(B) The incompressible Navier-Stokes Equation

See also Chapter 2 from Frisch 1995.

**Velocity-pressure formulation**

\[
\partial_t \mathbf{v} + (\mathbf{v} \cdot \nabla) \mathbf{v} = -\nabla p + \nu \Delta \mathbf{v} \\
\nabla \cdot \mathbf{v} = 0 \\
\mathbf{v}|_{\partial \Omega} = 0
\]

Here \( D_t = \partial_t + \mathbf{v} \cdot \nabla \) is material or convective derivative; \( \nu \) is kinematic viscosity.

**Pressure and Poisson equation:**

\[
\nabla \cdot [(\mathbf{v} \cdot \nabla) \mathbf{v}] = \partial_i((v_j \partial_j)v_i) = (\partial_i v_j)(\partial_j v_i) = (\nabla \mathbf{v})^T : \nabla \mathbf{v} \\
-\Delta p = (\nabla \mathbf{v})^T : \nabla \mathbf{v}
\]

N-S on \( \partial \Omega \):

\[
0 = -\nabla p + \nu \frac{\partial^2 \mathbf{v}}{\partial n^2}
\]

Neumann b.c.

\[
\frac{\partial p}{\partial n} = \nu n_i \frac{\partial^2 v_i}{\partial n^2}
\]

**Vorticity-velocity formulation**

\[
\mathbf{\omega} = \nabla \times \mathbf{v} = \text{vorticity}
\]

**identity:** \( \mathbf{v} \times \mathbf{\omega} = \nabla (\frac{1}{2} v^2) - (\mathbf{v} \cdot \nabla) \mathbf{v} \)

**Proof:**

\[
(\mathbf{v} \times \mathbf{\omega})_i = \epsilon_{ijk} \epsilon_{lmk} v_j \partial_l v_m \\
= (\delta_{il} \delta_{jm} - \delta_{im} \delta_{jl}) v_j \partial_l v_m \\
= v_j \partial_i v_j - (v_j \partial_j) v_i
\]

\[
\therefore \text{N-S} \implies \partial_t \mathbf{v} = \mathbf{v} \times \mathbf{\omega} - \nabla p' + \nu \Delta \mathbf{v}
\]
\[ p' = p + \frac{1}{2} \nu^2 \]
\[ \mathbf{v} \times \omega = \text{vortex force} \]

\textbf{identity:} \( \nabla \times (\mathbf{v} \times \omega) = -(\mathbf{v} \cdot \nabla)\omega + (\omega \cdot \nabla)\mathbf{v} \)

Proof: Use \( \nabla \times (a \times b) = a(\nabla \cdot b) - b(\nabla \cdot a) + (b \cdot \nabla)a - (a \cdot \nabla)b \) and incompressibility. Thus

\[ \nabla \times (\mathbf{NS}) \implies \partial_t \omega + (\mathbf{v} \cdot \nabla)\omega = (\omega \cdot \nabla)\mathbf{v} + \nu \Delta \omega \]

Here \((\omega \cdot \nabla)\mathbf{v}\) is the \textit{vortex-stretching term}.

\textbf{Poisson equation for velocity:} \(-\Delta \mathbf{v} = \nabla \times \omega\)

Proof: use \( \nabla \times (\nabla \times \mathbf{a}) = -\Delta \mathbf{a} + \nabla (\nabla \cdot \mathbf{a}) \) to take curl of \( \omega = \nabla \times \mathbf{v} \)

\textbf{Biot-Savart formula:} For \( D(r, r') \) the Green’s function of the Laplacian with Dirichlet b.c.

\[ \mathbf{v}(r) = \int_V d^d r' \ D(r, r') (\nabla_{r'} \times \omega)(r') \]
\[ = \int_V d^d r' \ K(r, r') \times \omega(r') + \int_{\partial V} d S' D(r, r') \mathbf{n} \times \omega(r'), \]

with \( K(r, r') = -\nabla_{r'} D(r, r') \). This is called the “Biot-Savart formula” because of an analogy with magnetostatics:

\[ \nabla \times \mathbf{B} = 4\pi \mathbf{J} \]
\[ \mathbf{B} \leftrightarrow \mathbf{v} \]
\[ \mathbf{J} \leftrightarrow \omega \]

\textbf{Symmetries of NS}

A group \( G \) of transformations of \( \mathbf{v}(r, t) \) is \textit{symmetry group} of NS if and only if

\[ \forall g \in G, \mathbf{v} \text{ a NS solution.} \implies g\mathbf{v} \text{ a NS solution.} \]

