# Annexe A

# Polynômes orthogonaux

## A.1 Polynômes de Legendre

On appelle *polynôme de Legendre* de degré $n$, le polynôme défini par la relation de récurrence

$$(n+1)P_{n+1}(x) = (2n+1)xP_n(x) - nP_{n-1}(x)$$

initialisée par

$$P_0(x) = 1 \quad P_1(x) = x$$

Les premiers polynômes sont

$$\begin{aligned}
&P_0(x) = 1 \\
&P_1(x) = x \\
&P_2(x) = (3x^2 - 1)/2 \\
&P_3(x) = (5x^3 - 3x)/2 \\
&P_4(x) = (35x^4 - 30x^2 + 3)/8 \\
&P_5(x) = (63x^5 - 70x^3 + 15x)/8 \\
&P_6(x) = (231x^6 - 315x^4 + 105x^2 - 5)/16
\end{aligned}$$

(1) Les polynômes de Legendre sont solutions de l'équation différentielle

$$(1-x^2)y'' - 2xy' + n(n+1)y = 0$$

(2) Les polynômes de Legendre satisfont la relation de récurrence

$$(1-x^2)P_n'(x) = -nxP_n(x) + nP_{n-1}(x)$$

(3) Formule de Rodrigues

$$P_n(x) = \frac{(-1)^n}{2^n n!} \frac{d^n}{dx^n}(1-x^2)^n$$

(4) Majorations

$$\forall x \in [-1,+1], \qquad |P_n(x)| \leq 1$$

$$\forall x \in [-1,+1], \qquad |P_n'(x)| \leq \frac{n(n+1)}{2}$$

$$\forall x \in [-1,+1], \qquad |P_n(x)| \leq \frac{1}{\sqrt{8\pi n(1-x^2)}}$$

$$\frac{1-P_n^2(x)}{(2n-1)(n+1)} \leq P_n^2(x) - P_{n-1}(x)P_{n+1}(x) \leq \frac{2n+1}{3n(n+1)}$$

(5) Les polynômes de Legendre sont des polynômes orthogonaux relativement à la fonction de poids $\omega(x) = 1$ sur l'intervalle $[-1,+1]$.

$$\int_{-1}^{+1} P_n(x)P_m(x)dx = \frac{2}{2n+1}\delta_{n,m}$$

En particulier, $P_n(1) = 1$ et

$$\|P_n\|_2 = \left(\int_{-1}^{+1} P_n^2(x)dx\right)^{1/2} = \sqrt{\frac{2}{2n+1}}$$

(6) Les polynômes de Legendre vérifient la formule

$$\int_{-1}^{+1} P_n(x)\frac{dx}{\sqrt{1-x}} = \frac{2^{3/2}}{2n+1}$$

## A.2 Polynômes de Laguerre

On appelle *polynôme de Laguerre* d'ordre $n$, le polynôme défini par la relation de récurrence

$$(n+1)L_{n+1}(x) = (2n+1-x)L_n(x) - nL_{n-1}(x)$$

et les conditions d'initialisation

$$L_0(x) = 1 \quad L_1(x) = 1-x$$

Pour $\alpha > -1$. On appelle *polynôme de Laguerre généralisé* d'ordre $n$ et on note $L_n^{(\alpha)}(x)$ le polynôme défini par la relation de récurrence

$$(n+1)L_{n+1}^{(\alpha)}(x) = (2n+\alpha+1-x)L_n^{(\alpha)}(x) - (n+\alpha)L_{n-1}^{(\alpha)}(x)$$

initialisée par

$$L_0^{(\alpha)}(x) = 1 \quad L_1^{(\alpha)}(x) = 1 + \alpha - x$$

Le polynôme de Laguerre proprement dit correspond au cas $\alpha = 0$. Les premiers polynômes sont

$$L_0(x) = 1$$

$$L_1(x) = 1 - x$$

$$L_2(x) = \tfrac{1}{2}x^2 - 2x + 1$$

$$L_3(x) = \tfrac{-1}{6}x^3 + \tfrac{3}{2}x^2 - 3x + 1$$

$$L_4(x) = \tfrac{1}{24}x^4 - \tfrac{2}{3}x^3 + 3x^2 - 4x + 1$$

$$L_5(x) = \tfrac{-1}{120}x^5 + \tfrac{5}{24}x^4 - \tfrac{5}{3}x^3 + 5x^2 - 5x + 1$$

$$L_6(x) = \tfrac{1}{720}x^6 - \tfrac{1}{20}x^5 + \tfrac{5}{8}x^4 - \tfrac{10}{3}x^3 + \tfrac{15}{2}x^2 - 6x + 1$$

