ANOVA

análisis de varianza

Carlos Carleos, Norberto Corral

4 de marzo de 2024

Planteamiento

- Sean q poblaciones x_i $(i = 1, \ldots, q)$
  - niveles o modalidades de un "factor"
- $x_i = \mu_i + \epsilon \equiv \mathcal{N}(\mu_i, \sigma)$ con $\epsilon \equiv \mathcal{N}(0, \sigma) = \mathcal{N}_1(0, \sigma^2)$
- De cada x_i se conoce una muestra aleatoria simple de tamaño n_i: $x_{i1}, \ldots, x_{in_i}$
- Tamaño muestral total: $n = \sum_{i=1}^{q} n_i$
- Otra parametrización: $\mu_i = \mu + \alpha_i$ con $\mu = \frac{\sum n_i \mu_i}{n}$
- $\sum_{i=1}^{q} n_i \alpha_i = 0$
- Si $\forall\, i,\ n_i = \frac{n}{q}$ el modelo se dice *equilibrado* o *balanceado*

Planteamiento

Hipótesis previas

$$\forall\, i = 1, \ldots, q \quad \vec{x}_i = (x_{i1}, \ldots, x_{in_i})^t \equiv \mathcal{N}_{n_i}\left(\mu_i \vec{1}_{n_i}, \sigma^2\, I_{n_i}\right)$$

- independencia (muestras aleatorias simples)
- gausianidad
- homoscedasticidad (igualdad de varianzas)

Planteamiento

Hipótesis del análisis de varianza (ANOVA)

$$
\begin{array}{lllll}
H_0 & \equiv & \forall\, i,j,\;\; \mu_i = \mu_j & \equiv & \forall\, i,\;\; \alpha_i = 0 \\
H_1 & \equiv & \exists\, i,j,\;\; \mu_i \neq \mu_j & \equiv & \exists\, i,\;\; \alpha_i \neq 0
\end{array}
$$

- H_0: el factor no influye en la respuesta
- H_1: el factor sí influye en la respuesta

Repaso de álgebra lineal

- Matriz simétrica $A = [a_{ij}]_{i,j}$ si $a_{ij} = a_{ji} \iff A = A^t$
  - todos sus autovalores $(\lambda_i)_i$ son reales; autovectores: $(\vec{u}_i)_i$
  - $A = U\,\Lambda\,U^t$ con $\Lambda = \mathrm{diag}(\ldots, \lambda_i, \ldots)$ y $U = [\ldots, \vec{u}_i \ldots]$
- Matriz idempotente: $A\,A = A$
  - (autovalor A) $\in \{0, 1\}$ pues si $\vec{x} \neq \vec{0}$ es autovector no nulo

$$\lambda\,\vec{x} = A\,\vec{x} = A\,A\,\vec{x} = A\,\lambda\,\vec{x} = \lambda\,A\,\vec{x} = \lambda^2\vec{x}$$

$$\Longrightarrow \qquad \lambda = 0 \quad \cup \quad \left\{\vec{x} = \lambda\vec{x} \implies \lambda = 1\right\}$$

- Traza: $A = [a_{ij}]_{i,j} \implies \mathrm{tr}\,A = \sum_i a_{ii}$
  - $a = \mathrm{tr}[a]$
  - $\mathrm{tr}(A\,B) = \mathrm{tr}(B\,A)$
  - $\mathrm{tr}(A\,B\,C) = \mathrm{tr}(B\,C\,A) = \mathrm{tr}(C\,A\,B)$
  - $\mathrm{E}\,[\mathrm{tr}\,A] = \mathrm{tr}\,\mathrm{E}\,[A]$

Matriz de varianzas y covarianzas

$$\mathrm{Var}(\vec{x}) = \mathrm{Cov}(\vec{x}) = \mathrm{Cov}(\vec{x},\vec{x}) = \mathrm{E}\left[(\vec{x}-\mathrm{E}[\vec{x}])(\vec{x}-\mathrm{E}[\vec{x}])^t\right]$$

$$= \mathrm{E}\left[\begin{pmatrix}(x_1-\mathrm{E}[x_1])\\ \vdots \\ (x_q-\mathrm{E}[x_q])\end{pmatrix}\begin{bmatrix}(x_1-\mathrm{E}[x_1]) & \dots & (x_q-\mathrm{E}[x_q])\end{bmatrix}\right] =$$

$$= \begin{bmatrix}\mathrm{E}\left[(x_1-\mathrm{E}[x_1])^2\right] & \dots & \mathrm{E}[(x_1-\mathrm{E}[x_1])(x_q-\mathrm{E}[x_q])] \\ \vdots & \ddots & \vdots \\ \mathrm{E}[(x_1-\mathrm{E}[x_1])(x_q-\mathrm{E}[x_q])] & \dots & \mathrm{E}\left[(x_q-\mathrm{E}[x_q])^2\right]\end{bmatrix}$$

- intradiagonal: $\mathrm{E}\left[(x_i-\mathrm{E}[x_i])^2\right] = \mathrm{Var}(x_i)$
- extradiagonal: $\mathrm{E}[(x_i-\mathrm{E}[x_i])(x_j-\mathrm{E}[x_j])] = \mathrm{Cov}(x_i,x_j)$

Matriz de varianzas y covarianzas

$$\mathrm{Var}(\vec{x}) = \mathrm{Cov}(\vec{x}) = \mathrm{Cov}(\vec{x},\vec{x}) = \mathrm{E}\left[(\vec{x}-\mathrm{E}\left[\vec{x}\right])(\vec{x}-\mathrm{E}\left[\vec{x}\right])^t\right] =$$

$$= \mathrm{E}\left[\vec{x}\,\vec{x}^t\right] - \mathrm{E}\left[\vec{x}\,\mathrm{E}\left[\vec{x}\right]^t\right] - \mathrm{E}\left[\mathrm{E}\left[\vec{x}\right]\ \vec{x}^t\right] + \mathrm{E}\left[\mathrm{E}\left[\vec{x}\right]\mathrm{E}\left[\vec{x}\right]^t\right] =$$

$$= \mathrm{E}\left[\vec{x}\,\vec{x}^t\right] - \mathrm{E}\left[\vec{x}\right]\ \mathrm{E}\left[\vec{x}\right]^t - \mathrm{E}\left[\vec{x}\right]\ \mathrm{E}\left[\vec{x}^t\right] + \mathrm{E}\left[\vec{x}\right]\ \mathrm{E}\left[\vec{x}\right]^t =$$

$$= \mathrm{E}\left[\vec{x}\,\vec{x}^t\right] - \mathrm{E}\left[\vec{x}\right]\ \mathrm{E}\left[\vec{x}\right]^t$$

Formas cuadráticas

Dados una matriz $A\ (n, n)$ simétrica e idempotente con rango$(A) = r$ y un vector aleatorio $\vec{x} \equiv \mathcal{N}_n\left(\vec{\mu}, \sigma^2\, I_n\right)$, se verifican las siguientes propiedades:

