Crib Notes on Campbell-Baker-Hausdorff expansions

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Consider/introduce auxiliary scaling parameter t, for counting powers, ultimately set to $t = 1$. For matrices, operators, etc, A and B,

$$e^{tA}e^{tB} \equiv e^{Z(t,A,B)}.$$

Based on Lemmata 1,2, and 3, below,

$$Z \equiv \ln(e^{tA}e^{tB}) = (e^{tA}e^{tB} - 1) - \frac{1}{2}(e^{tA}e^{tB} - 1)^2 + \frac{1}{3}(e^{tA}e^{tB} - 1)^3 + ...$$

is evaluated recursively [1] through algorithms in Applications 1,2,3,...,

$$Z = t(A+B) + \frac{t^2}{2}[A,B] + \frac{t^3}{12}\Big([[A,B],B] + [A,[A,B]]\Big) + \frac{t^4}{24}[[[B,A],A],B]$$

$$-\frac{t^5}{720}([[[[A,B],B],B],B] + [[[[B,A],A],A],A]) + \frac{t^5}{360}([[[[A,B],B],B],A] + [[[[B,A],A],A],B])$$

$$-\frac{t^5}{120}([[[[A,B],B],A],B] + [[[[B,A],A],B],A]) + ...$$

• Powers of t higher than the first have coefficients which are always commutators—they are in the Lie Algebra. (Campbell, 1897; Poincaré, 1899. Structures Lie's converse (third fundamental) theorem: exponentiation of the algebra yields the simply-connected group.)

• $Z(t,A,B) = -Z(-t,B,A)$, whence even powers of t are $A - B$ antisymmetric, while odd ones are symmetric.

• Thompson representation:

$$Z(t,A,B) = t\Big(e^{-tW}Ae^{tW} + e^{t\tilde{W}}Be^{-t\tilde{W}}\Big),$$

where W and $\tilde{W}$ are in the Lie Algebra (A, B, and commutators), and $\tilde{W}(t,A,B) = W(-t,B,A) = \frac{A+B}{4} + ...$

• Zassenhaus expansion:

$$e^{t(A+B)} = e^{tA}\ e^{tB}\ e^{-\frac{t^2}{2}[A,B]}\ e^{\frac{t^3}{6}(2[B,[A,B]]+[A,[A,B]])}\ e^{t^4...}...$$

• Triple formula:

$$e^{tV(t)} = e^{tA}e^{tB}e^{tA},$$

so that $V(t,A,B)$ is an even function of t, $V(t) = V(-t)$. Evaluated by, e.g., Application 1:

$$V = 2A + B + \frac{t^2}{6}[(A+B),[B,A]] + ...$$

Note the duality between B and $-V$.

Lemma 1:

$$\delta e^Z = \int_0^1 ds\ e^{(1-s)Z}\ \ \delta Z\ \ e^{sZ},$$

for any matrix (noncommutative) Z. E.g., $\delta = \frac{\partial}{\partial t}$.

Provable directly from finite N defn of exponential, then $N \to \infty$.

Alternative proof: Consider Δ as operator δ acting on everything to its right.

$$\frac{d}{ds}\left(e^{-sZ}\ \Delta\ e^{sZ}\right) = e^{-sZ}\ [\Delta, Z]\ e^{sZ}\ ;$$

then integrate by $\int_0^1 ds$ to obtain

$$e^{-sZ}\ \Delta\ e^{sZ} - \Delta = \int_0^1 ds\ e^{-sZ}\ [\Delta, Z]\ e^{sZ},$$

hence

$$[\Delta, e^Z] = \delta e^Z = \int_0^1 ds\ e^{(1-s)Z}\ \ \delta Z\ \ e^{sZ}.$$

Lemma 2 (Hadamard formula): $e^A B\ e^{-A} = e^{[A}\ B \equiv B + [A, B] + \frac{1}{2!}[A, [A, B]] + ...$

Proof: Note left commutation $[A, B] \equiv Ad(A)\ B$ acts on B like a derivative operator—obeys operator Leibniz' chain rule. For a parameter s,

$$\frac{d}{ds}\left(e^{sA}\ B\ e^{-sA}\right) = \left[A\ ,\ e^{sA}\ B\ e^{-sA}\right],$$

so $f \equiv e^{sA}\ B\ e^{-sA}$ satisfies

$$\frac{df}{ds} = [A, f],$$

with B.C. $f(0) = B$. In turn, this is formally solved by the series in s, $\quad f(s) = e^{s[A}\ f(0)$.

Alternatively, it can be proved by induction in powers of s,

$$\frac{d^n f}{ds^n} = [A, [A, [A, ..., f]...,],],].$$

These two lemmata lead to

Lemma 3 (Campbell-Poincaré fundamental identity):

$$(\delta e^Z)\ e^{-Z} = \frac{e^{[Z} - 1}{[Z}\ \ \delta Z\ ,$$

or equivalently,

$$\delta Z = \frac{[Z}{e^{[Z} - 1}\ \left((\delta Z)\ e^{-Z}\right),$$

where the fraction is the celebrated generating function of the Bernoulli numbers. Other equivalent forms are,

$$e^{-Z}\delta e^{Z} = \frac{1-e^{-[Z}}{[Z} \quad \delta Z = \delta Z \; \frac{e^{Z]}-1}{Z]} \; ,$$

etc.

