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Local or Nonlocal?
Orthonormal Divergence-free Wavelet Analysis of Nonlinear Interactions in Turbulence

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Abstract

Using orthonormal divergence-free vector wavelet, we analyzed nonlinear transfer in a three-dimensional homogeneous, isotropic turbulence. Analogous Fourier analysis is also carried out. It is verified that energy is transferred locally. We also find that, in terms of wavelet analysis and geometrically partitioned Fourier band average analysis, the contribution of local interactions to the transfer is not negligible compared to that of nonlocal ones. On the other hand, linearly partitioned Fourier band average analysis drastically changes the qualitative appearance of transfer process, i.e. the result shows the predominance of nonlocal interactions.

Keywords: orthonormal divergence-free wavelet, homogeneous isotropic turbulence, nonlinear interactions.

Energy in turbulence cascades toward more and more smaller scales. But how? As is concisely reviewed in Frisch's textbook [1], the classical phenomenology of Kolmogorov's, which is inspired by Richardson's work, is based on the two basic assumptions: the *localness* of the transfer process and the *scale-invariance* of dynamics in the inertial range. Recent development of numerical computations leads to a consensus on the former assumption, whose literal expression sounds somewhat paradoxical; the energy is *locally transferred* predominantly by *the nonlocal interactions* [2, 3]. This implies that the triad interactions primarily relevant to the transfer process are constituted by such wavenumbers that one of them is much smaller than the other two. This feature is also verified in terms of EDQNM closure theory.

The latter assumption, on the other hand, naturally leads to an idea of *scaling laws* of various quantities such as velocity correlation functions. Wavelet analysis is regarded one of the promising tools for analyzing such scaling behaviour because of the dyadic dilating property of the wavelet basis. (Though wavelet often gets its reputation by its capability of simultaneous capturing of both spatial scale and location.) The analyses of turbulence in terms of wavelets have been carried out by many authors. For example, Meneveau analysed nonlinear transfer though each term of the obtained expansion is not divergence-free [4].

Recently we proved a general procedure to construct the orthonormal complete, divergence-free wavelet basis on a periodic box $\mathbf{T}^3 = [0, L]^3$ [5]. The basis is given by a unitary transform of *complex helical waves* [6]. Utilizing the Fourier transform of three-dimensional type ϵ mother wavelet $\widehat{\psi}_\epsilon(\boldsymbol{k})$ and the spherical coordinate system basis in the Fourier space $\{\boldsymbol{e}_r(\boldsymbol{k}), \boldsymbol{e}_\vartheta(\boldsymbol{k}), \boldsymbol{e}_\varphi(\boldsymbol{k})\}$ [7], one can obtain the solenoidal vector wavelet according to the formula

$$\psi_{j\epsilon l\sigma}(\boldsymbol{x}) := 2^{-\frac{3}{2}j} \sum_{\boldsymbol{k}\in\mathbf{Z}^3\setminus\{\mathbf{0}\}} \widehat{\psi}_\epsilon\left(\frac{\boldsymbol{k}}{2^j}\right) \frac{\boldsymbol{e}_\vartheta(\boldsymbol{k}) + i\sigma \boldsymbol{e}_\varphi(\boldsymbol{k})}{\sqrt{2}} \times \exp\left[2\pi i \boldsymbol{k}\cdot\left(\frac{\boldsymbol{x}}{L} - \frac{\boldsymbol{l}}{2^j}\right)\right], \quad (1)$$

where j is a nonnegative integer that represents spatial resolution, $\boldsymbol{l} \in (\mathbf{Z}/2^j\mathbf{Z})^3$ indicates the position, and $\sigma = \pm 1$ corresponds to the sign of helicity of the wavelet. We call the wavelet *helical wavelet* hereafter. One of the remarkable feature of the basis is that no novel algorithm is required to obtain the expansion coefficient. But FFT and wavelet transform algorithm for scalar function are enough. The helical wavelet is applied to the analysis of intermittency of turbulence [8].