- $A = U\,\Lambda\,U^t = (U_1\ \ U_2)\begin{pmatrix} I_r & \\ & 0 \end{pmatrix}\begin{pmatrix} U_1^t \\ U_2^t \end{pmatrix} = U_1\,U_1^t$

  con U_1 vectores propios asociados al valor propio 1
  con U_2 vectores propios asociados al valor propio 0
  y $U^t\,U = I_n$
- $\vec{x}^t\,A\,\vec{x} = \vec{x}^t\,U_1\,U_1^t\,\vec{x}$

Formas cuadráticas

- esperanza

$$
\begin{aligned}
\mathrm{E}\left[\vec{x}^t\, A\, \vec{x}\right] &= \mathrm{E}\left[\vec{x}^t\, U_1\, U_1^t\, \vec{x}\right] = \mathrm{E}\left[\mathrm{tr}\left\{\vec{x}^t\, U_1\, U_1^t\, \vec{x}\right\}\right] \\
&= \mathrm{E}\left[\mathrm{tr}\left\{U_1\, U_1^t\, \vec{x}\, \vec{x}^t\right\}\right] = \mathrm{tr}\left\{U_1\, U_1^t\, \mathrm{E}\left[\vec{x}\, \vec{x}^t\right]\right\} \\
&= \mathrm{tr}\left\{U_1\, U_1^t\, \left(\mathrm{Cov}(\vec{x}) + \mathrm{E}\left[\vec{x}\right]\, \mathrm{E}\left[\vec{x}^t\right]\right)\right\} \\
&= \mathrm{tr}\left\{U_1\, U_1^t\, \left(\sigma^2\, I + \mathrm{E}\left[\vec{x}\right]\, \mathrm{E}\left[\vec{x}^t\right]\right)\right\} \\
&= \mathrm{tr}\left\{\sigma^2\, U_1\, U_1^t\right\} + \mathrm{tr}\left\{U_1\, U_1^t\, \mathrm{E}\left[\vec{x}\right]\, \mathrm{E}\left[\vec{x}^t\right]\right\} \\
&= \sigma^2\, \mathrm{tr}(U_1\, U_1^t) + \mathrm{tr}\left\{\mathrm{E}\left[\vec{x}^t\right]\, U_1\, U_1^t\, \mathrm{E}\left[\vec{x}\right]\right\} \\
&= \sigma^2\, \mathrm{rango}(A) + \mathrm{E}\left[\vec{x}^t\right]\, A\, \mathrm{E}\left[\vec{x}\right] \\
&= \sigma^2\, r + \mathrm{E}\left[\vec{x}^t\right]\, A\, \mathrm{E}\left[\vec{x}\right]
\end{aligned}
$$

Formas cuadráticas

- Si $A\,\vec{\mu} = \vec{0}$ entonces $\vec{x}^t\,A\,\vec{x} \equiv \sigma^2\,\chi^2_r$. Demostración:

$$\vec{x}^t\,A\,\vec{x} = \vec{x}^t\,U_1\,U_1^t\,\vec{x} = \vec{y}_1^t\,\vec{y}_1, \qquad \text{con } \vec{y}_1 = U_1^t\,\vec{x}$$

$$\vec{\gamma} = \mathrm{E}\left[\vec{y}_1\right] = \mathrm{E}\left[U_1^t\,\vec{x}\right] = U_1^t\,\mathrm{E}\left[\vec{x}\right] = U_1^t\,\vec{\mu}$$

$$U_1\,\vec{\gamma} = U_1\,U_1^t\,\vec{\mu} = A\,\vec{\mu} = \vec{0}$$

$$\vec{\gamma} = I_r\,\vec{\gamma} = U_1^t\,U_1\,\vec{\gamma} = U_1^t\,\vec{0} = \vec{0}$$

$$\mathrm{Cov}(\vec{y}_1) = U_1^t\,\mathrm{Cov}(\vec{x})\,U_1 = \sigma^2\,U_1^t\,U_1 = \sigma^2\,I_r$$

En consecuencia, $\vec{y}_1 \equiv U_1^t\,\mathcal{N}_n\left(\vec{\mu}, \sigma^2\,I\right) = \mathcal{N}_r\left(\vec{0}, \sigma^2\,I_r\right)$

$$\vec{y}_1^t\,\vec{y}_1 = \sum_{j=1}^{r} y_{1j}^2 = \sum_{j=1}^{r} \sigma^2 \left(\frac{y_{1j}}{\sigma}\right)^2 \equiv \sigma^2 \sum_{j=1}^{r} \underbrace{\left[\mathcal{N}\left(0,1\right)\right]^2}_{\text{indep.}} = \sigma^2 \chi^2_r$$

Análisis de varianza

Sea el vector columna $n \times 1$: $\vec{x} = \begin{pmatrix} \vec{x}_1 \\ \vec{x}_2 \\ \vdots \\ \vec{x}_q \end{pmatrix}$

yuxtaposición de los vectores $n_i \times 1$: $\vec{x}_i = \begin{pmatrix} x_{i1} \\ x_{i2} \\ \vdots \\ x_{in_i} \end{pmatrix}$

para $i = 1, \ldots, q$

Análisis de varianza

$$\vec{1}_n = \begin{pmatrix} 1 \\ \vdots \\ 1 \end{pmatrix}_{n\times 1} \qquad J = \frac{1}{n}\,\vec{1}_n \vec{1}_n^t = \begin{pmatrix} \frac{1}{n} & \frac{1}{n} & \cdots & \frac{1}{n} \\ \frac{1}{n} & \frac{1}{n} & \cdots & \frac{1}{n} \\ \vdots & \vdots & \ddots & \vdots \\ \frac{1}{n} & \frac{1}{n} & \cdots & \frac{1}{n} \end{pmatrix}_{n\times n}$$

J es simétrica e idempotente

al multiplicar, genera un vector columna con la media:

$$J\,\vec{x} = \frac{1}{n}\,\vec{1}_n\,\vec{1}_n^t\,\vec{x} = \vec{1}_n\,\frac{1}{n}\,\vec{1}_n^t\,\vec{x} = \bar{x}\,\vec{1}_n$$

Análisis de varianza

$$H = I - J = \begin{pmatrix} 1-\frac{1}{n} & -\frac{1}{n} & \dots & -\frac{1}{n} \\ -\frac{1}{n} & 1-\frac{1}{n} & \dots & -\frac{1}{n} \\ \vdots & \vdots & \ddots & \vdots \\ -\frac{1}{n} & -\frac{1}{n} & \dots & 1-\frac{1}{n} \end{pmatrix}$$

H es simétrica e idempotente

Análisis de varianza

H es la matriz de centrado

al multiplicar, sustrae la media:

$$\begin{aligned} H\,\vec{x} &= \left(I_n - \frac{1}{n}\,\vec{1}_n\,\vec{1}_n^t\right)\vec{x} = \vec{x} - \vec{1}_n\,\frac{1}{n}\,\vec{1}_n^t\,\vec{x} \\ &= \vec{x} - \vec{1}_n\,\bar{x} = \begin{pmatrix} \vec{x}_1 - \bar{x}\,\vec{1}_{n_1} \\ \vec{x}_2 - \bar{x}\,\vec{1}_{n_2} \\ \vdots \\ \vec{x}_q - \bar{x}\,\vec{1}_{n_q} \end{pmatrix} \end{aligned}$$

