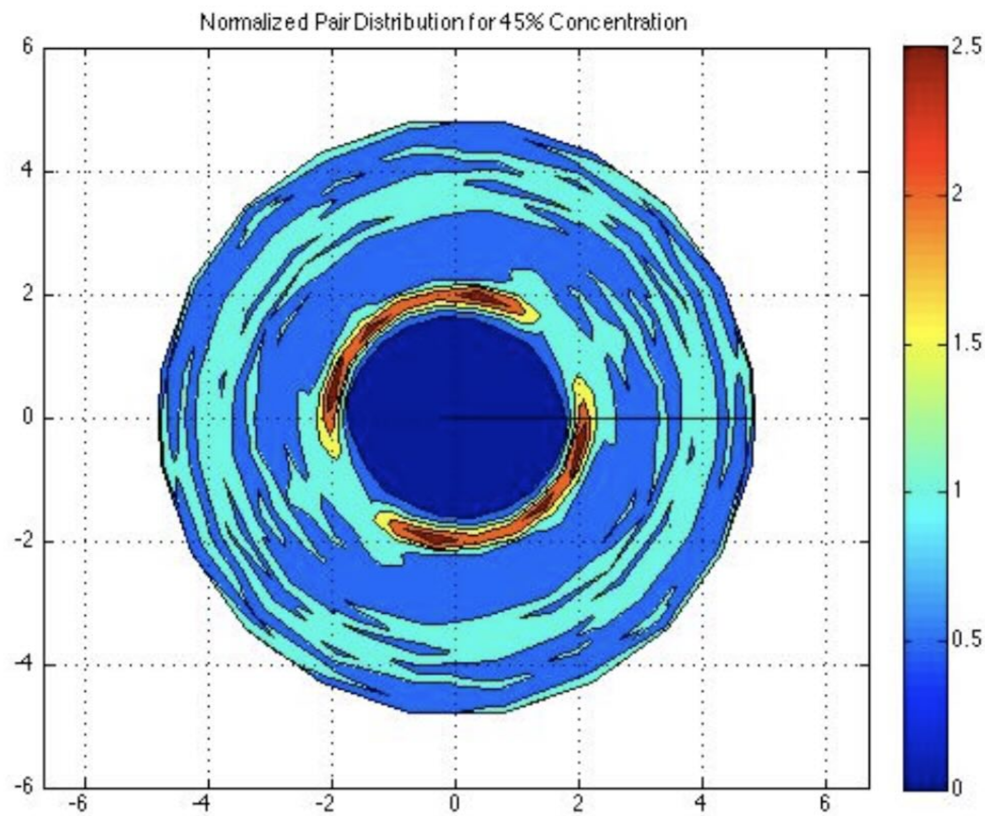
A Glossary of Terms for Fluid Mechanics

Eleanor T Leighton
David T. Leighton, Jr.

Department of Chemical and Biomolecular Engineering
University of Notre Dame



Diffusive Press
https://www.diffusivepress.org

Published by Diffusive Press
https://www.diffusivepress.org

About the Cover: The front cover image shows the particle pair distribution for a 45% volume fraction suspension of spheres undergoing simple shear flow. The anisotropic distribution arises from particle contact in the compression quadrant of the shear flow, and results in the fascinating non-Newtonian rheology of such suspensions.

A Glossary of Terms for Fluid Mechanics

E. T. Leighton

D. T. Leighton

Department of Chemical & Biomolecular Engineering

University of Notre Dame

To "walk the walk" in any discipline it is necessary to first be able to "talk the talk". Thus, we provide the following glossary of terms used in CBE30355 Transport I. It is not a comprehensive list, of course, and many additional terms, dimensionless variables, and phenomena could be listed. Still, it covers the main ones and should help you with the "language" of fluid mechanics - it originated as a set of flash cards which were prepared by a student taking Transport for this very purpose. We have divided the terms into groups including mathematical operators, symbol definitions, defining terms and phenomena, dimensionless groups, and a few key names in fluid mechanics. The material is listed in alphabetical order in each category, however some of the material we will get to only fairly late in the course. Most of the terms, etc., are described in more detail in the class notes, in class, in the supplemental readings, or in the textbook. For convenience, a hyperlink to a pertinent Wikipedia article is provided for each term for further clarification.

Mathematical Operators

Term	**Definition**
Anti-symmetric Tensor	A tensor is anti-symmetric with respect to an index subset if it alternates sign when any two of the subset indices are interchanged. For example $A_{ijk} = -A_{jik}$ holds when the tensor is anti-symmetric with respect to its first two indices. It does not need to have any symmetries with respect to other indices! If a tensor changes sign under exchange of any pair of its indices (such as the third-order alternating tensor ε_{ijk}), then the tensor is completely anti-symmetric. Any second order tensor can be broken into the sum of symmetric and anti-symmetric tensors.
Body of Revolution	A 3-D shape that is swept out by rotating a closed 2-D curve (such as an ellipse, but it could be any planar shape) about an axis. The axis of this rotation then describes the orientation of the body of revolution. Rotation of a rectangle about the axis bisecting it produces a cylinder, for example.
Cross Product	$\mathbf{A} \times \mathbf{B}$ produces a vector perpendicular to both $\mathbf{A}$ and $\mathbf{B}$ with length proportional to $AB\sin\theta$, where θ is the internal angle between them. Example using determinants: $\mathbf{A} = a_1\hat{i} + a_2\hat{j} + a_3\hat{k}, \quad \mathbf{B} = b_1\hat{i} + b_2\hat{j} + b_3\hat{k}$ $$\mathbf{A} \times \mathbf{B} = \begin{vmatrix} \hat{i} & \hat{j} & \hat{k} \\ a_1 & a_2 & a_3 \\ b_1 & b_2 & b_3 \end{vmatrix} = (a_2b_3 - a_3b_2)\hat{i} - (a_1b_3 - a_3b_1)\hat{j} + (a_1b_2 - a_2b_1)\hat{k}$$
Curl	Cross product of the gradient operator with a vector: $\nabla \times \vec{u}$. Equal to the vorticity when applied to the velocity vector. The vorticity is twice the local angular velocity (rate of rotation) of the fluid.

Cylindrical Coordinates	The coordinate system $[r, \theta, z]$.
Director	A vector describing the orientation of a body of revolution, or the orientation vector associated with a structured fluid (e.g., a suspension of oriented rods).
Divergence	The inner product of the gradient operator with a vector: $$\nabla \cdot \vec{u}$$ Zero for incompressible fluids (or solenoidal vector fields).
Divergence Theorem	A way of converting surface integrals into volume integrals, e.g. $$\iint_S (\rho u_i) u_j n_j \, dA = \iiint_V \frac{\partial}{\partial x_j} (\rho u_i u_j) \, dV$$.
Dot Product	A scalar produced by two nonzero vectors **A** and **B**. Defined as $$\mathbf{A} \cdot \mathbf{B} = \|A\|\|B\| \cos \theta$$ where these are the vector magnitudes and θ is the angle. For tensors, the dot or inner product reduces combined order by two (e.g., 1+1-2 = 0).
Flat Earth Limit	Just as the world appears flat from a human length scale, so curvilinear and spherical coordinates can often be reduced to appropriately defined Cartesian coordinates in the limit when $\Delta R/R \ll 1$. Usually we take x, z to be tangential coordinates and $y = r - R$ to be normal to a surface.
Fore-and-Aft Symmetry	Objects where the front and back are mirror images (e.g., cylinder, dumbbell or a pair of spheres glued together) are invariant under sign change of the orientation director. Mathematically, all relationships are invariant to the sign of the director describing the orientation.
Grad Symbol	The gradient operator ("del") is ∇. Examples: Applied to scalar p: $$\nabla p = \frac{\partial p}{\partial x} \hat{e}_x + \frac{\partial p}{\partial y} \hat{e}_y + \frac{\partial p}{\partial z} \hat{e}_z$$ To vector $\tilde{u}$: $$\nabla \cdot \tilde{u} = \frac{\partial u_x}{\partial x} + \frac{\partial u_y}{\partial y} + \frac{\partial u_z}{\partial z}$$.
Index Notation	Also known as Einstein notation, this is the natural language for describing vectors, tensors, and fluid mechanics. The tensor order equals the number of free (unrepeated) indices (e.g., the matrix A_{ij} has two unrepeated indices). Repeated indices denote inner or dot products and implies summation.
Isotropic Tensor	A tensor invariant under rotation of its coordinate system. All scalars (0th-order tensors) are isotropic; vectors are not (except zero length). Rank-2 isotropic tensors are proportional to δ_{ij}; rank-3 to ε_{ijk}. Isotropic fourth order tensors contain the three possible combinations of pairs of Kronecker delta functions. Don't confuse isotropy with symmetry!
Kronecker Delta Function	The symbol δ_{ij} equals 1 if $i = j$, else 0. Represents the identity matrix in index notation and is key in tensor algebra.