In the present study, we concentrate on the inter-scale energy transfer so that the information with respect to ϵ, $\boldsymbol{l}$ and σ is not used. The velocity field is decomposed according to the resolution class (or spatial scales) as follows:

$$\boldsymbol{u}(\boldsymbol{x},t) = \sum_j \boldsymbol{u}_j(\boldsymbol{x},t), \tag{2}$$

where

$$\boldsymbol{u}_j(\boldsymbol{x},t) := \sum_{\epsilon,\boldsymbol{l},\sigma} \langle \boldsymbol{u}(\boldsymbol{x},t)\cdot\boldsymbol{\psi}_{j\epsilon\boldsymbol{l}\sigma}(\boldsymbol{x})\rangle \boldsymbol{\psi}_{j\epsilon\boldsymbol{l}\sigma}(\boldsymbol{x}),$$

and $\langle f\rangle := \int_{\mathrm{T}^3} f(\boldsymbol{x})\mathrm{d}\boldsymbol{x}/L^3$. Substituting this expression into the incompressible Navier-Stokes equation (NSE), and taking inner product with $\boldsymbol{u}_j$, one obtains the equations for the kinetic energy of each resolution class:

$$\frac{\mathrm{d}E_j}{\mathrm{d}t}(t) = \sum_k\sum_l \langle \boldsymbol{u}_j|\boldsymbol{u}_k|\boldsymbol{u}_l\rangle + \nu\sum_k\langle \boldsymbol{u}_j\cdot(\nabla^2\boldsymbol{u}_k)\rangle, \tag{3}$$

for every j, where $E_j(t) = \frac{1}{2}\langle \boldsymbol{u}_j\cdot\boldsymbol{u}_j\rangle$ and the bracket in the first term of RHS is defined by the integral

$$\langle \boldsymbol{u}_j|\boldsymbol{u}_k|\boldsymbol{u}_l\rangle := -\langle \boldsymbol{u}_j(\boldsymbol{x},t)\cdot(\boldsymbol{u}_k(\boldsymbol{x},t)\cdot\nabla)\boldsymbol{u}_l(\boldsymbol{x},t)\rangle. \tag{4}$$

Pressure term vanishes because the wavelet is divergence free $\nabla\cdot\boldsymbol{\psi}_{j\epsilon\boldsymbol{l}s} \equiv 0$, so are $\boldsymbol{u}_j$'s. In the following, we use the term *nonlinear transfer* (or simply *transfer*) to indicate nothing but the integral given by Eq. (4). By the term *from-mode* we denote the vector field that appears at $|\boldsymbol{u}_l\rangle$ *for convenience of description*; similarly we call $|\boldsymbol{u}_k|$ *by-mode* and $\langle\boldsymbol{u}_j|$ *to-mode*. We also use the term *receiving transfer* if the transfer is positive, and *giving transfer* if it is negative.

We analysed a snapshot data of the decaying homogeneous isotropic turbulence calculated by Kishiba *et al.* [9]. The NSE is solved by the pseudo-spectral method with polyhedral dealiasing method, periodic boundary conditions ($L = 2\pi$) and 128^3 grid points. The snapshot is taken at $t = 1.0$ in the time unit adopted in Ref. [9]. The Taylor microscale Reynolds number of the snapshot is $R_\lambda = 100$.

In Fig. 1, Fourier energy spectrum $E(k)$ and wavelet one E_j are depicted. In Figs. 1 and 2, each wavelet spectrum is plotted according to the wavenumber given by $k_j := \sqrt{\langle|\nabla\times\boldsymbol{u}_j|^2\rangle/\langle|\boldsymbol{u}_j|^2\rangle}$ which is related to the Taylor microscale of $\boldsymbol{u}_j$, say λ_j, by $k_j = \sqrt{5}/\lambda_j$. Fourier energy spectrum and its wavelet analog have their peak at $|\boldsymbol{k}| = 2$ and at $j = 2$, respectively. Fourier transfer function $T(k)$, dissipation function $-\nu k^2 E(k)$, and their wavelet analogs $\langle\boldsymbol{u}_j|\boldsymbol{u}|\boldsymbol{u}\rangle$ and $\nu\langle\boldsymbol{u}_j\cdot(\nabla^2\boldsymbol{u})\rangle$, respectively, are depicted in Fig. 2. Transfer function and its wavelet analog are positive for $|\boldsymbol{k}| \geq 6$ and for $j \geq 3$, respectively. On the whole, the nonlinear interaction reduces the energy of larger scale motions and increases that of smaller ones in this snapshot. The principal features of these spectra agrees each other qualitatively and, to some extent, quantitatively.