Análisis de varianza

$$
\begin{aligned}
\vec{x}^t\, H\, \vec{x} &= \vec{x}^t\, H\, H\, \vec{x} = \vec{x}^t\, H^t\, H\, \vec{x} \\
&= \left[(\vec{x}_1 - \bar{x}\,\vec{1}_{n_1})^t, \ldots, (\vec{x}_q - \bar{x}\,\vec{1}_{n_q})^t \right] \begin{pmatrix} \vec{x}_1 - \bar{x}\,\vec{1}_{n_1} \\ \vec{x}_2 - \bar{x}\,\vec{1}_{n_2} \\ \vdots \\ \vec{x}_q - \bar{x}\,\vec{1}_{n_q} \end{pmatrix} \\
&= \sum_{i=1}^{q} (\vec{x}_i - \bar{x}\,\vec{1}_{n_i})^t\, (\vec{x}_i - \bar{x}\,\vec{1}_{n_i}) \\
&= \sum_{i=1}^{q} \sum_{j=1}^{n_i} (x_{ij} - \bar{x})^2 = \mathrm{SCT}
\end{aligned}
$$

Análisis de varianza

$$H = I - J = I - D + D - J$$

con

$$D = \begin{pmatrix} J_1 & & & \\ & J_2 & & \\ & & \ddots & \\ & & & J_q \end{pmatrix}$$

con $J_i = \frac{1}{n_i} \vec{1}_{n_i} \vec{1}_{n_i}^t$

- $I - D$ es simétrica e idempotente
- $\text{tr}(I - D) = \text{tr}\, I - \text{tr}\, D = n - q = \text{rango}(I - D)$
- $D - J$ es simétrica e idempotente
- $\text{tr}(D - J) = \text{tr}\, D - \text{tr}\, J = q - 1 = \text{rango}(D - J)$

Análisis de varianza

$$D\,\vec{x} = \begin{pmatrix} J_1 & & & \\ & J_2 & & \\ & & \ddots & \\ & & & J_q \end{pmatrix} \begin{pmatrix} \vec{x}_1 \\ \vec{x}_2 \\ \vdots \\ \vec{x}_q \end{pmatrix} = \begin{pmatrix} J_1\,\vec{x}_1 \\ J_2\,\vec{x}_2 \\ \vdots \\ J_q\,\vec{x}_q \end{pmatrix} = \begin{pmatrix} \bar{x}_1\,\vec{1}_{n_1} \\ \bar{x}_2\,\vec{1}_{n_2} \\ \vdots \\ \bar{x}_q\,\vec{1}_{n_q} \end{pmatrix}$$

Análisis de varianza

$$(I - D)\,\vec{x} = \vec{x} - D\,\vec{x} = \begin{pmatrix} \vec{x}_1 - \bar{x}_1\,\vec{1}_{n_1} \\ \vec{x}_2 - \bar{x}_2\,\vec{1}_{n_2} \\ \vdots \\ \vec{x}_q - \bar{x}_q\,\vec{1}_{n_q} \end{pmatrix}$$

Análisis de varianza

$$\vec{x}^t\,(I - D)\,\vec{x} =$$

$$= \vec{x}^t \left[\begin{pmatrix} I_{n_1} & & & \\ & I_{n_2} & & \\ & & \ddots & \\ & & & I_{n_q} \end{pmatrix} - \begin{pmatrix} J_1 & & & \\ & J_2 & & \\ & & \ddots & \\ & & & J_q \end{pmatrix} \right] \vec{x}$$

$$= (\vec{x}_1^t, \ldots, \vec{x}_q^t) \begin{pmatrix} I_{n_1} - J_1 & & & \\ & I_{n_2} - J_2 & & \\ & & \ddots & \\ & & & I_{n_q} - J_q \end{pmatrix} \begin{pmatrix} \vec{x}_1 \\ \vec{x}_2 \\ \vdots \\ \vec{x}_q \end{pmatrix}$$

$$= \sum_{i=1}^{q} \vec{x}_i^t\,(I_{n_i} - J_i)\,\vec{x}_i = \sum_{i=1}^{q} \sum_{i=1}^{n_i} (x_{ij} - \bar{x}_i)^2 = \mathrm{SCE}$$

Análisis de varianza

$$(D-J)\,\vec{x} = D\,\vec{x} - J\,\vec{x} = \begin{pmatrix} J_1 & & & \\ & J_2 & & \\ & & \ddots & \\ & & & J_q \end{pmatrix} \begin{pmatrix} \vec{x}_1 \\ \vec{x}_2 \\ \vdots \\ \vec{x}_q \end{pmatrix} - J\,\vec{x}$$

$$= \begin{pmatrix} J_1\,\vec{x}_1 \\ J_2\,\vec{x}_2 \\ \vdots \\ J_q\,\vec{x}_q \end{pmatrix} - \bar{x}\,\vec{1}_n = \begin{pmatrix} \bar{x}_1\,\vec{1}_{n_1} \\ \bar{x}_2\,\vec{1}_{n_2} \\ \vdots \\ \bar{x}_q\,\vec{1}_{n_q} \end{pmatrix} - \bar{x}\,\vec{1}_n = \begin{pmatrix} (\bar{x}_1 - \bar{x})\,\vec{1}_{n_1} \\ (\bar{x}_2 - \bar{x})\,\vec{1}_{n_2} \\ \vdots \\ (\bar{x}_q - \bar{x})\,\vec{1}_{n_q} \end{pmatrix}$$

Análisis de varianza

Por ser $D-J$ simétrica e idempotente se tiene que

$$\vec{x}^t\,(D-J)\,\vec{x} = \vec{x}^t\,(D-J)^t\,(D-J)\,\vec{x}$$

$$= \left[(\bar{x}_1-\bar{x})\,\vec{1}^t_{n_1},\ldots,(\bar{x}_q-\bar{x})\,\vec{1}^t_{n_q}\right]\begin{pmatrix}(\bar{x}_1-\bar{x})\,\vec{1}_{n_1}\\ \vdots \\ (\bar{x}_q-\bar{x})\,\vec{1}_{n_q}\end{pmatrix}$$

$$= \sum_{i=1}^{q} n_i\,(\bar{x}_i-\bar{x})^2 = \text{SCF}$$

Análisis de varianza

$$
\begin{aligned}
\mathrm{SCT} &= \vec{x}^{\,t}\, H\, \vec{x} = \vec{x}^{\,t}\, (I - J)\, \vec{x} = \vec{x}^{\,t}\, (I - D + D - J)\, \vec{x} \\
&= \vec{x}\, (I - D)\, \vec{x} + \vec{x}\, (D - J)\, \vec{x} \\
&= \sum_{i=1}^{q} \sum_{j=1}^{n_i} (x_{ij} - \bar{x}_i)^2 + \sum_{i=1}^{q} n_i\, (\bar{x}_i - \bar{x})^2 \\
&= \mathrm{SCE} + \mathrm{SCF}
\end{aligned}
$$

