

Statistical Theory and Modeling (ST2601)

Lecture 9 - Information and ML in large samples

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- **The information in a likelihood function**
- **Maximum likelihood estimator in large samples**

The Big Picture

- Four stages of learning **modern statistical learning**.
 - 1 **Understand probability and statistical models.**
 - 2 **Mathematical derivation** of the MLE
 - ▶ Write up the log-likelihood $\ell(\theta)$
 - ▶ Calculate derivative $\ell'(\theta)$
 - ▶ Solve for the MLE from $\ell'(\theta) = 0$
 - 3 **Numerical optimization** for the MLE
 - ▶ Code up the log-likelihood $\ell(\theta)$
 - ▶ Use **automatic differentiation** to find $\ell'(\theta)$
 - ▶ Solve for the MLE using a **numerical optimizer**.
 - 4 **Probabilistic programming languages (PPL)** (Stan etc)
 - ▶ Express the statistical model, almost like in textbooks.
 - ▶ Let the framework to all the work for you.
- Learning 1 \rightarrow 2 \rightarrow 3 \rightarrow 4 makes Stage 4 understandable and explainable to clients, helps in debugging, allows you to go beyond models in manual.
- Stage 3 gives freedom when PPL doesn't do what you need.

iid Poisson model in Stan

■ IID Poisson model

$$Y_1, \dots, Y_N | \lambda \stackrel{\text{iid}}{\sim} \text{Pois}(\lambda)$$

```
data {  
  int<lower = 0> N;  
  int<lower = 0> y[N];  
}  
parameters {  
  real<lower = 0> lambda;  
}  
model {  
  lambda ~ gamma(1, 1);  
  y ~ poisson(lambda);  
}  
generated quantities {  
  int<lower = 0> y_tilde = poisson_rng(lambda);  
}
```

Negative Binomial regression in Turing.jl

```
# Negative binomial regression
@model function negbinomialReg(y, X,  $\tau$ ,  $\mu_0$ ,  $\sigma_0$ )
    p = size(X,2)
     $\beta$  ~ filldist(Normal(0,  $\tau$ ), p)
     $\lambda$  = exp.(X* $\beta$ )
     $\psi$  ~ LogNormal( $\mu_0$ ,  $\sigma_0$ )
    n = length(y)
    for i in 1:n
        y[i] ~ NegativeBinomial( $\psi$ ,  $\psi/(\psi + \lambda[i])$ )
    end
end
```

How informative is my data about the parameters?

- **Probabilistic model** $p(Y_1, \dots, Y_n | \theta)$ with **parameter** θ .

- Example: iid Poisson model:

$$Y_1, \dots, Y_N | \lambda \stackrel{\text{iid}}{\sim} \text{Pois}(\lambda)$$

- **Likelihood function** (assuming independent data)

$$L(\theta) = p(y_1, \dots, y_n | \theta) = \prod_{i=1}^n p(y_i | \theta)$$

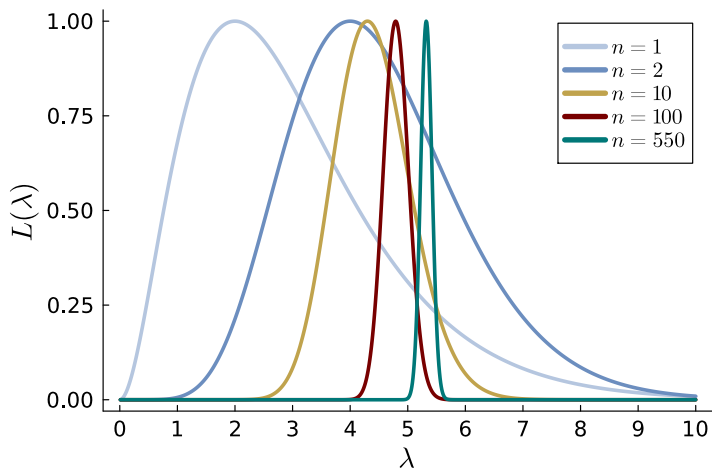
- **Log-likelihood function**

$$\ell(\theta) = \log L(\theta)$$

- **Observed information**: **Given a dataset** y_1, \dots, y_n , how much information is there about θ ?
- **Expected information**: **Before collecting data**, how much information can I expect to get about θ ?