\textbf{Space-translations:} \( g^\text{space}_a \mathbf{v}(r, t) = \mathbf{v}(r - a, t), \ a \in \mathbb{R}^d, \)

\textbf{Time-translations:} \( g^\text{time}_\tau \mathbf{v}(r, t) = \mathbf{v}(r, t - \tau), \ \tau \in \mathbb{R}, \)

\textbf{Galilean transformation:} \( g^\text{Gal}_u \mathbf{v}(r, t) = \mathbf{v}(r - u t, t) + u, \ u \in \mathbb{R}^d \)
Space-reflection (parity): \( P \mathbf{v}(\mathbf{r},t) = -\mathbf{v}(-\mathbf{r},t) \)

\[ \Lambda = \mathbb{R}^d \implies \text{Space-rotations: } g^\text{rot}_R \mathbf{v}(\mathbf{r},t) = R\mathbf{v}(R^{-1}\mathbf{r},t), \quad R \in SO(d) \]

\[ \nu = 0 \implies \text{Scale-invariance: } g^\text{scale,h}_\lambda \mathbf{v}(\mathbf{r},t) = \lambda^h \mathbf{v}(\lambda^{-1}\mathbf{r},\lambda^{h-1}t), \quad \lambda \in \mathbb{R}^+ \]

Note that space domain \( \tilde{\Lambda} = \lambda \Lambda \) and time interval \( \tilde{T} = \lambda^{1-h}T \). For \( \nu > 0 \), scale-invariance holds only with \( h = -1 \)

\[ g^\text{scale}_\lambda \mathbf{v}(\mathbf{r},t) = \lambda^{-1} \mathbf{v}(\lambda^{-1}\mathbf{r},\lambda^{-2}t) \]

**Proof for Galilean transformation:** Set \( \tilde{\mathbf{v}}(\mathbf{r},t) = \mathbf{v}(\mathbf{r} - \mathbf{u}t,t) + \mathbf{u} \)

\[
\begin{align*}
\partial_t \tilde{\mathbf{v}}(\mathbf{r},t) &= \partial_t \mathbf{v}(\mathbf{r} - \mathbf{u}t,t) - (\mathbf{u} \cdot \nabla) \mathbf{v}(\mathbf{r} - \mathbf{u}t,t) \\
(\tilde{\mathbf{v}}(\mathbf{r},t) \cdot \nabla) \tilde{\mathbf{v}}(\mathbf{r},t) &= [\mathbf{v}(\mathbf{r} - \mathbf{u}t,t) + \mathbf{u}] \cdot \nabla \mathbf{v}(\mathbf{r} - \mathbf{u}t,t)
\end{align*}
\]

\( \text{terms cancel!} \)

**Proof for scale-invariance:** Set \( \tilde{\mathbf{v}}(\mathbf{r},t) = \lambda^h \mathbf{v}(\lambda^{-1}\mathbf{r},\lambda^{h-1}t) \)

\[
\begin{align*}
\partial_t \tilde{\mathbf{v}}(\mathbf{r},t) &= \lambda^{2h-1} \mathbf{v}(\lambda^{-1}\mathbf{r},\lambda^{h-1}t) \\
(\tilde{\mathbf{v}}(\mathbf{r},t) \cdot \nabla) \tilde{\mathbf{v}}(\mathbf{r},t) &= \lambda^{2h-1} \mathbf{v}(\lambda^{-1}\mathbf{r},\lambda^{h-1}t) \cdot \nabla \mathbf{v}(\lambda^{-1}\mathbf{r},\lambda^{h-1}t) \\
\nabla \tilde{p}(\mathbf{r},t) &= \lambda^{2h-1} \nabla p(\lambda^{-1}\mathbf{r},\lambda^{h-1}t) \quad (\text{Why?}) \\
\nu \nabla \tilde{\mathbf{v}}(\mathbf{r},t) &= \lambda^{-2} \nu \nabla \mathbf{v}(\lambda^{-1}\mathbf{r},\lambda^{h-1}t)
\end{align*}
\]

For \( \nu > 0 \), \( h - 2 = 2h - 1 \implies h = -1 \)

Define the Reynolds number

\[ Re = \frac{UL}{\nu}, \quad L = \text{domain size}, \quad U = \text{characteristic velocity} \]

