Moment Generating Functions

Defn: The moment generating function of a real valued X is

$$M_X(t) = E(e^{tX})$$

defined for those real t for which the expected value is finite.

Defn: The moment generating function of $X \in R^p$ is

$$M_X(u) = E[e^{u^t X}]$$

defined for those vectors u for which the expected value is finite.

Formal connection to moments:

$$\begin{aligned} M_X(t) &= \sum_{k=0}^{\infty} E[(tX)^k]/k! \\ &= \sum_{k=0}^{\infty} \mu_k' t^k/k!\,. \end{aligned}$$

Sometimes can find power series expansion of M_X and read off the moments of X from the coefficients of $t^k/k!$.

Theorem: If M is finite for all $t \in [-\epsilon, \epsilon]$ for some $\epsilon > 0$ then

1. Every moment of X is finite.

2. M is C^∞ (in fact M is analytic).

3. $\mu'_k = \frac{d^k}{dt^k} M_X(0)$.

Note: C^∞ means has continuous derivatives of all orders. Analytic means has convergent power series expansion in neighbourhood of each $t \in (-\epsilon, \epsilon)$.

The proof, and many other facts about mgfs, rely on techniques of complex variables.

MGFs and Sums

If $X_1, \ldots, X_p$ are independent and $Y = \sum X_i$ then the moment generating function of Y is the product of those of the individual X_i:

$$E(e^{tY}) = \prod_i E(e^{tX_i})$$

or $M_Y = \prod M_{X_i}$.

Note: also true for multivariate X_i.

Problem: power series expansion of M_Y not nice function of expansions of individual M_{X_i}.

Related fact: first 3 moments (meaning μ, σ^2 and μ_3) of Y are sums of those of the X_i:

$$\begin{aligned} E(Y) &= \sum E(X_i) \\ \text{Var}(Y) &= \sum \text{Var}(X_i) \\ E[(Y - E(Y))^3] &= \sum E[(X_i - E(X_i))^3] \end{aligned}$$

but

$$\begin{aligned} &E[(Y - E(Y))^4] = \\ &\quad \sum \{E[(X_i - E(X_i))^4] - 3E^2[(X_i - E(X_i))^2]\} \\ &\qquad\qquad + 3\left\{\sum E[(X_i - E(X_i))^2]\right\}^2 \end{aligned}$$

Related quantities: **cumulants** add up properly.

Note: log of the mgf of Y is sum of logs of mgfs of the X_i.

Defn: the cumulant generating function of a variable X by

$$K_X(t) = \log(M_X(t))\,.$$

Then

$$K_Y(t) = \sum K_{X_i}(t)\,.$$

Note: mgfs are all positive so that the cumulative generating functions are defined wherever the mgfs are.

SO: K_Y has power series expansion:

$$K_Y(t) = \sum_{r=1}^{\infty} \kappa_r t^r / r!\,.$$

Defn: the κ_r are the cumulants of Y.

Observe

$$\kappa_r(Y) = \sum \kappa_r(X_i)\,.$$

Relation between cumulants and moments:

Cumulant generating function is

$$
\begin{aligned}
K(t) &= \log(M(t)) \\
&= \log(1 + [\mu_1 t + \mu_2' t^2/2 + \mu_3' t^3/3! + \cdots])
\end{aligned}
$$

Call quantity in $[\ldots]$ x; expand

$$\log(1+x) = x - x^2/2 + x^3/3 - x^4/4 \cdots .$$

Stick in the power series

$$x = \mu t + \mu_2' t^2/2 + \mu_3' t^3/3! + \cdots ;$$

Expand out powers of x; collect together like terms. For instance,

$$
\begin{aligned}
x^2 &= \mu^2 t^2 + \mu\mu_2' t^3 \\
&\qquad + [2\mu_3'\mu/3! + (\mu_2')^2/4]t^4 + \cdots \\
x^3 &= \mu^3 t^3 + 3\mu_2'\mu^2 t^4/2 + \cdots \\
x^4 &= \mu^4 t^4 + \cdots .
\end{aligned}
$$

Now gather up the terms. The power t^1 occurs only in x with coefficient μ. The power t^2 occurs in x and in x^2 and so on.

