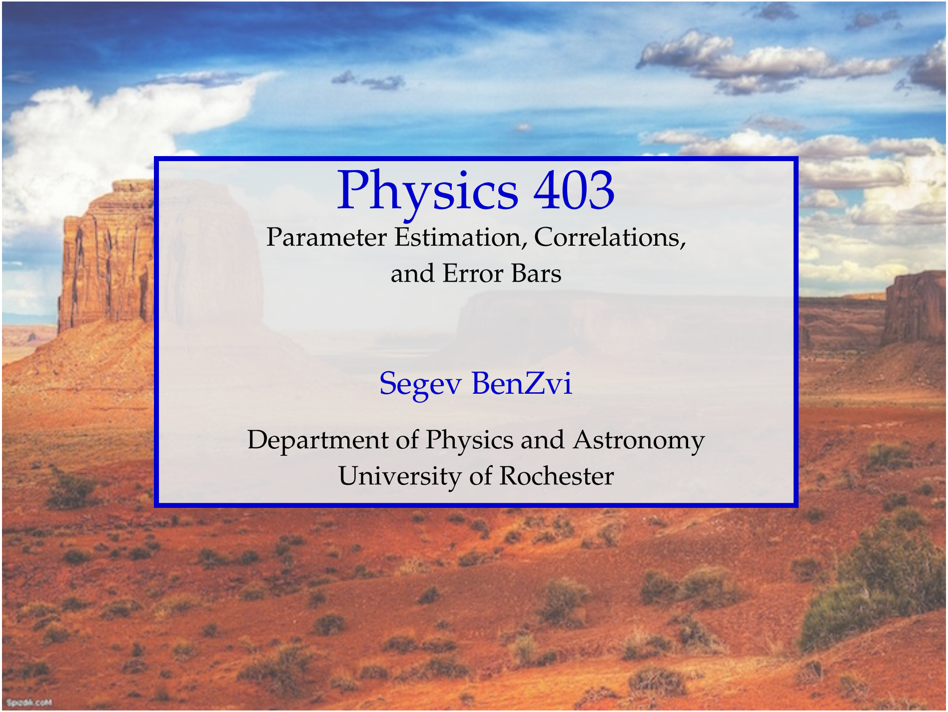

Physics 403

Parameter Estimation, Correlations, and Error Bars

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Announcements

Midterm:

- In class, Monday Feb. 29
- The exam will count for 20% of your final grade
- Material: basic rules of probability, common distributions, PDF/likelihood maximization and estimators
- Properties of PDFs: marginalization, transformation rules, etc.
- No numerical component, obviously, but you may get a conceptual question about it

Reading:

- Sivia, Ch. 3.2 and 3.3

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Best Estimates and Reliability

- Identify the best estimator $\hat{x}$ of a PDF by maximizing $p(x|D,I)$:

$$\left.\frac{dp}{dx}\right|_{\hat{x}} = 0, \qquad \left.\frac{d^2p}{dx^2}\right|_{\hat{x}} < 0$$

- We assessed the reliability of the estimator by Taylor expanding $L = \ln p$ about the best value and found that

$$\hat{\sigma}^2 = \left(-\left.\frac{d^2L}{dx^2}\right|_{\hat{x}}\right)^{-1}$$

- This only works when the quadratic approximation is reasonable
- For an asymmetric PDF, it's better to use a confidence interval when reporting the reliability of an estimate
- For a multimodal PDF, summarizing the PDF with an estimator is not very well defined or useful

Example Estimators from Last Class

- Best estimator of binomial probability p (n successes in N trials):

$$\hat{p} = \frac{n}{N}, \qquad \hat{\sigma}^2 = \frac{n(N-n)}{N^3} = \frac{\hat{p}(1-\hat{p})}{N}$$

- Arithmetic mean: best estimator of Gaussian with known variance σ^2:

$$\hat{\mu} = \frac{1}{N}\sum_{i=1}^{N} x_i, \qquad \hat{\sigma}^2 = \frac{\sigma^2}{N}$$

