

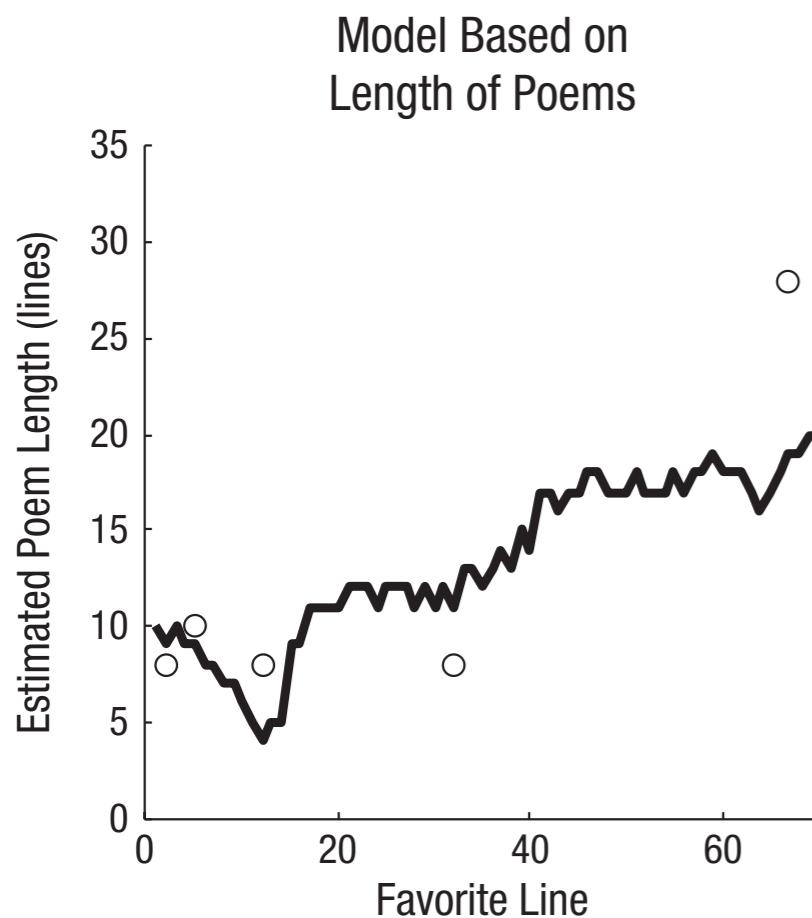
Solid lines are optimal Bayesian predictions

Critique of “Optimal predictions in everyday cognition”

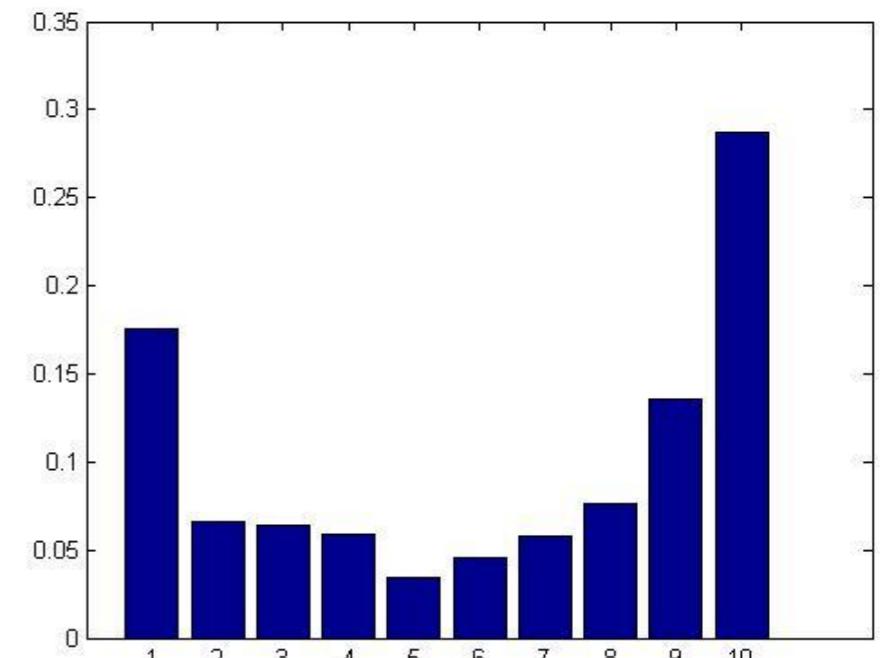
Marcus, G. and Davis, E. (2013) “How robust are probabilistic models of higher-level cognition?”

White dots are mean prediction of participants

Solid lines are Bayesian predictions



Favorite lines are not uniformly distributed across poem.



Distribution of favorite lines per decile of poem.

If Griffiths and Tenenbaum data is replotted to only show “additional length” on y-axis, the predictions can be impressive.

If distribution of favorite lines is taken into account, the predictions are way off.

Conclusions from optimal predictions in everyday cognition

- Critique for Marcus and Davis notwithstanding, there are surprisingly close fit between people's predictions and optimal Bayesian predictions.
- Implications
 1. In many cases, people seem to accurately absorb the statistics of their environment for everyday quantities.
 2. In addition, people use these learned statics in accordance with Bayesian inference.
 3. The simplifying assumptions of “equal likelihood of encounter across timespan” could also be important, given Marcus and Davis critique.

Typical use cases of Bayesian inference

Here is our posterior distribution:

$$P(h|D) = \frac{P(D|h)P(h)}{P(D)}$$

Usually, we want to compute the posterior expectation of some function $\phi(\cdot)$

$$E[\phi(h)|D] = \sum_h \phi(h)P(h|D)$$

(for discrete hypotheses)

$$E[\phi(h)|D] = \int \phi(h)P(h|D)dh$$

(for continuous hypotheses)

Examples of $\phi(\cdot)$

$\phi(h) = y \in C$ in number game (is new number y in the hypothesis?)

$\phi(h) = h$ for perceptual magnet model, we want the posterior mean

$\phi(h) = h$ for optimal predictions, we want the posterior mean (or posterior median, which is what is used in paper)

The computational challenges of Bayesian inference

$$P(h|D) = \frac{P(D|h)P(h)}{P(D)}$$

$$E[\phi(h)|D] = \sum_h \phi(h)P(h|D) \quad E[\phi(h)|D] = \int \phi(h)P(h|D)dh$$

The case of discrete hypotheses h (e.g., the number game):

- In most cases, there are so many hypotheses h that it is intractable to enumerate them all

The case of continuous hypotheses h (e.g., perceptual magnet, optimal predictions in everyday cognition):

- In some cases, we can use a conjugate prior or analytically compute the posterior
- Unfortunately, in most cases, the posterior does not have a simple form that we can work with.

In practice, we usually need to resort to approximate Bayesian inference. And we also want general purpose computational tools that don't require special-purpose derivations for each model.

Monte Carlo methods for approximate Bayesian inference

$$E[\phi(h)|D] \approx \frac{1}{M} \sum_m \phi(h^{(m)})$$

where samples $h^{(1)}, \dots, h^{(M)}$ are generated from $P(h|D)$

[Note: there are other popular approaches for approximate Bayesian inference, but we will focus on Monte Carlo methods since they are the most general]

We're going to discuss three Monte Carlo algorithms for Bayesian inference:

- Rejection sampling (for discrete data D only)
- Importance sampling
- Metropolis-Hastings algorithm (Markov Chain Monte Carlo)

Rejection sampling

Goal of approximate inference:

$$E[\phi(h)|D] \approx \frac{1}{M} \sum_m \phi(h^{(m)})$$

where samples $h^{(1)}, \dots, h^{(M)}$ are generated from $P(h|D)$

Simple algorithm for a rejection sampler:

```
m ← 1
while m < M do
    sample h(m) ~ P(h)
    sample D(m) ~ P(D|h(m))
    if D(m) and D match exactly then
        accept h(m) as a sample
        (if sampled and real
        data match)
        m ← m + 1
    end if
end while
```