Matrix Notation	Vectors and tensors are denoted by overbars or underbars (which may be lines or squiggles). The number of squiggles underneath the matrix symbol **A** indicates the order of the tensor. Alternatively, in classical Gibbs Dyadic Notation, vectors are bold lowercase letters (e.g., **a**) and matrices are bold uppercase letters (e.g., **A**). Index notation is less ambiguous.
Physical Tensor	A tensor whose sign does not depend on the choice of right- or left-handed coordinate system. Examples include position, velocity, mass, and stress. These are contrasted with pseudo tensors.
Pseudo Tensor	A tensor that changes sign under orientation-reversing coordinate transformations. Pseudo tensors convert to physical tensors by multiplication with another pseudo tensor (e.g., pseudo $\times$ pseudo = physical). Examples: angular velocity, torque, vorticity.
Rank of a Matrix	The dimension of the largest sub-matrix with a non-zero determinant. For example: $$\mathbf{A} = \begin{bmatrix} 2 & 5 \\ 3 & 6 \end{bmatrix} \Rightarrow \text{rank} = 2$$ A matrix is of full rank if its rank equals the minimum of the number of rows or columns. In dimensional analysis, the rank of a dimensional matrix is the number of independent fundamental units.
Repeated Index	In index notation, repeating an index implies summation (Einstein summation convention), representing inner or dot products: $$\mathbf{x} \cdot \mathbf{y} = x_i y_i = x_1 y_1 + x_2 y_2 + x_3 y_3$$ An index cannot be repeated more than twice in any single term.
Scalars	Point values or numbers with magnitude but no direction. For instance, u_1 is a scalar (one component), while u_i represents a vector.
Surface Integral	A generalization of multiple integrals to integration over surfaces. For example: $$\iint_D f\, dA \quad \text{or} \quad \iint_D \phi\, \mathbf{u} \cdot \mathbf{n}\, dA$$ where **n** is the normal vector to the surface.
Symmetric Tensor	A tensor that is invariant under a permutation of its vector arguments. In other words, a matrix A is the same as its transpose, i.e., $A_{ij} = A_{ji}$, or $\mathbf{A} = \mathbf{A}^T$. Any second-order tensor can be decomposed into the sum of symmetric and anti-symmetric tensors. A higher-order tensor may be symmetric with respect to some pairs of its indices and not others; for example, $A_{ijk} = p_i p_j n_k$ is symmetric with respect to i and j, but not i and k.
Tensor	A tensor can be represented as a multi-dimensional array of numerical values, or in other words, as a matrix in zero (scalar), one (vector), two (usual matrix), or higher number of dimensions.
Third Order Alternating Tensor	Symbol: ε_{ijk}. Also called the third-order Levi-Civita symbol. An anti-symmetric, isotropic pseudo-tensor used in curls and cross products in index notation. It has $3^3 = 27$ elements, only six of which are non-zero: $$\varepsilon_{123} = \varepsilon_{312} = \varepsilon_{231} = 1, \quad \varepsilon_{321} = \varepsilon_{213} = \varepsilon_{132} = -1.$$ ε_{ijk} is $+1$ if i, j, k are cyclic, and -1 if counter-cyclic.

Time Averaging	Used to average out fluctuations over a small time interval in turbulent flow. This process is used to develop a set of time-averaged equations for turbulent flow. For example: $$\overline{u}(t) = \frac{1}{\Delta t}\int_{t}^{t+\Delta t} u(\tau)\,d\tau.$$
Trace	The trace of an $n \times n$ square matrix A is defined to be the sum of the elements on the main diagonal of A. For example, if $$A = \begin{bmatrix} a & b & c \\ d & e & f \\ g & h & i \end{bmatrix}, \quad \text{then} \quad \operatorname{tr}(A) = a + e + i.$$ In index notation: $\operatorname{tr}(\delta_{ij}) = \delta_{ii} = 3$, or $\operatorname{tr}(A) = A_{ij}\delta_{ij} = A_{ii} = A_{jj}$.
Transpose	Notation: A' or A^T. The transpose of a matrix switches its rows and columns. For example, if $$A = \begin{bmatrix} 2 & 4 \\ 5 & 6 \end{bmatrix}, \quad \text{then} \quad A^T = \begin{bmatrix} 2 & 5 \\ 4 & 6 \end{bmatrix}.$$
Vector Notation	Example: $\vec{u}$ The single underbar (or squiggle) indicates a single vector consisting of the elements of $\vec{u}$. For example: $$\vec{u} = \begin{bmatrix} 0 \\ 2 \\ 4 \end{bmatrix}$$
Volume Integral	An integral over a three-dimensional domain, such as: $$\iiint_D f\,dx\,dy\,dz = \int_D f\,dV$$

Equations and Derivations

Term	Definition
Bernoulli's Equation	Conservation of mechanical energy in fluid flow (ignoring all frictional losses). $$p_1 + \frac{1}{2}\rho U_1^2 + \rho g h_1 = p_2 + \frac{1}{2}\rho U_2^2 + \rho g h_2$$ where • p is the local (static) pressure • ρ is the fluid density • U is the average fluid velocity • g is the gravitational acceleration • h is the height above a reference plane.
Biharmonic Equation	The equation governing the stream function ψ for 2-D Stokes flow: $$\nabla^4\psi = 0$$
Blasius Equation	The Blasius equation describes the stream function $f = f(\eta)$ for steady 2-D boundary layer flow on a semi-infinite flat plate aligned with a uniform external flow of speed U: $$f''' + ff'' = 0$$ with boundary conditions $f(0) = f'(0) = 0$, and $f'(\eta) \to 1$ as $\eta \to \infty$. Similarity variable: $$\eta = \left(\frac{U}{2\nu x}\right)^{1/2} y$$ The velocity in the x-direction is given by $u_x = f'(\eta)$.
Body Force	The force on each fluid element within the interior of a domain. For example, the gravitational body force: $$\vec{F}_{\text{body}} = \int_D \rho\vec{g}\, dV$$ where $\vec{g}$ is the gravitational acceleration vector, and dV is a differential volume element.
Buoyancy	For an object submerged in a fluid at rest, the fluid exerts a force equal to the weight of the displaced volume of fluid. This buoyant force is given by: $$\vec{F}_{\text{buoy}} = -\rho_f \vec{g} V_f$$ where ρ_f is the fluid density, $\vec{g}$ is the gravitational acceleration, and V_f is the volume of fluid displaced.

Cauchy Stress Equations	These equations represent the balance of linear momentum in a continuum. In vector form: $$\rho \frac{D\vec{u}}{Dt} = \nabla \cdot \boldsymbol{\sigma} + \rho \vec{g}$$ In index notation: $$\rho \left(\frac{\partial u_i}{\partial t} + u_j \frac{\partial u_i}{\partial x_j} \right) = \frac{\partial \sigma_{ij}}{\partial x_j} + \rho g_i$$ They describe how momentum changes due to gradients in the total stress and body forces due to gravity.
Continuity Equation	The continuity equation is the mathematical expression of mass conservation. In differential form: $$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \vec{u}) = 0$$ This states that the time rate of change of density equals the negative divergence of the mass flux vector. For an incompressible fluid (constant ρ): $$\nabla \cdot \vec{u} = 0$$ In index notation: $$\frac{\partial \rho}{\partial t} + \frac{\partial (\rho u_i)}{\partial x_i} = 0 \quad \text{or} \quad \frac{\partial \rho}{\partial t} + u_i \frac{\partial \rho}{\partial x_i} = -\rho \frac{\partial u_i}{\partial x_i}$$
Darcy's Law	Describes flow through a porous medium. Valid when the Reynolds number based on pore radius is small. In scalar form: $Q = -\frac{kA}{\mu} \frac{(P_b - P_a)}{L}$ where k is the intrinsic permeability, A is cross-sectional area, μ is viscosity, and L is the flow length. In vector form: $u_i = -\frac{k}{\mu} \frac{\partial p}{\partial x_i}$
Displacement Thickness	Denoted by δ^*, it measures the effect of the boundary layer in displacing the outer streamlines. Defined by $\delta^* = \int_0^\infty \left(1 - \frac{u}{U}\right) dy$, where u is local fluid velocity and U is the free-stream velocity.
$E^4\psi = 0$	$$E^4\psi = 0$$ This is equivalent to the biharmonic equation for two-dimensional Stokes flow, but for axisymmetric Stokes flows (e.g., flow past a sphere). Valid only for zero Reynolds number.
Euler Flow Equations	$$\text{Momentum:} \quad \frac{D\vec{u}}{Dt} = -\frac{1}{\rho}\nabla P$$ $$\text{Continuity:} \quad \nabla \cdot \vec{u} = 0$$ Equations governing inviscid flow. Valid at high Reynolds number. The assumption of inviscid flow eliminates the no-slip boundary condition, leading to discontinuities in the velocity at surfaces that must be resolved by the boundary-layer equations.

Falkner-Skan Equation	Generalizes the Blasius solution for high Reynolds number flow with uniform velocity U_0 into a wedge with internal angle $\pi\beta$. $$f''' + ff'' + \beta\left(1 - (f')^2\right) = 0$$ where $$\eta = y\left(\frac{U_0(m+1)}{2\nu x}\right)^{1/2}, \quad \beta = \frac{2m}{m+1}$$ m is a dimensionless exponent: $m = 0$ gives Blasius (flat plate), $m = 1$ gives stagnation point flow.
Fick's Law	Fick's first law states that the mass flux via diffusion goes from regions of high concentration to regions of low concentration with a magnitude proportional to the concentration gradient: $$\vec{J} = -D\nabla c$$
Fourier's Law of Heat Conduction	$$\vec{q} = -k\nabla T$$ Here, $\vec{q}$ is the local heat flux (energy/(area*time)), k is the material's thermal conductivity, and T is temperature. For anisotropic materials, this generalizes to: $$q_i = -k_{ij}\frac{\partial T}{\partial x_j}$$
Integrable Singularity	A function that goes to infinity within a domain, but its integral over the domain is finite. For example, $f(x) = x^{-1/2}$ is infinite at $x = 0$, but integrable over a domain including zero.
Invariant	A property that does not change under a given set of transformations or conditions.
Laplace's Equation	The scalar Laplace equation is: $$\nabla^2\phi = 0$$ In Cartesian coordinates: $$\nabla^2 f = \frac{\partial^2 f}{\partial x^2} + \frac{\partial^2 f}{\partial y^2} + \frac{\partial^2 f}{\partial z^2} = 0$$ Its solutions are called harmonic functions. It describes, among many other things, the velocity potential for inviscid, irrotational, incompressible flow.
Material Derivative	The time rate of change of a quantity ϕ following a fluid element (Lagrangian perspective): $$\frac{D\phi}{Dt} = \frac{\partial\phi}{\partial t} + \vec{u}\cdot\nabla\phi$$
Momentum Thickness	A measure of the momentum removed from a boundary layer due to viscous diffusion to a surface. Defined as: $$\theta = \int_0^\infty \frac{u}{U}\left(1 - \frac{u}{U}\right)dy$$ Used in the von Kármán momentum balance to determine the stress on a flat plate.