In Fig. 3, the energy budget of $j = 5$ *to-mode* due to nonlinear interactions $\langle\boldsymbol{u}_5|\boldsymbol{u}_k|\boldsymbol{u}_l\rangle$ is depicted as an illustrative example. Contours are drawn in order to grasp the amplitude of the cites intuitively. Solid lines surround such cites that have positive value, that is, the $j = 5$ mode receives kinetic energy due to the nonlinear transfer, and dashed lines are *vice versa*. Times symbols ($\times$) denote the cites whose values are identically zero.

It is a distinct feature with respect to *from-mode* $|\boldsymbol{u}_l\rangle$ that predominant transfers are concentrated on $l = 4$ and 6. Thus the nonlinear energy budget has, on the whole, a quite asymmetric distribution with respect to *from-modes* and *by-modes*. Contribution of the transfers outside these classes is less than 3 percent of the total receiving transfer and 13 percent of the total giving one. On the other hand three significant features with respect to the *by-mode* are seen; firstly, the *by-modes* of the predominant transfers, in contrast to those of *from-modes*, spread over the modes with $2 \leq k \leq 4$. It should be noted that the giving transfers have their peak at $\langle\boldsymbol{u}_5|\boldsymbol{u}_3|\boldsymbol{u}_6\rangle$. Secondly, the amplitude of the significant transfers does not have direct relation to their r.m.s. velocity amplitude $u_k := \sqrt{2E_k}$; for example, the contribution of $k = 3$ is larger than that of $k = 2$, though E_3 is smaller than E_2. Thirdly, the contributions of $k = 0$ and 1, which are regarded to correspond to large scale eddies, are relatively small.

Though we present here the results of nonlinear energy budget for E_5, we also verified numerically the following two facts for E_2, E_3 and E_4 (partly for E_6); (1) the contribution of *from-modes* and *by-modes* is quite asymmetric, i.e. the amplitude of (for some cases, even the sign of) $\langle\boldsymbol{u}_j|\boldsymbol{u}_k|\boldsymbol{u}_l\rangle$ is very different from $\langle\boldsymbol{u}_j|\boldsymbol{u}_l|\boldsymbol{u}_k\rangle$. (2) The transfer is remarkably concentrated on such ones whose *from-mode* number is $l = j-1$ for *receiving* ones, and $l = j+1$ for *giving* ones. The contribution of nonlinear transfer outside these bands is negligible.

Thus we verified that the energy is transferred *locally* in the sense that one of the two modes, *from-* or *by-mode*, in the predominant transfers has close spatial scale to that of *to-mode*. This is consistent with the numerical results by Domaradzki and Rogallo [2], and by Ohkitani and Kida [3].

Now we define the term *transfer due to local interactions* by such transfers that the resolution class of both *by-modes* and *from-modes* are $j-1$, j or $j+1$ when the *to-mode* class is j. According to this terminology, the contribution of local interactions is about 22 percent of the total *receiving transfer* and about 36 percent of the total *giving* one. If the definition of local interactions is enlarged to the nearest two neighboring classes, i.e $j-2 \le k, l \le j+2$, the contributions of them become about 65 percent of *receiving transfer* and about 71 percent of *giving* one. For E_3 and E_4, it is also verified that the portion of the transfers due to local interactions is not negligible compared to that due to nonlocal ones.

Significance of local interactions is now presented, though it seems inconsistent with the Fourier analysis results given by Domaradzki and Rogallo [2], and by Ohkitani and Kida [3]. It should be noted that the helical wavelet basis naturally partitions the Fourier space *geometrically*, i.e. the width of partitioned band grows in power of two as the corresponding wavenumber increases. The previous analyses were, on the contrary, based on the *linear equipartition* of Fourier space. Thus the reexamination of the Fourier analysis results is required in the light of *geometrically partitioned band average.*