- Weighted mean: best estimator of Gaussian with different error bars:

$$\hat{\mu} = \sum_{i=1}^{N} x_i w_i \Bigg/ \sum_{i=1}^{N} w_i\,, \qquad \hat{\sigma}^2 = \frac{1}{\sum_{i=1}^{N} w_i}, \qquad w_i = 1/\sigma_i^2$$

Caution: don't confuse width of distribution with uncertainty on the mean

Properties of a Good Estimator (for Frequentists)

A good estimator should be:

1. **Consistent**. The estimate tends toward the true value with more data:
$$\lim_{N\to\infty} \hat{\theta} = \theta$$
2. **Unbiased**. The expectation value is equal to the true value:
$$b = \langle\hat{\theta}\rangle - \theta = \int d\boldsymbol{x}\, p(\boldsymbol{x}|\theta)\, \hat{\theta}(\boldsymbol{x}) - \theta = 0$$
3. **Efficient**. The variance of the estimator is as small as possible (minimum variance bound, to be discussed):
$$\text{var}\,(\hat{\theta}) = \int d\boldsymbol{x}\, p(\boldsymbol{x}|\theta)\, (\hat{\theta}(\boldsymbol{x}) - \hat{\theta})^2$$
$$\text{MSE} = \langle(\hat{\theta}-\theta)^2\rangle = \text{var}\,(\hat{\theta}) + b^2$$

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Parameter Estimation in Higher Dimensions

- Moving to more dimensions:

$$x \to \boldsymbol{x}, \qquad p(x|D,I) \to p(\boldsymbol{x}|D,I)$$

- As in the 1D case, the posterior PDF still encodes all the information we need to get the best estimator.
- The maximum of the PDF gives the best estimate of the quantities $\boldsymbol{x} = \{x_j\}$.
- We solve the set of simultaneous equations

$$\left.\frac{\partial p}{\partial x_i}\right|_{\{\hat{x}_j\}} = 0$$

- **Question**: how to we make sure that we're at the maximum and not a minimum or a saddle point?

The Quadratic Approximation Revisited

- It's easier to deal with $L = \ln p(\{x_j\}|D, I)$, so let's do that. Let's also simplify to 2D, without loss of generality, so that $\boldsymbol{x} = (x, y)$.
- The maximum of the posterior satisfies

$$\left.\frac{\partial L}{\partial x}\right|_{\hat{x},\hat{y}} = 0 \quad \text{and} \quad \left.\frac{\partial L}{\partial y}\right|_{\hat{x},\hat{y}} = 0$$

- Look at the behavior of L about the maximum using its Taylor expansion:

$$L = L(\hat{x}, \hat{y}) + \frac{1}{2}\left.\frac{\partial^2 L}{\partial x^2}\right|_{\hat{x},\hat{y}}(x - \hat{x})^2 + \frac{1}{2}\left.\frac{\partial^2 L}{\partial y^2}\right|_{\hat{x},\hat{y}}(y - \hat{y})^2 + \left.\frac{\partial^2 L}{\partial x \partial y}\right|_{\hat{x},\hat{y}}(x - \hat{x})(y - \hat{y}) + \ldots$$

where the linear terms are zero because we're at the maximum.

The Hessian Matrix

- As in the 1D case, the quadratic terms in the expansion dominate the behavior near the maximum.
- **Insight**: rewrite the quadratic terms in matrix notation:

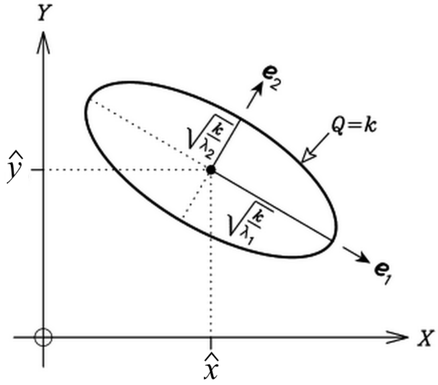
$$\begin{aligned} Q &= \frac{1}{2}\begin{pmatrix} x-\hat{x} & y-\hat{y} \end{pmatrix}\begin{pmatrix} A & C \\ C & B \end{pmatrix}\begin{pmatrix} x-\hat{x} \\ y-\hat{y} \end{pmatrix} \\ &= \frac{1}{2}(\boldsymbol{x}-\hat{\boldsymbol{x}})^\top \boldsymbol{H}(\hat{\boldsymbol{x}})(\boldsymbol{x}-\hat{\boldsymbol{x}}) \end{aligned}$$

