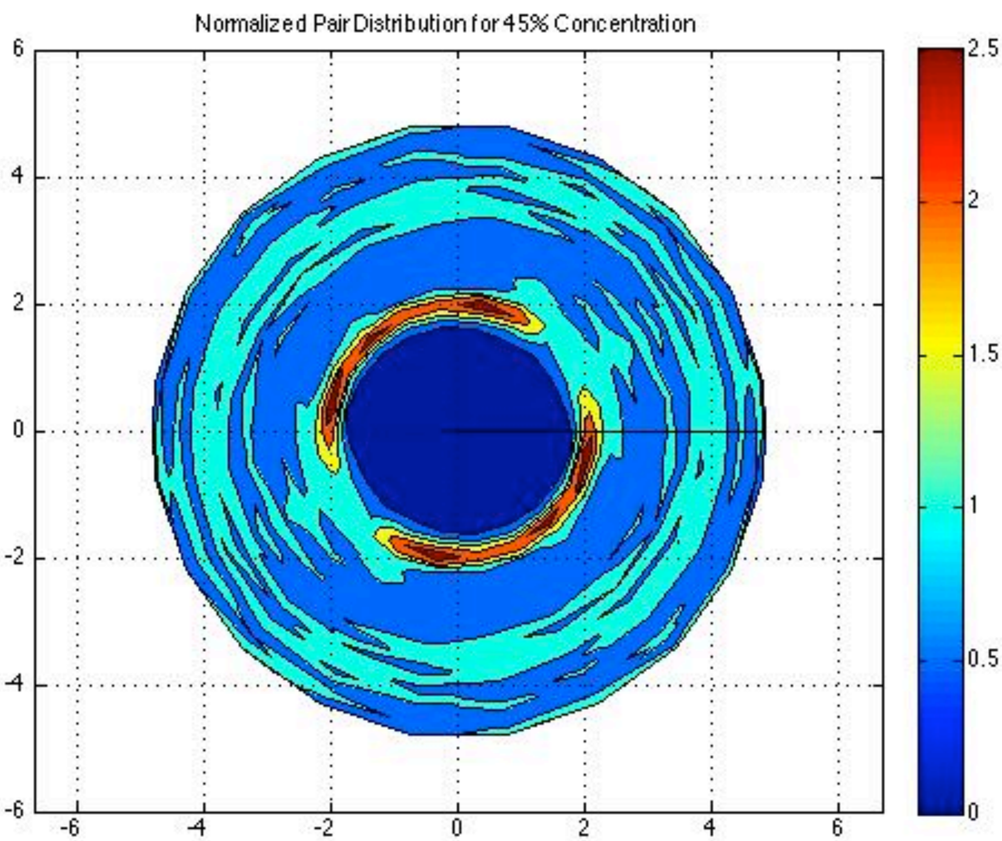
A Glossary of Terms for Fluid Mechanics

Eleanor T. Leighton
David T. Leighton, Jr.
Department of Chemical & Biomolecular Engineering
University of Notre Dame



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E. T. Leighton
D. T. Leighton
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In order to "walk the walk", it is useful 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. 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.

Mathematical Operators

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. Note that it doesn't have to have any symmetries with respect to the 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	Symbol: × $A \times B$ produces a vector perpendicular to both A and B with length proportional to $\|A\|\|B\|\sin(\theta)$ where θ is the internal angle. For instance, if

	$$A = a_1 i + a_2 j + a_3 k$$ $$B = b_1 i + b_2 j + b_3 k$$ the vector $A \times B$ is $$\begin{bmatrix} i & j & k \\ a_1 & a_2 & a_3 \\ b_1 & b_2 & b_3 \end{bmatrix} = (a_2 b_3 - a_3 b_2) i - (a_1 b_3 - a_3 b_1) j + (a_1 b_2 - a_2 b_1) k$$
Curl	Cross product of the gradient operator with a vector: $$\underset{\sim}{\nabla} \times \underset{\sim}{u}$$ 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 $[r, \theta, z]$ coordinate system.
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: $$\underset{\sim}{\nabla} \bullet \underset{\sim}{u}$$ Zero for incompressible fluids (or solenoidal vector fields).
Divergence Theorem	A way of converting surface integrals to volume integrals, e.g.: $$\int_{\partial D} (\rho u_i) u_j n_j \, dA = \int_{\partial D} \frac{\partial}{\partial x_j} (\rho u_i u_j) \, dA$$
Dot Product	Symbol: $\bullet$ A scalar number produced when there are two nonzero vectors **A** and **B.** It is produced by solving: $$\|A\| \|B\| \cos\theta$$ where $\| \ \|$ indicates the length of the vector. The dot or inner product between two tensors subtracts 2 from the combined order of the tensors (e.g., 1+1-2=0 as above, 2+2-2=2 for the dot product between two matrices, etc).