Navier-Stokes Equations	The key equation governing conservation of momentum for an incompressible, isotropic (Newtonian) fluid with constant viscosity. In index notation: $$\rho\left(\frac{\partial u_i}{\partial t}+u_j\frac{\partial u_i}{\partial x_j}\right)=-\frac{\partial p}{\partial x_i}+\mu\frac{\partial^2 u_i}{\partial x_j^2}+\rho g_i$$ In vector notation: $$\rho\left(\frac{\partial \vec{u}}{\partial t}+(\vec{u}\cdot\nabla)\vec{u}\right)=-\nabla p+\mu\nabla^2\vec{u}+\rho\vec{g}$$ Explanation of terms: • $\rho\frac{\partial \vec{u}}{\partial t}$: local (unsteady) acceleration • $\rho(\vec{u}\cdot\nabla)\vec{u}$: convective acceleration (nonlinear inertia) • $-\nabla p$: pressure gradient force • $\mu\nabla^2\vec{u}$: viscous diffusion of momentum • $\rho\vec{g}$: gravitational body force For constant density, pressure and gravity can be combined into an augmented pressure via application of the equation governing hydrostatics.
Momentum Flux	Net convection of momentum out of a control volume can be expressed as: $$\int_A \rho\vec{u}\,(\vec{u}\cdot\vec{n})\,dA$$ where $\vec{n}$ is the outward-facing normal vector to the surface A.
Newton's Law of Viscosity	Describes the shear stress due to a velocity gradient in a Newtonian fluid. In Cartesian coordinates: $$\tau_{yx}=\mu\left(\frac{\partial u_x}{\partial y}+\frac{\partial u_y}{\partial x}\right)$$ In index notation for incompressible isotropic fluid: $$\tau_{ij}=\mu\left(\frac{\partial u_i}{\partial x_j}+\frac{\partial u_j}{\partial x_i}\right)$$ This gives the viscous contribution to the total stress tensor.
Normal Equations	The normal equations used in linear least squares regression are: $$A^TA\vec{x}=A^T\vec{b}$$ Solves for the vector $\vec{x}$ that minimizes the 2-norm of the residual $\vec{r}=A\vec{x}-\vec{b}$.
Poiseuille's Law	Describes volumetric flow rate Q of a viscous fluid through a cylindrical pipe: $$Q=\frac{\pi\Delta PR^4}{8\mu L}$$ where ΔP is the pressure drop, R is the pipe radius, L is the length, and μ is the dynamic viscosity. Valid for steady, incompressible, laminar flow (Poiseuille flow).

<table>
<tr><td>Prandtl Boundary Layer Equations</td><td>The governing equations for a laminar boundary layer near a solid surface. Continuity:

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0$$

Momentum (in x-direction):

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} = -\frac{1}{\rho}\frac{\partial p}{\partial x} + \nu\frac{\partial^2 u}{\partial y^2}$$

In dimensionless form, assuming $\mathrm{Re}_L \gg 1$, transverse distances are scaled with boundary layer thickness $\delta \sim \sqrt{L\nu/U}$, and diffusion of momentum in the x-direction scales out. The external pressure distribution in the x-direction (calculated from the Euler flow solution) is impressed on the boundary layer.</td></tr>
<tr><td>Reynolds Lubrication Equation</td><td>The dimensionless form is:

$$\frac{\partial}{\partial x^*}\left(h^{*3}\frac{\partial P^*}{\partial x^*}\right) = 6\left[h^*\frac{\partial U^*}{\partial x^*} - U^*\frac{\partial h^*}{\partial x^*} + 2V^*\frac{\partial h^*}{\partial x^*}\right]$$

This relates the tangential pressure gradient between two surfaces to the gap height h^*, tangential surface velocity U^*, and approach velocity V^*. It is valid when $h/L \ll 1$. Boundary conditions on the pressure are usually given at $x^* = 0$ and $x^* = 1$.</td></tr>
<tr><td>Stokes Flow Equations</td><td>These are the momentum conservation equations for a fluid at zero Reynolds number (no inertia or gravity):

$$\frac{\partial \sigma_{ij}}{\partial x_j} = 0$$

They describe creeping flows such as those around small particles in a viscous fluid.</td></tr>
<tr><td>Stokes' Law</td><td>The drag force on a sphere of radius a moving with velocity $\vec{U}$ in a fluid at low Reynolds number is:

$$\vec{F} = -6\pi\mu a\vec{U}$$

This result is fundamental in low-Reynolds-number hydrodynamics and underlies many results in the theory of suspensions.</td></tr>
<tr><td>Stokes' Sedimentation Velocity</td><td>The sedimentation velocity U_s of a sphere of radius a and density difference $\Delta\rho$ in a fluid of viscosity μ at zero Reynolds number is:

$$U_s = \frac{2\Delta\rho g a^2}{9\mu}$$

where g is the acceleration due to gravity.</td></tr>
<tr><td>Surface Force</td><td>Forces exerted on the surface of a body. Examples include:

$$F_i = \int_S \sigma_{ij} n_j \, dA$$

which is the integrated surface force over surface S, where σ_{ij} is the stress tensor and n_j is the outward unit normal vector.
If shear stresses are zero (e.g., hydrostatics), the integrated normal force reduces to:

$$\vec{F} = \int_S -p\,\vec{n}\,dA$$

where p is the pressure, dA is a differential surface patch, and $\vec{n}$ is the unit normal vector.</td></tr>
</table>

Von Karman Momentum Balance	The surface shear stress τ_0 on a plate at high Reynolds number inside a boundary layer is related to the momentum and displacement thicknesses by: $$\frac{\tau_0}{\rho} = \frac{d}{dx}\left(u_\infty^2 \theta\right) + \delta^* u_\infty \frac{du_\infty}{dx}$$ Experimentally, it allows measurement of shear stresses by evaluating integrals of the tangential velocity u, which is often easier and more accurate than evaluating the normal derivative of the tangential velocity.

Symbol Definitions

Term	Definition
Adverse Pressure Gradient	An adverse pressure gradient occurs when $\frac{\partial p}{\partial x} > 0$. In boundary layer flow, adverse (positive) pressure gradients cause rapid growth in boundary layer thickness and often lead to flow separation.
Angular Velocity	Symbol: Ω (Greek letter Omega), units: radians per second. Angular velocity is defined as the rate of change of angular displacement. It is a pseudovector that specifies the angular speed (rotational speed) of an object and, in vector form, the axis about which the object rotates.
Augmented Pressure	Symbol: P. In flows within a homogeneous system, the augmented pressure is defined as: $P = p - \rho g \, \vec{e}_g \cdot \vec{x}$ where p is the local pressure, ρ the fluid density, g the acceleration due to gravity, $\vec{e}_g$ the unit vector in the gravitational direction, and $\vec{x}$ the position vector. This subtracts the hydrostatic pressure variation; the deviation from hydrostatics drives the flow.
Average Velocity	Symbol: U, units: meters per second (m/s). Defined as the volumetric flowrate divided by the cross-sectional area normal to the flow: $U = \frac{Q}{A}$ where Q is the volumetric flowrate and A the cross-sectional area perpendicular to flow.
Boundary Layer Coordinates	Coordinates used in boundary layer flow: • x: distance along a surface from the leading stagnation point. • y: distance normal to the surface. For boundary layer flow, x scales with the size of the object L, and y scales with the boundary layer thickness δ. In the boundary layer limit, $\delta/L \ll 1$.
Centrifugal Force	A pseudoforce which arises from the coordinate transformation from Cartesian coordinates to cylindrical (polar) coordinates. It is a source of (positive) momentum in the radial direction. Mathematically, in the Navier-Stokes equations it is given by $-\rho \frac{u_\theta^2}{r}$ where u_θ is the tangential velocity and r is the radial distance. It is the apparent force that explains why a satellite does not fall toward Earth.

Coefficient of Thermal Expansion	Defined as $$\beta = \frac{1}{V}\frac{\partial V}{\partial T}$$ or for ideal gases $$\beta = \frac{1}{T}$$ Important values: • Water (H_2O) $\approx 2 \times 10^{-4}\,\mathrm{K}^{-1}$ • Metals $\approx 5 \times 10^{-5}\,\mathrm{K}^{-1}$ This coefficient represents the amount a material expands when heated and is important in natural convection problems, such as drafts near windows.
Coriolis Force	An apparent force in the θ-direction caused by velocities in the radial and θ-directions, resulting from the transformation from Cartesian to cylindrical coordinates. Mathematically it is expressed as $$\rho\frac{u_\theta u_r}{r}$$ where u_θ is the θ-direction velocity, u_r is the radial velocity and r is the radial distance. It explains why low-pressure systems (e.g., hurricanes) circulate counterclockwise in the Northern Hemisphere, combining inward radial velocity due to pressure gradients with the Earth's rotation effects.
Critical Surface Roughness	Denoted $e^+ \approx 7$, it is the wall roughness magnitude e normalized by the viscous length scale in turbulent pipe flow. At this value, the roughness elements protrude beyond the viscous sublayer, causing the friction factor to depend mostly on roughness rather than the smooth pipe correlation.
Darcy Friction Factor	Defined as four times the Fanning friction factor. It is used to describe friction losses in pipe flow.
Density	Defined as mass per unit volume, $\rho = \frac{M}{V}$, with common units of $\mathrm{g/cm^3}$.
Density (Values)	Typical values include: • Water: $\rho \approx 1\,\mathrm{g/cm^3}$ • Air: $\rho \approx 1.2 \times 10^{-3}\,\mathrm{g/cm^3}$ • Mercury: $\rho \approx 13.6\,\mathrm{g/cm^3}$
Deviatoric Stress	The component of the stress tensor with the isotropic pressure removed. For an incompressible, isotropic fluid, the deviatoric stress tensor is: $$\tau_{ij} = \mu\left(\frac{\partial u_j}{\partial x_i} + \frac{\partial u_i}{\partial x_j}\right)$$ It is symmetric and traceless for incompressible fluids. It arises from the deformation of a fluid and is identically zero for isotropic fluids at rest (e.g., hydrostatics).