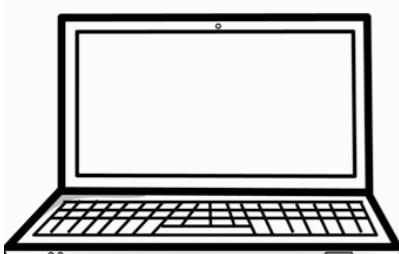
Pros and cons:

pros: very simple to implement

cons: extremely inefficient; only works for discrete data D

Example: rejection sampling for the number game

“filtered” samples that produced D exactly from one sample



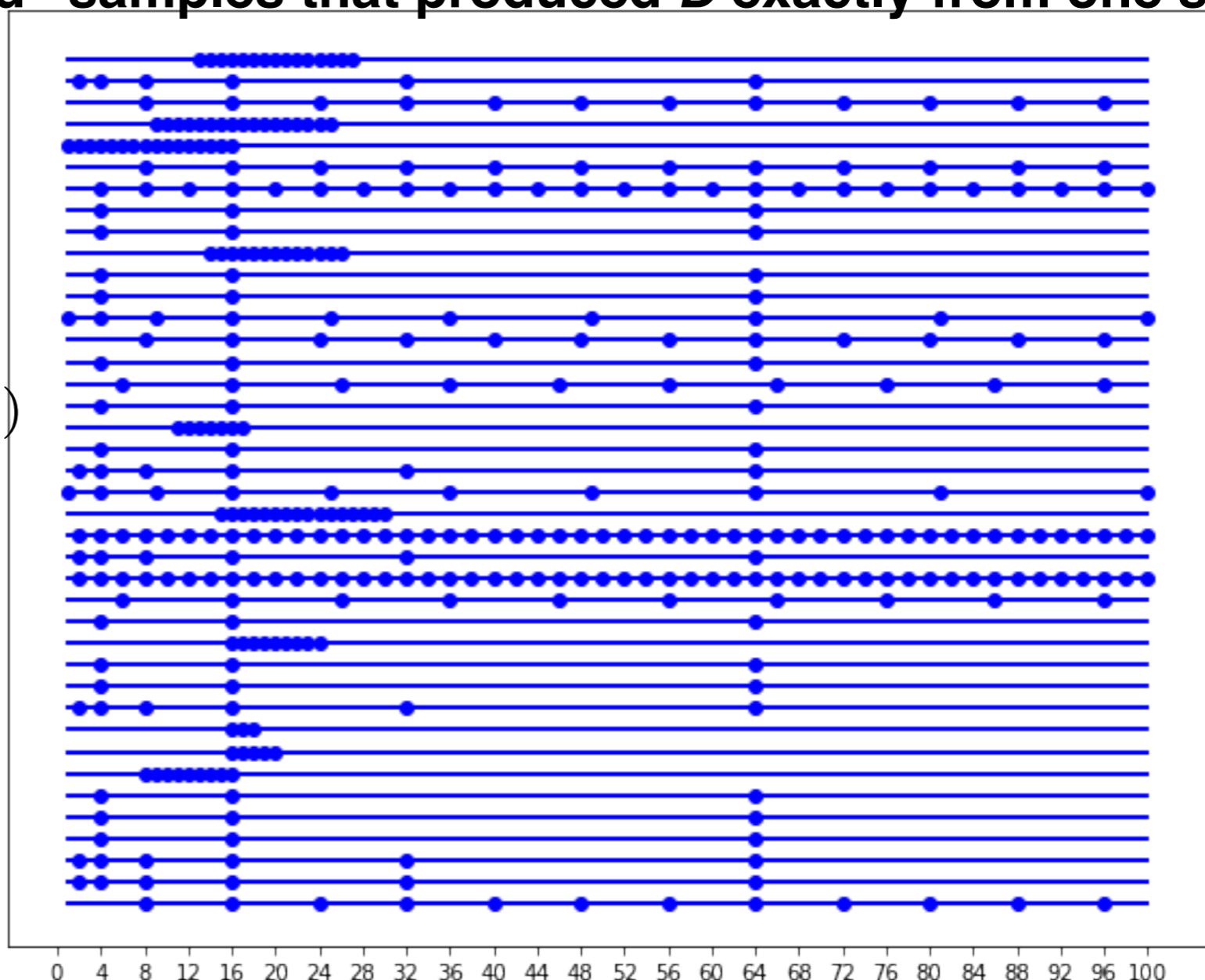
→ 16

rows are $h^{(m)}$

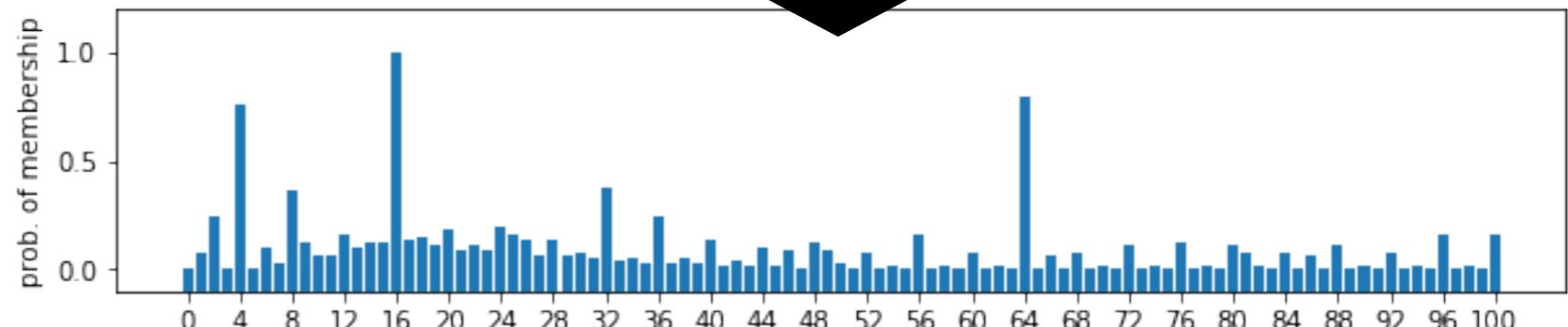
$$E[\phi(h)|D] \approx \frac{1}{M} \sum_m \phi(h^{(m)})$$

$$\phi(h) = y \in C$$

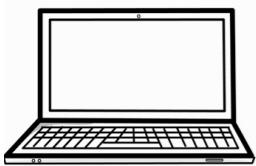
is new number y in the hypothesis?



compute prob. of membership (average)



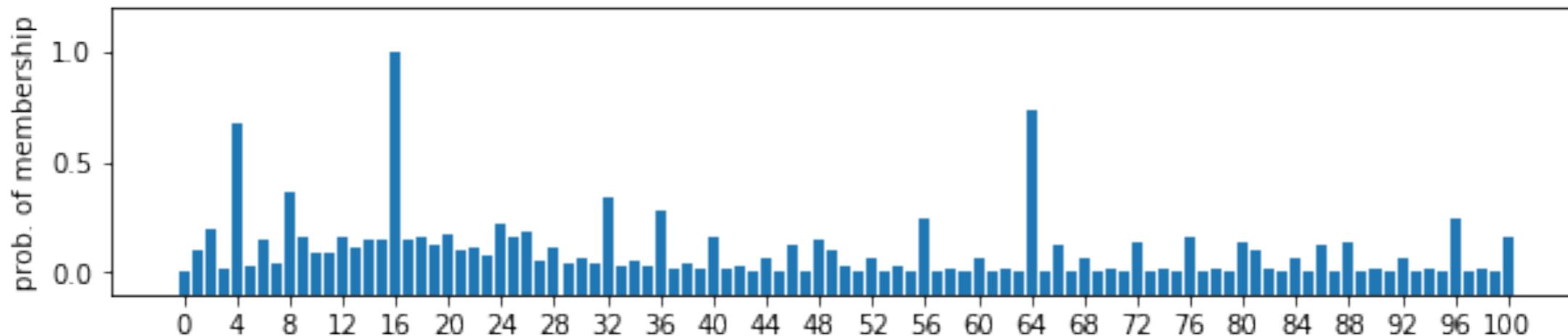
Example: rejection sampling for the number game