Análisis de varianza

```
summary(sleep)                         # ejemplo en R

## Vamos a suponer (incorrectamente; véase la ayuda
## "?sleep") que "sleep" contiene una variable
## respuesta que representa el tiempo "extra" de
## sueño en un grupo de control (group=1) de cierto
## experimento y en otro grupo de personas a las que
## se les ha administrado un medicamento (group=2).

X <- sleep$extra                    # respuesta
N <- length(X)                      # tamaño muestral
G <- sleep$group                    # factor

## H0: mu1=mu2 ; H1: mu1<>mu2
t.test (X ~ G, var.equal=TRUE)      # =aov <= q=2
```

Análisis de varianza

```
adeva <- aov(X~G)
tabla <- summary(adeva)[[1]]
sum(tabla[,"Sum Sq"])                  # SCT
tabla["Residuals","Sum Sq"]            # SCE
tabla[1,"Sum Sq"]                      # SCF
## para resolución matricial, hay que ordenar
orden <- order(G); X <- X[orden]; G <- G[orden]
I <- diag(N)
definirJ <- function (n) matrix(1/n, n, n)
J <- definirJ(N)
SCT <- X %*% (I-J) %*% X
Ni <- table(G)
D <- as.matrix(Matrix::bdiag(lapply(Ni, definirJ)))
SCE <- X %*% (I-D) %*% X
SCF <- X %*% (D-J) %*% X
```

Análisis de varianza

A simétrica idempotente de rango r

$\Longrightarrow \ \mathrm{E}\left[\vec{x}^t\, A\, \vec{x}\right] = \sigma^2\, r + \vec{\mu}\, A\, \vec{\mu}$

$\Longrightarrow \ \mathrm{E}\left[\mathrm{SCE}\right] = \mathrm{E}\left[\vec{x}^t\, (I - D)\, \vec{x}\right] = \sigma^2\, (n - q) + \vec{\mu}\, (I - D)\, \vec{\mu}$

En detalle:

$$
\begin{aligned}
\mathrm{E}\left[\mathrm{SCE}\right] &= \mathrm{E}\left[\vec{x}^t\, (I - D)\, \vec{x}\right] = \mathrm{E}\left[\mathrm{tr}(\vec{x}^t\, (I - D)\vec{x}\right] \\
&= \mathrm{E}\left[\mathrm{tr}([I - D]\, \vec{x}\, \vec{x}^t)\right] = \mathrm{tr}\left\{\mathrm{E}\left[(I - D)\, \vec{x}\, \vec{x}^t\right]\right\} \\
&= \mathrm{tr}\left\{(I - D)\, \mathrm{E}\left[\vec{x}\, \vec{x}^t\right]\right\} \\
&= \mathrm{tr}\left\{(I - D)\, \left(\mathrm{Cov}(\vec{x}) + \mathrm{E}\left[\vec{x}\right]\, \mathrm{E}\left[\vec{x}^t\right]\right)\right\} \\
&= \mathrm{tr}\left\{(I - D)\, \left(\sigma^2\, I + \mathrm{E}\left[\vec{x}\right]\, \mathrm{E}\left[\vec{x}^t\right]\right)\right\} \\
&= \sigma^2\, \mathrm{tr}(I - D) + \mathrm{tr}\left\{(I - D)\, \mathrm{E}\left[\vec{x}\right]\, \mathrm{E}\left[\vec{x}^t\right]\right\} \\
&= \sigma^2\, (n - q) + \mathrm{tr}\left\{\mathrm{E}\left[\vec{x}^t\right]\, (I - D)\, \mathrm{E}\left[\vec{x}\right]\right\} \\
&= \sigma^2\, (n - q) + \mathrm{E}\left[\vec{x}^t\right]\, (I - D)\, \mathrm{E}\left[\vec{x}\right]
\end{aligned}
$$

Análisis de varianza

$$\mathrm{E}[\vec{x}] = \begin{pmatrix} \mathrm{E}[\vec{x}_1] \\ \mathrm{E}[\vec{x}_2] \\ \vdots \\ \mathrm{E}[\vec{x}_q] \end{pmatrix} = \begin{pmatrix} \mu_1 \, \vec{1}_{n_1} \\ \mu_2 \, \vec{1}_{n_2} \\ \vdots \\ \mu_q \, \vec{1}_{n_q} \end{pmatrix}$$

$$\begin{aligned} (I - D)\,\mathrm{E}[\vec{x}] &= \begin{pmatrix} I_{n_1} - J_1 & & & \\ & I_{n_2} - J_2 & & \\ & & \ddots & \\ & & & I_{n_q} - J_q \end{pmatrix} \begin{pmatrix} \mu_1 \, \vec{1}_{n_1} \\ \mu_2 \, \vec{1}_{n_2} \\ \vdots \\ \mu_q \, \vec{1}_{n_q} \end{pmatrix} \\ &= \begin{pmatrix} \vdots \\ (I_{n_i} - J_i)\,\mu_i \, \vec{1}_{n_i} \\ \vdots \end{pmatrix} = \begin{pmatrix} \vdots \\ H_i \, \mu_i \, \vec{1}_{n_i} \\ \vdots \end{pmatrix} = \vec{0} \end{aligned}$$

$$\Longrightarrow \mathrm{E}\left[\vec{x}^t\right] (I - D)\,\mathrm{E}[\vec{x}] = \mathrm{E}\left[\vec{x}^t\right] \vec{0} = 0 \Longrightarrow \mathrm{E}[\mathrm{SCE}] = \sigma^2 (n - q)$$

Análisis de varianza

A simétrica idempotente de rango r

$\Longrightarrow \; \mathrm{E}\left[\vec{x}^t\, A\, \vec{x}\right] = \sigma^2\, r + \vec{\mu}\, A\, \vec{\mu}$

$\Longrightarrow \; \mathrm{E}\,[\mathrm{SCF}] = \mathrm{E}\left[\vec{x}^t\,(D-J)\,\vec{x}\right] = \sigma^2\,(q-1) + \vec{\mu}\,(D-J)\,\vec{\mu}$

En detalle:

$$
\begin{aligned}
\mathrm{E}\,[\mathrm{SCF}] &= \mathrm{E}\left[\vec{x}^t\,(D-J)\vec{x}\right] = \mathrm{E}\left[\mathrm{tr}\left\{\vec{x}^t\,(D-J)\,\vec{x}\right\}\right] \\
&= \mathrm{E}\left[\mathrm{tr}\left\{(D-J)\,\vec{x}\,\vec{x}^t\right\}\right] = \mathrm{tr}\left\{(D-J)\,\mathrm{E}\left[\vec{x}\,\vec{x}^t\right]\right\} \\
&= \mathrm{tr}\left\{(D-J)\,\left(\mathrm{Cov}(\vec{x}) + \mathrm{E}\,[\vec{x}]\;\mathrm{E}\left[\vec{x}^t\right]\right)\right\} \\
&= \mathrm{tr}\left\{(D-J)\,\left(\sigma^2\, I + \mathrm{E}\,[\vec{x}]\;\mathrm{E}\left[\vec{x}^t\right]\right)\right\} \\
&= \mathrm{tr}\left\{\sigma^2\,(D-J)\right\} + \mathrm{tr}\left\{(D-J)\,\mathrm{E}\,[\vec{x}]\;\mathrm{E}\left[\vec{x}^t\right]\right\} \\
&= \sigma^2\;\mathrm{tr}(D-J) + \mathrm{tr}\left\{\mathrm{E}\left[\vec{x}^t\right]\;(D-J)\,\mathrm{E}\,[\vec{x}]\right\} \\
&= \sigma^2\,(q-1) + \mathrm{E}\left[\vec{x}^t\right]\;(D-J)\,\mathrm{E}\,[\vec{x}]
\end{aligned}
$$