Putting these together gives

$$
\begin{aligned}
K(t) = {} & \\
& \mu t + [\mu_2' - \mu^2]t^2/2 \\
& + [\mu_3' - 3\mu\mu_2' + 2\mu^3]t^3/3! \\
& + [\mu_4' - 4\mu_3'\mu - 3(\mu_2')^2 + 12\mu_2'\mu^2 - 6\mu^4]t^4/4! \cdots
\end{aligned}
$$

Comparing coefficients to $t^r/r!$ we see that

$$
\begin{aligned}
\kappa_1 &= \mu \\
\kappa_2 &= \mu_2' - \mu^2 = \sigma^2 \\
\kappa_3 &= \mu_3' - 3\mu\mu_2' + 2\mu^3 = E[(X-\mu)^3] \\
\kappa_4 &= \mu_4' - 4\mu_3'\mu - 3(\mu_2')^2 + 12\mu_2'\mu^2 - 6\mu^4 \\
&= E[(X-\mu)^4] - 3\sigma^4 \,.
\end{aligned}
$$

Check the book by Kendall and Stuart (or the new version called *Kendall's Theory of Advanced Statistics* by Stuart and Ord) for formulas for larger orders r.

Example: If $X_1, \ldots, X_p$ are independent and X_i has a $N(\mu_i, \sigma_i^2)$ distribution then

$$\begin{aligned}
M_{X_i}(t) =& \int_{-\infty}^{\infty} e^{tx} e^{-\frac{1}{2}(x-\mu_i)^2/\sigma_i^2} dx/(\sqrt{2\pi}\sigma_i) \\
=& \int_{-\infty}^{\infty} e^{t(\sigma_i z+\mu_i)} e^{-z^2/2} dz/\sqrt{2\pi} \\
=& e^{t\mu_i} \int_{-\infty}^{\infty} e^{-(z-t\sigma_i)^2/2+t^2\sigma_i^2/2} dz/\sqrt{2\pi} \\
=& e^{\sigma_i^2 t^2/2+t\mu_i} .
\end{aligned}$$

So cumulant generating function is:

$$K_{X_i}(t) = \log(M_{X_i}(t)) = \sigma_i^2 t^2/2 + \mu_i t \,.$$

Cumulants are $\kappa_1 = \mu_i$, $\kappa_2 = \sigma_i^2$ and every other cumulant is 0.

Cumulant generating function for $Y = \sum X_i$ is

$$K_Y(t) = \sum \sigma_i^2 t^2/2 + t \sum \mu_i$$

which is the cumulant generating function of $N(\sum \mu_i, \sum \sigma_i^2)$.

Example: Homework: derive moment and cumulant generating function and moments of a Gamma rv.

Now suppose $Z_1, \ldots, Z_\nu$ independent $N(0,1)$ rvs.

By definition: $S_\nu = \sum_1^\nu Z_i^2$ has χ_ν^2 distribution. It is easy to check $S_1 = Z_1^2$ has density

$$(u/2)^{-1/2} e^{-u/2} / (2\sqrt{\pi})$$

and then the mgf of S_1 is

$$(1 - 2t)^{-1/2}.$$

It follows that

$$M_{S_\nu}(t) = (1 - 2t)^{-\nu/2}$$

which is (homework) moment generating function of a Gamma$(\nu/2, 2)$ rv.

SO: χ_ν^2 dstbn has Gamma$(\nu/2, 2)$ density:

$$(u/2)^{(\nu-2)/2} e^{-u/2} / (2\Gamma(\nu/2)).$$

Example: The Cauchy density is

$$\frac{1}{\pi(1+x^2)};$$

corresponding moment generating function is

$$M(t) = \int_{-\infty}^{\infty} \frac{e^{tx}}{\pi(1+x^2)} dx$$

which is $+\infty$ except for $t = 0$ where we get 1.

Every t distribution has exactly same mgf. So: can't use mgf to distinguish such distributions.

Problem: these distributions do not have infinitely many finite moments.

So: develop substitute for mgf which is defined for every distribution, namely, the characteristic function.

Characteristic Functions

Definition: The characteristic function of a real rv X is

$$\phi_X(t) = E(e^{itX})$$

where $i = \sqrt{-1}$ is the imaginary unit.

Aside on complex arithmetic.

Complex numbers: add $i = \sqrt{-1}$ to the real numbers.

Require all the usual rules of algebra to work.

So: if i and any real numbers a and b are to be complex numbers then so must be $a + bi$.

Multiplication: If we multiply a complex number $a + bi$ with a and b real by another such number, say $c+di$ then the usual rules of arithmetic (associative, commutative and distributive laws) require

$$\begin{aligned}(a+bi)(c+di) =& ac + adi + bci + bdi^2 \\ =& ac + bd(-1) + (ad + bc)i \\ =& (ac - bd) + (ad + bc)i\end{aligned}$$

so this is precisely how we define multiplication.