→ 16

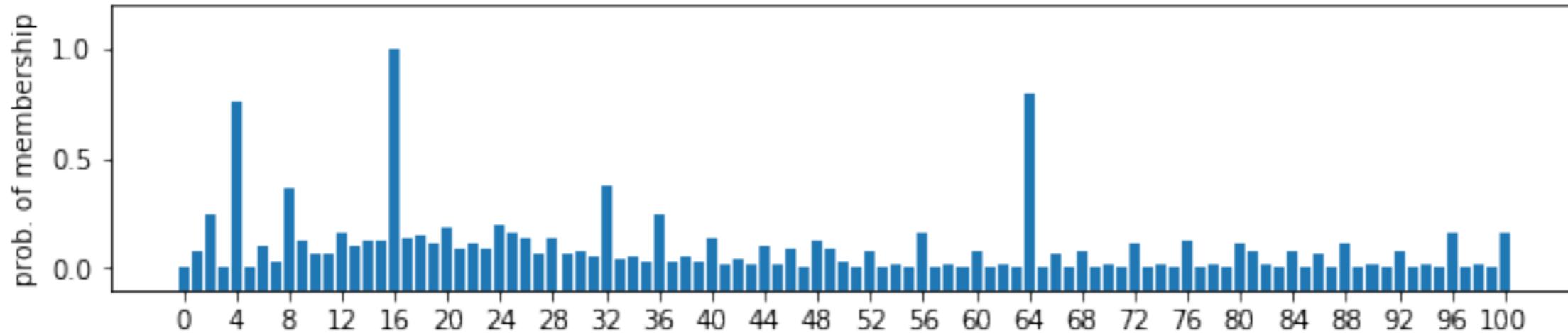
Exact Bayesian inference

$X=[16]$



Rejection sampling (100 included samples)

$X=[16]$



Efficiency is only about 2% for the set [16]

(meaning we throw away 98% of samples, or we need about 4900 samples to get the desired 100)

Example: rejection sampling for the number game

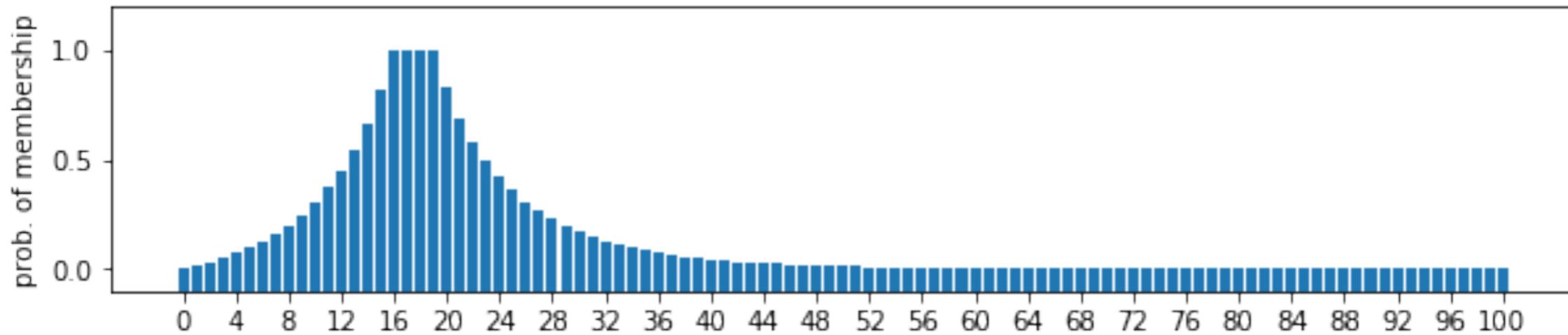
This algorithm scales very badly as we get more data.



→ 16, 19

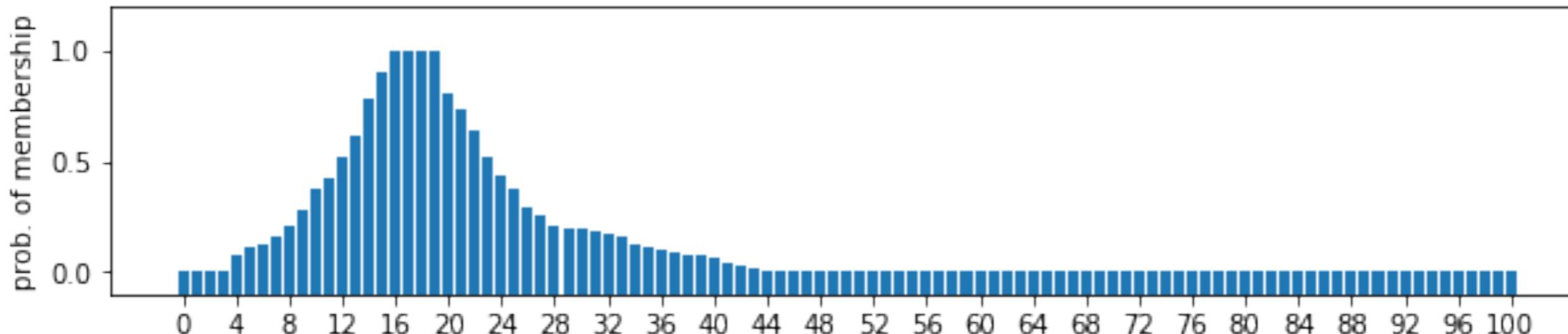
Exact Bayesian inference

$X=[16,19]$



Rejection sampling (100 included samples)

$X=[16,19]$



Efficiency is REALLY BAD, accepting only 0.04% for the set [16,19] (we need about 265,000 samples to get 100 we can use)

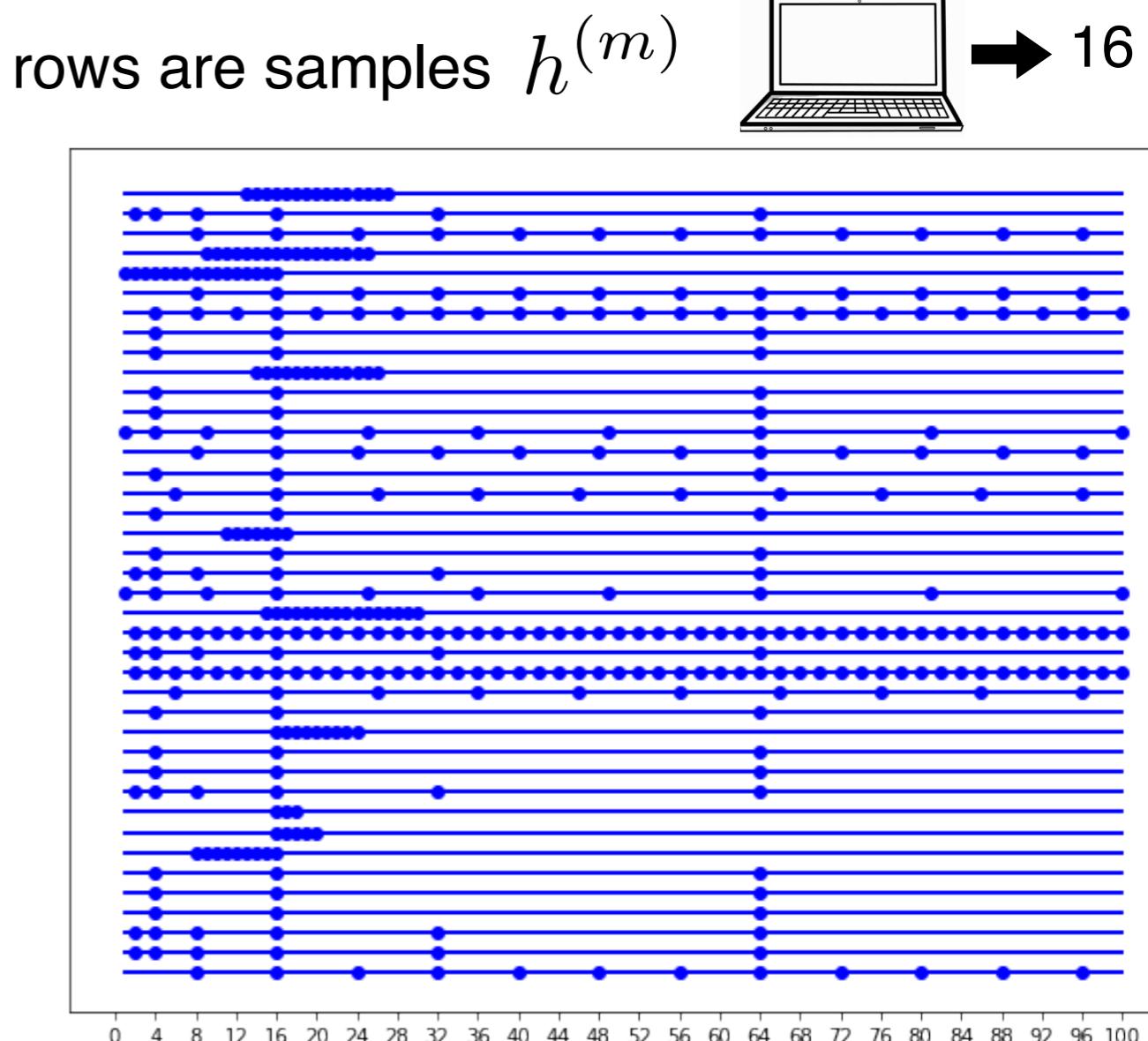
Important aside: Probabilistic inference is very flexible!