  where $\boldsymbol{H}(\hat{\boldsymbol{x}})$ is a 2×2 real symmetric matrix with components

$$A = \left.\frac{\partial^2 L}{\partial x^2}\right|_{\hat{x},\hat{y}}, \quad B = \left.\frac{\partial^2 L}{\partial y^2}\right|_{\hat{x},\hat{y}}, \quad C = \left.\frac{\partial^2 L}{\partial x \partial y}\right|_{\hat{x},\hat{y}}$$

- Note: $\boldsymbol{H}(\hat{\boldsymbol{x}})$, the matrix of second derivatives, is called the Hessian matrix of L.

Geometrical Interpretation



- Contour of Q in xy plane is an ellipse centered at $(\hat{x}, \hat{y})$
- Orientation and eccentricity are determined by the values of A, B, and C
- Principal axes correspond to the eigenvectors of $\boldsymbol{H}$. I.e., if we solve

$$\boldsymbol{Hx} = \lambda \boldsymbol{x}$$

$$\begin{pmatrix} A & C \\ C & B \end{pmatrix} \begin{pmatrix} x \\ y \end{pmatrix} = \lambda \begin{pmatrix} x \\ y \end{pmatrix}$$

we get two eigenvalues λ_1 and λ_2 which are inversely related to the square of the semi-major and semi-minor axes of the ellipse

Condition for a Maximum

- $L(\hat{\boldsymbol{x}})$ is a maximum if the quadratic form $Q(\boldsymbol{x}-\hat{\boldsymbol{x}}) = Q(\Delta\boldsymbol{x}) < 0\ \forall\boldsymbol{x}$.
- $\boldsymbol{H}$ is real and symmetric, so there exists an orthogonal matrix $\boldsymbol{O} = \begin{pmatrix}\boldsymbol{e}_1 & \boldsymbol{e}_2\end{pmatrix}$ such that

$$\boldsymbol{O}^\top\boldsymbol{H}\boldsymbol{O} = \boldsymbol{D} = \begin{pmatrix}\lambda_1 & 0\\ 0 & \lambda_2\end{pmatrix}$$

  where $\boldsymbol{e}_1$ and $\boldsymbol{e}_2$ are the eigenvectors of $\boldsymbol{H}$.
- Therefore, $\boldsymbol{H} = \boldsymbol{O}\boldsymbol{D}\boldsymbol{O}^\top$, and we can express Q as

$$\begin{aligned}Q &\propto \Delta\boldsymbol{x}^\top\boldsymbol{H}\Delta\boldsymbol{x}\\ &= \Delta\boldsymbol{x}^\top(\boldsymbol{O}\boldsymbol{D}\boldsymbol{O}^\top)\Delta\boldsymbol{x}\\ &= (\boldsymbol{O}^\top\Delta\boldsymbol{x})^\top\boldsymbol{D}(\boldsymbol{O}^\top\Delta\boldsymbol{x}) = \Delta\boldsymbol{x}'^\top\boldsymbol{D}\Delta\boldsymbol{x}'\\ &= \lambda_1(x-\hat{x})^2 + \lambda_2(y-\hat{y})^2\end{aligned}$$

- $\therefore Q < 0$ iff λ_1 and λ_2 are both negative.