Drag Coefficient	A dimensionless quantity representing drag force normalized by dynamic pressure and reference area: $$F = C_D \cdot \frac{1}{2}\rho U^2 A$$ For a flat plate, a local drag coefficient is defined as: $$C_D^{(\text{loc})} = \frac{\tau_w}{\frac{1}{2}\rho U^2}$$ where τ_w is the wall shear stress. Important at high Reynolds number.
Eddy Viscosity	Used in modeling turbulent shear stress: $$\tau_{yx}^{\text{turb}} = -\{\mu_T\}\left(\frac{\partial u}{\partial y}\right)$$ where μ_T is the eddy viscosity, estimated using Prandtl's mixing length theory: $$\mu_T \sim \rho \ell^2 \left\lvert \frac{\partial u}{\partial y} \right\rvert$$ Here, ℓ is the mixing length (eddy size), and $\partial u/\partial y$ is the shear rate (the rate with which eddies exchange places).
Euler's Constant γ	The Euler constant $\gamma \approx 0.5772$ arises in a number of problems, particularly integrals of exponentials and logarithms. In fluid mechanics, it appears in Lamb's solution to flow past a circle (infinite cylinder) at low Reynolds number (see Stokes' Paradox).
Fanning Friction Factor f_f	The wall shear stress divided by the dynamic pressure in turbulent pipe flow. Used for calculating pressure drop in pipes.
Favorable Pressure Gradient	$$\frac{\partial p}{\partial x} < 0$$ A negative pressure gradient retards boundary layer growth and delays boundary layer separation.
Fluctuation Velocity	The instantaneous deviation from the average velocity in turbulent flow.
Friction Velocity	$$v_* = \sqrt{\tau_w/\rho}$$ where τ_w is the wall shear stress and ρ is the fluid density. The appropriate velocity scaling in turbulent flow near a wall.
Head Loss	Loss in hydrostatic head due to flow. Useful for pipe flow calculations at high Reynolds number. For pipes: $$h_L = \frac{\Delta P}{\rho g} = 4 f_f \frac{L}{D}\frac{\langle u\rangle^2}{2g}$$ and for fittings: $$h_L = \frac{\Delta P}{\rho g} = K\frac{\langle u\rangle^2}{2g}$$ where K values are determined empirically.

Kinematic Viscosity	The diffusion coefficient for momentum, often called momentum diffusivity. Symbol: ν. Common units: cm^2/s (stokes). Related by $\nu = \mu/\rho$, where μ is the dynamic viscosity and ρ is the density. Typical values: water ≈ 0.01 stokes, air ≈ 0.15 stokes, mercury ≈ 0.0011 stokes, glycerine ≈ 11 stokes (strongly temperature-dependent).
Kinetic Energy/Volume	Also called dynamic pressure. Given by $\frac{1}{2}\rho u^2$. This is the pressure increase you would measure if the flow were brought to rest isentropically.
Mass Flux	Defined as $\rho\vec{u}$, with units of mass per area per time. Equivalent to momentum per volume.
Mean Free Path Length	In a gas, the average distance a molecule travels before colliding with another. Given by $$\lambda = \frac{1}{\sqrt{2}\pi d^2 n}$$ where d is the molecular diameter and n is the number density. The continuum hypothesis breaks down at distances comparable to or smaller than λ.
Moment of Inertia	A mass property describing a body's resistance to angular acceleration. For a volume V, $$I = \int_V \rho s^2 \, dV$$ where s is the perpendicular distance to the axis of rotation.
Momentum Flux	Also called the stress tensor. Symbol: σ_{ij}. It represents the force per unit area exerted by fluid of greater i on fluid of lesser i in the j-direction. It is the flux of momentum per area per time due to surface forces. Except in special cases (e.g., body torque per unit volume), the stress tensor is symmetric.
Momentum Diffusion	$\mu \dfrac{\partial^2 u_x}{\partial y^2}$ describes viscous diffusion of x-momentum in the y-direction.
Normal Stress	Symbol: σ_{xx}, e.g., normal stress in the x-direction. Defined as the component of the force vector perpendicular to a cross-sectional area. Mathematically, $$\vec{f}_n = (\vec{f} \cdot \vec{n})\,\vec{n}$$ where $\vec{f}$ is the force per area vector (surface stress) and $\vec{n}$ is the unit normal vector to the surface.
Plus Units	Dimensionless variables used in turbulent flow near a boundary. Typically denoted with a superscript +, such as velocity normalized by the friction velocity, distance from the wall normalized by the viscous length scale, and time normalized by ν/v_*^2, where ν is kinematic viscosity and v_* is friction velocity.
Pressure	Symbol: p. Common unit: Pascal (Pa), defined as $\text{N/m}^2 = \text{kg}/(\text{m}\cdot\text{s}^2)$. Pressure is the average of the normal stresses in a fluid, i.e., $$p = -\frac{1}{3}(\sigma_{xx} + \sigma_{yy} + \sigma_{zz})$$ Pressure is also the normal force per unit area exerted on a fluid at rest. One atmosphere is 1.013×10^5 Pa, equivalent to about 10.3 meters of water.
Reynolds Stress	The added momentum flux (stress) due to turbulent velocity fluctuations, often expressed as $-\rho\langle u_i' u_j' \rangle$.
Shape Factor	It is a dimensionless measure of the shape of the boundary layer velocity profile, defined as $H = \delta^*/\theta$. For laminar flow over a flat plate, $H = 2.59$; it is smaller in turbulent boundary layer flow.

Shear Stress	$$\tau_{yx} = \mu \left(\frac{\partial u_x}{\partial y} + \frac{\partial u_y}{\partial x} \right)$$ Shear stress arises from the force vector component parallel to a surface. It is one of the off-diagonal elements of the stress tensor. For Newtonian fluids in laminar flow, the shear stress is proportional to the strain rate.
Shear Rate (Rate of Strain)	Symbol: $$\dot{\gamma} \; or \; \frac{d\gamma}{dt}$$ In simple shear flow, the shear rate is defined as $\dot{\gamma} = \frac{U}{D}$, where U is the relative tangential velocity and D is the plate separation. More generally, it is the magnitude of the symmetric part of the rate of strain tensor. Units: 1/time.
Speed of Sound (V_s)	The speed at which pressure disturbances (sound waves) propagate through a fluid. For an ideal gas: $$V_s = \sqrt{\left(\frac{\partial P}{\partial \rho} \right)_s} = \sqrt{\frac{\gamma RT}{M}}$$ where P is pressure, T is temperature, R is the gas constant, M is molar mass, and γ is the heat capacity ratio. When the flow velocity U approaches V_s, compressibility effects become important and shock waves can develop.
Surface Tension	Usually given the symbol γ, Γ, or σ. It is a measure of the energy required to increase the surface area between two immiscible fluids. Units: energy/area (e.g., dyne/cm, or erg/cm^2). Surface tension causes droplets and bubbles to adopt spherical shapes to minimize surface area. For pure water in air, $\gamma \approx 70\,\text{dyne/cm}$. Surfactants can reduce this value significantly.
Thermal Diffusivity	The rate at which heat diffuses through a material. Defined as: $$\alpha = \frac{k}{\rho C_p}$$ where k is thermal conductivity, ρ is density, and C_p is specific heat at constant pressure. Units: length^2/time.
Torque (or Couple)	A measure of the tendency of a force to rotate an object about an axis. Given by: $$\vec{M} = \vec{R} \times \vec{F}$$ where $\vec{R}$ is the position vector and $\vec{F}$ is the applied force. Units: force $\times$ length (same as energy, e.g., N m or erg).
Unit Normal	A unit vector perpendicular to a surface element dA. To extract the component of a vector $\vec{f}$ normal to the surface, compute: $$\vec{f}_n = (\vec{f} \cdot \hat{n})\hat{n}$$ which gives the projection of $\vec{f}$ onto the normal direction.
Viscosity	Symbol: μ. Common unit: g/(cm $\cdot$ s) (poise). Units: mass/(length $\cdot$ time). Values you need to know: Water: $0.01\,\text{P} = 1\,\text{cP}$ (centipoise) Air: $0.00018\,\text{P} = 0.018\,\text{cP}$ Glycerine: $\sim 14\,\text{P}$ (very temperature sensitive!)

Viscous Length Scale	Symbol: $$\lambda = \nu / u_*$$ The ratio of kinematic viscosity to the friction velocity. Represents the length scale over which viscous effects are significant in turbulent flow.
Volumetric Flux	Defined as volume per unit area per unit time. Same as velocity. Given by $$\vec{u} = \frac{\text{volume}}{\text{area} \times \text{time}}$$
Von Karman Constant	Symbol: $$\kappa = 0.36 \; (or \; 0.40)$$ A fitting parameter used in Prandtl Mixing Length Theory to determine the length scale of turbulent eddies.
Vorticity	Symbol: $$\vec{\omega} = \nabla \times \vec{u} \;\; or \;\; \omega_i = \varepsilon_{ijk} \frac{\partial u_k}{\partial x_j}$$. ω_i is a pseudovector, u_k is a physical vector. Vorticity is twice the local angular velocity (rate of rotation) of a fluid.
Young's Modulus of Elasticity	Symbol: E. Common units: psi, Pa, dyne/cm^2. Defined as $E = \frac{\text{shear stress}}{\text{strain}}$. Young's modulus is the measure of stiffness of a linearly elastic material. It is the ratio of stress to strain along an axis and is the solid analog to the dynamic viscosity of a liquid.