Observed information

- **Given a dataset**, how much information is there about θ ?
- **How peaked** is the likelihood function?



Observed information

- The **second derivative** measures the curvature of a function

$$f''(x) = \frac{d^2}{dx^2} f(x) = \frac{d}{dx} f'(x)$$

- **Observed information** from n observations

$$J_n(\hat{\theta}) = -\ell''(\hat{\theta})$$

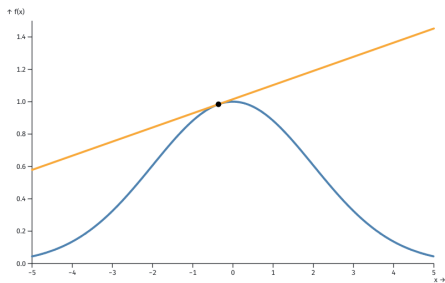
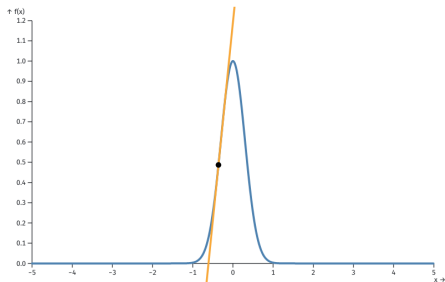
where $\hat{\theta}$ is the maximum likelihood estimate (MLE).

- Often written as

$$\left. \frac{d^2}{d\theta^2} \ell(\theta) \right|_{\theta=\hat{\theta}}$$

- Why a negative sign? The second derivative is negative at the maximum. We like information to be a positive number.
- Why the **log**-likelihood function? Suggested by likelihood theory. Log-likelihood is approx quadratic in large samples.

Second derivative measures curvature



Observed information in the iid Poisson model

- IID Poisson model

$$Y_1, \dots, Y_N | \lambda \stackrel{\text{iid}}{\sim} \text{Pois}(\lambda)$$

- Log-likelihood

$$\ell(\lambda) = \sum_{i=1}^n \log p(y_i | \lambda)$$

- Log density for i th observation

$$\log p(y_i | \lambda) = \log \left(\frac{\lambda^{y_i} e^{-\lambda}}{y_i!} \right) = y_i \log(\lambda) - \lambda - \log(y_i!)$$

- Log-likelihood

$$\begin{aligned} \ell(\lambda) &= \sum_{i=1}^n (y_i \log(\lambda) - \lambda - \log(y_i!)) \\ &= \log(\lambda) \sum_{i=1}^n y_i - n\lambda - \sum_{i=1}^n \log(y_i!) \end{aligned}$$

Observed information in the iid Poisson model

- Log-likelihood (constants in orange)

$$\ell(\lambda) = \log(\lambda) \sum_{i=1}^n y_i - n\lambda - \sum_{i=1}^n \log(y_i!)$$

- First derivative

$$\ell'(\lambda) = \frac{\sum_{i=1}^n y_i}{\lambda} - n$$

- Solving $\ell'(\lambda) = 0$ gives the MLE $\hat{\lambda} = \frac{\sum_{i=1}^n y_i}{n} = \bar{y}$.

- Second derivative

$$\ell''(\lambda) = -\frac{\sum_{i=1}^n y_i}{\lambda^2} = -\frac{n\bar{y}}{\lambda^2}$$

- Observed information

$$\mathcal{J}_n(\hat{\lambda}) = -\ell''(\hat{\lambda}) = \frac{n\bar{y}}{\hat{\lambda}^2} = \frac{n\bar{y}}{\bar{y}^2} = \frac{n}{\bar{y}}$$

- Information grows linearly in sample size n . Always true for iid

Expected information

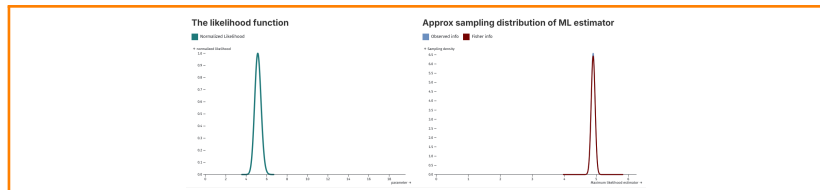
- The observed information varies from dataset to dataset.
- **Expected information:** Before collecting data, how information can I expected to get about θ ?
- The expected information **over all possible datasets**

$$\mathcal{I}_n(\theta) = \mathbb{E}(\mathcal{J}_n(\theta))$$

$\mathcal{J}_n(\theta)$ is the observed information from dataset (Y_1, \dots, Y_n) .

