

Hypothesis Testing

Saravanan Vijayakumaran
sarva@ee.iitb.ac.in

Department of Electrical Engineering
Indian Institute of Technology Bombay

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Basics of Hypothesis Testing

What is a Hypothesis?

One situation among a set of possible situations

Example (Radar)

EM waves are transmitted and the reflections observed.

Null Hypothesis Plane absent

Alternative Hypothesis Plane present

For a given set of observations, either hypothesis may be true.

What is Hypothesis Testing?

- A statistical framework for deciding which hypothesis is true
- Under each hypothesis the observations are assumed to have a known distribution
- Consider the case of two hypotheses (binary hypothesis testing)

$$\begin{aligned}H_0 &: \mathbf{Y} \sim P_0 \\H_1 &: \mathbf{Y} \sim P_1\end{aligned}$$

\mathbf{Y} is the random observation vector belonging to \mathbb{R}^n for $n \in \mathbb{N}$

- The hypotheses are assumed to occur with given prior probabilities

$$\begin{aligned}\Pr(H_0 \text{ is true}) &= \pi_0 \\ \Pr(H_1 \text{ is true}) &= \pi_1\end{aligned}$$

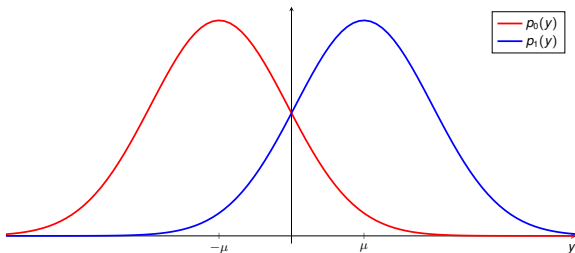
where $\pi_0 + \pi_1 = 1$.

Location Testing with Gaussian Error

- Let observation set be \mathbb{R} and $\mu > 0$

$$H_0 : Y \sim N(-\mu, \sigma^2)$$

$$H_1 : Y \sim N(\mu, \sigma^2)$$



- Any point in \mathbb{R} can be generated under both H_0 and H_1
- What is a **good decision rule** for this hypothesis testing problem which takes the prior probabilities into account?

What is a Decision Rule?

- A decision rule for binary hypothesis testing is a partition of \mathbb{R}^n into Γ_0 and Γ_1 such that

$$\delta(\mathbf{y}) = \begin{cases} 0 & \text{if } \mathbf{y} \in \Gamma_0 \\ 1 & \text{if } \mathbf{y} \in \Gamma_1 \end{cases}$$

We decide H_i is true when $\delta(\mathbf{y}) = i$ for $i \in \{0, 1\}$

- For the location testing with Gaussian error problem, one possible decision rule is

$$\Gamma_0 = (-\infty, 0]$$

$$\Gamma_1 = (0, \infty)$$

and another possible decision rule is

$$\Gamma_0 = (-\infty, -100) \cup (-50, 0)$$

$$\Gamma_1 = [-100, -50] \cup [0, \infty)$$

- Given that partitions of the observation set define decision rules, what is the optimal partition?

Which is the Optimal Decision Rule?

- The optimal decision rule minimizes the probability of decision error
- For the binary hypothesis testing problem of H_0 versus H_1 , the conditional decision error probability given H_i is true is

$$\begin{aligned}P_{e|i} &= \Pr[\text{Deciding } H_{1-i} \text{ is true} | H_i \text{ is true}] \\&= \Pr[Y \in \Gamma_{1-i} | H_i] \\&= 1 - \Pr[Y \in \Gamma_i | H_i] \\&= 1 - P_{c|i}\end{aligned}$$

- Probability of decision error is

$$P_e = \pi_0 P_{e|0} + \pi_1 P_{e|1}$$

- Probability of correct decision is

$$P_c = \pi_0 P_{c|0} + \pi_1 P_{c|1} = 1 - P_e$$

Which is the Optimal Decision Rule?