Condition for a Maximum

- The eigenvalues of $\boldsymbol{H}$ are given by

$$\lambda_{1(2)} = \frac{1}{2}\operatorname{Tr}\boldsymbol{H} + (-)\sqrt{(\operatorname{Tr}\boldsymbol{H})^2/4 - \det\boldsymbol{H}}$$

  where

$$\operatorname{Tr}\boldsymbol{H} = A + B, \qquad \det\boldsymbol{H} = AB - C^2$$

- **Intuition**: what happens if the cross term $C = 0$? Then the principal axes of the ellipse defined by Q are aligned with the x and y axes and the eigenvalues reduce to

$$\lambda_1 = A, \qquad \lambda_2 = B$$

- Analogous to the 1D case, we can associate the "error bars" on $\hat{x}$ and $\hat{y}$ as the inverse root of the diagonal terms of the Hessian, or

$$\hat{\sigma}_x^2 = |\lambda_1|^{-1} = \left(-\left.\frac{\partial^2 L}{\partial x^2}\right|_{\hat{x},\hat{y}}\right)^{-1}, \qquad \hat{\sigma}_y^2 = |\lambda_2|^{-1} = \left(-\left.\frac{\partial^2 L}{\partial y^2}\right|_{\hat{x},\hat{y}}\right)^{-1}$$

General Case: $C \neq 0$

- What happens when the off-diagonal term of $\boldsymbol{H}$ is nonzero?
- Let's work in 2D. If we were only interested in the reliability of $\hat{x}$, then we would evaluate the behavior of the marginal distribution

$$p(x|D,I) = \int_{-\infty}^{\infty} p(x,y|D,I)\, dy$$

about the maximum

- Using our quadratic approximation, $p(x,y|D,I) = \exp L \propto \exp Q$:

$$\begin{aligned} p(x|D,I) &\approx \int_{-\infty}^{\infty} \exp\left(\frac{1}{2}\Delta\boldsymbol{x}^\top \boldsymbol{H} \Delta\boldsymbol{x}\right) dy \\ &= \int_{-\infty}^{\infty} \exp\left(\frac{1}{2}(Ax^2 + By^2 + 2Cxy)\right) dy, \end{aligned}$$

where (without loss of generality) we set $\hat{x} = \hat{y} = 0$.

General Case: $C \neq 0$

Solving the Gaussian Integral

Factor out terms in x, and explicitly change signs because we know that $Q < 0$:

$$\begin{aligned} p(x|D,I) &= \int_{-\infty}^{\infty} e^{-\frac{1}{2}(Ax^2+By^2+2Cxy)}\, dy \\ &= e^{-\frac{1}{2}Ax^2} \int_{-\infty}^{\infty} e^{-\frac{1}{2}(By^2+2Cxy)}\, dy \\ &= e^{-\frac{1}{2}\left(A+\frac{C^2}{B}\right)x^2} \int_{-\infty}^{\infty} e^{-\frac{1}{2}B\left(y+\frac{Cx}{B}\right)^2}\, dy \end{aligned}$$

where we completed the square:
$By^2 + 2Cxy = B(y + Cx/B)^2 - C^2x^2/B$, allowing us to rearrange the xy cross term.
The remaining integral is a Gaussian integral of form

$$\int_{-\infty}^{\infty} \exp\left(-\frac{u^2}{2\sigma^2}\right) du = \sigma\sqrt{2\pi}$$

General Case: $C \neq 0$

Expressions for σ_x and σ_y

- Therefore, the marginal distribution becomes

$$p(x|D,I) = \sqrt{\frac{2\pi}{B}} \exp\left(-\frac{1}{2}\frac{AB - C^2}{B}x^2\right)$$
$$= \sqrt{\frac{2\pi}{B}} \exp\left(-\frac{x^2}{2\sigma_x^2}\right),$$

where

$$\sigma_x^2 = \frac{-B}{AB - C^2} = \frac{-H_{yy}}{\det \boldsymbol{H}}$$

- Similarly, if we solve instead for $p(y|D,I)$, we'll find that

$$\sigma_y^2 = \frac{-A}{AB - C^2} = \frac{-H_{xx}}{\det \boldsymbol{H}}$$

- Note: we absorbed a negative sign back into A and B to match the properties of the Hessian.

