

A new discrete calculus of variations and its applications in statistical physics

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(Dated: April 23, 2021)

For a discrete function $f(x)$ on a discrete set, the finite difference can be either forward and backward. However, we observe that if $f(x)$ is a sum of two functions $f(x) = f_1(x) + f_2(x)$ defined on the discrete set, the first order difference of $\Delta f(x)$ is equivocal for we may have $\Delta^f f_1(x) + \Delta^b f_2(x)$ where Δ^f and Δ^b denotes the forward and backward difference respectively. Thus, the first order variation equation for this function $f(x)$ gives many solutions which include both true and false one. A proper formalism of the discrete calculus of variations is proposed to single out the true one by examination of the second order variations, and is capable of yielding the exact form of the distributions for Boltzmann, Bose and Fermi system without requiring the numbers of particle to be infinitely large. The advantage and peculiarity of our formalism are explicitly illustrated by the derivation of the Bose distribution.

Keywords: statistical distribution, discrete calculus of variations, most probable distribution

Introduction The method of most probable distribution (MPD) is the most common way used to derive various statistical distributions in mathematics, physics, chemistry, materials science and computational science, etc. The original data are usually discrete rather than continuous, so we must be able to deal with the differences, difference quotients and sums of discrete functions, instead of the differentials, derivatives and integrations of the continuous functions. However, we immediately run into a problem: For a discrete function that has extremals, the difference can be forward, backward, central, and even more complicated combinations of these differences, so that the first order variation equation leads to many solutions which can not be all true. By the true solution, we mean that it is realistic or physical. There has been no satisfactory procedure to single out the true one in its own right. Thus the derivation of the exact form of the distribution functions for Boltzmann, Bose and Fermi system obtained from the MPD has been an open problem for nearly one century. [1, 2] In present work, I report a discrete calculus of variations to resolve this problem.

A new discrete calculus of variations Let us first define an *individual function* (IF) $f(x)$ of variable x on an interval C , which amounts to that the exponential of the function $f(x)$ as $\exp f(x)$ can not be further factorized. We can therefore define the sum of two IFs $f(x) = f_1(x) + f_2(x)$, and the sum of many IFs. Secondly we define the *unidirectional differences* of the IF $f(x)$, which means that when taking the finite differences of different orders for the function $f(x)$, we take *forward or backward* differences in all first, second, and higher order variation. For instance, the *forward directional differences* of the IF $f(x)$ are $(\Delta^f) f(x) = f(x+h) - f(x)$, $(h > 0)$, $(\Delta^f)^2 f(x) = f(x+2h) - f(x+h) - (f(x+h) - f(x)) = f(x+2h) - 2f(x+h) + f(x)$, and so forth; and the *backward unidirectional differences* of the IF $f(x)$ are $(\Delta^b) f(x) = f(x) - f(x-k)$, $(k > 0)$, $(\Delta^b)^2 f(x) = f(x) - f(x-k) - (f(x-k) - f(x-2k)) = f(x) - 2f(x-k) + f(x-2k)$, and so forth. Thus, the *forward directional difference quotients* are $(\Delta^f) f(x)/h$, $(\Delta^f)^2 f(x)/h^2$, ...; and similarly, the *backward directional difference quotients* are $(\Delta^b) f(x)/k$, $(\Delta^b)^2 f(x)/k^2$, ... Specially for $h = 1$, we have $(\Delta^f)^i f(x)/h = (\Delta^f)^i f(x)$, $(i = 1, 2, 3, \dots)$; and similarly for $k = 1$, we have $(\Delta^b)^i f(x)/k = (\Delta^b)^i f(x)$. The *unidirectional differences* are similar to the treatment of the parameter $\lambda \in \mathbb{R}$ in the usual calculus of variation in which for the given variational parameter λ , we must keep using this parameter λ in all orders of variations. [3] However, the different point of the new procedure is that, once $f(x) = f_1(x) + f_2(x)$, Δf does mean four combinations: $(\Delta^f) f_1(x) + (\Delta^f) f_2(x)$, $(\Delta^f) f_1(x) + (\Delta^b) f_2(x)$, $(\Delta^b) f_1(x) + (\Delta^f) f_2(x)$, and $(\Delta^b) f_1(x) + (\Delta^b) f_2(x)$, which can be simply named by 1f2f, 1f2b, 1b2f and 1b2b, respectively. Moreover, the second order variations are must be taken *unidirectionally*, so $\Delta^2 f$ for the combination 1f2f, 1f2b, 1b2f and 1b2b gives, $(\Delta^f)^2 f_1(x) + (\Delta^f)^2 f_2(x)$, $(\Delta^f)^2 f_1(x) + (\Delta^b)^2 f_2(x)$, $(\Delta^b)^2 f_1(x) + (\Delta^f)^2 f_2(x)$, and $(\Delta^b)^2 f_1(x) + (\Delta^b)^2 f_2(x)$, respectively.

The problem is formulated in the following. We at first deal with a discrete IF $\Psi(n)$ defined, for convenience, on the interval of semi-positive integers $n \in \mathbb{Z}^+$, which has the local maxima and minima, subject to some equality constraints $\psi = (\psi_1, \psi_2, \psi_3, \dots) = \mathbf{0}$. For finding the local maxima and minima of the function $\Psi(n)$, we construct a

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