Defining Terms and Phenomena

Term	Definition
Aeroelastic Flutter	An instability arising from the interaction between lateral forces due to vortex shedding and the natural resonant frequencies of a structure. This is what caused the collapse of the Tacoma Narrows Bridge, for example. Closely related to the von Karman vortex street.
Affine Stretching	Stretching dependent and independent variables by scaling parameters. Useful to find self-similar solutions.
Angle of Attack	The angle between a reference line on a body and the direction of travel through a fluid. For a wing, it is the angle the wing is pitched up. A high angle of attack increases both lift and drag, and may lead to boundary layer separation (stall).
Approximate Dynamic Similarity	Only the important dimensionless groups are preserved in dimensional scaling using this method. In scale models of ships, for example, the Froude number (Fr) is preserved, while the Reynolds number (Re) is kept "high".
Average vs. Centerline Velocity	Because of no-slip at the wall, in laminar flow through a conduit the centerline velocity is always greater than the average velocity. For a circular tube it is 2x the average, while for channel flow it is 1.5x the average. This is important: it is what makes clearing bubbles from a syringe possible. The convective effects of this ratio gave rise to the meniscus accumulation in squeeze flow. Most importantly, it leads to Taylor dispersion (the spread of a slug of solute in chromatography).
BEP (Best Efficiency Point)	As you move away from the line containing this point on a pump curve, the pump efficiency goes down.
Bingham Plastic	A fluid with a linear relationship between stress and strain, but which also has a yield stress associated with it. Mayonnaise is a good example.
Boston Molasses Flood	In 1919, downtown Boston was flooded by molasses from a burst tank, probably caused in part by thermal expansion of the molasses on a warm day in January.
Boundary Condition	A constraint on a dependent variable at the boundary in a differential equation. In fluid mechanics, it is usually a prescribed velocity or shear stress.
Boundary Layer	The thin region in the immediate vicinity of a bounding surface (such as a wall) where the viscous terms (e.g., diffusion) necessary to satisfy the no-slip condition come into play.
Boundary Layer Separation	Occurs when the boundary layer becomes detached from the surface of the object. In high Reynolds number flow past a bluff body, separation leads to a lack of pressure recovery and increased drag. On an aircraft wing it leads to stall.
Brownian Motion	In a liquid, molecules bounce off one another constantly, making particles move around randomly (a non-continuum effect). This phenomenon gives rise to diffusion. It is primarily important for particles approximately 1 μm or less in diameter.
Buckingham π Theorem	The number of dimensionless groups required to solve a problem is equal to the number of dependent and independent parameters minus the rank of the dimensional matrix (number of independent fundamental units).
Buffer Region	The transition region between the viscous sublayer and the turbulent core in turbulent flow.

Canonical Form	In defining a similarity variable and similarity rule for a self-similar solution, put all complexity in the independent variable with the lowest highest derivative. In mechanics this usually means either the time (t) or time-like (x) variable.
Cavitation	Cavitation is the formation of a bubble of vapor in a liquid due to flow conditions. Effectively, this occurs when the total pressure less the dynamic pressure equals the vapor pressure, leading to the liquid boiling. It often occurs in pumps and at propeller tips due to the very high velocities and corresponding dynamic pressures. Once out of the high velocity region, cavitation bubbles collapse releasing sound (important if you are on a submarine!) and, if near a surface, a high velocity jet which causes local surface wear.
Channel Flow	Pressure-driven flow in a channel. Two-dimensional analog to Poiseuille flow in a tube.
Chaos Theory	It studies the behavior of dynamical systems that are highly sensitive to initial conditions—also known as the butterfly effect. Small differences in initial conditions yield widely diverging outcomes for these systems, rendering detailed long-term prediction impossible in general. Weather is a good example of a chaotic system.
Coanda Effect	The phenomenon which causes a ball to be pulled into a jet of air, often confused with Bernoulli forces. A high Reynolds number free jet tends to expand, entraining surrounding fluid. This causes it to be sucked towards an adjacent tangential surface, inducing a lateral force. If the surface is curved, the jet can actually be redirected around the object. Used to produce high lift at low velocities in some aircraft.
Cold Gas Approximation	An approximation used in studying the expanding shockwave due to a point source explosion, associated with G. I. Taylor. For a very strong explosion, the "back pressure" due to the atmosphere does not matter, and only the initial density of the air needs to be considered. Taylor showed that with this approximation, dimensional analysis alone could be used to determine the shock radius as a function of time, and used it to calculate the (then classified) yield of U.S. atomic bomb tests from pictures released by the Army.
Colloid	A colloidal particle is one for which colloidal forces (such as Brownian motion, electrostatic repulsion, van der Waals forces, etc.) are significant. They are primarily "small" (less than 1 micron in diameter); however, the classification also depends on the other forces in the system. Typically, suspensions exhibit colloidal behavior for Brownian Peclet numbers less than 10^2 or so. Colloids contribute to the osmotic pressure of a suspension and are important additives to blood substitutes, for example.
Continuum Hypothesis	The approximation of the discrete nature of a fluid by a continuum with a velocity, density, etc., defined at every point. The approximation breaks down when length scales approach the mean free path length of a molecule in a gas, molecular dimensions in a fluid, or granular dimensions in a suspension.
Convection	Convection is the concerted, collective movement of groups of molecules within fluids due to the local average velocity, which leads to the transport of mass, momentum, and energy.
Couette Flow	The laminar flow of a viscous fluid in the space between two cylinders, one of which is rotating relative to the other. The flow is driven by viscous drag force acting on the fluid because of cylinder rotation, and there is no pressure gradient by symmetry. Plane-Couette flow is the limit of small gap width to cylinder radius ratio and is equivalent to the motion produced by the relative tangential motion of two parallel planes.
Creep	The tendency of a solid material to flow (exhibit fluid-like behavior) under the influence of mechanical stresses.

Crookes Radiometer	A demonstration of the conservation of momentum, but not the momentum associated with light. Originally explained by Reynolds, it illustrates the phenomenon of thermal transpiration.
CSTR	A continuous flow stirred tank reactor, a common ideal reactor type in chemical engineering. Behavior in a CSTR is usually approximated by assuming perfect mixing, such that the output composition is identical to the composition inside the reactor.
D'Alembert's Paradox	Inviscid, irrotational flow (e.g., potential flow) past a cylinder yields zero drag. The paradox is resolved because the boundary layer separates, leading to loss of pressure recovery and drag.
Dependent Parameter	A parameter that depends on the values given to other, independent parameters that it is a function of.
Dependent and Independent Variables	Variables used in an experiment or model are usually divided into two types. The dependent variable represents the output or effect (e.g., velocity, temperature, pressure), and its value depends on independent variables such as position and time (e.g., x, y, t).
Diffusion Length	The distance a quantity diffuses during time interval Δt. This applies to mass, momentum, and energy. For momentum, the diffusion length is $\sqrt{\nu \Delta t}$, where ν is the kinematic viscosity. Replace ν with D (mass diffusivity) or α (thermal diffusivity) for mass or energy diffusion, respectively.
Diffusion Time	The time required for a quantity to diffuse a distance L. Applies to mass, momentum, and energy. For momentum, the time is L^2/ν. This is the characteristic time for steady-state in plane Couette flow if the upper plate is impulsively started and the plates are separated by L.
Dilatant	A fluid whose viscosity increases with increasing strain rate. Also called shear thickening. Common in suspensions such as cornstarch in water. Caused by jamming due to shear and used in flexible body armor.
Dimensional Analysis	All physical relationships must reduce to equivalent relations between dimensionless groups. This allows a reduction of the number of parameters which must be considered in describing a problem.
Disturbance Velocity	The change in velocity distribution due to the presence of a particle. For example, for a sphere in a simple shear flow, this would be the difference between the velocity distributions with and without the presence of the sphere. Such disturbance velocities decay to zero far from the particle (e.g., in the far-field).
Dynamic Similarity	The basis of scaling analysis. If all dimensionless groups are the same for problems of different scale, then the behavior (scaled dependent parameter or variable) will be the same as well. It can either be strict or approximate depending on whether all or some of the dimensionless groups are preserved.
Electro-Osmosis	The motion of liquid induced by an applied potential across a porous material, capillary tube, membrane, microchannel, or any other fluid conduit. This technique is an essential component in chemical separation techniques, notably capillary electrophoresis. It results from the body force applied by a tangential electric field to counter-ions in a fluid in the thin layer near a charged surface, and results in an apparent wall slip, yielding flow in a tube or channel without requiring the shear and dispersion which would result from a pressure gradient.
Electrophoresis	The motion of charged particles or molecules relative to a fluid due to an electric field. It is the basis for a number of analytical techniques used to separate molecules by size, charge, or binding affinity.

Eulerian Approach	Tracking the velocity field at an instant of time relative to a defined (laboratory) coordinate system. For most fluid problems, this perspective is the one used.
Far-Field	In fluid mechanics, this refers to the leading order term in the disturbance velocity or pressure produced by an object as you move far away from it. For example, the far-field disturbance velocity produced by a settling sphere in Stokes flow decays as a/r, where a is the radius of the sphere and r is the radial distance from it.
First Order Linear ODE	First order linear ordinary differential equations take the form: $$\frac{dy}{dx} + p(x)y = f(x)$$ This is one of the few general classes of differential equation for which a general solution can always be written down. You should know the general solution, or at least know where to find it!
Free Surface	A surface that is not constrained by a solid boundary. Usually the interface between two fluids (e.g., oil-water or water-air).
Friction Loss Factors	Empirically determined K values that contribute to head loss in pipe flow. The losses scale with the dynamic pressure (kinetic energy per unit volume) of the fluid.
Fundamental Units	A set of fundamental units is a set of units for physical quantities from which every other unit can be generated (e.g., time, distance, density, temperature, energy). The optimum choice is not always obvious, but is usually mass, length, and time.
Geometric Ratios	The ratio of length scales used in scale-up and dimensional modeling. For dynamic similarity, all geometric ratios (length/height, etc.) must be preserved so that the geometry is the same.
Gimli Glider	The case where a Boeing 757 ran out of fuel due to a fuel density unit conversion error, becoming a glider at 30,000 ft. Amazingly, the pilots managed to land it in one piece at Gimli Air Force Base in Canada.
Hydraulic Jack	A hydraulic jack uses an incompressible fluid that is forced into a cylinder by a pump or plunger to lift heavy loads. The ratio of the area of the plunger (or feeding tube) to the area over which the force is applied amplifies the force, since pressure $P = F/A$ is preserved.
Hydroplaning	An inertially driven phenomenon which occurs when a wheel encounters a layer of water at sufficient speed. Simplistically, hydroplaning results when the dynamic pressure $\frac{1}{2}\rho u^2$ times an appropriate area equals the vehicle weight. Since the tires also support the vehicle weight, this occurs when the dynamic pressure roughly equals the tire pressure. At this point, the tires lose frictional contact with the road. Tire treads are designed to channel water, increasing (somewhat) the velocity at which hydroplaning occurs.
Hydrostatic Head	The pressure head given by $p + \rho gh$. It represents the potential energy or pressure available to drive fluid flow. This, plus the dynamic pressure (kinetic energy per unit volume), gives the total head of the fluid.
Hydrostatics	The branch of fluid mechanics that studies fluids at rest.
Ideal Flow (Potential Flow)	Obtained for an inviscid, incompressible, irrotational flow. If the velocity (e.g., vector field) is irrotational, it must be the gradient of a scalar function. If the fluid is incompressible, this velocity potential also satisfies Laplace's equation. Ideal (potential) flow around an object violates the no-slip condition.