$$E[\phi(h)|D] \approx \frac{1}{M} \sum_m \phi(h^{(m)})$$

If we can compute the posterior, or draw samples from the posterior, we can automatically reason about a huge range of questions $\phi(\cdot)$

Examples of reusing the sample for new queries

- Is 64 a member of the set? (**probability is 0.73**)
- Are both 36 and 64 members of the set? (**0.36**)
- Is there a member of the set greater than or equal to 80? (**0.27**)
- If we sample a new number from the hypothesis, what is the chance it will be 64? (**0.16**)
- If we sample a new number from the hypothesis, what is the chance it will be 80? (**0.02**)



The type of flexibility in reasoning is natural in Bayesian models, but it is difficult to capture in neural networks trained with supervised learning, or model-free reinforcement learning.

Inference flexibility is not specific to rejection sampling, but to Bayesian models in general.

Importance sampling

We want to approximate posterior expectation:

$$\begin{aligned} E[\phi(h)|D] &= \sum_h \phi(h) P(h|D) \\ &= \sum_h \phi(h) \frac{P(h|D)}{Q(h)} Q(h) \end{aligned}$$

introduce a distribution Q we can easily sample from (and which is nonzero where the posterior is non-zero)

$$\approx \frac{1}{M} \sum_m \phi(h^{(m)}) \frac{P(h^{(m)}|D)}{Q(h^{(m)})} \quad \text{draw samples from } Q$$

importance sampling

$$= \frac{1}{M} \sum_m w^{(m)} \phi(h^{(m)}) \quad \text{for } w^{(m)} = \frac{P(h^{(m)}|D)}{Q(h^{(m)})}$$

where samples $h^{(1)}, \dots, h^{(M)}$ are generated from $Q(h^{(m)})$

More commonly, we don't know normalizing constant for either P or Q , so we use:

$$E[\phi(h)|D] \approx \frac{1}{\sum_m w^{(m)}} \sum_m w^{(m)} \phi(h^{(m)})$$

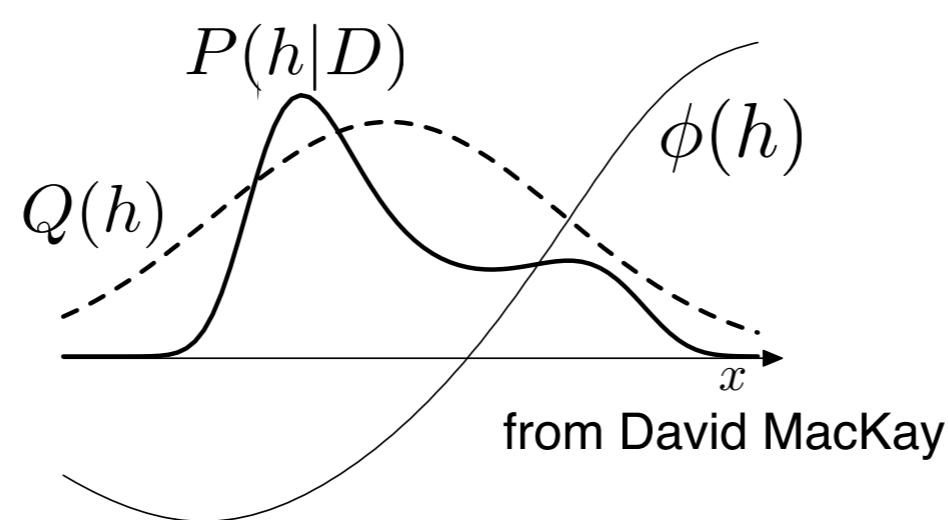
Importance sampling

$$E[\phi(h)|D] \approx \frac{1}{\sum_m w^{(m)}} \sum_m w^{(m)} \phi(h^{(m)})$$

where samples $h^{(1)}, \dots, h^{(M)}$ are generated from $Q(h^{(m)})$

Strategy:

We replace average over all hypotheses with a set of weighted samples, which correct for discrepancy between posterior and Q



$$w^{(m)} = \frac{P(h^{(m)}|D)}{Q(h^{(m)})}$$

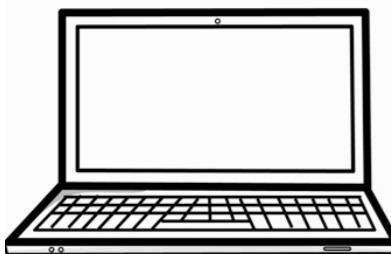
We can set Q as the prior to get “**Likelihood weighted sampling**”

Pros and cons:

pros: far more efficient than rejection sampling, and works for continuous data
cons: its effectiveness strongly depends on how close Q is to the posterior

Example: likelihood weighted sampling

non-zero weights (and more specific have larger weight)