- Maximizing the probability of correct decision will minimize probability of decision error
- Probability of correct decision is

$$\begin{aligned}P_c &= \pi_0 P_{c|0} + \pi_1 P_{c|1} \\&= \pi_0 \int_{\Gamma_0} p_0(y) dy + \pi_1 \int_{\Gamma_1} p_1(y) dy \\&= \pi_0 \int_{\Gamma_0} p_0(y) dy + \pi_1 \left[1 - \int_{\Gamma_0} p_1(y) dy \right] \\&= \pi_1 + \int_{\Gamma_0} [\pi_0 p_0(y) - \pi_1 p_1(y)] dy\end{aligned}$$

- To maximize P_c , we choose the partition $\{\Gamma_0, \Gamma_1\}$ as

$$\begin{aligned}\Gamma_0 &= \{y \in \mathbb{R} | \pi_0 p_0(y) \geq \pi_1 p_1(y)\} \\ \Gamma_1 &= \{y \in \mathbb{R} | \pi_0 p_0(y) < \pi_1 p_1(y)\}\end{aligned}$$

- The points y for which $\pi_0 p_0(y) = \pi_1 p_1(y)$ can be in either Γ_0 and Γ_1 (the optimal decision rule is not unique)

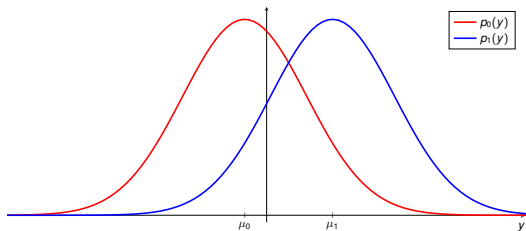
Location Testing with Gaussian Error

- Let $\mu_1 > \mu_0$ and $\pi_0 = \pi_1 = \frac{1}{2}$

$$H_0 : Y = \mu_0 + Z$$

$$H_1 : Y = \mu_1 + Z$$

where $Z \sim N(0, \sigma^2)$



$$p_0(y) = \frac{1}{\sqrt{2\pi\sigma^2}} e^{-\frac{(y-\mu_0)^2}{2\sigma^2}}$$

$$p_1(y) = \frac{1}{\sqrt{2\pi\sigma^2}} e^{-\frac{(y-\mu_1)^2}{2\sigma^2}}$$

Location Testing with Gaussian Error

- Optimal decision rule is given by the partition $\{\Gamma_0, \Gamma_1\}$

$$\Gamma_0 = \{y \in \mathbb{R} \mid \pi_0 p_0(y) \geq \pi_1 p_1(y)\}$$

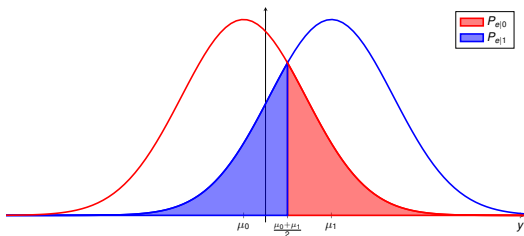
$$\Gamma_1 = \{y \in \mathbb{R} \mid \pi_0 p_0(y) < \pi_1 p_1(y)\}$$

- For $\pi_0 = \pi_1 = \frac{1}{2}$

$$\Gamma_0 = \left\{ y \in \mathbb{R} \mid y \leq \frac{\mu_1 + \mu_0}{2} \right\}$$

$$\Gamma_1 = \left\{ y \in \mathbb{R} \mid y > \frac{\mu_1 + \mu_0}{2} \right\}$$

Location Testing with Gaussian Error



$$P_{e|0} = \Pr \left[Y > \frac{\mu_0 + \mu_1}{2} \mid H_0 \right] = Q \left(\frac{\mu_1 - \mu_0}{2\sigma} \right)$$

$$P_{e|1} = \Pr \left[Y \leq \frac{\mu_0 + \mu_1}{2} \mid H_1 \right] = \Phi \left(\frac{\mu_0 - \mu_1}{2\sigma} \right) = Q \left(\frac{\mu_1 - \mu_0}{2\sigma} \right)$$

$$P_e = \pi_0 P_{e|0} + \pi_1 P_{e|1} = Q \left(\frac{\mu_1 - \mu_0}{2\sigma} \right)$$