Since \( \tilde{L} = \lambda L, \tilde{U} = \lambda^h U \)

\[ \tilde{Re} = \lambda^{h+1} Re = Re, \quad \text{if } h = -1 \]

**Principle of hydrodynamic similarity:** Two flows with the same geometry but different scale are essentially identical if the Reynolds numbers are the same.
Non-dimensionalization:

\[
\hat{\mathbf{v}} = \frac{\mathbf{v}}{U}, \\
\hat{\mathbf{r}} = \frac{\mathbf{r}}{L}, \\
\hat{t} = \frac{(U/L)t}{T} = t/T
\]

\[\Rightarrow \]

\[\partial_t \hat{\mathbf{v}} + (\hat{\mathbf{v}} \cdot \hat{\nabla})\hat{\mathbf{v}} = -\hat{\nabla}\hat{p} + \frac{1}{Re} \hat{\Delta} \hat{\mathbf{v}}\]

An important consequence of the similarity principle is the fact that the rescaled energy dissipation \( D = \varepsilon(t)/(U^3/M) \) in decaying grid turbulence with inflow velocity \( U \) and mesh size \( M \) can be a function only of \( Re_M = UM/\nu \), dimensionless time \( \hat{t} = Ut/M \), and scale-independent geometric properties of the grid. See homework!

The hydrodynamic similarity principle is a special case of the Buckingham II-Theorem, which implies among other things that, if there are \( n \) quantities \( Q_i \), \( i = 1, ..., n \) and \( k \) independent physical dimensions, then there are exactly \( p = n - k \) independent dimensionless number groups \( \Pi_j = Q_1^{a_{1j}} Q_2^{a_{2j}} \cdots Q_n^{a_{nj}}, j = 1, ..., p \) for rational numbers \( a_{ij}, i = 1, ..., n, j = 1, ..., p \). See:

Buckingham, E. “On physically similar systems; illustrations of the use of dimensional equations,” Physical Review. 4 345–376 (1914)

Thus, from the three quantities \( U, L, \nu \) with two independent dimensions of \( (\text{length}) \) and \( (\text{time}) \), one can construct a single dimensionless group, which may be the Reynolds number \( Re = UL/\nu \) or, alternatively, some rational power of it, such as \( \sqrt{Re} \).

Incompressible fluctuating hydrodynamics: We mention here that effects of thermal noise on incompressible fluids can be described by a nonlinear Langevin equation/stochastic PDE

\[\partial_t \mathbf{v} + (\mathbf{v} \cdot \nabla)\mathbf{v} = -\nabla p + \nu \Delta \mathbf{v} + \mathbf{f}\]

where \( p \) is chosen to enforce \( \nabla \cdot \mathbf{v} = 0 \) and \( f_i(x, t) \) is a Gaussian space-time white-noise random
process with mean zero and covariance prescribed by a fluctuation-dissipation relation:

$$\langle f_i(x, t)f_j(x', t') \rangle = \frac{2\nu k_B T}{\rho} \delta_{ij} \Delta_x \delta^d(x - x') \delta(t - t')$$

where $k_B = 1.3806 \times 10^{-23}$ J/K is Boltzmann’s constant. If the same rescaling is performed as for the deterministic equation, one obtains

$$\partial_t \hat{\mathbf{v}} + (\hat{\mathbf{v}} \cdot \nabla) \hat{\mathbf{v}} = -\nabla \hat{p} + \frac{1}{Re} \Delta \hat{\mathbf{v}} + \hat{\mathbf{f}}$$

where $\hat{\mathbf{f}} = Lf/U^2$ has covariance

$$\langle \hat{f}_i(\hat{x}, \hat{t})\hat{f}_j(\hat{x}', \hat{t}') \rangle = \frac{2}{Re} \epsilon^d \delta_{ij} \Delta_x \delta^d(\hat{x} - \hat{x}') \delta(\hat{t} - \hat{t}')$$

with parameter $\epsilon^d = k_B T/(\rho U^2 L^d)$ that compares thermal fluctuation energy to total hydrodynamic energy of density $\sim \rho U^2$ in a volume of order $L^d$, so that $\epsilon \propto 1/L$. As we shall see later, even if $U$ and $L$ are chosen to be small velocity and length-scales corresponding to the tiniest turbulent eddies, generally $\epsilon \ll 1$ and the direct effects of thermal noise are small.