(1) Les polynômes de Laguerre sont solutions de l'équation différentielle

$$xy'' + (\alpha + 1 - x)y' + ny = 0$$

(2) Les polynômes de Laguerre satisfont les relations de récurrence, pour $\alpha$ entier

$$xL_n'(x) = nL_n(x) - nL_{n-1}(x)$$

$$x\frac{dL_n^{(\alpha)}(x)}{dx} = nL_n^{(\alpha)}(x) - (n+\alpha)L_{n-1}^{(\alpha)}(x)$$

$$L_{n+1}^{(\alpha-1)}(x) = L_n^{(\alpha)}(x) - L_{n-1}^{(\alpha)}(x)$$

$$xL_n^{(\alpha+1)}(x) = (x-n)L_n^{(\alpha)}(x) - (n+\alpha)L_{n-1}^{(\alpha)}(x)$$

$$xL_n^{(\alpha+1)}(x) = (n+\alpha+1)L_n^{(\alpha)}(x) - (n+1)L_{n+1}^{(\alpha)}(x)$$

$$(n+\alpha)L_n^{(\alpha-1)}(x) = (n+1)L_{n+1}^{(\alpha)}(x) - (n+1-x)L_n^{(\alpha)}(x)$$

(3) Formule de Rodrigues

$$L_n^{(\alpha)}(x) = \frac{e^x}{n!x^\alpha}\frac{d^n}{dx^n}\left(x^{n+\alpha}e^{-x}\right)$$

(4) Majorations

$$\forall x \geq 0, \qquad |L_n(x)| \leq e^{x/2}$$

$$\forall x \geq 0, \forall \alpha \geq 0 \qquad \left|L_n^{(\alpha)}(x)\right| \leq \frac{\Gamma(\alpha+n+1)}{n!\Gamma(\alpha+1)}e^{x/2}$$

(5) Les polynômes de Laguerre sont des polynômes orthogonaux relativement à la fonction de poids $\omega(x) = x^\alpha e^{-x}$ définie sur l'intervalle $]0, \infty[$

$$\int_0^\infty L_n^{(\alpha)}(x) L_m^{(\alpha)}(x) x^\alpha e^{-x} dx = \frac{\Gamma(\alpha+n+1)}{n!} \delta_{n,m}$$

(6) L'intégrale du produit de deux polynômes de Laguerre vérifie

$$\int_0^x L_n(t) L_m(x-t) dt = L_{m+n}(x) - L_{m+n+1}(x)$$

(7) Si $Re(\alpha) > -1$ et $Re(\beta) > 0$, on a

$$\Gamma(\alpha+\beta+n+1) \int_0^x (x-t)^{\beta-1} t^\alpha L_n^{(\alpha)}(t) dt = \Gamma(\alpha+n+1)\Gamma(\beta) x^{\alpha+\beta} L_n^{(\alpha+\beta)}(x)$$

et

$$\int_x^\infty e^{-t} L_n^{(\alpha)}(t) dt = e^{-x} \left( L_n^{(\alpha)}(x) - L_{n-1}^{(\alpha)}(x) \right)$$

## A.3 Polynômes de Tchebychev

Les *polynômes de Tchebychev* (de première espèce) d'ordre $n$, sont définis par la relation de récurrence

$$T_{n+1}(x) = 2x T_n(x) - T_{n-1}(x)$$

et les conditions d'initialisation

$$T_0(x) = 1 \quad T_1(x) = x$$

Les premiers polynômes sont

$$\begin{aligned}
T_0(x) &= 1 \\
T_1(x) &= x \\
T_2(x) &= 2x^2 - 1 \\
T_3(x) &= 4x^3 - 3x \\
T_4(x) &= 8x^4 - 8x^2 + 1 \\
T_5(x) &= 16x^5 - 20x^3 + 5x \\
T_6(x) &= 32x^6 - 48x^4 + 18x^2 - 1
\end{aligned}$$

(1) Le polynôme $T_n$ peut être défini par la relation

$$T_n(\cos\theta) = \cos(n\theta)$$

ou bien encore par la relation

$$T_n(x) = \frac{1}{2} \left( \left( x + \sqrt{x^2+1} \right)^n + \left( x - \sqrt{x^2-1} \right)^n \right)$$