This P_e is for $\pi_0 = \pi_1 = \frac{1}{2}$

Location Testing with Gaussian Error

- Suppose $\pi_0 \neq \pi_1$
- Optimal decision rule is still given by the partition $\{\Gamma_0, \Gamma_1\}$

$$\Gamma_0 = \{y \in \mathbb{R} \mid \pi_0 p_0(y) \geq \pi_1 p_1(y)\}$$

$$\Gamma_1 = \{y \in \mathbb{R} \mid \pi_0 p_0(y) < \pi_1 p_1(y)\}$$

- The partitions specialized to this problem are

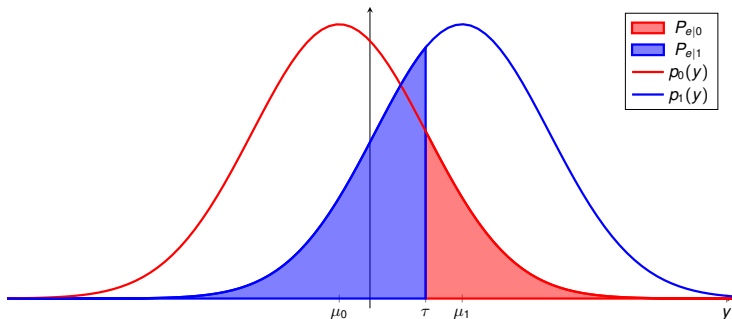
$$\Gamma_0 = \left\{ y \in \mathbb{R} \mid y \leq \frac{\mu_1 + \mu_0}{2} + \frac{\sigma^2}{(\mu_1 - \mu_0)} \log \frac{\pi_0}{\pi_1} \right\}$$

$$\Gamma_1 = \left\{ y \in \mathbb{R} \mid y > \frac{\mu_1 + \mu_0}{2} + \frac{\sigma^2}{(\mu_1 - \mu_0)} \log \frac{\pi_0}{\pi_1} \right\}$$

Location Testing with Gaussian Error

Suppose $\pi_0 = 0.6$ and $\pi_1 = 0.4$

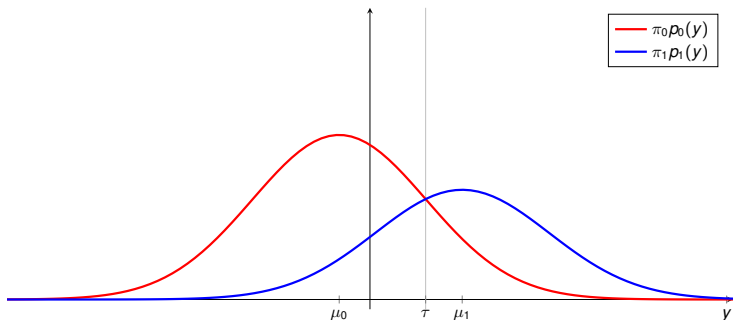
$$\tau = \frac{\mu_1 + \mu_0}{2} + \frac{\sigma^2}{(\mu_1 - \mu_0)} \log \frac{\pi_0}{\pi_1} = \frac{\mu_1 + \mu_0}{2} + \frac{0.4054\sigma^2}{(\mu_1 - \mu_0)}$$



Location Testing with Gaussian Error

Suppose $\pi_0 = 0.6$ and $\pi_1 = 0.4$

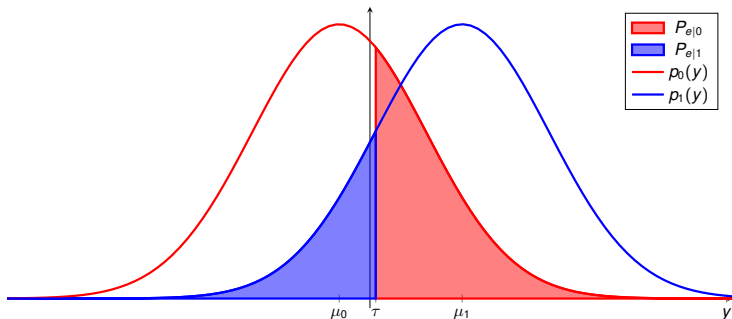
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Location Testing with Gaussian Error