Independent Parameter	A parameter that is, in general, set independently (as opposed to a dependent parameter). The choice of independent vs. dependent parameters is not always obvious, depending on how a problem is set up. Lengths are usually independent parameters, velocities and forces can be either dependent or independent depending on your point of view.
Inertial Forces	The convective forces in a fluid flow due to fluid inertia: $\rho\mathbf{u}\cdot\nabla\mathbf{u}$. For unsteady problems, it also includes the acceleration term $\rho\frac{\partial\mathbf{u}}{\partial t}$.
Inviscid	No viscosity.
Irrotational	No rotation (or vorticity). Usually (but not always!) only found in inviscid flows, as the no-slip condition (and shear stress) at a solid boundary is a source of vorticity.
Isotropic	Invariant to the rotation of a coordinate system. The identity matrix is isotropic, for example, but all vectors (other than zero) are not isotropic. A fluid without structure is isotropic, but a suspension of rods (or even spheres) may not be.
Jeffrey's Orbits	A non-spherical particle in low Reynolds number shear flow will rotate in an irregular manner called a Jeffrey's Orbit. In particular, rod-like particles in a simple shear flow will tend to spend most of their time aligned in the direction of motion. This results in a dilute suspension of such particles exhibiting non-isotropic behavior, and can be used to create composite materials that have specific anisotropic conductivities, etc. The effect is also used in microfluidic systems to focus and orient particles.
Johnstown Flood 1889	Resulted from the catastrophic failure of the South Fork Dam, worsened by several days of heavy rainfall. The dam was located 14 miles upriver and 400 ft above the town. When it failed, the water's flow rate reportedly equaled that of the Mississippi River. Demonstrates principles of hydrostatics (force on the dam prior to failure), conversion of hydrostatic head to kinetic energy, and subsequent conversion back to pressure (F/A) as the flood devastated the town. The dam's remnants are preserved as a national memorial.
Knudsen Diffusion	Occurs when the system's length scale is comparable to or smaller than the mean free path of particles. Applicable mainly to gases, since liquids have extremely short mean free paths. Relevant in gas diffusion into porous catalysts.
Lagrangian Approach to Modeling Fluids	Describes fluid properties (velocity, density, pressure, etc.) by following individual fluid elements over time. Tracks the evolution of the position and velocity of particles starting from their initial position x_0. Useful in celestial mechanics, particulate flow systems, and continuous pasteurization process analysis.
Laminar vs. Turbulent Flow	Laminar flow involves smooth, orderly layers of fluid sliding over one another. Turbulent flow is chaotic, time-dependent, and complex to describe mathematically. For circular pipes, once the Reynolds number exceeds approximately 2100, turbulent disturbances will not revert to laminar behavior.
Law of the Wall	States that the mean velocity of a turbulent flow is proportional to the logarithm of the distance from a point in the fluid to the wall. Derived from the Prandtl mixing length theory.
Lift and Drag	A fluid flowing past a solid surface exerts forces on it. Lift is the component of the force perpendicular to the direction of the flow, while drag is the component parallel to the flow direction.
Lift/Drag Ratio	An aircraft remains airborne because lift equals its weight. Engines provide thrust to overcome drag only. A typical commercial airliner has a lift-to-drag (L/D) ratio around 20, explaining why such planes do not ascend vertically.

Lubrication Flows	Fluid flow in thin films, where hydrodynamic forces keep solid surfaces out of contact, reducing wear. There is a separation of length scales such that the gap width $H \ll L$, where H is the film thickness and L is the flow length scale. Due to the thin gap, the flow is quasi-parallel, and viscous effects usually dominate the forces.
Magneto-hydrodynamics (MHD)	The study of the dynamics of electrically conducting fluids in magnetic fields. Examples of such fluids include plasmas, liquid metals, and electrolytes. Magnetic fields induce currents in the moving fluid, which in turn exert forces on the fluid and alter the magnetic field itself.
Magnus Effect	The rotation of a ball in a high Reynolds number airstream causes a deflection of the boundary layer and wake in the direction of rotation. By conservation of momentum, this induces a force on the ball perpendicular to its motion. Topspin causes a ball to dive, while backspin causes it to rise. This effect is important in many ball sports.
Manometer	An instrument that uses a column of liquid (commonly mercury or water) to measure pressure. The pressure is determined from the displacement of the fluid column using hydrostatic principles.
Matched Asymptotic Expansions	A method for finding approximate solutions to equations by solving simplified versions valid in different regions (e.g., near and far from a boundary). The inner and outer solutions are then combined into a composite solution valid over the whole domain. Used in boundary layer theory.
Matching Conditions	The rules by which inner and outer solutions in matched asymptotic expansions are joined. For example, in boundary layer theory, the limit of the inner (viscous) solution as $y \to \infty$ must match the limit of the outer (inviscid) solution as $y \to 0$.
Minimum Dissipation Theorem	Among all divergence-free (solenoidal) vector fields satisfying given boundary conditions, the one that also satisfies the Stokes Flow equations minimizes viscous dissipation (drag). This principle has useful corollaries in low Reynolds number flows.
Momentum per unit volume	Defined as $\rho\vec{u}$, where ρ is the density and $\vec{u}$ is the velocity vector. This quantity is also known as the mass flux vector.
Morgan's Theorem	1. If a problem, including boundary conditions, is invariant to a one-parameter group of continuous transformations, then the number of independent variables may be reduced by one. 2. The reduction is accomplished by choosing as new dependent and independent variables combinations which are invariant under the transformations. This is the theorem used to guarantee the existence of self-similar solutions (provided condition 1 is satisfied!).
Newtonian Fluid	A fluid in which the stress is linearly proportional to the strain rate. In simple shear flow, the relationship is given by $\frac{F}{A} = \mu\frac{U}{D}$, where μ is the viscosity, U is the velocity, and D is the distance over which the velocity changes. Newtonian fluids are isotropic and have no yield stress.
Normal Stress Differences	Occur when the normal stresses in a shear flow differ in the flow, gradient, or vorticity directions. Common in polymeric fluids and concentrated suspensions. These differences can lead to phenomena such as the rod-climbing (Weissenberg) effect.
No-slip Condition	At a solid boundary, the velocity of the fluid matches that of the surface (i.e., fluid sticks to the wall). This condition results from the presence of viscosity and is violated in inviscid flow. For such flows, a boundary layer forms to reconcile this discontinuity.

NPSHR	The *Net Positive Suction Head Required* at the pump inlet to avoid cavitation. At standard conditions, the available head is approximately 1 atm minus the vapor pressure of the fluid. This minus upstream pressure losses must exceed NPSHR to prevent cavitation.
Orifice Meter	It consists of a straight length of pipe inside which an abrupt constriction (orifice) creates a pressure drop, whose magnitude is typically proportional to the kinetic energy per unit volume of the fluid. Thus, the measured pressure drop is used to calculate the fluid velocity.
Osmotic Pressure	The minimum pressure applied to a solution to prevent the inward flow of water across a semi-permeable membrane. Important in cell biology. In reverse osmosis (RO) systems, applying a pressure greater than this can produce pure water from salt water. It arises from the entropy of the solution or suspension.
Pathlines	Paths followed by fluid elements. Usually captured by time-lapsed photography.
Pelton Wheel	A classic example of a water turbine. Nozzles direct forceful, high-speed water jets against a rotary series of spoon-shaped buckets. The water kinetic energy exerts torque on the bucket and wheel system, spinning the wheel.
Pipe Fitting K values	Pressure drop in turbulent flow through a fitting is approximately $\frac{1}{2}\rho u^2 K$, where K is determined empirically.
Plane-Couette Flow (Simple Shear Flow)	Used to study the rheology of fluids and produced in the narrow gap (low Reynolds number flow) between concentric rotating cylinders, or by the relative tangential motion of two parallel planes. There is no pressure gradient.
Plane-Poiseuille Flow	The 2-D analog of Poiseuille flow: laminar, pressure-driven flow between two parallel plates. The velocity profile is symmetric and quadratic in position across the gap.
Poiseuille Flow	Laminar, pressure-driven flow through a circular tube.
Prandtl Mixing Length Theory	In turbulent flow, as two eddies exchange places across streamlines, they lead to momentum, mass, and energy transfer. The rate of exchange is assumed proportional to the shear rate, and the length scale of the eddies is proportional to the distance from the bounding wall.
Pressure Recovery	The recovery of pressure on the backside of a bluff body in high Reynolds number flow reduces drag. This only occurs if the boundary layer remains attached. Modifications on truck trailers often delay separation and promote pressure recovery, reducing drag and improving fuel economy.
Pseudoplastic	Viscosity decreases with increased shear rate. Also called shear thinning. Very common in polymer melts because the shear causes polymer chains to stretch out in the flow direction and disentangle, reducing viscosity.
Pump Curve	The relationship between added hydrostatic head and flow rate for a pump. Pump curves show operating ranges of specific pumps. The desired head gain and flow rate can be identified on the graph to determine if it lies within the recommended range. Also used to calculate pump efficiency.
Pyroclastic Flows	The flow of a mixture of hot ash and air resulting from a volcanic eruption. Gravity-driven flow down the mountain; despite high temperature, the ash makes the mixture denser than unheated air. Very fast and dangerous, more so than lava flows.