Application Algorithm 1. (Poincaré. Readily exhibits Z construction out of nested commutators, and applied mathematicians and Lie Group textbooks like it, cf. [2], but clumsy computationally).

Set now $e^{Z(t)} = e^{A}e^{tB}$. For $\delta Z = \partial_t Z \equiv Z'$ in Lemma 3, note that

$$B = e^{-Z}\delta e^{Z} = \frac{1-e^{-[Z}}{[Z} \; Z',$$

hence

$$Z' = \frac{[Z}{1-e^{-[Z}} \; B = \psi\left(e^{[Z}\right) \; B,$$

where

$$\psi(x) \equiv \frac{x\ln x}{x-1} = 1 - \sum_{n=1}^{\infty} \frac{(1-x)^n}{n(n+1)} \; .$$

(NB. $\psi(e^{-y}) = \sum_{n=0}^{\infty} B_n \frac{y^n}{n!}$, for the Bernoulli numbers: $B_0 = 1$, $B_1 = -\frac{1}{2}$, $B_2 = \frac{1}{6}$, $B_4 = -\frac{1}{30}$,...)

Since, from Lemma 2, $e^{[Z} = e^{[A}e^{t[B}$, this reads

$$Z'(t) = \psi\left(e^{[A}e^{t[B}\right) \; B,$$

and so one may integrate over t from $Z(0) = A$, to finally obtain

$$Z(1) = A + \left(\int_0^1 dt \; \psi\left(e^{[A}e^{t[B}\right)\right) \; B.$$

It is manifest that all subleading terms to $A+B$ are commutators, so Z is in the Lie Algebra.

This is essentially an algorithm to produce the series by judicious power expansion of ψ and its arguments. For example, if only the term linear in B is sought (e.g.[3]), trivially, then,

$$Z = A + \psi(e^{[A}) \; B + O(B^2) = A + \frac{[A}{1-e^{-[A}} \; B + O(B^2),$$

where all expansion coefficients are simply related to the Bernoulli numbers as above.
(**Corollary**: If $O(B^2)$ terms vanish, e.g. by virtue of special relations such as $[A,B] = sB$, it follows that $Z = A + \frac{s}{1-\exp(-s)}B = A + \psi(e^s)B$. Taking inverses and rescaling yields a braiding relation, $e^{A}e^{B} = e^{(\exp s)B} \; e^{A}$.)

Application Algorithm 2. By virtue of its mechanical recursiveness, this one is favored by phycisists, e.g. [4]. Set $e^{Z(t)} \equiv e^{tA}e^{tB}$. Operate both sides by $\delta = \partial_t$, and multiply by e^{-Z} on the right. By Lemmata 3, and 2,

$$\frac{e^{[Z}-1}{[Z} \; Z' = A + e^{t[A} \; B.$$

Now, setting

$$Z \equiv \sum_{n=1}^{\infty} t^n Z_n \ ,$$

the Z_ns can be solved for recursively in the power of t^{n-1} components of this eqn, so

$$Z_1 = A + B \quad \Longrightarrow \quad Z_2 \quad \Longrightarrow \quad Z_3 \quad \Longrightarrow \quad ...$$

Manifestly, again, for $n > 1$, each Z_n is a function of commutators only.

• $Z(t, A, B) = -Z(-t, B, A)$, $\Longrightarrow$ even powers of t are $A - B$ antisymmetric, while odd ones are symmetric.

Application Algorithm 3. (Hausdorff, cf [5]. Most systematic as a power expansion in A or B.)

Consider the *replacement operators*

$$\delta_A \equiv \left(\delta A \frac{\partial}{\partial A}\right), \qquad \delta_B \equiv \left(\delta B \frac{\partial}{\partial B}\right),$$

which act on functions of A and B to successively replace each occurrence of A by δA, to first order, preserving the orderings, in accord with Leibniz's rule. Seek a symmetry of $Z(A, B)$, upon infinitesimal dilation of B, $\delta B = \epsilon B$, i.e. find $\delta A = -\epsilon D(A, B)$ s.t., to $O(\epsilon^2)$,

$$Z(A, B) = Z(A - \epsilon D, B + \epsilon B) + O(\epsilon^2),$$

so that

$$e^A e^B = e^{A-\epsilon D} e^{B+\epsilon B} = e^A (1 - \epsilon e^{-A} \delta_A e^A)(1 + \epsilon B) e^B + O(\epsilon^2).$$

So, evaluating $\delta_A e^A$ by Lemma 3, one has to $O(\epsilon^2)$,

$$\frac{1 - e^{-[A}}{[A} \ D = B,$$

whence

$$D = \frac{[A}{1 - e^{-[A}} \ B.$$

Consequently, $\delta Z = \delta_A Z + \delta_B Z = 0$ amounts to

$$\left(\left(\frac{[A}{1 - e^{-[A}} \ B\right) \frac{\partial}{\partial A}\right) Z = \left(B \frac{\partial}{\partial B}\right) Z.$$

The l.h.side raises the power of B, so the eqn may be solved recursively in each term Z_n of $O(B^n)$ in Z,

$$Z_n = \frac{1}{n} \left(\left(\frac{[A}{1 - e^{-[A}} \ B\right) \frac{\partial}{\partial A}\right) Z_{n-1},$$

that is,

$$Z_0 = A, \qquad Z_1 = \frac{[A}{1 - e^{-[A}} \ B = D, \qquad ...$$

etc, as in Application 1.

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