Suppose $\pi_0 = 0.4$ and $\pi_1 = 0.6$

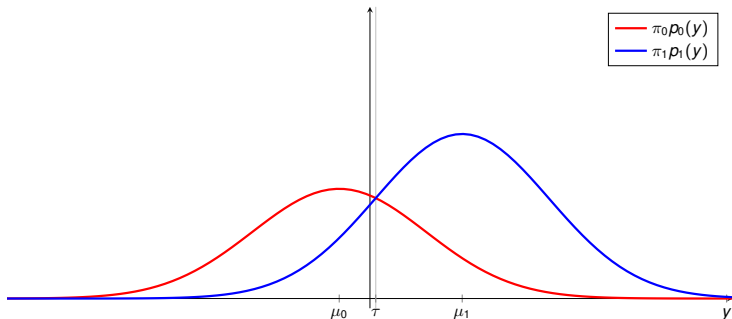
$$\tau = \frac{\mu_1 + \mu_0}{2} + \frac{\sigma^2}{(\mu_1 - \mu_0)} \log \frac{\pi_0}{\pi_1} = \frac{\mu_1 + \mu_0}{2} - \frac{0.4054\sigma^2}{(\mu_1 - \mu_0)}$$



Location Testing with Gaussian Error

Suppose $\pi_0 = 0.4$ and $\pi_1 = 0.6$

$$\tau = \frac{\mu_1 + \mu_0}{2} + \frac{\sigma^2}{(\mu_1 - \mu_0)} \log \frac{\pi_0}{\pi_1} = \frac{\mu_1 + \mu_0}{2} - \frac{0.4054\sigma^2}{(\mu_1 - \mu_0)}$$



M -ary Hypothesis Testing

- M hypotheses with prior probabilities $\pi_i, i = 1, \dots, M$

$$H_1 : \mathbf{Y} \sim P_1$$

$$H_2 : \mathbf{Y} \sim P_2$$

$$\vdots$$

$$H_M : \mathbf{Y} \sim P_M$$

- A decision rule for M -ary hypothesis testing is a partition of Γ into M disjoint regions $\{\Gamma_i | i = 1, \dots, M\}$ such that

$$\delta(\mathbf{y}) = i \text{ if } \mathbf{y} \in \Gamma_i$$

We decide H_i is true when $\delta(\mathbf{y}) = i$ for $i \in \{1, \dots, M\}$

- Minimum probability of error rule is

$$\delta_{\text{MPE}}(\mathbf{y}) = \arg \max_{1 \leq i \leq M} \pi_i p_i(\mathbf{y})$$

Maximum A Posteriori Decision Rule

- The a posteriori probability of H_i being true given observation \mathbf{y} is

$$P \left[H_i \text{ is true} \middle| \mathbf{y} \right] = \frac{\pi_i p_i(\mathbf{y})}{p(\mathbf{y})}$$

- The MAP decision rule is given by

$$\delta_{\text{MAP}}(\mathbf{y}) = \arg \max_{1 \leq i \leq M} P \left[H_i \text{ is true} \middle| \mathbf{y} \right] = \delta_{\text{MPE}}(\mathbf{y})$$

MAP decision rule = MPE decision rule

Maximum Likelihood Decision Rule

- The ML decision rule is given by

$$\delta_{\text{ML}}(\mathbf{y}) = \arg \max_{1 \leq i \leq M} p_i(\mathbf{y})$$

- If the M hypotheses are equally likely, $\pi_i = \frac{1}{M}$
- The MPE decision rule is then given by

$$\delta_{\text{MPE}}(\mathbf{y}) = \arg \max_{1 \leq i \leq M} \pi_i p_i(\mathbf{y}) = \delta_{\text{ML}}(\mathbf{y})$$

For equal priors, ML decision rule = MPE decision rule

Irrelevant Statistics

Irrelevant Statistics

- In this context, the term statistic means an observation
- For a given hypothesis testing problem, all the observations may not be useful

Example (Irrelevant Statistic)

$$\mathbf{Y} = [Y_1 \quad Y_2]$$

$$H_1 : Y_1 = A + N_1, \quad Y_2 = N_2$$

$$H_0 : Y_1 = N_1, \quad Y_2 = N_2$$

where $A > 0$, $N_1 \sim N(0, \sigma^2)$, $N_2 \sim N(0, \sigma^2)$.