Quasi-Parallel Flows	Flows predominantly in one direction. Usually occurs when there is a separation of length scales, with velocity in the long direction much greater than in the thin direction, simplifying the flow equations.
Rate of strain tensor	Rate of deformation of a fluid (tensor): $\dfrac{\partial u_i}{\partial x_j}$. The symmetric part, e_{ij}, is given by $$e_{ij} = \frac{1}{2}\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right).$$
Recirculating Wake	A wake is the region of disturbed flow immediately behind a moving or stationary solid body, caused by flow of surrounding fluid around the body. At high Reynolds number flow past a blunt object, the boundary layer separates, creating a reverse flow region moving toward the body (upstream), causing recirculation. This effect can be used for energy saving, e.g., paddling a kayak upriver behind bridge pylons.
Reference Frame	A coordinate system used to represent and measure properties of objects, such as their position and orientation, at different moments of time. In fluid mechanics, it is usually very useful to choose a reference frame in which the boundary has a convenient representation.
Relaxation Time	The time a fluid needs to regain its equilibrium structure after being stressed. Relaxation usually results from thermal (Brownian) processes.
Residence Time	The average amount of time that a fluid element spends in a particular system: $$\tau = \frac{V}{Q}$$ where τ is the residence time, V is the volume of the system, and Q is the volumetric flow rate.
Rheology	The study of fluid stress-strain relationships.
Rotlet	The far-field disturbance velocity of a particle with applied torque in Stokes flow. One of the fundamental singularities of Stokes flow, it is the disturbance velocity produced by a sphere rotating in a viscous fluid at zero Reynolds number. Also called a couplet.
Separation of Length Scales	Occurs when one dimension of the problem is much greater than another. In fluid mechanics, this leads to simplification: velocities in the long direction are much greater than in the thin direction, while derivatives (e.g., viscous terms) in the thin direction are much greater than those in the long direction.
Shell Balance	A shell is a differential element of fluid flow. By examining forces on a small portion of a body, one can integrate over the flow to understand the larger flow behavior. The balance determines what goes into and out of the shell.
Similarity Transform	A technique that reduces the number of independent variables a problem depends on. For example, converting a 2-D partial differential equation into an ordinary differential equation, simplifying the solution.
Squeeze Flow	A lubrication flow that results from the normal motion between two surfaces, e.g., squeezing two plates together.
Stagnation Flow	Flow resulting from fluid directed normal to a surface, such as a jet of water hitting a plate.
Stagnation Point	The point on a surface in a stagnation flow where the local velocity of the fluid is zero.

Stall	Occurs when the boundary layer over a wing separates from the plane, greatly increasing drag. This slows the plane and greatly reduces lift. The wing control surfaces on the trailing edges become ineffective inside the separation bubble, making stall difficult to recover from and increasing crash risk.
Static Pressure	The local pressure in a fluid flow.
Steady-State	If a system is in steady state, the observed behavior does not change with time in an Eulerian reference frame: $$\frac{\partial(\text{properties})}{\partial t} = 0$$
Stokes-Einstein Diffusivity	$$D_0 = \frac{kT}{6\pi\mu a}$$ where k is Boltzmann's constant, T is the absolute temperature, and a is the radius of a sphere (or effective particle radius). This relates the diffusion coefficient of colloidal particles to thermal energy and viscous drag.
Stokes Flow Reversibility	For flows at Reynolds number $Re = 0$, the linearity of flow equations ensures that reversal in time is equivalent to reversal in direction. Reversing boundary conditions reverses the entire flow field, as if playing a movie backwards.
Stokeslet	The disturbance velocity due to a point force in creeping flow. It represents the far field velocity induced by any object with a net force (e.g., a settling sphere). It is a fundamental singularity of Stokes flow.
Stokes Paradox	The impossibility of solving creeping flow past a cylinder (2-D analog of sphere flow) due to inertia effects always being significant, no matter how slow the flow. For example, a thin layer of hair can block a drain despite occupying a small surface fraction.
Strain	Symbol: ε or γ. The ratio of deformation over initial length.
Streaklines	Streaks of dye originating from a fixed point in a flow. A common method for flow visualization.
Stream Function	A mathematical function whose value is constant along a streamline.
Streamlines	Curves everywhere tangent to the velocity vector at an instant in time. For unsteady flows, streamlines must be computed from the velocity field and cannot be visualized directly. For steady flows, streamlines, pathlines, and streaklines coincide.
Stresslet	The far field disturbance velocity of a force-free and torque-free particle in creeping flow (e.g., a freely suspended sphere in simple shear flow at zero Reynolds number). It is a fundamental singularity in Stokes flow.
Strict Dynamic Similarity	All dimensionless groups in dimensional scaling are preserved exactly. Achieving this is very difficult in fluid mechanics scale-up.
Taylor-Couette Vortices	In Couette flow, when the inner cylinder's angular velocity exceeds a threshold, the flow becomes unstable and forms axisymmetric toroidal vortices called Taylor vortices. Further increases in speed lead to more instability and eventual turbulence.

Taylor Dispersion	Important in chromatography, this is the dispersion of a solute slug in the flow direction caused by solute molecules convecting at different velocities. In Poiseuille flow through a tube of radius a, the dimensionless Taylor dispersivity is $$K_D = 1 + \frac{U^2 a^2}{48 D^2}$$ where U is average velocity and D is molecular diffusivity.
Tollmien-Schlichting Waves	Unstable laminar flow past a flat plate at high Reynolds number exhibits 2-D Tollmien-Schlichting waves ("roll waves"). These can be predicted by instability analysis of the Navier-Stokes equations.
Total Pressure (Stagnation Pressure)	The sum of the static and dynamic pressure.
Turbulent Core	The region in turbulent flow where momentum transfer is dominated by turbulent velocity fluctuations, e.g., the Reynolds stress.
Unidirectional Flow	Flow occurring in only one direction (distinct from quasi-parallel flow where flow is mostly in one direction). For an incompressible fluid, this leads to simplifications including elimination of nonlinear inertial terms via continuity.
Venturi Meter	A device that constricts flow smoothly through a throat where differential pressure sensors measure pressure before and within the constriction. Velocity and flow rate are calculated from Bernoulli's Equation using the pressure difference.
Viscous Forces	The forces in fluid flow due to viscosity, often expressed as $\mu \nabla^2 \mathbf{u}$.
Viscous Sublayer	The near-wall region in turbulent flow where momentum transfer is dominated by viscous effects rather than turbulent velocity fluctuations.
Von Karman Vortex Street	A repeating pattern of swirling vortices caused by unsteady flow separation around blunt bodies. Responsible for phenomena such as the "singing" of suspended cables and vibration of car antennas at specific speeds. Related to aeroelastic flutter.
Yield Stress	A critical shear stress threshold below which some fluids do not flow. Examples include mayonnaise and frozen orange juice. Yield stresses are also engineered into food products like ranch dressing to prevent phase separation.

Dimensionless Groups

The use of dimensionless groups is an excellent way of qualitatively (and even quantitatively) studying transport phenomena. If a problem is scaled correctly, these dimensionless groups will determine the relative significance of physical mechanisms (e.g., gravity, surface tension, inertia, viscous diffusion of momentum, etc.). A very large number of such groups have been defined over the centuries, and many groups are simply combinations of other dimensionless groups. Some also have multiple definitions, or may be applied in different ways. This list is by no means complete, but contains some of the more commonly applied dimensionless groups in Transport (and one really obscure one).

Term	Definition
Biot Number (Bi)	Definition: $$\mathrm{Bi} = \frac{hL}{k}$$ where h is the surface heat transfer coefficient, k is the thermal conductivity, and L is the characteristic length scale of the object. This number represents the ratio of external to internal heat transfer resistance in a solid. For small Bi, external heat transfer resistance dominates and the object maintains a uniform internal temperature. For large Bi, heat transfers rapidly at the surface while internal temperature gradients can be significant.
Bond Number (Bo)	Definition: $$\mathrm{Bo} = \frac{\Delta\rho\, g\, a^2}{\gamma}$$ where a is the radius of curvature or radius of an object, $\Delta\rho$ is the density difference, g is the gravitational acceleration, and γ is the surface tension. This number represents the ratio of gravitational to surface tension forces. For example, the dynamics of waves depend on the Bond number. When Bo is large, gravity dominates and wave motion results from gravity-inertia interaction. When Bo is small, surface tension dominates and capillary waves form, governed by surface tension-inertia interaction.
Brownian Peclet Number (Pe)	Definition: $$Pe = \frac{\dot{\gamma}\mu a^3}{k_B T}$$ where a is the radius of a sphere, k_B is Boltzmann's constant, T is the absolute temperature, μ is the dynamic viscosity, and $\dot{\gamma}$ is the shear rate. This is the ratio of viscous forces to Brownian motion. Concentrated suspensions of very small (e.g., colloidal) particles will undergo a jamming transition when $Pe \sim 1$. In modern body armor, the low shear rate associated with normal motion is at low Pe and permits unjammed low viscosity, while the high shear rate (and Pe) associated with being shot or stabbed causes the material to stiffen, spreading the impact and preventing penetration.
Capillary Number (Ca)	Definition: $$Ca = \frac{\mu\dot{\gamma}a}{\sigma}$$ where σ is the surface tension, $\dot{\gamma}$ is the shear rate, and a is a drop radius or curvature length scale. The Capillary number is the ratio of viscous forces to capillary forces. It is useful in studying drop dynamics and breakup in emulsions. For example, in a simple shear flow, a drop will break up into two daughter drops (plus tiny satellite drops) when the Capillary number exceeds a critical value of order 1, depending on the internal-to-external viscosity ratio.