$T_n(x)$ est un polynôme de degré $n$ dont le coefficient de plus haut degré est $2^{n-1}$ vérifiant

$$T_n(1) = 1 \quad \forall n$$

Ces polynômes vérifient la relation

$$T_n(-x) = (-1)^n T_n(x)$$

(2) Les polynômes de Tchebychev sont solutions de l'équation différentielle

$$(1-x^2)y'' - xy' + n^2 y = 0$$

(3) Les polynômes de Tchebychev satisfont la relation de récurrence

$$(1-x^2)T_n'(x) = -nxT_n(x) + nT_{n-1}(x)$$

(4) Pour $i = 0, ..., n$ la relation du produit de deux polynômes

$$2T_i(x)T_n(x) = T_{n+i}(x) + T_{n-i}(x)$$

(5) Majorations

$$\forall x \in [-1,1], \qquad |T_n(x)| \leq 1$$

$$\forall x \in [-1,1], \qquad \left|\frac{dT_n(x)}{dx}\right| \leq n^2$$

(6) Les polynômes de Tchebychev sont des polynômes orthogonaux relativement à la fonction de poids définie sur l'intervalle $[-1,1]$

$$\omega(x) = \frac{1}{\sqrt{1-x^2}}$$

$$\int_{-1}^{+1} T_n(x)T_m(x)\frac{dx}{\sqrt{1-x^2}} = \frac{\pi}{2}\delta_{n,m} \qquad n \neq 0$$

$$\int_{-1}^{+1} T_0^2(x)\frac{dx}{\sqrt{1-x^2}} = \pi$$

(7) Si $\nu$ désigne la partie entière de $n/2$, les monômes s'expriment en fonction des polynômes de Tchebychev

$$x^n = \frac{1}{2^{n-1}}\left[T_n + C_n^1 T_{n-2} + \cdots + C_n^{\nu-1}T_{n+2-2\nu} + C_n^{\nu}T_{n-2\nu}\left(\frac{3-(-1)^n}{4}\right)\right]$$

(8) Entre les abscisses

$$x_k^+ = \cos\left(\frac{2k\pi}{n}\right)$$

pour lesquelles $T_n(x_k^+) = +1$ et les abscisses

$$x_k^- = \cos\left(\frac{(2k+1)\pi}{n}\right)$$

pour lesquelles $T_n(x_k^-) = -1$, le polynôme de Tchebychev de degré $n$ admet exactement $n$ racines réelles données par

$$\cos\left(\frac{(2k+1)\pi}{2n}\right) \qquad k = 0, 1, \ldots, n-1$$

## A.4 Polynômes d'Hermite

Les *polynômes d'Hermite d'ordre* $n$ sont les polynômes définis par la relation de récurrence

$$H_{n+1}(x) = 2xH_n(x) - 2nH_{n-1}(x)$$

et les conditions d'initialisation

$$H_0(x) = 1 \quad H_1(x) = 2x$$

Les premiers polynômes sont

$$\begin{aligned}
H_0(x) &= 1\\
H_1(x) &= 2x\\
H_2(x) &= 4x^2 - 2\\
H_3(x) &= 8x^3 - 12x\\
H_4(x) &= 16x^4 - 48x^2 + 12\\
H_5(x) &= 32x^5 - 160x^3 + 120x\\
H_6(x) &= 64x^6 - 480x^4 + 720x^2 - 120
\end{aligned}$$

(1) Les polynômes d'Hermite satisfont l'équation différentielle

$$y'' - 2xy' + 2ny = 0$$

(2) Les polynômes d'Hermite vérifient la relation de récurrence

$$H_n'(x) = 2nH_{n-1}(x)$$

(3) Formule de Rodrigues

$$H_n(x) = (-1)^n e^{x^2} \frac{d^n}{dx^n}(e^{-x^2})$$

(4) Majorations

$$|H_n(x)| < e^{x^2/2} k 2^{n/2} \sqrt{n!} \qquad \textit{avec} \qquad k \simeq 1,086435...$$

(5) Les polynômes d'Hermite sont des polynômes orthogonaux relativement à la fonction de poids $\omega(x) = e^{-x^2}$

$$\int_{-\infty}^{+\infty} H_n(x)H_m(x)e^{-x^2}dx = \sqrt{\pi}2^n n! \delta_{n,m}$$