16

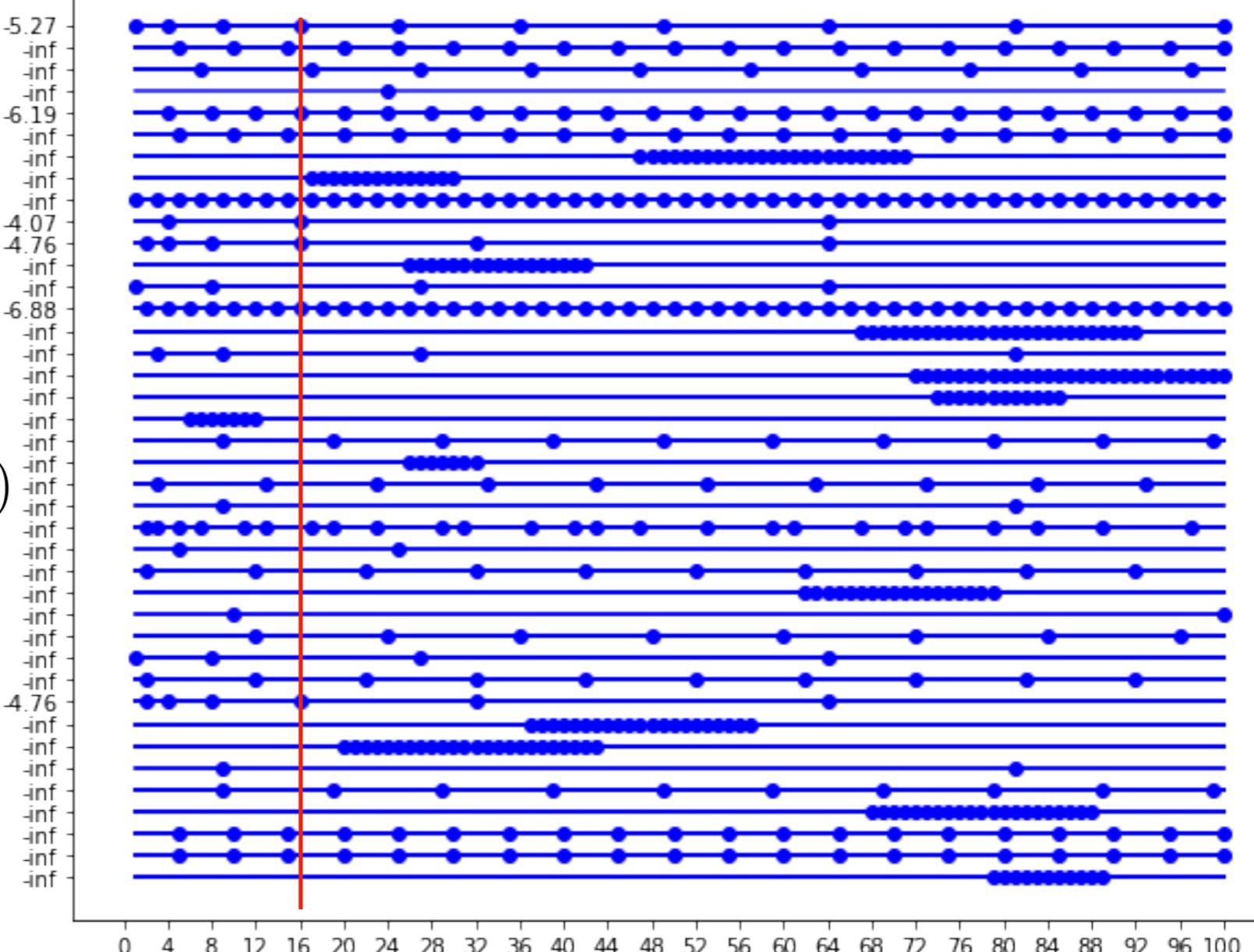
rows are samples from prior
 $h^{(m)}$

$$Q(h) \leftarrow P(h) \quad \log(w^{(m)})$$

$$E[\phi(h)|D] \approx \frac{1}{\sum_m w^{(m)}} \sum_m w^{(m)} \phi(h^{(m)})$$

$$\phi(h) = y \in C$$

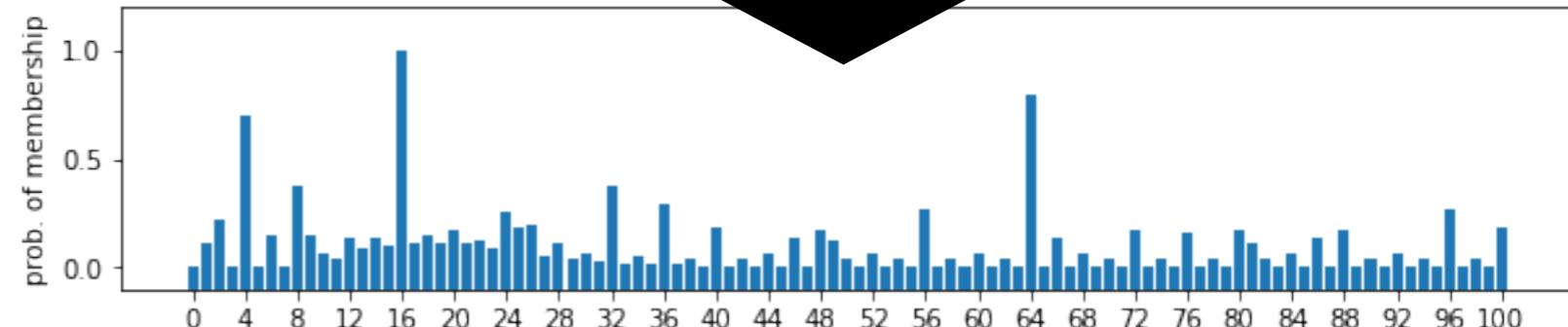
is new number y in the hypothesis?



compute prob. of membership

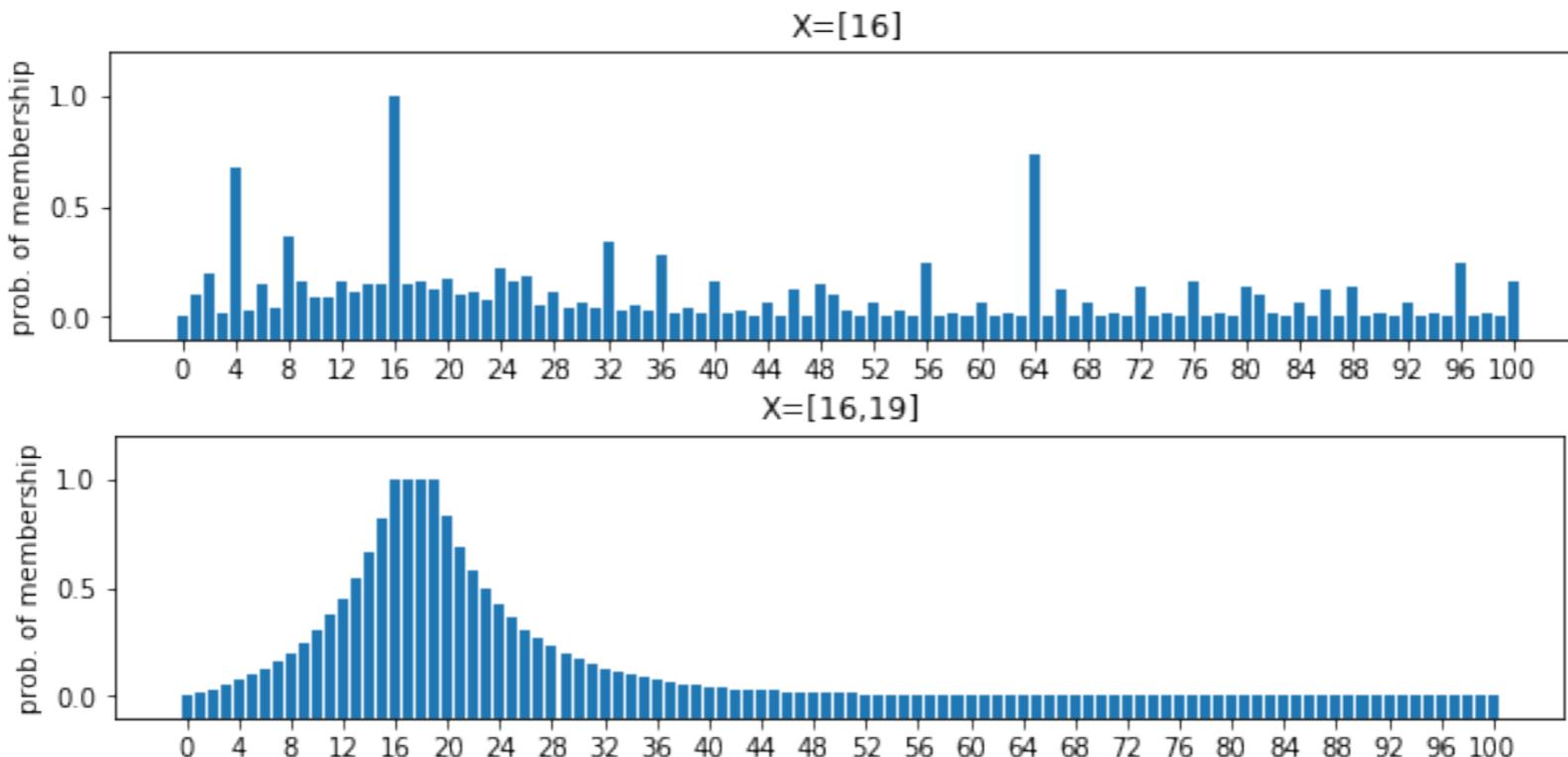
(weighted average)

X=[16] (image sampler)