Deborah Number (De)	Definition: $$De = \frac{\lambda}{t_p}$$ where λ is the stress relaxation time and t_p is the time scale of observation. In a viscoelastic fluid, structures created by shear or strain will eventually relax to equilibrium. In non-steady flow, such a fluid behaves like a Newtonian fluid at low De (relaxation is fast relative to the oscillation period), and like an elastic solid at high De. The Deborah number is similar to the Weissenberg number (used for steady flows), and both are zero for Newtonian fluids.
Drag Coefficient (C_D)	The dimensionless drag on an object, scaled with the inertial forces in a system. Defined by: $$C_D = \frac{F_{\text{drag}}}{\frac{1}{2}\rho U^2 A}$$ where A is the projected area normal to the flow. For high Reynolds number, this is an $O(1)$ function of an object's shape.
Froude Number (Fr)	The ratio of inertial forces to gravitational forces, defined by: $$Fr = \frac{U^2}{Lg}$$ Used along with the Reynolds number in preserving strict dynamic similarity in scaling models where gravity is important. For example, in ship modeling, Fr is preserved and Re is kept high to achieve approximate dynamic similarity. Note that some texts use the square root of this definition of Fr.
Grashof Number (Gr)	This is the ratio of buoyancy due to thermal expansion to viscous dissipation, given by: $$Gr = \frac{g\beta\Delta T H^3}{\nu^2}$$ where β is the coefficient of thermal expansion, ΔT is the temperature difference, H is a vertical length scale, and ν is the kinematic viscosity. It is important in natural convection. If Gr is sufficiently high, the flow may become turbulent, much like exceeding a critical Reynolds number.
Leighton Number (Le)	Defined in our work on the lubrication transition of a sphere rolling down a plane in a viscous fluid as the ratio of shear to sedimentation Reynolds numbers (Smart et al., Phys. Fluids, 1993). Proposed as a named group by Coussot & Ancey (PRE 1999), it governs the transition from frictional to lubricated interactions in suspensions and wet granular flows. Two definitions are: $$Le = \frac{\mu_0\dot{\gamma}b}{N\epsilon} \quad \text{or} \quad Le = \frac{\mu_0\dot{\gamma}}{\sigma}$$ where $\mu_0\dot{\gamma}$ is the viscous stress, N is the particulate normal stress, b is the particle length scale, ϵ is the particle roughness length scale, and σ is the total stress. The alternate definition is from Huang et al., PRL 2005.

Lift Coefficient (C_L)	The dimensionless lift force on an object, scaled by inertial forces. Defined as $$C_L = \frac{L}{\frac{1}{2}\rho U^2 S}$$ where S is the planform area (e.g., the surface area of a wing, or area aligned with the flow).
Mach Number (M)	The ratio of an object's speed to the speed of sound in the fluid: $$M = \frac{U}{V_s}$$ If $M \ll 1$, compressibility effects are negligible and the flow can be considered incompressible, even in gases like air.
Nusselt Number (Nu)	Defined as $$\mathrm{Nu} = \frac{hL}{k}$$ where h is the heat transfer coefficient, k the thermal conductivity, and L a characteristic length scale. This is the dimensionless heat transfer coefficient. For a sphere in a stationary fluid, $\mathrm{Nu} = 2$ (pure conduction with L equal to the sphere diameter). In flowing fluids, convective transfer raises Nu. Not to be confused with the Biot number.
Peclet Number (Pe)	Ratio of convective to diffusive transport. For mass transfer: $$\mathrm{Pe} = \frac{LU}{D} = \mathrm{Re} \cdot \mathrm{Sc}$$ For heat transfer: $$\mathrm{Pe} = \frac{LU}{\alpha} = \mathrm{Re} \cdot \mathrm{Pr}$$ where D is the mass diffusivity, α the thermal diffusivity. Plays the same role in scalar transport as Re in momentum transfer. Even if $\mathrm{Re} \ll 1$, Pe can still be $O(1)$ or larger in viscous fluids due to large Pr or Sc.
Prandtl Number (Pr)	Defined as the ratio of momentum diffusivity (kinematic viscosity) to thermal diffusivity: $$\mathrm{Pr} = \frac{\nu}{\alpha}$$ where ν is the kinematic viscosity and α is the thermal diffusivity. It indicates the relative rates of momentum and heat diffusion in a fluid. Pr is $O(1)$ for gases, approximately 7 for water, and very large for viscous liquids. It determines the relative thicknesses of momentum and thermal boundary layers, with the thickness ratio scaling as $\mathrm{Pr}^{1/2}$.
Rayleigh Number (Ra)	Defined as: $$\mathrm{Ra} = \frac{g\beta \Delta T H^3}{\nu\alpha} = \mathrm{Gr} \cdot \mathrm{Pr}$$ where g is gravitational acceleration, β is the coefficient of thermal expansion, ΔT is the temperature difference, H is the characteristic height, ν is the kinematic viscosity, and α is the thermal diffusivity. The Rayleigh number quantifies the influence of buoyancy relative to viscous dissipation and governs thermal convection onset. When the critical Rayleigh number is exceeded, buoyancy-driven instabilities like convection rolls can occur.

Reynolds Number (Re)	Defined as: $$\mathrm{Re} = \frac{UD}{\nu}$$ where U is the characteristic velocity, D is the characteristic length (e.g., pipe diameter), and ν is the kinematic viscosity. The Reynolds number compares inertial to viscous forces. For high Re, flow behavior is dominated by inertia (e.g., drag $\sim \frac{1}{2}\rho U^2 A$); for low Re, viscous forces dominate (e.g., drag $\sim \mu A \frac{U}{D}$). It governs transition to turbulence and is the most important dimensionless group in fluid mechanics.
Richardson Number (Ri)	Definition: $$\mathrm{Ra} = \frac{\Delta\rho\, g\, H}{\rho_0 U^2}$$ where $\Delta\rho$ is the characteristic density difference in the system. This number is the ratio of gravitational forces to inertial forces in a stratified system. It is very similar to 1/Fr, and plays an important role in mixing and natural/forced convection problems. For example, when mixing two fluids with a density difference $\Delta\rho$ in a tank of height H, the vertical mixing velocities must be large enough that Ri $\ll 1$, or else density stratification will impede mixing.
Schmidt Number (Sc)	Definition: $$\mathrm{Sc} = \frac{\nu}{D}$$ where D is the mass diffusivity. This number is the ratio of momentum diffusion (kinematic viscosity) to mass diffusion. It determines the relative thickness of momentum transfer and mass transfer boundary layers (scales as $\mathrm{Sc}^{1/2}$). For gases it is $\mathcal{O}(1)$, but for liquids it is very large (e.g., $\mathcal{O}(500)$ or greater).
Sherwood Number (Sh)	Defined as $$\mathrm{Sh} = \frac{k_m L}{D}$$ where k_m is the mass transfer coefficient, D the molecular diffusivity and L a characteristic length scale. This is the dimensionless mass transfer coefficient, analogous to the Nusselt number for heat transfer. For a sphere in a stationary fluid, Sh = 2 (pure diffusion with L equal to the sphere diameter). In flowing fluids, convective transfer raises Sh. Correlations show a very strong link between Nu and Sh for equivalent geometries (e.g., the Chilton-Colburn analogy).
Strouhal Number (Sr)	Definition: $$\mathrm{Sr} = \frac{fL}{U}$$ where f is the frequency of oscillation. It is the ratio of the convective time scale L/U (the time for fluid to pass by an object, for example) to the period of oscillation. It is important in analyzing oscillatory motion of an object, or in phenomena such as the waving of a flag or the periodic shedding of vortices behind an object.
Taylor Number (Ta)	Definition: $$\mathrm{Ta} = \frac{\Omega^2 R\, \Delta R^3}{\nu^2}$$ where ΔR is the gap width, R is the average radius of the two cylinders, and Ω is the angular velocity of the inner cylinder. This number is the ratio of centrifugal forces to viscous dissipation in Taylor-Couette flow (Couette flow with a rotating inner cylinder). If the rotation exceeds the critical Taylor number (1712 for thin gaps), the flow becomes unstable to axisymmetric Taylor vortices.

Weissenberg Number (Wi)	It is a dimensionless number used in the study of viscoelastic flows. In steady shear flows, it is defined as the product of the shear rate and the relaxation time of the fluid: $$\mathrm{Wi} = \dot{\gamma}\,\lambda$$ where λ is the relaxation time (the time for fluid structure to relax to an isotropic equilibrium distribution). For $\mathrm{Wi} \gg 1$, polymer molecules are stretched out in the shear flow, leading to normal stress differences and phenomena such as the rod-climbing effect or die swell in extrusion.
Womersley Number (α)	This dimensionless number is important in oscillatory flows in tubes and channels. It is defined as: $$\alpha = a\sqrt{\frac{\omega}{\nu}}$$ where ω is the angular frequency of oscillation, a is the tube radius, and ν is the kinematic viscosity. If $\alpha \ll 1$, the tube radius is much smaller than the diffusion length $(\nu/\omega)^{1/2}$, and the flow resembles a time-varying Poiseuille profile (parabolic). If $\alpha \gg 1$, the flow profile becomes flat with a thin boundary layer near the walls, where the shear decays rapidly.

Some Important Historical Fluid Mechanicians

Here we have a list of just a few of the fluid mechanicians we have mentioned in class. Many, many others could be listed as well, of course - including some who are still active. Often, these researchers have had their main contribution outside of the area of fluid mechanics (e.g., Newton is *not* principally known for Newton's law of viscosity!).

Name	**Era**	**Noted Contribution to Fluid Mechanics**
Archimedes	250 B.C.	Studied buoyancy, among other things. *On Floating Bodies*. Archimedes' Principle: a body immersed in a fluid experiences a buoyant force equal to the weight of the fluid it displaces.
Hero of Alexandria	ca. 120 B.C.	Studied hydrostatics. *Pneumatics*. Hero's Fountain example in class.
Isaac Newton	1642–1727	Studied friction, viscosity, and orifices. Published *Principia* in 1713.
Leonhard Euler	1707–1783	Developed the equation of motion for frictionless fluids (and lots of other things!).
Claude Louis Navier and **George Gabriel Stokes**	1785–1836 1819–1903	Incorporated viscous terms into the equation describing fluid motion, leading to the Navier–Stokes Equations.
William Froude	1810–1879	Model testing and scaling laws for ship design.
Osborne Reynolds	1842–1919	Transition to turbulence.
Ludwig Prandtl	1875–1953	Introduced the concept of viscous boundary layers.
Theodore von Karman	1881–1963	Turbulence and vortex shedding.
Sir Geoffrey Taylor	1883–1975	Tackled many problems. Widely considered the preeminent fluid mechanician of the 20th century.
George Batchelor	1920–2000	Turbulence and particle dynamics.
Andreas Acrivos	1928–2025	Particle dynamics and asymptotic methods.