Order statistics - derivations

Let $X_1, X_2, \cdots, X_n$ denote independent continuous random variables with cdf $F(x)$ and pdf $f(x)$. We will denote the *ordered* random variables with $X_{(1)}, X_{(2)}, \cdots, X_{(n)}$, where $X_{(1)} \le X_{(2)} \le \ldots \le X_{(n)}$.

Probability density function of the j_{th} order statistic.

$$g_{X_{(j)}}(x) = \frac{n!}{(n-j)!(j-1)!} \left[F_X(x)\right]^{j-1} \left[1 - F_X(x)\right]^{n-j} f_X(x).$$

Proof:
We will find the cdf of the j_{th} order statistic and then the pdf by taking the derivative of the cdf. The cdf is denoted by $F_{X_{(j)}}(x) = P(X_{(j)} \le x)$. Now let's introduce a discrete random variable Y that counts the number of variables less than or equal to x. The statement $P(X_{(j)} \le x)$ is the same as $P(Y \ge j)$. Why? If we call "success" the event $X_i \le x$ then $Y \sim b(n,p)$ or $Y \sim b(n, F_X(x))$.

$$\begin{aligned}
F_{X_{(j)}}(x) &= P(X_{(j)} \le x) = P(Y \ge j) = \sum_{k=j}^{n} \binom{n}{k} p^k (1-p)^{n-k} \\
F_{X_{(j)}}(x) &= \sum_{k=j}^{n} \binom{n}{k} F_X(x)^k [1 - F_X(x)]^{n-k}
\end{aligned}$$

Now the pdf:

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$$\begin{aligned}
g_{X_{(j)}}(x) &= \frac{dF_{X_{(j)}}(x)}{dx} \\
&= \sum_{k=j}^{n} \binom{n}{k} k F_X(x)^{k-1} f_X(x) [1 - F_X(x)]^{n-k} \\
&- \sum_{k=j}^{n} \binom{n}{k} (n-k) F_X(x)^k [1 - F_X(x)]^{n-k-1} f_X(x)
\end{aligned}$$

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$$\begin{aligned}
&= \binom{n}{j} j f_X(x) F_X(x)^{j-1} [1 - F_X(x)]^{n-j} \qquad \text{(when } k = j\text{)} \\
&+ \sum_{k=j+1}^{n} \binom{n}{k} k F_X(x)^{k-1} f_X(x) [1 - F_X(x)]^{n-k} \\
&- \sum_{k=j}^{n-1} \binom{n}{k} (n-k) F_X(x)^k [1 - F_X(x)]^{n-k-1} f_X(x) \qquad \text{(last term is zero when } k = n\text{)} \\
&= \frac{n!}{(n-j)!j!} j f_X(x) F_X(x)^{j-1} f_X(x) [1 - F_X(x)]^{n-j} \\
&+ \sum_{k=j}^{n-1} \binom{n}{k+1} (k+1) F_X(x)^k f_X(x) [1 - F_X(x)]^{n-k-1} \\
&- \sum_{k=j}^{n-1} \binom{n}{k} (n-k) F_X(x)^k [1 - F_X(x)]^{n-k-1} f_X(x) \\
&= \frac{n!}{(n-j)!(j-1)!} \left[F_X(x)\right]^{j-1} \left[1 - F_X(x)\right]^{n-j} f_X(x).
\end{aligned}$$

Note: $\binom{n}{k+1}(k+1) = \binom{n}{k}(n-k)$, so the last 2 terms before the last line cancel!

An intuitive derivation of the density function of the j_{th} order statistic. This intuitive derivation is based on this result $P(y \leq Y \leq y+dy) \approx f(y)dy$.

Consider the j_{th} order statistic $X_{(j)}$. If $X_{(j)}$ is in the neighborhood of x then there are
$j-1$ random variables less than x, each one with probability $p_1 = P(X \leq x) = F_X(x)$,
1 random variable near x, with probability $p_2 = P(x \leq X \leq x+dx) \approx f_X(x)dx$, and
$n-j$ random variables larger than x, with probability $p_3 = P(X > x) = 1 - P(X \leq x) = 1 - F_X(x)$.

Therefore,

$$\begin{aligned} P(x \leq X_{(j)} \leq x+dx) &\approx g_{X_{(j)}}(x)dx \\ &= \binom{n}{j-1, 1, n-j} p_1^{j-1} p_2^1 p_3^{n-j} \qquad \text{(multinomial distribution)} \\ &= \frac{n!}{(j-1)!(n-j)!} F_X(x)^{j-1} f_X(x) dx [1-F_X(x)]^{n-j}. \end{aligned}$$

Therefore,
$g_{X_{(j)}}(x) = \frac{n!}{(j-1)!(n-j)!} F_X(x)^{j-1} f_X(x) [1-F_X(x)]^{n-j}$.

Using this intuitive derivation we can now find the joint probability density function of $X_{(i)}, X_{(j)}$. Using the same approximation as above $P(u \leq X_{(i)} \leq u+du, v \leq X_{(j)} \leq v+dv) \approx g_{X_{(i)},X_{(j)}}(u,v)dudv$. For $u<v$ we need to have the following arrangement:

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$i-1$	Random variables less than u, each one with probability $p_1 = P(X \leq u) = F_X(u)$
1	Random variables near u with probability $p_2 = P(u \leq X \leq u+du) \approx f_X(u)du$
$j-1-i$	Random variables between u and v with probability $p_3 = P(u \leq X \leq v) = F_X(v) - F_X(u)$
1	Random variables near v with probability $p_4 = P(v \leq X \leq v+dv) \approx f_X(v)dv$
$n-j$	Random variables larger than v, each one with probability $p_5 = P(X > v) = 1 - F_X(v)$

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Using the multinomial distribution we have:

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$$\begin{aligned} P(u \leq X_{(i)} \leq u+du, v \leq X_{(j)} \leq v+dv) &\approx g_{X_{(i)},X_{(j)}}(u,v)dudv \\ &= \binom{n}{i-1, 1, j-1-i, 1, n-j} p_1^{i-1} p_2^1 p_3^{j-1-i} p_4^1 p_5^{n-j} \end{aligned}$$

Therefore,
$g_{X_{(i)},X_{(j)}}(u,v)dudv = \binom{n}{i-1,1,j-1-i,1,n-j} F_X(u)^{i-1} f_X(u) du [F_X(v) - F_X(u)]^{j-1-i} f_X(v) dv [1-F_X(v)]^{n-j}$

or

$$g_{X_{(i)},X_{(j)}}(u,v) = \frac{n!}{(i-1)!(j-1-i)!(n-j)!} F_X(u)^{i-1} f_X(u) [F_X(v) - F_X(u)]^{j-1-i} f_X(v) [1-F_X(v)]^{n-j}.$$