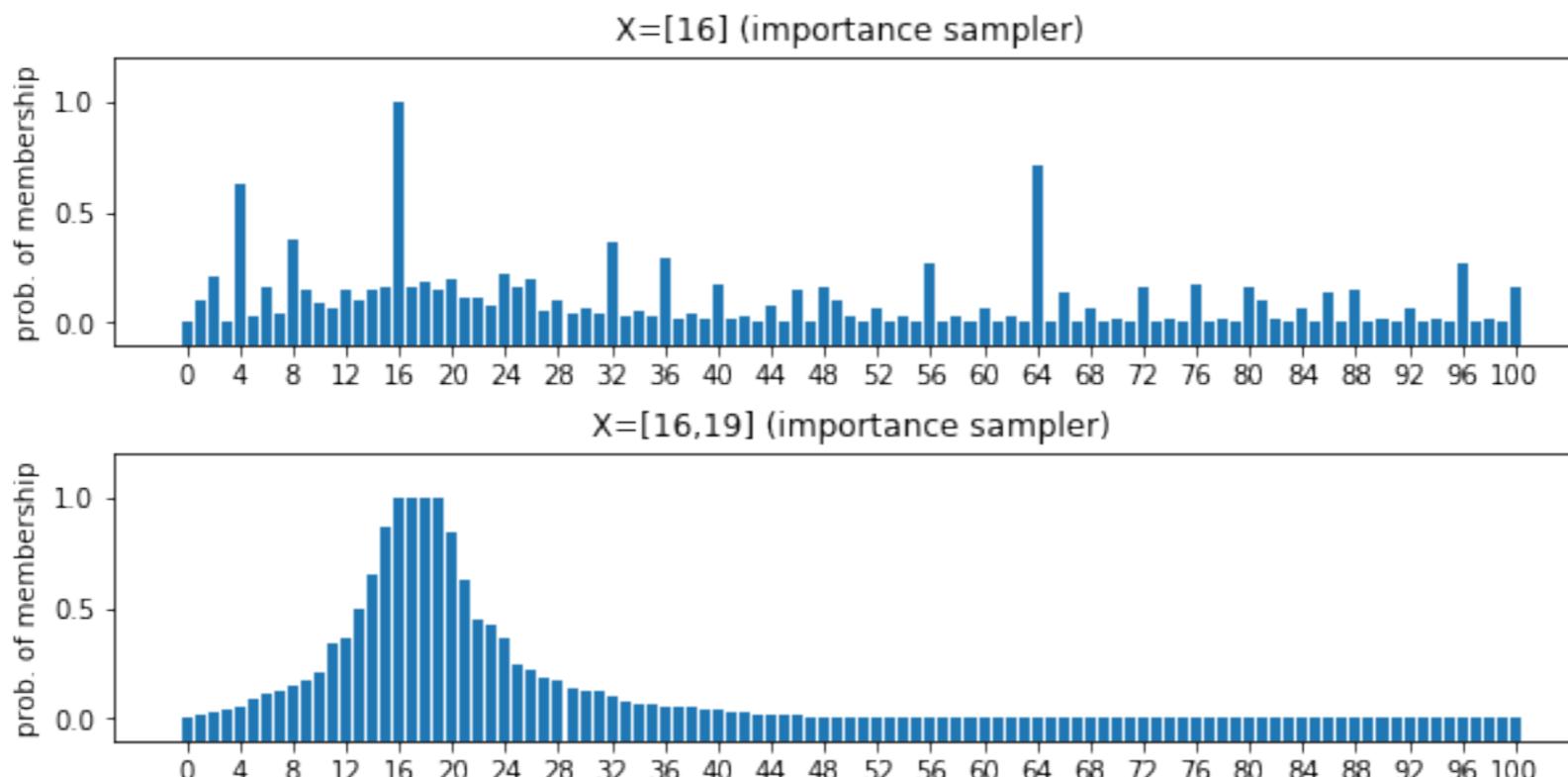


Example: likelihood weighted sampling

Exact Bayesian inference



Importance sampling (with only 2000 samples)



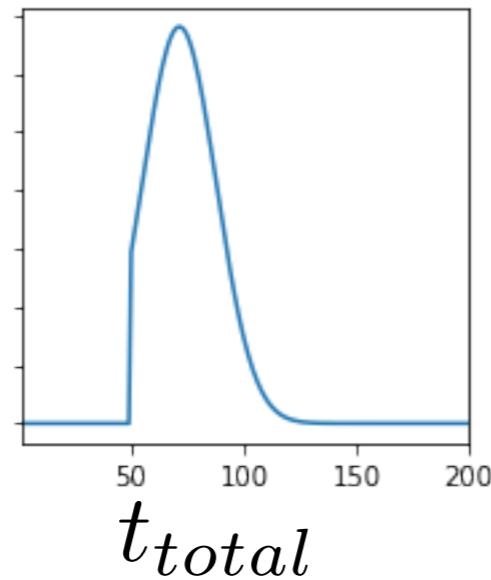
Example: Importance sampling for “Optimal Predictions”

Examples of non-standard posterior distributions

Lifespan posterior

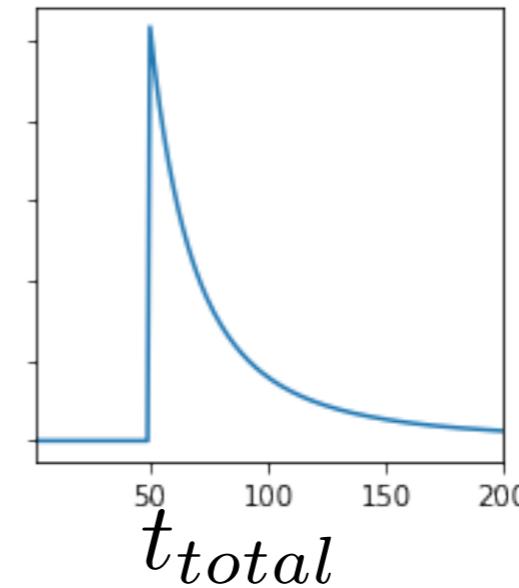
$$P(t_{total} | t = 50)$$

relative probability



Movie gross posterior

$$P(t_{total} | t = 50)$$



Posterior mean $E[t_{total} | t = 50]$

Exact inference: 74.3 82.6

Importance sampler
(with 400 samples) 74.0 82.8

$$Q(t_{total}) = \text{Uniform}(1, 200)$$

Metropolis-Hastings algorithm

(example of Markov Chain Monte Carlo (MCMC))

Goal of approximate inference:

$$E[\phi(h)|D] \approx \frac{1}{T} \sum_t \phi(h^{(t)})$$

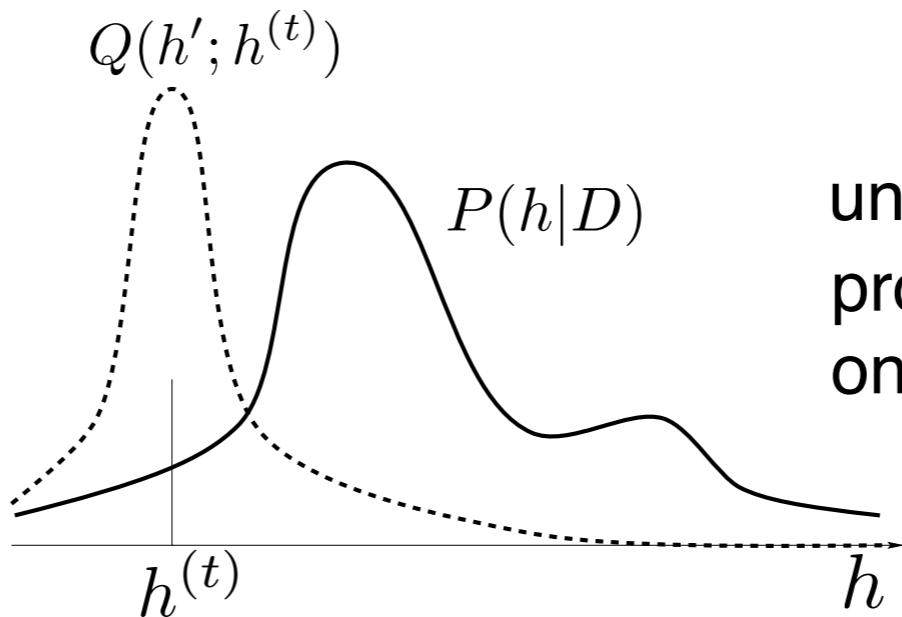
where the sequence of samples $h^{(1)}, \dots, h^{(T)}$ converges to the posterior $P(h|D)$

Proposal distribution:

$$Q(h'; h^{(t)})$$

proposed sample

$$h'$$



unlike importance sampling
proposal h' depends
on the current sample $h^{(t)}$

Acceptance ratio:

$$a = \frac{P(h'|D)Q(h^{(t)}; h')}{P(h^{(t)}|D)Q(h'; h^{(t)})}$$

If $a \geq 1$ then the new state is accepted.
Otherwise, the new state is accepted with probability a

If the step is accepted, we set $h^{(t+1)} \leftarrow h'$

If the step is rejected, we set $h^{(t+1)} \leftarrow h^{(t)}$ (**warning! common mistake**)