(6) Formules d'intégration

$$\int_0^x H_n(t)e^{-t^2}dt = H_{n-1}(0) - e^{-x^2}H_{n-1}(x)$$

$$\int_0^x H_n(t)dt = \frac{1}{2(n+1)}\left(H_{n+1}(x) - H_{n+1}(0)\right)$$

$$\int_{-\infty}^{+\infty} H_{2n}(tx)e^{-t^2}dt = \sqrt{\pi}\frac{(2n)!}{n!}(x^2-1)^n$$

$$\int_{-\infty}^{+\infty} te^{-t^2}H_{2n+1}(tx)dt = \sqrt{\pi}\frac{(2n+1)!}{n!}x(x^2-1)^n$$

## A.5 Polynômes de Gegenbauer

Les *polynômes de Gegenbauer* $G_n^{(\alpha)}$ de degré $n$, sont les polynômes définis par la relation de récurrence pour $\alpha > -1/2$

$$(n+1)G_{n+1}^{(\alpha)}(x) = 2(n+\alpha)G_n^{(\alpha)}(x) - (n+2\alpha-1)G_{n-1}^{(\alpha)}(x)$$

et les conditions d'initialisation

$$G_0^{(\alpha)}(x) = 1 \quad G_1^{(\alpha)}(x) = 2\alpha x \quad \text{si} \quad \alpha \neq 0 \quad G_1^{(0)}(x) = 2x$$

Les premiers polynômes sont pour $\alpha = 1$

$$\begin{aligned}
G_0(x) &= 1\\
G_1(x) &= 2x\\
G_2(x) &= 4x^2 - 1\\
G_3(x) &= 8x^3 - 4x\\
G_4(x) &= 16x^4 - 12x^2 + 1\\
G_5(x) &= 32x^5 - 32x^3 + 6x\\
G_6(x) &= 64x^6 - 80x^4 + 24x^2 - 1
\end{aligned}$$

(1) Les polynômes de Gegenbauer sont solutions de l'équation différentielle

$$(1-x^2)y'' - (2\alpha+1)xy' + n(n+2\alpha)y = 0$$

(2) Les polynômes de Gegenbauer vérifient les relations de récurrence

$$(1-x^2)\frac{dG_n^{(\alpha)}}{dx}(x) = -nxG_n^{(\alpha)}(x) + (n+2\alpha-1)G_{n-1}^{(\alpha)}(x)$$

$$(n+\alpha)G_{n+1}^{(\alpha-1)}(x) = (\alpha-1)\left(G_{n+1}^{(\alpha)}(x) - G_{n-1}^{(\alpha)}(x)\right)$$

(3) Formule de Rodrigues

$$G_n^{(\alpha)}(x) = \frac{(-1)^n}{2^n n!} \frac{\Gamma(\alpha+1/2)\Gamma(n+2\alpha)}{\Gamma(2\alpha)\Gamma(\alpha+n+1/2)} \frac{d^n}{dx^n}\left((1-x^2)^{\alpha+n-\frac{1}{2}}\right)$$

(4) Les polynômes de Gegenbauer sont des polynômes orthogonaux sur l'intervalle $]-1,+1[$ relativement à la fonction de poids $\omega(x) = (1-x^2)^{\alpha-\frac{1}{2}}$, on a si $\alpha \neq 0$

$$\int_{-1}^{+1} G_n^{(\alpha)}(x) G_m^{(\alpha)}(x)(1-x^2)^{\alpha-\frac{1}{2}}\,dx = \frac{\pi 2^{1-2\alpha}}{n!(n+\alpha)!} \frac{\Gamma(n+2\alpha)}{\Gamma(\alpha)^2} \delta_{n,m}$$

et si $\alpha = 0$

$$\int_{-1}^{+1} G_n^{(0)}(x) G_m^{(0)}(x)(1-x^2)^{-\frac{1}{2}}\,dx = \frac{2\pi}{n^2} \delta_{n,m}$$

(5) Formule d'intégration

$$\frac{n(2\alpha+n)}{2\alpha} \int_0^x G_n^{(\alpha)}(t)(1-t^2)^{\alpha-\frac{1}{2}}\,dx = G_{n-1}^{(\alpha+1)}(0) - (1-x^2)^{\alpha+\frac{1}{2}} G_{n-1}^{(\alpha+1)}(x)$$