Connection to Variance and Covariance

- Recall the definition of variance for a 1D PDF:

$$\text{var}\,(x) = \langle (x-\mu)^2 \rangle = \int dx\, (x-\mu)^2\, p(x|D,I)$$

- This can extended using the 2D PDF

$$\sigma_x^2 = \langle (x-\hat{x})^2 \rangle = \iint dx\, dy\, (x-\hat{x})^2\, p(x,y|D,I)$$

- If we use the quadratic approximation for $p(x,y|D,I)$, we find

$$\sigma_x^2 = \frac{-B}{AB-C^2} = \frac{-H_{yy}}{\det \boldsymbol{H}}$$

and similarly,

$$\sigma_y^2 = \langle (y-\hat{y})^2 \rangle = \frac{-A}{AB-C^2} = \frac{-H_{xx}}{\det \boldsymbol{H}},$$

the same expressions we just derived (convince yourself).

Connection to Variance and Covariance

- Also recall the definition of covariance:

$$\begin{aligned}\sigma_{xy}^2 &= \langle (x-\hat{x})(y-\hat{y}) \rangle \\ &= \iint dx\, dy\, (x-\hat{x})(y-\hat{y})\, p(x,y|D,I) \\ &= \frac{C}{AB-C^2} \\ &= \frac{H_{xy}}{\det \boldsymbol{H}}\end{aligned}$$

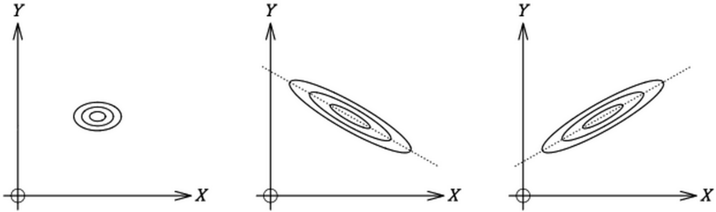
  if we use the quadratic expansion of $p(x,y|D,I)$.
- Putting it all together: the covariance matrix, defined a couple of weeks ago, is the negative inverse of the Hessian matrix:

$$\begin{pmatrix} \sigma_x^2 & \sigma_{xy} \\ \sigma_{xy} & \sigma_y^2 \end{pmatrix} = \frac{1}{AB-C^2} \begin{pmatrix} -B & C \\ C & -A \end{pmatrix} = \begin{pmatrix} A & C \\ C & B \end{pmatrix}^{-1} = -\boldsymbol{H}^{-1}(\hat{\boldsymbol{x}})$$

Covariance Matrix

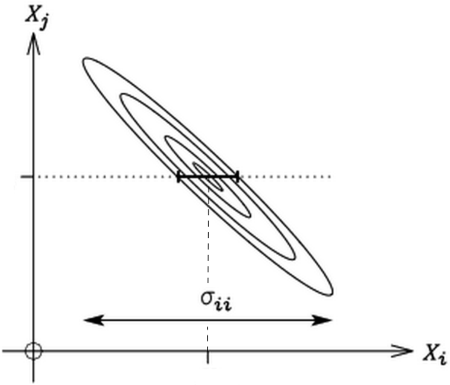
Geometric Interpretation

- $C = 0$ implies x and y are completely uncorrelated. The contours of the posterior PDF are symmetric



- As C increases, the PDF becomes more and more elongated
- For $C = \pm\sqrt{AB}$, the contours are infinitely wide in one direction (though the prior on x or y could vanish somewhere)
- Also, while $C = \pm\sqrt{AB}$ implies $\hat{x}$ and $\hat{y}$ are totally unreliable, the linear correlation $y = \pm mx$ (with $m = \sqrt{AB}$) can still be inferred

Caution: Using the Correct Error Bar



- Be careful about calculating the uncertainty on a parameter in a multidimensional PDF
- **Right**: $\sigma_{ii}^2 = -H_{ii}^{-1}$, from marginalization of $p(\boldsymbol{x}|D, I)$
- **Wrong**: get σ_{ii}^2 by holding parameters $x_{j\neq i}$ fixed at their *optimal values* (underestimate!)
- See difference in error bars from two procedures at left
- Reason: when using the Hessian, don't confuse the inverse of the diagonals of $\boldsymbol{H}$ for the diagonals of $\boldsymbol{H}^{-1}$