Análisis de varianza

$$\mathrm{E}\left[\vec{x}\right] = \begin{pmatrix} \mathrm{E}\left[\vec{x}_1\right] \\ \vdots \\ \mathrm{E}\left[\vec{x}_q\right] \end{pmatrix} = \begin{pmatrix} \mu\,\vec{1}_{n_1} + \alpha_1\,\vec{1}_{n_1} \\ \vdots \\ \mu\,\vec{1}_{n_q} + \alpha_q\,\vec{1}_{n_q} \end{pmatrix} = \mu\,\vec{1}_n + \begin{pmatrix} \alpha_1\,\vec{1}_{n_1} \\ \vdots \\ \alpha_q\,\vec{1}_{n_q} \end{pmatrix}$$

Análisis de varianza

$$J \begin{pmatrix} \alpha_1 \vec{1}_{n_1} \\ \vdots \\ \alpha_q \vec{1}_{n_q} \end{pmatrix} = \tfrac{1}{n} \vec{1}\, \vec{1}^t \begin{pmatrix} \alpha_1 \vec{1}_{n_1} \\ \vdots \\ \alpha_q \vec{1}_{n_q} \end{pmatrix} = \vec{1}\, \tfrac{1}{n} \sum n_i \, \alpha_i = \vec{0}$$

$$\implies (D - J)\, \mathrm{E}[\vec{x}] = \mu\, (D - J)\, \vec{1} + (D - J) \begin{pmatrix} \alpha_1 \vec{1}_{n_1} \\ \vdots \\ \alpha_q \vec{1}_{n_q} \end{pmatrix}$$

$$= \vec{0} + D \begin{pmatrix} \alpha_1 \vec{1}_{n_1} \\ \vdots \\ \alpha_q \vec{1}_{n_q} \end{pmatrix} - J \begin{pmatrix} \alpha_1 \vec{1}_{n_1} \\ \vdots \\ \alpha_q \vec{1}_{n_q} \end{pmatrix}$$

$$= D \begin{pmatrix} \alpha_1 \vec{1}_{n_1} \\ \vdots \\ \alpha_q \vec{1}_{n_q} \end{pmatrix} - \vec{0} = \begin{pmatrix} J_1 & & & \\ & J_2 & & \\ & & \ddots & \\ & & & J_q \end{pmatrix} \begin{pmatrix} \alpha_1 \vec{1}_{n_1} \\ \vdots \\ \alpha_q \vec{1}_{n_q} \end{pmatrix} = \begin{pmatrix} \alpha_1 \vec{1}_{n_1} \\ \vdots \\ \alpha_q \vec{1}_{n_q} \end{pmatrix}$$

Análisis de varianza

Por tanto,

$$\begin{aligned} \mathrm{E}\left[\vec{x}^t\right] (D-J)\,\mathrm{E}\left[\vec{x}\right] &= \left(\alpha_1\,\vec{1}^t_{n_1},\ldots,\alpha_q\,\vec{1}^t_{n_q}\right)\begin{pmatrix}\alpha_1\,\vec{1}_{n_1}\\ \vdots \\ \alpha_q\,\vec{1}_{n_q}\end{pmatrix} \\ &= \sum_{i=1}^{q}\alpha_i^2\vec{1}^t_{n_i}\,\vec{1}_{n_i} = \sum_{i=1}^{q} n_i\,\alpha_i^2 \end{aligned}$$

y se obtiene

$$\mathrm{E}\left[\mathrm{SCF}\right] = \sigma^2\,(q-1) + \sum n_i\,\alpha_i^2$$

Análisis de varianza

Distribución de la SCE:

Suponiendo que $\vec{x}_i \equiv \mathcal{N}_{n_i}\left(\mu_i \,\vec{1}, \sigma^2 \, I_{n_i}\right)$ para $i = 1, \ldots, q$ y que las $\vec{x}_i$ son independientes, se verifica que

$$\text{SCE} = \vec{x}^t \,(I - D)\,\vec{x} \equiv \sigma^2 \,\chi^2_{n-q}$$

Para demostrar esta propiedad, bastará ver que $\text{E}\left[(I - D)\,\vec{x}\right] = \vec{0}$.

Análisis de varianza

$$
\begin{aligned}
\mathrm{E}\left[(I-D)\,\vec{x}\right] &= (I-D)\,\mathrm{E}\left[\vec{x}\right] = \mathrm{E}\left[\vec{x}\right] - D\,\mathrm{E}\left[\vec{x}\right] \\
&= \begin{pmatrix} \mu_1\,\vec{1}_{n_1} \\ \vdots \\ \mu_q\,\vec{1}_{n_q} \end{pmatrix} - \begin{pmatrix} J_1 & & \\ & \ddots & \\ & & J_q \end{pmatrix} \begin{pmatrix} \mu_1\,\vec{1}_{n_1} \\ \vdots \\ \mu_q\,\vec{1}_{n_q} \end{pmatrix} \\
&= \begin{pmatrix} \mu_1\,\vec{1}_{n_1} \\ \vdots \\ \mu_q\,\vec{1}_{n_q} \end{pmatrix} - \begin{pmatrix} \mu_1\,J_1\,\vec{1}_{n_1} \\ \vdots \\ \mu_q\,J_q\,\vec{1}_{n_q} \end{pmatrix} \\
&= \vec{0}
\end{aligned}
$$

Análisis de varianza

Distribución de la SCF bajo H_0:

$$\mathrm{SCF} = \vec{x}^t \, (D - J) \, \vec{x} \overset{H_0}{\equiv} \sigma^2 \, \chi^2_{q-1}$$

Dado que $D - J$ es idempotente, bastará comprobar que $\mathrm{E}\left[(D - J)\,\vec{x}\right] = \vec{0}$.

$$\mathrm{E}\left[(D - J)\,\vec{x}\right] = (D - J)\,\mathrm{E}\left[\vec{x}\right] = D\,\mathrm{E}\left[\vec{x}\right] - J\,\mathrm{E}\left[\vec{x}\right] = \vec{0}$$

ya que bajo $H_0 \equiv \mu_1 = \cdots = \mu_q$ y $\mathrm{E}\left[\vec{x}\right] = \mu\,\vec{1}$, con lo cual

$$D\,\mu\,\vec{1} = \mu \begin{pmatrix} J_1 & & \\ & \ddots & \\ & & J_q \end{pmatrix} \begin{pmatrix} \vec{1}_{n_1} \\ \vdots \\ \vec{1}_{n_q} \end{pmatrix} = \mu \begin{pmatrix} J_1\,\vec{1}_{n_1} \\ \vdots \\ J_q\,\vec{1}_{n_q} \end{pmatrix} = \mu\,\vec{1}$$

$$J\,\mathrm{E}\left[\vec{x}\right] = J\,\mu\vec{1} = \mu\,J\,\vec{1} = \mu\,\vec{1}$$