- If N_1 and N_2 are independent, Y_2 is irrelevant.
- If N_1 and N_2 are correlated, Y_2 is relevant.

- Need a method to recognize irrelevant components of the observations

Characterizing an Irrelevant Statistic

Theorem

For M -ary hypothesis testing using an observation $\mathbf{Y} = [\mathbf{Y}_1 \quad \mathbf{Y}_2]$, the statistic \mathbf{Y}_2 is irrelevant if the conditional distribution of \mathbf{Y}_2 , given \mathbf{Y}_1 and H_i , is independent of i . In terms of densities, the condition for irrelevance is

$$p(\mathbf{y}_2|\mathbf{y}_1, H_i) = p(\mathbf{y}_2|\mathbf{y}_1) \quad \forall i.$$

Proof

$$\delta_{\text{MPE}}(\mathbf{y}) = \arg \max_{1 \leq i \leq M} \pi_i p_i(\mathbf{y}) = \arg \max_{1 \leq i \leq M} \pi_i p(\mathbf{y}|H_i)$$

$$\begin{aligned} p(\mathbf{y}|H_i) &= p(\mathbf{y}_1, \mathbf{y}_2|H_i) = p(\mathbf{y}_2|\mathbf{y}_1, H_i)p(\mathbf{y}_1|H_i) \\ &= p(\mathbf{y}_2|\mathbf{y}_1)p(\mathbf{y}_1|H_i) \end{aligned}$$

$$\delta_{\text{MPE}}(\mathbf{y}) = \arg \max_{1 \leq i \leq M} \pi_i p(\mathbf{y}_2|\mathbf{y}_1)p(\mathbf{y}_1|H_i) = \arg \max_{1 \leq i \leq M} \pi_i p(\mathbf{y}_1|H_i)$$

Example of an Irrelevant Statistic

Example (Independent Noise)

$$\mathbf{Y} = [Y_1 \quad Y_2]$$

$$H_1 : Y_1 = A + N_1, \quad Y_2 = N_2$$

$$H_0 : Y_1 = N_1, \quad Y_2 = N_2$$

where $A > 0$, $N_1 \sim N(0, \sigma^2)$, $N_2 \sim N(0, \sigma^2)$, $N_1 \perp N_2$.

$$\rho(\mathbf{y}_2 | \mathbf{y}_1, H_0) = \rho(\mathbf{y}_2)$$

$$\rho(\mathbf{y}_2 | \mathbf{y}_1, H_1) = \rho(\mathbf{y}_2)$$

Example of a Relevant Statistic

Example (Correlated Noise)

$$\mathbf{Y} = [Y_1 \quad Y_2]^T$$

$$H_1 : Y_1 = A + N_1, \quad Y_2 = N_2$$

$$H_0 : Y_1 = N_1, \quad Y_2 = N_2$$

where $A > 0$, $N_1 \sim N(0, \sigma^2)$, $N_2 \sim N(0, \sigma^2)$, $\mathbf{C}_Y = \sigma^2 \begin{bmatrix} 1 & \rho \\ \rho & 1 \end{bmatrix}$

$$p(y_2|y_1, H_0) = \frac{1}{\sqrt{2\pi(1-\rho^2)\sigma^2}} e^{-\frac{(y_2 - \rho y_1)^2}{2(1-\rho^2)\sigma^2}},$$

$$p(y_2|y_1, H_1) = \frac{1}{\sqrt{2\pi(1-\rho^2)\sigma^2}} e^{-\frac{[y_2 - \rho(y_1 - A)]^2}{2(1-\rho^2)\sigma^2}}$$

Thanks for your attention