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Gaussian PDF: Both μ and σ^2 Unknown

- Last time we derived best estimators for a Gaussian distribution using
$$p(\mu|\sigma,D,I),$$
i.e., σ was given. Now we have the tools to calculate
$$p(\mu|D,I) = \int_0^\infty p(\mu,\sigma|D,I)\,d\sigma.$$
I.e., we can calculate the best estimator for σ^2 not known *a priori*.
- First we have to express the joint posterior PDF to a likelihood and prior using Bayes' Theorem:
$$p(\mu,\sigma|D,I) \propto p(D|\mu,\sigma,I)\,p(\mu,\sigma|I)$$
- If the data are independent, then by the product rule
$$p(D|\mu,\sigma,I) = (2\pi\sigma^2)^{-N/2}\exp\left[-\frac{1}{2\sigma^2}\sum_{i=1}^{N}(x_i-\mu)^2\right]$$

Gaussian PDF: Priors on μ, σ

- Now we need to define the prior $p(\mu, \sigma|I)$. Let's assume the priors for μ and σ are independent:

$$p(\mu, \sigma|I) = p(\mu|I)\, p(\sigma|I)$$

- Since μ is a location parameter it makes sense to choose a uniform prior

$$p(\mu|I) = \frac{1}{\mu_{\text{max}} - \mu_{\text{min}}}$$

- Since σ is a scale parameter we'll use a Jeffreys prior:

$$p(\sigma|I) = \frac{1}{\sigma \ln\left(\sigma_{\text{max}}/\sigma_{\text{min}}\right)}$$

- Let's also assume the prior ranges on μ and σ are large and don't cut off the integration in a weird way

Aside: Parameterization of σ

- Note that we parameterized our width prior in terms of σ, not the variance σ^2. Does the parameterization make a difference?
- For the Jeffreys prior in σ,

$$p(\sigma|I)\;d\sigma = k\frac{d\sigma}{\sigma}$$

  where k depends on the limits of σ.
- Now convert to variance ν. Since $\sigma = \sqrt{\nu}$,

$$d\sigma = \frac{d\nu}{2\sqrt{\nu}}$$

- Therefore,

$$p(\sigma|I)\;d\sigma = p(\nu|I)\;d\nu = k\frac{d\nu}{2\nu} = k'\frac{d\nu}{\nu}$$

- So the Jeffreys prior has the same form if we work in terms of σ or σ^2.

Posterior PDF of μ

- Substitute the likelihood and prior into our expression for $p(\mu|D,I)$:

$$p(\mu|D,I) \propto \int_0^\infty p(D|\mu,\sigma,I)\, p(\mu|I)\, p(\sigma|I)\, d\sigma$$
$$= \frac{(2\pi)^{-N/2}}{\Delta\mu \ln(\sigma_{\max}/\sigma_{\min})} \int_{\sigma_{\min}}^{\sigma_{\max}} \sigma^{-(N+1)}\, e^{-\frac{1}{2\sigma^2}\sum_{i=1}^N (x_i-\mu)^2}\, d\sigma$$

- Let $\sigma = 1/t$ so that $d\sigma = -dt/t^2$:

$$p(\mu|D,I) \propto \int_{t_{\min}}^{t_{\max}} t^{N-1}\, e^{-t^2 \sum_{i=1}^N (x_i-\mu)^2}\, dt$$

- Change variables again so that $\tau = t\sqrt{\sum(x_i-\mu)^2}$:

$$p(\mu|D,I) \propto \left[\sum_{i=1}^N (x_i-\mu)^2\right]^{-N/2}$$

Best Estimator and Reliability

- As in past calculations, we maximize $L = \ln p$:

$$L = -\frac{N}{2} \ln \left[\sum_{i=1}^{N} (x_i - \mu)^2 \right]$$

$$\left. \frac{dL}{d\mu} \right|_{\hat{\mu}} = \frac{N \sum_{i=1}^{N} (x_i - \hat{\mu})}{\sum_{i=1}^{N} (x_i - \hat{\mu})^2} = 0$$