Análisis de varianza

$$\text{CME} = \frac{\text{SCE}}{n - q}$$

Se verifica que $\text{E}[\text{CME}] = \sigma^2$ y por tanto es un estimador insesgado de la varianza de los residuos. Además,

$$\frac{\text{CME}\,(n - q)}{\sigma^2} \equiv \chi^2_{n-q}$$

Análisis de varianza

$$\mathrm{CMF} = \frac{\mathrm{SCF}}{q-1}$$

$$\mathrm{E}\left[\mathrm{CMF}\right] = \sigma^2 + \frac{\sum_{i=1}^{q} n_i\, \alpha_i^2}{q-1}$$

Bajo $H_0 \equiv \alpha_i = 0 \,\forall\, i$, se cumple que $\mathrm{E}\left[\mathrm{CMF} \mid H_0\right] = \sigma^2$. Además

$$\frac{\mathrm{CMF}\,(q-1)}{\sigma^2} \overset{H_0}{\equiv} \chi^2_{q-1}$$

Análisis de varianza

CMF y CME son independientes:

- $\vec{x} \equiv \mathcal{N}(\cdot,\cdot) \implies \begin{cases} (I-D)\vec{x} \equiv \mathcal{N}(\cdot,\cdot) \\ (D-J)\vec{x} \equiv \mathcal{N}(\cdot,\cdot) \end{cases}$
- $\operatorname{Cov}[(I-D)\vec{x},(D-J)\vec{x}] = (I-D)\operatorname{Var}(\vec{x})(D-J) = (I-D)\sigma^2 I(D-J) = \sigma^2(I-D)(D-J) = \sigma^2(D-J-DD+DJ) = \sigma^2(D-J-D+J) = \mathbf{0}$
- $(I-D)\vec{x}$ independiente de $(D-J)\vec{x}$
- $\vec{x}^t(I-D)\vec{x}$ independiente de $\vec{x}^t(D-J)\vec{x}$
- SCE independiente de SCF

Análisis de varianza

El cociente

$$\frac{\text{CMF}}{\text{CME}} = \frac{\text{CMF}/\sigma^2}{\text{CME}/\sigma^2}$$

tiende a tomar valores cercanos a uno bajo H_0, y más grandes bajo H_1.
Por otra parte, CMF y CME son independientes, luego

$$\frac{\text{CMF}}{\text{CME}} \overset{H_0}{\equiv} \frac{\frac{\chi^2_{q-1}}{q-1}}{\frac{\chi^2_{n-q}}{n-q}} = F_{q-1,n-q}$$

En consecuencia, la región crítica del contraste viene dada por la expresión

$$\text{R.C.} = \left\{ \frac{\text{CMF}}{\text{CME}} > k \right\} \text{ con } P[\text{R.C.} \mid H_0] = \alpha$$

Análisis de varianza

Tabla ANOVA

Fuente de variación	S.C.	g.l.	C.M.	F
Entre / Factor	SCF	$q-1$	CMF	$\frac{\text{CMF}}{\text{CME}}$
Dentro / Error	SCE	$n-q$	CME	
Total	SCT	$n-1$		

Ejemplo

Considérense los datos siguientes incluidos en R:

```
> aves <- data.frame (peso = chickwts$weight,
                      come = factor(chickwts$feed,
                                    labels =
                   c("caseína","fabona","linaza",
                     "har.hueso","soja","girasol")))
> summary (aves)
```

```
      peso                  come
 Min.    :108.0   caseína   :12
 1st Qu.:204.5   fabona    :10
 Median :258.0   linaza    :12
 Mean    :261.3   har.hueso:11
 3rd Qu.:323.5   soja      :14
 Max.    :423.0   girasol   :12
```

Ejemplo

- Se repartió aleatoriamente en seis grupos una remesa de pollos recién nacidos.
- Cada grupo recibió un complemento alimenticio distinto.
- Se registró el peso en gramos tras seis semanas.

- ¿Influye el complemento en el peso?

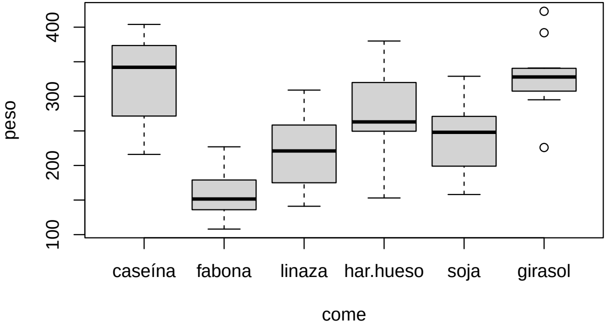
Ejemplo

```
> options (digits = 3)
> RcmdrMisc::numSummary (aves$peso, groups=aves$come)
```

	mean	sd	IQR	0%	25%	50%	75%	100%	data:n
caseína	324	64.4	93.5	216	277	342	371	404	12
fabona	160	38.6	39.2	108	137	152	176	227	10
linaza	219	52.2	79.8	141	178	221	258	309	12
har.hueso	277	64.9	70.5	153	250	263	320	380	11
soja	246	54.1	63.2	158	207	248	270	329	14
girasol	329	48.8	27.5	226	313	328	340	423	12

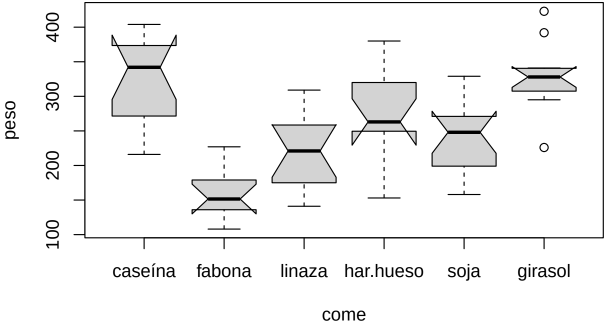
Ejemplo

```
> boxplot (peso ~ come, aves)
```



Ejemplo

```
> boxplot (peso ~ come, aves, notch=TRUE)
```



Ejemplo

```
> bartlett.test (peso ~ come, aves)

        Bartlett test of homogeneity of variances

data:  peso by come
Bartlett's K-squared = 3, df = 5, p-value = 0.7
> car::leveneTest (peso ~ come, aves)
Levene's Test for Homogeneity of Variance (center = median)
      Df F value Pr(>F)
group  5    0.75   0.59
      65
```

Ejemplo

```
> summary (aov (peso ~ come, aves))
             Df Sum Sq Mean Sq F value   Pr(>F)
come          5 231129   46226    15.4 5.9e-10 ***
Residuals    65 195556    3009
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘
```

Contrastes a posteriori

$$H_0^{\text{ANOVA}} : \mu_1 = \cdots = \mu_q \qquad \equiv \qquad \bigcap_{1 \leq i < j \leq q} H_0^{ij} : \mu_i = \mu_j$$

¿Qué H_0^{ij} se rechazan?