- Also called the **Fisher information**.
- Designing experiments and data collection (**active learning**).
- Also in **sampling distribution of the MLE** in large samples.

Likelihood and Information - widget



Maximum likelihood estimator in large samples

- **Sampling distribution of the MLE** in large datasets

$$\hat{\theta}_n \overset{\text{approx}}{\sim} N\left(\theta, \frac{1}{\mathcal{I}_n(\theta)}\right) \text{ for large } n$$

- MLE is **asymptotically unbiased** (as $n \rightarrow \infty$).
- **Asymptotically efficient** (lowest possible variance among unbiased estimators. **Cramér-Rao lower bound**).
- In large samples $\mathcal{I}_n(\theta) \approx \mathcal{J}_n(\hat{\theta})$, so we can use $\mathcal{J}_n(\hat{\theta})$.
- The beauty: a computer can compute $\hat{\theta}_n$ and $\mathcal{J}_n(\hat{\theta}_n)$. 🥰

Maximum likelihood in large samples - example

MLE sampling distribution for large n

$$\hat{\theta}_n \stackrel{\text{approx}}{\sim} N\left(\theta, \frac{1}{\mathcal{J}_n(\hat{\theta}_n)}\right) \text{ for large } n$$

IID Poisson model

$$\hat{\lambda}_n(Y_1, \dots, Y_n) \stackrel{\text{approx}}{\sim} N\left(\lambda, \frac{1}{\mathcal{J}_n(\hat{\lambda}_n)}\right) = N\left(\lambda, \frac{1}{n/\bar{y}}\right) = N\left(\lambda, \frac{\bar{y}}{n}\right)$$

In this case we can compute the **true sampling variance**

$$\mathbb{V}(\hat{\lambda}) = \mathbb{V}(\bar{Y}) = \frac{\mathbb{V}(Y_i)}{n} = \frac{\lambda}{n}$$

since variance = mean for Poisson.

Multi-parameter case

- Multi-parameter models: $p(y_1, \dots, y_n | \boldsymbol{\theta})$ where $\boldsymbol{\theta} = (\theta_1, \dots, \theta_p)^\top$ is a vector with parameters.
- Example: Negative binomial with $\boldsymbol{\theta} = (r, \mu)^\top$

$$Y_1, \dots, Y_N | r, \mu \stackrel{\text{iid}}{\sim} \text{NegBin}(r, \mu)$$

- Example: Two-dimensional **observed information matrix**)

$$\frac{\partial^2 \ell(\boldsymbol{\theta})}{\partial \boldsymbol{\theta} \partial \boldsymbol{\theta}^\top} = \begin{pmatrix} \frac{\partial^2}{\partial \theta_1^2} \ell(\theta_1, \theta_2) & \frac{\partial^2}{\partial \theta_1 \partial \theta_2} \ell(\theta_1, \theta_2) \\ \frac{\partial^2}{\partial \theta_2 \partial \theta_1} \ell(\theta_1, \theta_2) & \frac{\partial^2}{\partial \theta_2^2} \ell(\theta_1, \theta_2) \end{pmatrix}$$

- **Sampling distribution of the MLE** in large samples

$$\hat{\boldsymbol{\theta}}_n \stackrel{\text{approx}}{\sim} N\left(\boldsymbol{\theta}, \mathcal{J}_n^{-1}(\hat{\boldsymbol{\theta}}_n)\right) \text{ for large } n$$

where N is the multivariate normal distribution and $\mathcal{J}_n^{-1}(\hat{\boldsymbol{\theta}}_n)$ is the matrix inverse of $\mathcal{J}_n(\hat{\boldsymbol{\theta}}_n)$.