To investigate the difference between the present result and the previous ones, we decomposed the velocity field orthogonally in two ways: the *geometrical decomposition* given by

$$\boldsymbol{u} = \sum_j \boldsymbol{u}_j^{\mathrm{G}}, \quad \text{where } \boldsymbol{u}_j^{\mathrm{G}} := \phi_{[\frac{2}{3}2^j, \frac{2}{3}2^{j+1})} \otimes \boldsymbol{u}, \quad (5)$$

and the *linear decomposition* given by

$$\boldsymbol{u} = \sum_j \boldsymbol{u}_j^{\mathrm{L}}, \quad \text{where } \boldsymbol{u}_j^{\mathrm{L}} := \phi_{[6j+\frac{1}{2}, 6j+\frac{13}{2})} \otimes \boldsymbol{u}, \quad (6)$$

where $\otimes$ denotes convolution, and $\phi_{[a,b)}(\boldsymbol{x})$ is the inverse Fourier transform of a step function given by $\widehat{\phi}_{[a,b)}(\boldsymbol{k}) := 1$ for $a \le |\boldsymbol{k}| < b$ elsewhere 0. Substituting these expressions into NSE, and taking inner product with each component, we have the analogous dynamical systems to Eq (3) for band averaged kinetic energy $E_j^P(t) := \frac{1}{2}\langle \boldsymbol{u}_j^P \cdot \boldsymbol{u}_j^P \rangle$, hereafter P stands for L or G.

In Fig 4, the $\boldsymbol{u}_j^P$ analogs of Eq. (4), $\langle \boldsymbol{u}_j^P | \boldsymbol{u}_k^P | \boldsymbol{u}_l^P \rangle$, are depicted. The resolution classes depicted are $j=5$ for geometrical decomposition and $j=4$ for linear decomposition. They are so carefully chosen that their Taylor microscales are almost same; the corresponding wavenumber of $\boldsymbol{u}_5^G$ is 27.62 and that of $\boldsymbol{u}_4^L$ is 27.10. The contours and symbols in the figure are added in the same manner as in Fig 3 for the help of readers. It is clearly illustrated in Fig. 4(a) that the geometrical decomposition analysis gives a consistent result with the wavelet analysis, i.e. both local and nonlocal interactions contribute to the local nonlinear transfer at the same order. On the other hand, it is quite remarkable that the linear decomposition analysis gives a qualitatively different result. The nonlinear transfers are concentrated on small number of the cites whose *by-modes* correspond to the smallest wavenumber resolutions, $k=0$ and 1, and *from-modes* are $l=j\pm 1$. The contribution of the cites with $(k,l)=(0,3)$, and $(1,3)$ to the total receiving transfer is 81 percent, and $(0,5)$ and $(1,5)$ to the giving one is 75 percent. All the interactions of these cites are all nonlocal in the sense that the ratio of the maximum side of triad to the minimum one is larger than two. This analysis supports the picture of *local transfer by nonlocal interactions*, which was reported in Refs. [2, 3].

It is an interesting result that, being independent of the way of decomposing, the transfers primarily relevant to the energy budget of j-th component are concentrated on such bands whose *from-mode* numbers are $l=j-1$ and $j+1$, the nearest scale from-mode bands. Thus the picture of local nonlinear transfer remains unaffected against the decomposition methods.

In conclusion, some remarks should be made. The concentration of transfers on the nearest *from-mode* bands, and thus the asymmetry of the contribution between *from-modes* and *by-mode* are remarkable. This result is overlooked in the previous studies based on the representation such that the coefficients of nonlinear interaction terms of NSE are symmetrized with respect to the wavenumbers. It is, however, an open question whether it is accidental or gives some clues to the dynamical processes. Universal range dynamics and statistics of turbulence rely on the idea of *scaling laws* and hierarchical structures of eddies [1]. It seems more natural to treat the velocity field under the geometrical decomposition technique than the linear one. Helical wavelet basis naturally decomposes the Fourier space geometrically, and henceforth each helical wavelet function gives a concrete mathematical expression of *an "eddy" of wavenumber* κ discussed by Tennekes and Lumley (in §8.2 of Ref. [10]).

The detailed analysis of nonlinear transfer is now underway.

Acknowledgement

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Figure captions

Fig.1. Fourier energy spectrum $E(k)$ (line with closed circles) and wavelet one E_j (line with open circles). Wavelet energy spectrum is plotted according to the wavenumbers given by $k_j := \sqrt{\langle|\nabla \times \boldsymbol{u}_j|^2\rangle / \langle|\boldsymbol{u}_j|^2\rangle}$.