- This can only be satisfied if the numerator is zero, so

$$\hat{\mu} = \bar{x} = \frac{1}{N} \sum_{i=1}^{N} x_i$$

- In other words, the best estimate of the PDF is still just the arithmetic mean of the measurements x_i

Best Estimator and Reliability

- The second derivative gives the estimate of the width:

$$\left.\frac{d^2L}{d\mu^2}\right|_{\hat{\mu}} = -\frac{N^2}{\sum_{i=1}^{N}(x_i - \hat{\mu})^2}$$

- Therefore, setting $\hat{\sigma}^2 = -(d^2L/d\mu^2)^{-1}$ we find that

$$\mu = \hat{\mu} \pm \frac{S}{\sqrt{N}},$$

where we define

$$S^2 = \frac{1}{N}\sum_{i=1}^{N}(x_i - \hat{\mu})^2 = \frac{1}{N}\sum_{i=1}^{N}(x_i - \bar{x})^2$$

- This is almost the usual definition of sample variance but it's narrower because we divide by $1/N$ instead of $1/(N-1)$.

Aside: Uniform Distribution in σ

- Suppose at the beginning of this problem we didn't choose a Jeffreys prior for σ, but a uniform prior such that

$$p(\sigma|I) = \begin{cases} \text{constant} & \sigma > 0 \\ 0 & \text{otherwise} \end{cases}$$

- In this case, the posterior PDF would have been

$$p(\mu|D,I) \propto \left[\sum_{i=1}^{N}(x_i - \mu)^2\right]^{-(N-1)/2}$$

and the width estimator would have been the usual sample variance

$$S^2 = \frac{1}{N-1}\sum_{i=1}^{N}(x_i - \hat{\mu})^2 = \frac{1}{N-1}\sum_{i=1}^{N}(x_i - \bar{x})^2$$

- In other words, the Jeffreys prior gives us a narrower constraint on $\hat{\mu}$!

Student-t Distribution

- What is the shape of the PDF with unknown σ $p(\mu|D,I) \propto \left[\sum_{i=1}^{N}(x_i-\mu)^2\right]^{-N/2}$? First, write

$$\sum_{i=1}^{N}(x_i-\mu)^2 = N(\bar{x}-\mu)^2 + V,$$

where

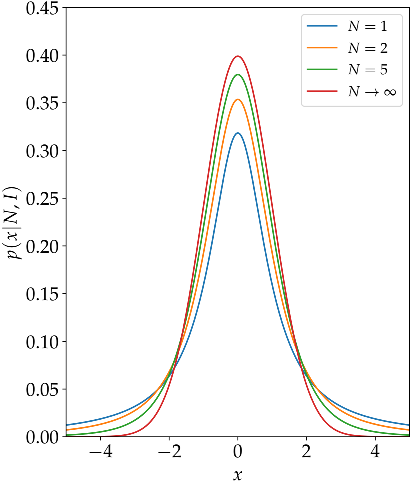
$$V = \sum_{i=1}^{N}(x_i-\bar{x})^2$$

- Substituting into the PDF gives

$$p(\mu|D,I) \propto \left[N(\bar{x}-\mu)^2 + V\right]^{-N/2}$$

- This is the heavy-tailed Student-t distribution, used for estimating μ when σ is unknown and N is small

Student-t Distribution



- Published pseudonymously by William S. Gosset of Guinness Brewery in 1908 [1]
- t-distributions describe small samples drawn from a normally distributed population
- Used to estimate the error on a mean when only a few samples N are available, σ unknown
- Basis of the frequentist t-test to compare two data sets
- As $N \to$ large, the tails of the distribution are killed off (Central Limit Theorem)