“Invviscid Invariants” of 3D NS

Momentum:

$$\mathbf{g}(\mathbf{r}, t) = \rho \mathbf{v}(\mathbf{r}, t) = \text{momentum density}$$

$$\text{NS} \implies \partial_t \mathbf{g} + \nabla \cdot \mathbf{T} = 0$$

$$\mathbf{T} = P\mathbf{I} + \rho \mathbf{v}\mathbf{v}^T - 2\eta \mathbf{S} = \text{stress tensor (spatial momentum flux)}$$

$$\mathbf{S} = \frac{\nabla \mathbf{v} + (\nabla \mathbf{v})^T}{2} = \text{strain tensor, } (\nabla \mathbf{v})_{ij} = \partial_i v_j$$

Global conservation:

$$\mathbf{P}(t) = \int_{\Lambda} \mathbf{g}(\mathbf{r}, t)d^d\mathbf{r} = \text{total momentum}$$

$$\frac{d\mathbf{P}(t)}{dt} = 0 \text{ for } \Lambda = \mathbb{R}^d \text{ on } \mathbb{T}^d$$

Local conservation: $B \subset \Lambda$

$$\mathbf{P}_B(t) = \int_B \mathbf{g}(\mathbf{r}, t)d^d\mathbf{r} = \text{momentum in } B$$
\[
\frac{d\mathbf{P}_B(t)}{dt} = - \int_{\partial B} \mathbf{T} \cdot d\mathbf{A} = \text{flow of momentum across boundary of } B
\]

**Energy:**

\[
e(r, t) = \frac{1}{2} \nu^2(r, t) \quad (k(r, t) = \frac{1}{2} \rho \nu^2(r, t))
\]

\[
\partial_t e + \nabla \cdot \mathbf{J}_E = -\varepsilon_E
\]

with

\[
\mathbf{J}_E = (e + p)\mathbf{v} - \nu \nabla e
\]

\[
\varepsilon_E = \nu |\nabla \mathbf{v}|^2 = \nu \sum_{ij} (\partial_i v_j)^2 (= \varepsilon)
\]

\[
E(t) = \int e(r, t)d^d r, \quad \mathcal{E}_E(t) = \int \varepsilon_E(r, t)d^d r
\]

\[
\frac{\partial E}{\partial t} = -\varepsilon_E, \quad \nu \to 0 \implies \text{formally } \varepsilon_E = 0, \quad dE/dt = 0
\]

**Helicity (d = 3):**

\[
h(r, t) = \mathbf{v}(r, t) \cdot \mathbf{\omega}(r, t)
\]

\[
\partial_t h + \nabla \cdot \mathbf{J}_H = -\varepsilon_H
\]

with

\[
\mathbf{J}_H = h\mathbf{v} + (p - e)\mathbf{\omega} - \nu \nabla h
\]

\[
\varepsilon_H = 2\nu \nabla \mathbf{v} : \nabla \mathbf{\omega} = 2\nu \sum_{ij} (\partial_i v_j)(\partial_j \omega_i)
\]

\[
H(t) = \int h(r, t)d^3 r, \quad \mathcal{E}_H(t) = \int \varepsilon_H(r, t)d^3 r
\]

\[
\frac{dH}{dt}(t) = -\mathcal{E}_H, \quad \nu \to 0 \implies \text{formally } \mathcal{E}_H = 0, \quad dH/dt = 0
\]
The helicity integral

\[ H = \int d^3 x \, \mathbf{v}(x, t) \cdot \mathbf{\omega}(x, t) \]

has an interesting interpretation in terms of the topology of vortex-lines. For example, for two vortex tubes \( T_1, T_2 \) with vorticity fluxes \( \Phi_1, \Phi_2 \) (and no twist!)

\[ H = 2lk(T_1, T_2)\Phi_1\Phi_2 \]

where \( lk(T_1, T_2) \) is the Gauss linking number:

Figure 1. \( H = \pm 2\Phi_1\Phi_2 \)

More generally, the helicity represents the average self-linking of the vortex lines. See:


Proof for energy: $e = \frac{1}{2}v_i^2$

$$\partial_t e = v_i \dot{v}_i$$

$$= v_i \left[-(v \cdot \nabla) v_i - \partial_i p + \nu \partial_j^2 v_i\right]$$

$$= -(v \cdot \nabla)(\frac{1}{2}v_i^2) - \partial_i(p v_i) + \partial_j(\nu v_i \partial_j v_i) - \nu(\partial_j v_i)^2$$

$$= -\nabla \cdot [(e + p)v] + \nabla \cdot [\nu \nabla e] - \varepsilon_k$$

Proof for helicity: $h = v_i \omega_i$

$$\partial_t h = v_i \dot{\omega}_i + \dot{v}_i \omega_i$$

$$= v_i \left[-(v \cdot \nabla) \omega_i + (\omega_j \partial_j) v_i + \nu \partial_j^2 \omega_i\right]$$

$$+ \omega_i \left[-(v \cdot \nabla) v_i - \partial_i p + \nu \partial_j^2 v_i\right]$$

$$= -(v \cdot \nabla)(v_i \omega_i) + (\omega \cdot \nabla)(\frac{1}{2}v_i^2 - p)$$

$$+ \nu \partial_j(v_i \partial_j \omega_i + \omega_j \partial_j v_i) - 2\nu \partial_j v_i \partial_j \omega_i$$

$$= -\nabla \cdot [h v + (p - e)\omega] + \nabla \cdot [\nu \nabla h] - \varepsilon_H$$

Remark # 1: Set $S_{ij} = \frac{1}{2}(\partial_i v_j + \partial_j v_i)$ and $\Omega_{ij} = \frac{1}{2}(\partial_i v_j - \partial_j v_i) = -\frac{1}{2} \varepsilon_{ijk} \omega_k$. Then, $\varepsilon_E = \nu |\nabla v|^2 = \nu(S^2 + \Omega^2) = \nu(S^2 + \frac{1}{2} \omega^2)$ using $\varepsilon_{ijk} \varepsilon_{ijl} = 2 \delta_{kl}$. From

$$-\Delta p = (\nabla v) : \nabla v$$

$$= S^2 - \Omega^2 = S^2 - \frac{1}{2} \omega^2$$

$$\Rightarrow \int S^2 d^d r = \frac{1}{2} \int \omega^2 d^d r$$

$$\therefore \mathcal{E}_E = 2\nu \int S^2 d^d r = \nu \int \omega^2 d^d r = 2\nu \Omega$$

$$\Omega = \frac{1}{2} \int \omega^2 d^d r = \text{enstrophy}$$

Note that only $2\nu S^2$ represents the true dissipation, in that it is only this term which appears in the equation for internal energy $e_0$ and which describes local heating of the fluid.

Remark # 2 (d=2): $\partial_t \omega + \nabla \cdot [v \omega] = \nu \Delta \omega$ (no vortex stretching!)

$$\partial_t \left(\frac{1}{2} \omega^2\right) + \nabla \cdot \left[\frac{1}{2} \omega^2 v - \nu \nabla (\frac{1}{2} \omega^2)\right] = -\nu |\nabla \omega|^2.$$
Instead there is an extra term $\omega^T S \omega$ for $d = 3$!

\[
\Gamma(t) = \int \omega(r, t)d^2r = \text{total circulation}
\]
\[
P(t) = \frac{1}{2} \int |\nabla \omega(r, t)|^2 d^2r = \text{palinstrophy}
\]

\[
\Rightarrow
\]
\[
\frac{d\Gamma}{dt}(t) = 0
\]
\[
\frac{d\Omega}{dt}(t) = -2\nu P(t)
\]
\[
\therefore \text{formally } \nu \to 0 \Rightarrow \frac{d\Omega}{dt} = 0
\]

Remark # 3: Since the mean dissipation

\[
\varepsilon = \nu \langle |\nabla v|^2 \rangle,
\]

it follows that

\[
\langle |\nabla v|^2 \rangle \sim \frac{\varepsilon}{\nu} \sim \mathcal{O}(Re)
\]
as $Re \to \infty$. Thus, the velocity field must be non-differentiable (in mean-square sense) as $Re \to \infty$. This was described by Onsager (1945) as a “violet catastrophe”, or what physicists now call an “ultraviolet (or short-distance) divergence.” Also

\[
\varepsilon = 2\nu \Omega
\]

where $\Omega = \frac{1}{2} \langle \omega^2 \rangle$ is the enstrophy. Thus

\[
\Omega \sim \frac{\varepsilon}{2\nu} \sim \mathcal{O}(Re).
\]

Hence, turbulence at high Reynolds number has some efficient mechanism of generation of large amounts of enstrophy. This mechanism was identified by G.I. Taylor (1917, 1937) as vortex-stretching, a vorticity-magnification due to turbulent vortex-line growth (see below!)