Contrastes a posteriori

criterio de Bonferroni

- hay $\frac{q\,(q-1)}{2}$ parejas de grupos
- contrastar H_0^{ij} a nivel $\alpha^* = \frac{2\alpha}{q\,(q-1)}$

$$P\left[\text{rechazar alguna } H_0^{ij} \mid H_0^{\text{ANOVA}}\right] \leq \sum_{1\leq i<j\leq q} P\left[\text{rechazar } H_0^{ij} \mid H_0^{ij}\right] = \frac{q\,(q-1)}{2}\,\alpha^* = \alpha$$

- estadístico de contraste

$$\frac{\bar{X}_i - \bar{X}_j}{\sqrt{\left(\frac{1}{n_i}+\frac{1}{n_j}\right)\text{CME}}} \overset{H_0^{ij}}{\equiv} t_{n-q}$$

Contrastes a posteriori

En el ejemplo

```
> q <- length (levels (aves$come))
> q
[1] 6
> q * (q-1) / 2
[1] 15
```

Contrastes a posteriori

```
> pairwise.t.test (aves$peso, aves$come, "none")

        Pairwise comparisons using t tests with pooled SD

data:  aves$peso and aves$come

          caseína fabona linaza har.hueso soja
fabona    2e-09   -      -      -         -
linaza    1e-05   0.02   -      -         -
har.hueso 0.05    7e-06  0.01   -         -
soja      7e-04   3e-04  0.20   0.17      -
girasol   0.81    8e-10  6e-06  0.03      3e-04

P value adjustment method: none
> ## 12 de 15 rechazos al 5%
```

Contrastes a posteriori

```
> pairwise.t.test (aves$peso, aves$come, "bonferroni")
        Pairwise comparisons using t tests with pooled SD

data:  aves$peso and aves$come

          caseína fabona linaza har.hueso soja
fabona    3e-08   -      -      -         -
linaza    2e-04   0.228  -      -         -
har.hueso 0.684   1e-04  0.202  -         -
soja      0.010   0.005  1.000  1.000     -
girasol   1.000   1e-08  9e-05  0.397     0.004

P value adjustment method: bonferroni
> ##  8 de 15 rechazos al 5%
```

Contrastes a posteriori

criterio de Tukey

- basado en la distribución del *recorrido estudentizado*
  - $Y_1, \ldots, Y_q \equiv \mathcal{N}(0,1)$ independientes
  - $Z \equiv \chi^2_r$ independiente de las $Y_1, \ldots, Y_q$
  - entonces $\frac{Y_{(q)} - Y_{(1)}}{\sqrt{Z/r}} \equiv Q_{q,r}$ `ptukey(,q,r)` en R
- en ANOVA para contrastar H_0^{ij} se calcula el P-valor

$$P\left[Q_{q,n-q} > \frac{|\bar{X}_i - \bar{X}_j|}{\sqrt{\frac{\text{CME}}{2}\left(\frac{1}{n_i} + \frac{1}{n_j}\right)}} \right]$$

Contrastes a posteriori

```
> r <- nrow (aves) - q                    # q=6 r=65
> distro <- replicate (1e5,
  {
      medias <- rnorm (q)
      numerador <- diff (range (medias))
      denominador <- sqrt (rchisq (1, r) / r)
      numerador / denominador
  })
> alfas <- c (0.01, 0.025, 0.05, 0.1, 0.5,
              0.9, 0.95, 0.975, 0.99)
> rbind (sim = quantile (distro, alfas),
         num = qtukey (alfas, q, r))
       1% 2.5%   5%  10%  50%  90%  95% 97.5%  99%
sim 0.866 1.06 1.25 1.48 2.49 3.76 4.16  4.53 5.00
num 0.862 1.06 1.24 1.48 2.49 3.75 4.15  4.52 4.97
```

Contrastes a posteriori

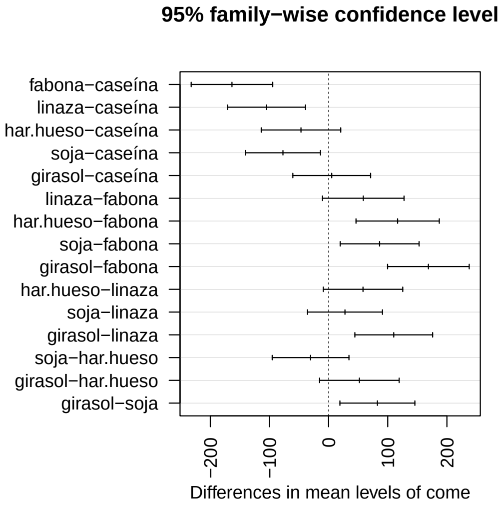
```
> a <- aov (peso ~ come, aves)
> TukeyHSD (a)                    # 8 rechazos de 15 al 5%
```

Contrastes a posteriori

```
  Tukey multiple comparisons of means
    95% family-wise confidence level

Fit: aov(formula = peso ~ come, data = aves)

$come
                     diff     lwr   upr p adj
fabona-caseína    -163.38 -232.35 -94.4 0.000
linaza-caseína    -104.83 -170.59 -39.1 0.000
har.hueso-caseína  -46.67 -113.91  20.6 0.332
soja-caseína       -77.15 -140.52 -13.8 0.008
girasol-caseína      5.33  -60.42  71.1 1.000
linaza-fabona       58.55  -10.41 127.5 0.141
har.hueso-fabona   116.71   46.34 187.1 0.000
soja-fabona         86.23   19.54 152.9 0.004
girasol-fabona     168.72   99.75 237.7 0.000
har.hueso-linaza    58.16   -9.07 125.4 0.128
soja-linaza         27.68  -35.68  91.0 0.793
girasol-linaza     110.17   44.41 175.9 0.000
soja-har.hueso     -30.48  -95.38  34.4 0.739
girasol-har.hueso   52.01  -15.22 119.2 0.221
girasol-soja        82.49   19.13 145.9 0.004
```

Contrastes a posteriori

```
> m <- par("mar") ; par(mar=m+c(0,10,0,0)) # aumenta margen izq.
> plot (TukeyHSD (a), las=2)      # etiquetas horizontales (?par)
> par(mar=m)                      # recupera margen izq. habitual
```