Addition: follow usual rules to get

$$(a+bi)+(c+di)=(a+c)+(b+d)i\,.$$

Additive inverses: $-(a+bi)=-a+(-b)i$.

Multiplicative inverses:

$$\begin{aligned}\frac{1}{a+bi} &= \frac{1}{a+bi}\frac{a-bi}{a-bi} \\ &= \frac{a-bi}{a^2-abi+abi-b^2i^2} \\ &= \frac{a-bi}{a^2+b^2}\,.\end{aligned}$$

Division:

$$\begin{aligned}\frac{a+bi}{c+di} &= \frac{(a+bi)}{(c+di)}\frac{(c-di)}{(c-di)} \\ &= \frac{ac-bd+(bc+ad)i}{c^2+d^2}\,.\end{aligned}$$

Notice: usual rules of arithmetic don't require any more numbers than

$$x+yi$$

where x and y are real.

Transcendental functions: For real x have $e^x = \sum x^k/k!$ so

$$e^{x+iy} = e^x e^{iy}.$$

How to compute e^{iy}?

Remember $i^2 = -1$ so $i^3 = -i$, $i^4 = 1$ $i^5 = i^1 = i$ and so on. Then

$$\begin{aligned} e^{iy} =& \sum_0^\infty \frac{(iy)^k}{k!} \\ =& 1 + iy + (iy)^2/2 + (iy)^3/6 + \cdots \\ =& 1 - y^2/2 + y^4/4! - y^6/6! + \cdots \\ & + iy - iy^3/3! + iy^5/5! + \cdots \\ =& \cos(y) + i\sin(y) \end{aligned}$$

We can thus write

$$e^{x+iy} = e^x(\cos(y) + i\sin(y))$$

Identify $x + yi$ with the corresponding point (x, y) in the plane. Picture the complex numbers as forming a plane.

Now every point in the plane can be written in polar co-ordinates as $(r \cos \theta, r \sin \theta)$ and comparing this with our formula for the exponential we see we can write

$$x + iy = \sqrt{x^2 + y^2}\, e^{i\theta} = re^{i\theta}$$

for an angle $\theta \in [0, 2\pi)$.

Multiplication revisited: $x+iy = re^{i\theta}$, $x'+iy' = r'e^{i\theta'}$.

$$(x + iy)(x' + iy') = re^{i\theta}r'e^{i\theta'} = rr'e^{i(\theta+\theta')}.$$

We will need from time to time a couple of other definitions:

Definition: The **modulus** of $x + iy$ is

$$|x + iy| = \sqrt{x^2 + y^2}.$$

Definition: The **complex conjugate** of $x+iy$ is $\overline{x + iy} = x - iy$.

Some identities: $z = x + iy = re^{i\theta}$ and $z' = x' + iy' = r'e^{i\theta'}$. Then

$$z\overline{z} = x^2 + y^2 = r^2 = |z|^2$$

$$\frac{z'}{z} = \frac{z'\overline{z}}{|z|^2} = rr'e^{i(\theta'-\theta)}$$

$$\overline{re^{i\theta}} = re^{-i\theta}.$$

Notes on calculus with complex variables.

Essentially usual rules apply so, for example,

$$\frac{d}{dt}e^{it} = ie^{it}\,.$$

We will (mostly) be doing only integrals over the real line; the theory of integrals along paths in the complex plane is a very important part of mathematics, however.

FACT: (not used explicitly in course). If $f : \mathbb{C} \mapsto \mathbb{C}$ is differentiable then f is analytic (has power series expansion).

End of Aside

Characteristic Functions

Definition: The characteristic function of a real rv X is

$$\phi_X(t) = E(e^{itX})$$

where $i = \sqrt{-1}$ is the imaginary unit.

Since

$$e^{itX} = \cos(tX) + i\sin(tX)$$

we find that

$$\phi_X(t) = E(\cos(tX)) + iE(\sin(tX)).$$

Since the trigonometric functions are bounded by 1 the expected values must be finite for all t.

This is precisely the reason for using characteristic rather than moment generating functions in probability theory courses.

Theorem 1 *For any two real rvs X and Y the following are equivalent:*

1. *X and Y have the same distribution, that is, for any (Borel) set A we have*

$$P(X \in A) = P(Y \in A)\,.$$

2. *$F_X(t) = F_Y(t)$ for all t.*

3. *$\phi_X(t) = E(e^{itX}) = E(e^{itY}) = \phi_Y(t)$ for all real t.*

Moreover, all of these are implied if there is a positive ϵ such that for all $|t| \le \epsilon$

$$M_X(t) = M_Y(t) < \infty\,.$$