Best Estimate of σ

- Now that we've calculate the best estimate of a mean, what's the best estimate of σ given a set of measurements?
- Start with the posterior PDF $p(\sigma|D,I)$:

$$\begin{aligned} p(\sigma|D,I) &= \int_{-\infty}^{\infty} p(\mu,\sigma|D,I)\,d\mu \\ &= \int_{-\infty}^{\infty} p(D|\mu,\sigma,I)\,p(\mu|I)\,p(\sigma|I)\,d\mu \end{aligned}$$

- Plugging in our likelihood and priors gives

$$\begin{aligned} p(\sigma|D,I) &= \frac{(2\pi)^{-N/2}}{\Delta\mu\ln\left(\sigma_{\text{max}}/\sigma_{\text{min}}\right)}\sigma^{-(N+1)}\int_{\mu_{\text{min}}}^{\mu_{\text{max}}} e^{-\frac{1}{2\sigma^2}\sum_{i=1}^{N}(x_i-\mu)^2}\,d\mu \\ &\propto \sigma^{-(N+1)}\,e^{-\frac{V}{2\sigma^2}}\int_{\mu_{\text{min}}}^{\mu_{\text{max}}} e^{-\frac{N(\bar{x}-\mu)^2}{2\sigma^2}}\,d\mu \end{aligned}$$

χ^2 Distribution

- Ignoring all constant terms (including the integral over μ) leaves

$$p(\sigma|D,I) \propto \sigma^{-N} \exp\left(-\frac{V}{2\sigma^2}\right)$$

- Note that if we had used a uniform prior for σ we would have

$$p(\sigma|D,I) \propto \sigma^{-(N-1)} \exp\left(-\frac{V}{2\sigma^2}\right)$$

Let's maximize this expression:

$$L = \ln p = -(N-1)\ln\sigma - \frac{V}{2\sigma^2}$$

$$\left.\frac{dL}{d\sigma}\right|_{\hat{\sigma}} = \frac{-(N-1)}{\sigma} + \frac{V}{\sigma^3} = 0$$

$$\therefore \hat{\sigma}^2 = \frac{V}{N-1} = \frac{1}{N-1}\sum_{i=1}^{N}(x_i - \bar{x})^2 = s^2$$

χ^2 Distribution

- Taking the second derivative of L gives

$$\left.\frac{d^2L}{d\sigma^2}\right|_{\hat{\sigma}} = \frac{N-1}{\hat{\sigma}^2} - \frac{3V}{\hat{\sigma}^4}$$
$$= \frac{(N-1)\hat{\sigma}^2}{\hat{\sigma}^4} - \frac{3(N-1)\hat{\sigma}^2}{\hat{\sigma}^4}$$
$$= -\frac{2(N-1)}{\hat{\sigma}^2}$$

- Therefore, the optimal value of the width is

$$\sigma = \hat{\sigma} \pm \frac{\hat{\sigma}}{\sqrt{2(N-1)}}$$

- Note: with the change of variables $X = V/\sigma^2$, we see that

$$p(\sigma|D,I) \propto \sigma^{-(N-1)} \exp\left(-\frac{X}{2}\right)$$

is the χ^2_ν distribution with $\nu = 2(N-1)$.

Summary

- We related the width of a multidimensional distribution — the Hessian matrix $\boldsymbol{H}$ — to the covariance matrix via

$$[\sigma^2]_{ij} = [-\boldsymbol{H}^{-1}]_{ij}$$

- **Caution**: the right way to get the uncertainty on a parameter from a multidimensional distribution is to marginalize $p(x, y, \ldots | D, I)$
- The wrong way to get the uncertainty on a parameter from such a distribution is to fix parameters $y, z, \ldots$ at the optimal values and find the uncertainty on x
- When marginalizing σ in a Gaussian distribution, we obtain the Student-t distribution
- Whem marginalizing μ in a Gaussian distribution, we obtain the $\chi^2_{2(N-1)}$ distribution

References I

[1] "Student" (W.S. Gosset). "The Probable Error of a Mean". In: *Biometrika* 6 (1908), pp. 1–25.