Fig.2. Fourier transfer function $T(k)$ (solid line), dissipation function $-\nu k^2 E(k)$ (dashed line), and their wavelet analogs $\langle \boldsymbol{u}_j | \boldsymbol{u} | \boldsymbol{u} \rangle$ (solid line with open circles) and $\nu\langle \boldsymbol{u}_j \cdot (\nabla^2 \boldsymbol{u})\rangle$ (dashed line with closed circles). Wavelet analogs are plotted same manner as wavelet energy spectrum in Fig. 1.

Fig.3. Nonlinear transfers to $j = 5$ mode in term of wavelet decomposition. The solid (open) circles denote the receiving (resp. giving) transfers. Contours are drawn according to the amplitude of each transfer. Increment interval is fixed to 10% of the maximum of absolute values of transfers. The value on the cites with times symbols is identically zero.

Fig.4. Nonlinear transfers in term of Fourier analysis ; (a) to $j = 5$ mode of geometrical decomposition, (b) to $j = 4$ mode of linear decomposition. -The contours and symbols are drawn in the same manner as Fig. 3.

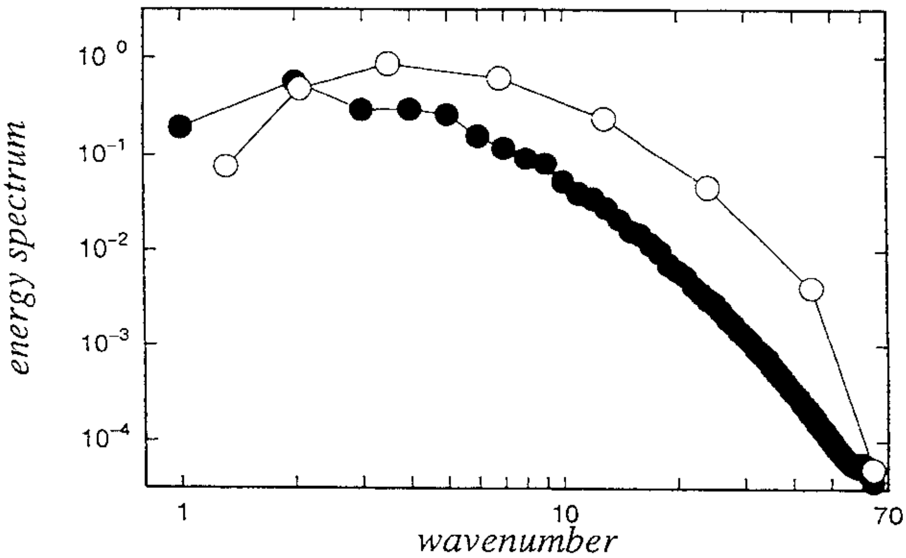

Figure 1
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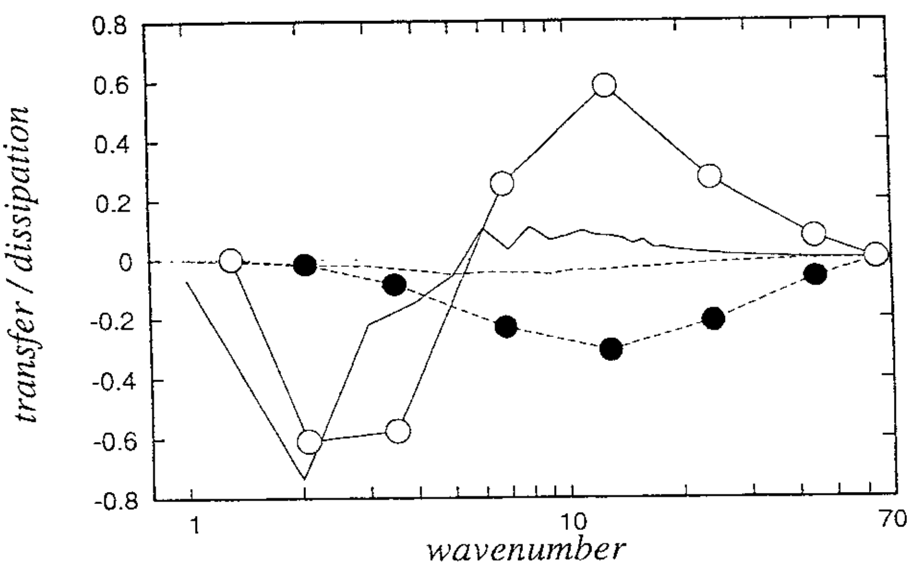