## A.6 Polynômes de Jacobi

Les *polynômes de Jacobi* de degré $n$, notés $J_n^{(\alpha,\beta)}(x)$ ou $J_n(x)$ lorsqu'il n'y a pas ambiguïté, sont les polynômes définis par la relation de récurrence pour $\alpha > -1$ et $\beta > -1$

$$a_n J_{n+1}(x) = (b_n + x c_n) J_n(x) - d_n J_{n-1}(x)$$

initialisée par

$$J_0(x) = 1 \quad J_1(x) = (\alpha-\beta)/2 + (1+(\alpha+\beta)/2)x$$

avec les coefficients suivants

$$\begin{aligned}
a_n &= 2(n+1)(n+\alpha+\beta+1)(2n+\alpha+\beta) \\
b_n &= (2n+\alpha+\beta+1)(\alpha^2-\beta^2) \\
c_n &= (2n+\alpha+\beta) \\
d_n &= 2(n+\alpha)(n+\beta)(2n+\alpha+\beta+2)
\end{aligned}$$

Les premiers polynômes sont pour $\alpha = 1$ et $\beta = 0$

$$
\begin{aligned}
J_0(x) &= 1\\
J_1(x) &= (3x+1)/2\\
J_2(x) &= (5x^2+2x-1)/2\\
J_3(x) &= \frac{35}{8}x^3 + 15x^2 - \frac{15}{8}x - \frac{3}{8}\\
J_4(x) &= \frac{63}{8}x^4 + \frac{7}{2}x^3 - \frac{21}{4}x^2 - \frac{3}{2}x + \frac{3}{8}\\
J_5(x) &= \frac{231}{16}x^5 + \frac{105}{16}x^4 - \frac{105}{8}x^3 - \frac{35}{8}x^2 + \frac{35}{16}x + \frac{5}{16}
\end{aligned}
$$

(1) Les polynômes de Jacobi satisfont l'équation différentielle

$$(1-x^2)y'' + (\beta - \alpha - (\alpha+\beta+2)x)y' + n(n+\alpha+\beta+1)y = 0$$

(2) En posant $\lambda = 2n+\alpha+\beta$, les polynômes de Jacobi vérifient les relations

$$\lambda(1-x^2)J_n'(x) = n(\alpha - \beta - \lambda x)J_n(x) + 2(n+\alpha)(n+\beta)J_{n-1}(x)$$

$$J_n^{(\alpha,\beta-1)}(x) - J_n^{(\alpha-1,\beta)}(x) = J_{n-1}^{(\alpha,\beta)}(x)$$

$$\lambda J_n^{(\alpha,\beta-1)}(x) = (n+\alpha+\beta)J_n^{(\alpha,\beta)}(x) + (n+\alpha)J_{n-1}^{(\alpha,\beta)}(x)$$

$$(1-x)J_n^{(\alpha+1,\beta)}(x) + (1+x)J_n^{(\alpha,\beta+1)}(x) = 2J_n^{(\alpha,\beta)}(x)$$

(3) Formule de Rodrigues

$$J_n(x) = \frac{(-1)^n}{2^n n!}\frac{1}{(1-x)^\alpha(1+x)^\beta}\frac{d^n}{dx^n}\left((1-x^2)^n(1-x)^\alpha(1+x)^\beta\right)$$

(4) Les polynômes de Jacobi sont des polynômes orthogonaux sur l'intervalle $]-1,1[$ relativement à la fonction de poids

$$\omega(x) = (1-x)^\alpha(1+x)^\beta$$

$$\int_{-1}^{+1} J_n(x)J_m(x)(1-x)^\alpha(1+x)^\beta dx = u_n\delta_{n,m}$$

avec

$$u_n = \frac{2^{\alpha+\beta+1}}{2n+\alpha+\beta+1}\frac{\Gamma(n+\alpha+1)\Gamma(n+\beta+1)}{n!\Gamma(n+\alpha+\beta+1)}$$

(5) Formule d'intégration

$$2n\int_0^x J_n^{(\alpha,\beta)}(t)(1-t)^\alpha(1+t)^\beta dt = J_{n-1}^{(\alpha+1,\beta+1)}(0) - h(x)J_{n-1}^{(\alpha+1,\beta+1)}(x)$$

où $h(x) = (1-x)^{1+\alpha}(1+x)^{1+\beta}$

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