Metropolis-Hastings algorithm and MCMC

Tricks of the trade:

- If we use a symmetric distribution for Q , like a Gaussian, we can simplify the acceptance ratio to:

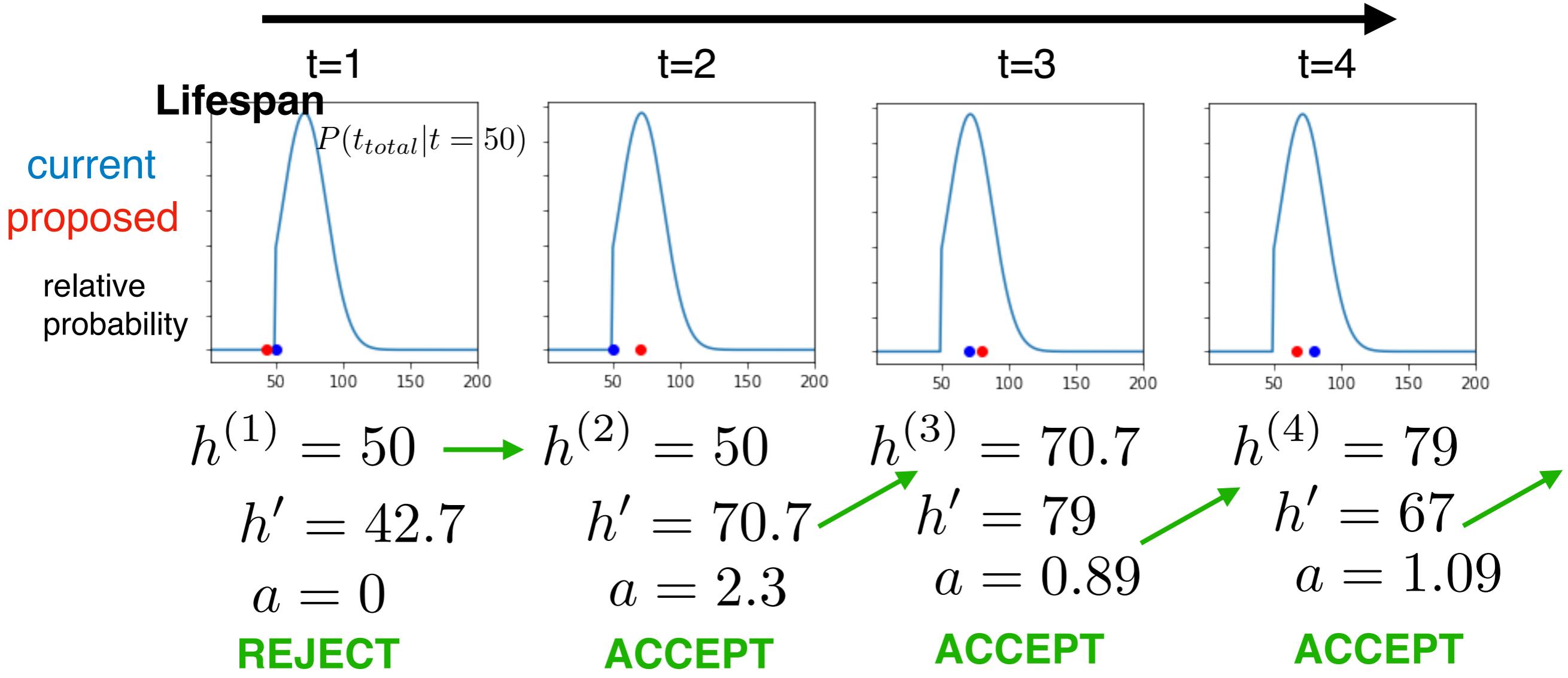
$$a = \frac{P(h')}{P(h^{(t)})}$$

- Samples are correlated with one another, so you typically throw out the samples at the beginning of your chain (called burn in)
- It is good practice to run multiple chains with different starting points, to examine convergence.
- MCMC can be used as a stochastic search algorithm as well

Pros and cons:

- pros: very general; Q is important, but it does not need be as carefully constructed as with importance sampling
- cons: samples are correlated with each other; it can take a very long time to converge

Example of Metropolis-Hastings for “Optimal Predictions”



Acceptance ratio:

$$a = \frac{P(h')}{P(h^{(t)})}$$

If $a \geq 1$ then the new state is accepted.

Otherwise, the new state is accepted with probability a

Proposal function:

$$Q(h'; h^{(t)}) = N(h^{(t)}, 15)$$

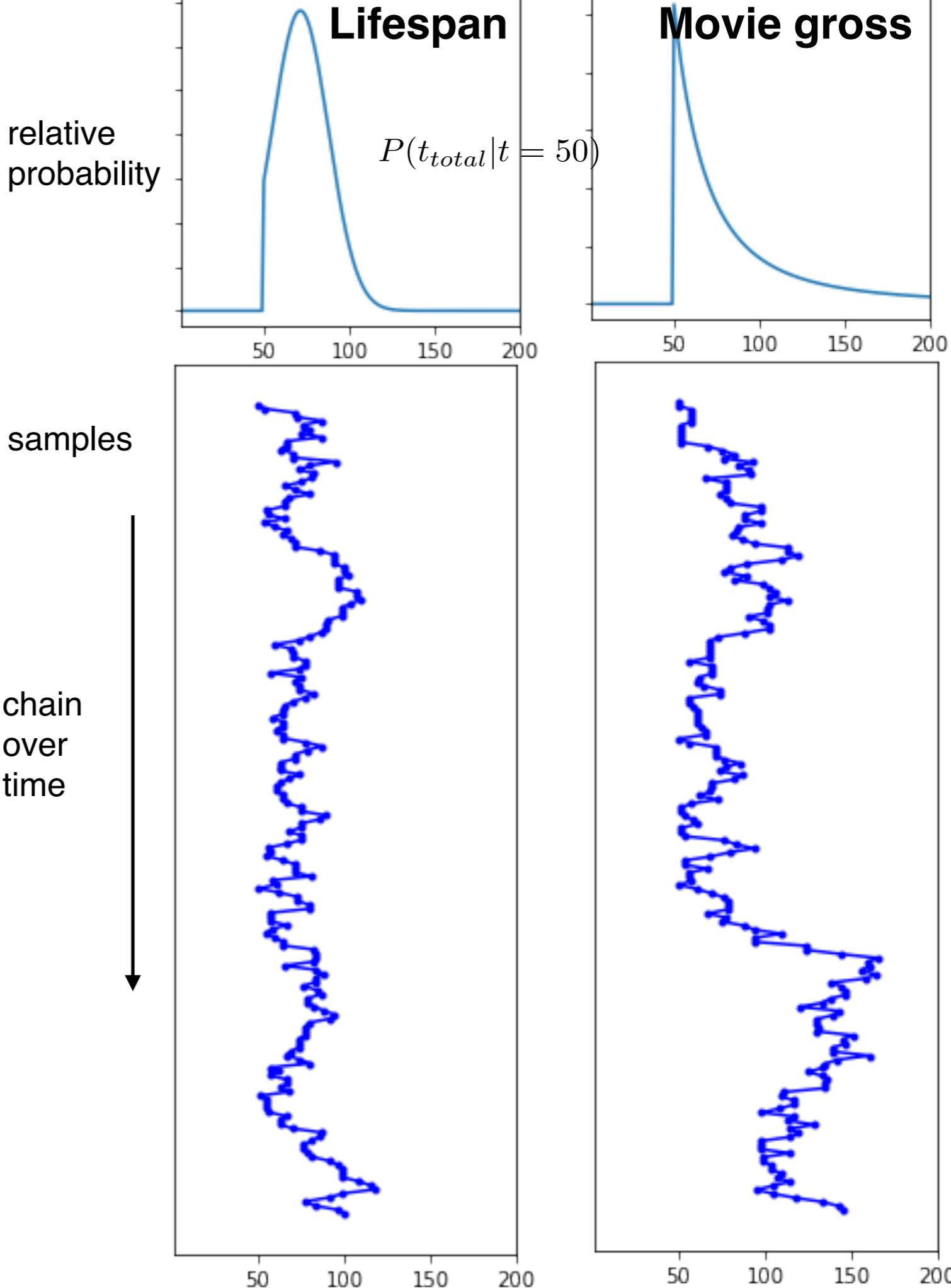
Example of Metropolis-Hastings for “Optimal Predictions”