Figure 2
K. Kishida, K. Araki, S Kishiba and K. Suzuki

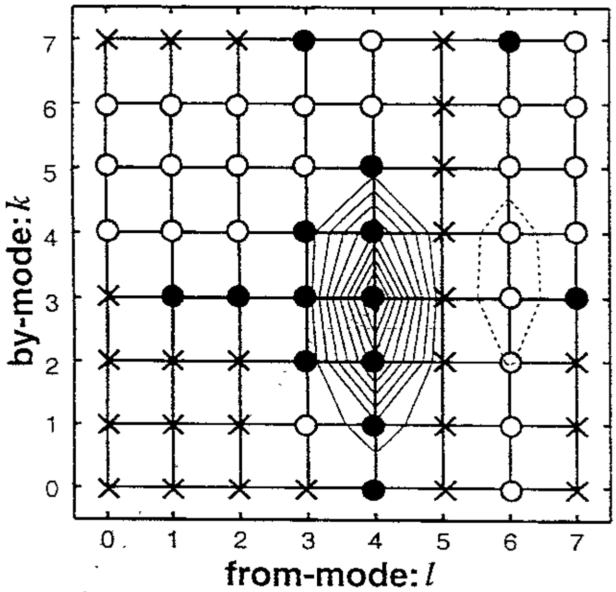

Figure 3

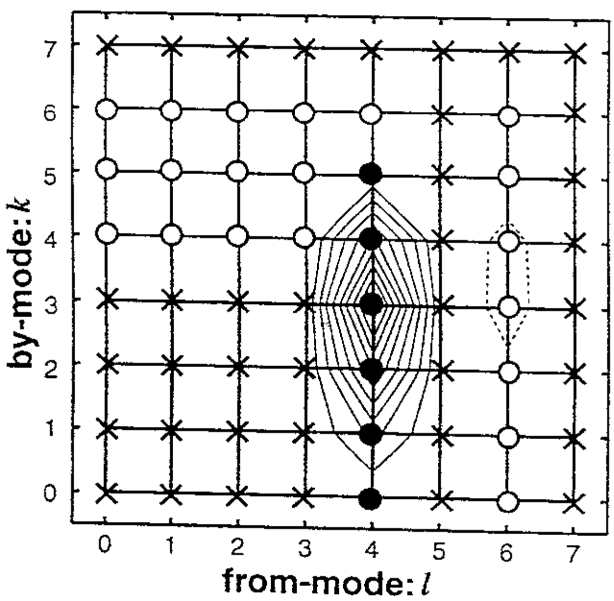

Figure 4(a)

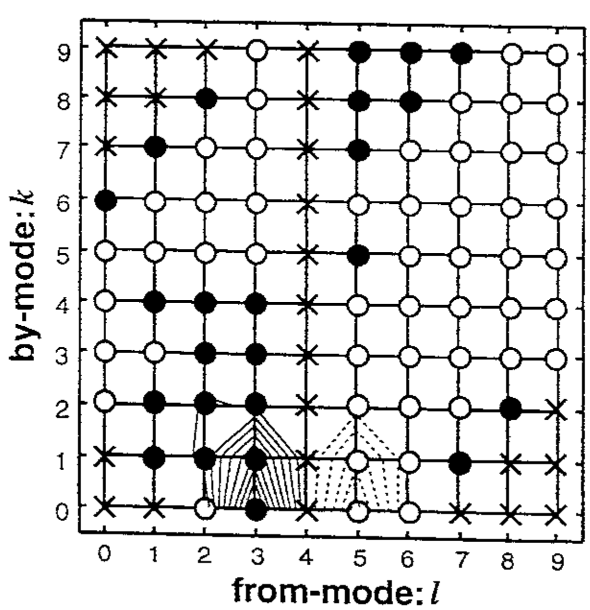

Figure 4(b)

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