Incoherencias entre ANOVA y contrastes a posteriori

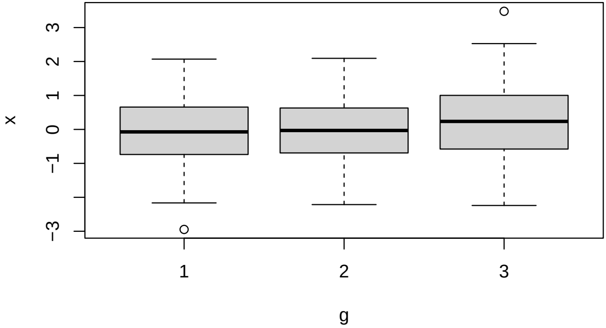
```
> set.seed (129)     # anova => H1 ; bonferroni => H0
> mu <- c (0, 0, 0.2)
> q <- length(mu)
> m <- 100
> g <- factor (rep (1:q, each=m))
> x <- unlist (lapply (mu,
                          function (mui) rnorm (m, mui)))
> a <- aov (x ~ g)
> summary (a)
             Df Sum Sq Mean Sq F value Pr(>F)
g             2      7    3.35    3.11  0.046 *
Residuals   297    320    1.08
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 '
```

Incoherencias entre ANOVA y contrastes a posteriori

```
> options (digits = 7)
> pairwise.t.test (x, g, "bonf")
        Pairwise comparisons using t tests with pooled SD

data:  x and g

  1     2
2 1.000 -
3 0.063 0.157

P value adjustment method: bonferroni
```

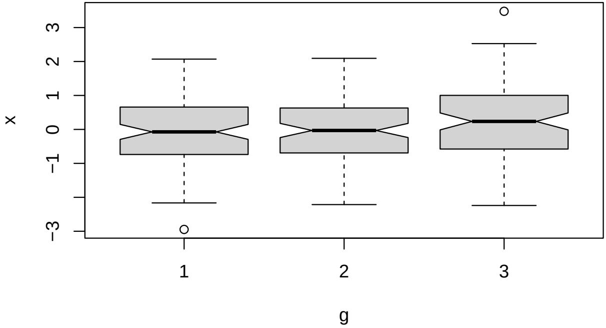
Incoherencias entre ANOVA y contrastes a posteriori

```
> boxplot (x ~ g)
```



Incoherencias entre ANOVA y contrastes a posteriori

```
> boxplot (x ~ g, notch=TRUE)
```



Incoherencias entre ANOVA y contrastes a posteriori

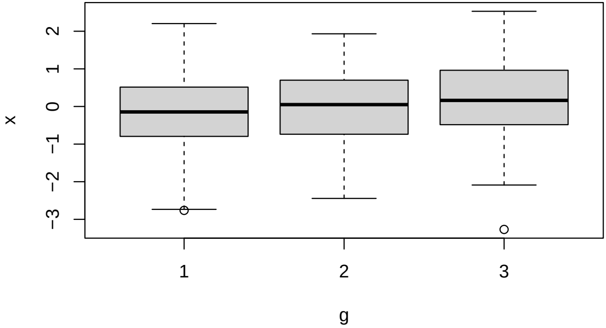
```
> set.seed (614)    # anova => H0 ; bonferroni => H1
> mu <- c (0, 0, 0.2)
> q <- length(mu)
> m <- 100
> g <- factor (rep (1:q, each=m))
> x <- unlist (lapply (mu,
                        function (mui) rnorm (m, mui)))
> a <- aov (x ~ g)
> summary (a)
             Df  Sum Sq Mean Sq F value Pr(>F)
g             2    5.99   2.995   2.955 0.0536 .
Residuals   297  301.09   1.014
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘
```

Incoherencias entre ANOVA y contrastes a posteriori

```
> pairwise.t.test (x, g, "bonf")
        Pairwise comparisons using t tests with pooled SD

data:  x and g

  1     2
2 0.546 -
3 0.048 0.831

P value adjustment method: bonferroni
```

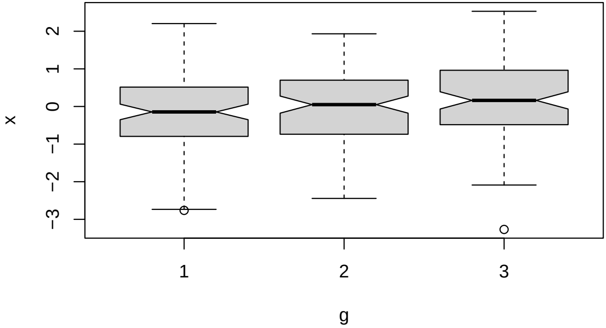
Incoherencias entre ANOVA y contrastes a posteriori

```
> boxplot (x ~ g)
```



Incoherencias entre ANOVA y contrastes a posteriori

```
> boxplot (x ~ g, notch=TRUE)
```



Incoherencias: frecuencia

```
> alfa <- 0.05 ; mu <- c (0, 0, 0.2) ; q <- length(mu)
> m <- 100 ; g <- factor (rep (1:q, each=m))
> table (data.frame (t (replicate (10000, {
      x <- unlist (lapply (mu,
                function (mui) rnorm (m, mui)))
      a <- aov (x ~ g)
      H1anova <- summary(a)[[1]] ["g", "Pr(>F)"] <= alfa
      H1bonfe <- any (na.omit (c (pairwise.t.test
                                        (x,g,"bonf")$p.value))
                          <= alfa)
      c (H1anova=H1anova, H1bonfe=H1bonfe)
  }))))
       H1bonfe
H1anova FALSE TRUE
  FALSE  7099   37
  TRUE    308 2556
```

Incoherencias: búsqueda de semillas para ejemplos

```
> rechazos <- sapply (1:1000, function(semilla){
      set.seed (semilla)
      x <- unlist (lapply (mu,
            function (mui) rnorm (m, mui)))
      a <- aov (x ~ g)
      H1anova <- summary(a)[[1]] ["g", "Pr(>F)"] <= alfa
      H1bonfe <- any (na.omit (c (pairwise.t.test
                              (x,g,"bonf")$p.value))
                  <= alfa)
      c (H1anova=H1anova, H1bonfe=H1bonfe)
  })
```

Incoherencias: búsqueda de semillas para ejemplos

```
> options (width = 55)
> (semillas <- which (xor (rechazos[1,], rechazos[2,])))
 [1] 122 129 153 218 226 246 267 268 343 369 371 377
[13] 383 397 414 437 457 513 610 614 619 646 654 658
[25] 670 677 706 741 744 762 777 779 793 895 906 930
[37] 973
> rechazos [, semillas]
         [,1]  [,2]  [,3]  [,4]  [,5]  [,6]  [,7]
H1anova  TRUE  TRUE  TRUE  TRUE  TRUE  TRUE  TRUE
H1bonfe FALSE FALSE FALSE FALSE FALSE FALSE FALSE
         [,8]  [,9] [,10] [,11] [,12] [,13] [,14]
H1anova  TRUE  TRUE  TRUE  TRUE  TRUE  TRUE  TRUE
H1bonfe FALSE FALSE FALSE FALSE FALSE FALSE FALSE
        [,15] [,16] [,17] [,18] [,19] [,20] [,21]
H1anova  TRUE  TRUE  TRUE  TRUE  TRUE FALSE  TRUE
H1bonfe FALSE FALSE FALSE FALSE FALSE  TRUE FALSE
        [,22] [,23] [,24] [,25] [,26] [,27] [,28]
H1anova  TRUE  TRUE  TRUE  TRUE  TRUE  TRUE  TRUE
```