Posterior mean

$$E[t_{total} | t = 50]$$

	Lifespan	Movie
Exact Inference:	74.3	82.6

Metropolis-Hastings (MCMC; 1000 samples)	74.4	83.0
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Probabilistic programming

- Probabilistic programming is a powerful approach for writing Bayesian models
- The probabilistic model is defined in a structured description language (much like a programming language) using random elements
- Due to random elements, every time the program executes it returns a different output
- Convenient when the prior is too complex to write down as a set of hypotheses, or the model is awkward to write as a probabilistic graphical model (see lecture on graphical models)
- This is a very general way to think about Bayesian modeling — most Bayesian models can be written as simple probabilistic programs

Probabilistic programming: A simple example

Preliminary definitions

```
def flip(theta=0.5):  
    return random.random() < theta
```

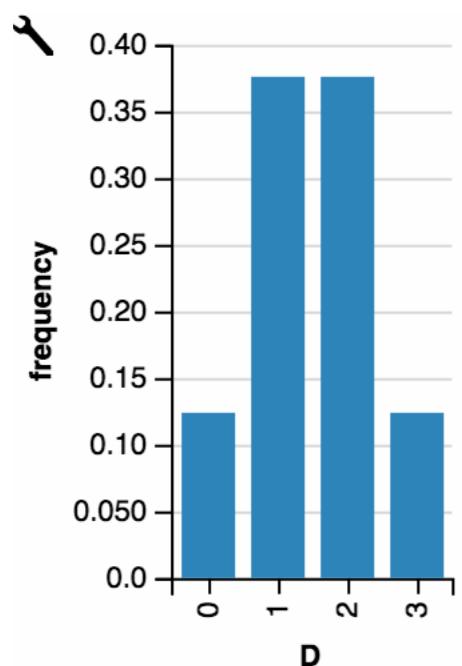
Simple probabilistic program

```
A = flip()  
B = flip()  
C = flip()  
D = A + B + C
```

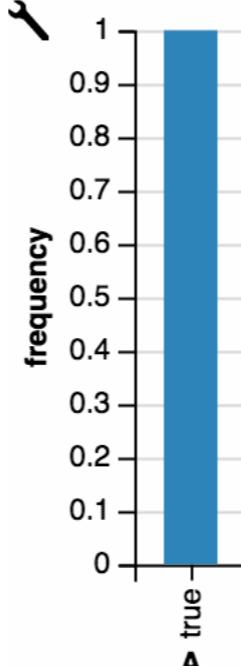
Bayesian inference

(again, notice productivity of reasoning abilities!)

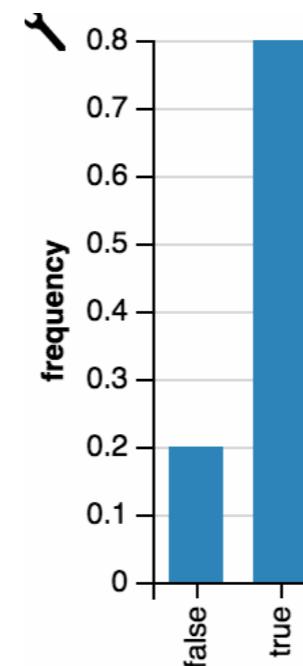
$$P(D)$$



$$P(A|D = 3)$$



$$P(A|D \geq 2)$$



Example from Noah Goodman and Josh Tenenbaum
<https://probmods.org/>

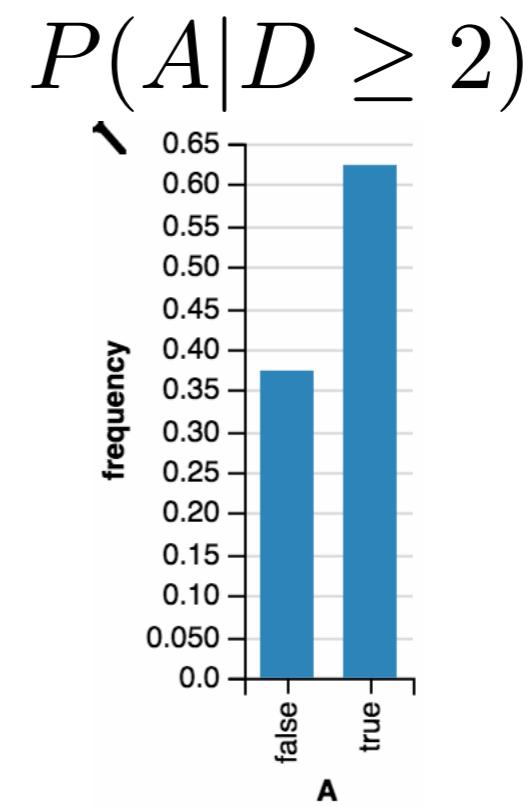
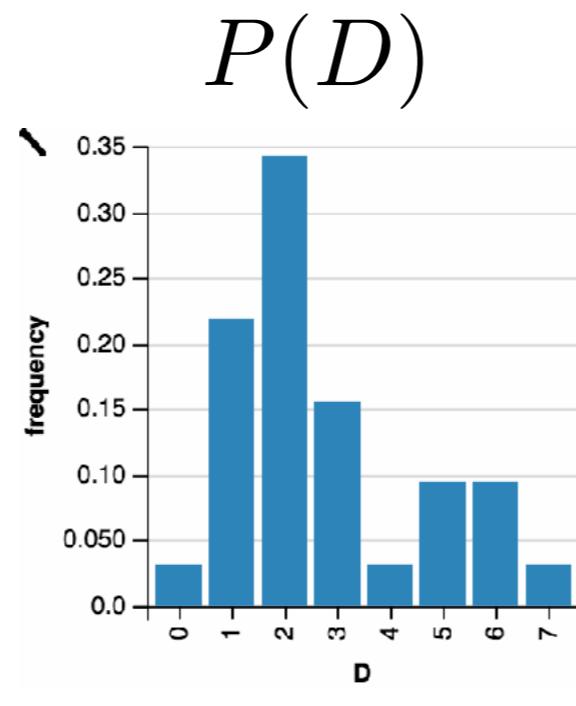
Probabilistic programming: Another example

Simple probabilistic program (yet more complex than before)

```
A = flip()  
B = flip()  
C = flip()  
if C:  
    D = A + B + C  
else:  
    E = flip()  
    F = (2*flip())**2  
    D = A + B + C +E + F
```

Key idea: A probabilistic program is a generative process for producing data

Bayesian inference



Key resource on probabilistic programming perspective to cognitive modeling (probmods.org)

Probabilistic Models of Cognition

2nd Edition

by Noah D. Goodman & Joshua B. Tenenbaum

This book explores the probabilistic approach to cognitive science, which models learning and reasoning as inference in complex probabilistic models. We examine how a broad range of empirical phenomena, including intuitive physics, concept learning, causal reasoning, social cognition, and language understanding, can be modeled using a functional probabilistic programming language called WebPPL.

Citation

N. D. Goodman and J. B. Tenenbaum (2016).
Probabilistic Models of Cognition (2nd ed.).
Retrieved 2018-4-2 from <https://probmods.org/>
[\[bibtex\]](#)

Open source

- [Book content](#)
Markdown code for the book chapters
- [WebPPL](#)
A probabilistic programming language for the web

Previous edition

The first edition of this book used the probabilistic programming language Church and can be found [here](#).

Chapters

1. [Introduction](#)
A brief introduction to the philosophy.
2. [Generative models](#)
Representing working models with probabilistic programs.
3. [Conditioning](#)
Asking questions of models by conditional inference.
4. [Patterns of inference](#)
Causal and statistical dependence. Conditional dependence.
5. [Models for sequences of observations](#)
Generative models of the relations between data points
6. [Inference about inference](#)
Models on models on models
7. [Algorithms for inference](#)

Key principles of Bayesian models of cognition

- Start with analyzing the computational problem that has to be solved, and describe it as a problem of Bayesian inference
- A successful computational level model provides strong constraints when developing an algorithmic and implementational level model
- Bayesian inference provides a flexible framework for testing different hypotheses about representation, without having to worry about how to define special algorithms for inference and learning