This cannot occur in 2D! In 2D:

\[
\frac{d\Omega}{dt} = -2\nu P(t) \leq 0 \Rightarrow \Omega(t) \leq \Omega(t_0)
\]
Thus,

\[ \varepsilon(t) = 2\nu\Omega(t) \leq 2\nu\Omega(t_0) = O\left(\frac{1}{Re}\right) \]

and \( \lim_{\nu \to 0} \varepsilon(t) = 0 \) in 2D!

**Kelvin Circulation Theorem**

Circulation around loop \( C \):

\[ \Gamma_C = \oint_C \mathbf{v} \cdot d\mathbf{x} = \int_S \omega \cdot d\mathbf{A} \quad \text{(Stokes theorem)} \]

where \( S \) is any surface that spans the loop \( C \):

\[ \text{Figure 2. Vorticity flux through surface } S \text{ bounded by } C. \]

**Lagrangian map**

\[
\frac{d\mathbf{X}}{dt}(a, t) = \mathbf{v}(\mathbf{X}(a, t), t) \\
\mathbf{X}(a, 0) = a
\]
\[
\Gamma_C(t) = \oint_{C(t)} \mathbf{v}(t) \cdot d\mathbf{x}
\]

Kelvin Theorem

\[
\frac{d}{dt} \Gamma_C(t) = \nu \oint_{C(t)} \Delta \mathbf{v}(t) \cdot d\mathbf{x}
\]

\[
\nu \to 0 \implies \frac{d}{dt} \Gamma_C(t) = 0
\]

Note: Kelvin’s Theorem is equivalent to the Navier-Stokes equations!

Figure 3. Evolution of a material loop \(C(t)\)

Proof of Kelvin Theorem:

\[
\Gamma_{C(t)} = \oint_{C(t)} \mathbf{v}(t) \cdot d\mathbf{l} \\
= \oint_{C(0)} \mathbf{v}(\mathbf{X}(t), t) \cdot d\mathbf{l}(t)
\]

\[
\frac{d}{dt} \mathbf{v}(\mathbf{X}(t), t) = (D_t \mathbf{v})(\mathbf{X}(t), t)
\]

\[
= -\nabla p(\mathbf{X}(t), t) + \nu \Delta \mathbf{v}(\mathbf{X}(t), t)
\]

\[
d\mathbf{l}(t + \Delta t) = d\mathbf{l}(t) + \Delta t (d\mathbf{l}(t) \cdot \nabla)\mathbf{v}(\mathbf{r}, t)
\]

\[
\therefore \ d\mathbf{l}(t) = (d\mathbf{l}(t) \cdot \nabla)\mathbf{v}(\mathbf{X}(t), t)
\]
Finally,

\[
\frac{d\Gamma_{C(t)}}{dt} = \oint_C \left[ -\nabla p \cdot dl + \mathbf{v} \cdot (dl \cdot \nabla)\mathbf{v} + \nu \Delta \mathbf{v} \cdot dl \right]
\]

\[
= \nu \oint_{C(t)} \Delta \mathbf{v} \cdot dl
\]

Taylor’s Vortex-Stretching Picture

Figure 5. A vortex tube is being stretched.
\[
\frac{\omega}{\omega_0} = \frac{\omega dA \ell}{\omega_0 dA_0 d\ell_0}
\]

\[
\therefore \quad dA \ell = dA_0 d\ell_0 \text{ from incompressibility}
\]

and since also \( \omega dA = \omega_0 dA_0 \) from Kelvin-Helmholtz

\[
\therefore \quad \frac{\omega}{\omega_0} = \frac{d\ell}{d\ell_0} \gg 1
\]

Since the volume of the tube is also conserved,

\[
\int \omega^2(t) d^3x \gg \int \omega_0^2 d^3x
\]


Does this argument justify

\[
\lim_{\nu \to 0} \varepsilon = \lim_{\nu \to 0} \nu \int \omega^2 d^3x \neq 0?
\]

Problem:

\[
\frac{d}{dt} \Gamma_c(t) = \nu \oint_{C(t)} \nabla \cdot \mathbf{v} \cdot d\mathbf{l}
\]

\to 0 \text{ when } \nu \to 0???

In fact, circulations are not conserved in high Reynolds number turbulence, except in some average sense! Although Taylor’s idea is doubtless part of the final answer, the details are still not understood.

It is possible to neglect the effects of viscosity on the large-scales, as we discuss next...
NOTES & REFERENCES

Mathematics of the Navier-Stokes equation


http://www.cloymath.org/millenium/Navier-Stokes_Equations

Pressure Boundary Conditions


Helicity Conservation