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 where $\Delta R/R << 1$. Usually we take x and z to be the tangential directions, and y = r-R to be the normal direction.
Fore-and-Aft Symmetry	The front and the back of a body are reflections of each other (e.g. a cylinder or a football, a dumbbell or a pair of spheres glued together). Mathematically, all relations for such an object are invariant to the *sign* of the director describing the orientation.
Grad	Symbol: ∇ The gradient (or partial derivative), also called 'del' because of its shape, is a vector operator! Examples: $$\tilde{\nabla} \bullet \tilde{u} = \frac{\partial u_x}{\partial x} + \frac{\partial u_y}{\partial y} + \frac{\partial u_z}{\partial z}$$ $$\tilde{\nabla} p = \frac{\partial p}{\partial x}\hat{e}_x + \frac{\partial p}{\partial y}\hat{e}_y + \frac{\partial p}{\partial z}\hat{e}_z$$
Index Notation	Also called Einstein Notation, this is the natural language for describing vectors, tensors, and fluid mechanics. The order of a tensor is equal to the number of unrepeated indices in the subscript (e.g., the matrix A_{ij} has two unrepeated indices) and repeated indices imply summation (inner or dot product).
Isotropic Tensor	A tensor is isotropic if it is invariant under rotation of its coordinate system. All scalars are isotropic, all vectors (except zero length vectors) aren't. Isotropic second order tensors are proportional to δ_{ij}, isotropic third order tensors are proportional to ε_{ijk}, and isotropic fourth order tensors contain the three possible combinations of pairs of Kronecker delta functions. Don't confuse isotropy with symmetry!
Kronecker Delta Function	Symbol: δ_{ij} The index notation representation of the identity matrix. The function is one if the indices are equal (i = j) and zero otherwise.
Matrix Notation	Example: $\underset{\approx}{A} = \begin{bmatrix} 3 & 5 \\ 2 & 4 \end{bmatrix}$

	Vectors and tensors are denoted by either overbars or underbars (which may be lines or squiggles). The number of squiggles underneath the $\underset{\approx}{A}$ indicate the order of the tensor (in this case, a matrix). Alternatively, in classical Gibbs Dyadic Notation vectors are denoted by bold-face lower case letters (e.g., **a**) and matrices by bold-face upper case letters (e.g., **A**). Index notation is much less ambiguous!
Physical Tensor	The sign of a physical tensor doesn't depend on whether you have a right or left handed coordinate system. The opposite of a pseudo tensor. Examples include position, velocity, mass, stress, etc.
Pseudo Tensor	A tensor that changes sign under an orientation reversing coordinate transformation. In general, a pseudo tensor will change sign depending on whether you use a right or left handed coordinate system. You convert from a pseudo tensor to a physical tensor by multiplication with another pseudo tensor (e.g., pseudo * pseudo = physical, physical * pseudo = pseudo, etc.). Examples include angular velocity, torque, vorticity, etc.
Rank of a Matrix	The dimension of the largest sub-matrix with a non-zero determinant in a matrix. For example: $$\underset{\approx}{A} = \left\lvert \begin{bmatrix} 2 & 5 \\ 3 & 6 \end{bmatrix} \right\rvert = -3 \neq 0 \text{, rank=2 (e.g., full rank)}$$ In dimensional analysis, the rank of the dimensional matrix is the number of *independent* fundamental units involved in a problem.
Repeated Index	Repeated indices in a product implies summation, and is the index notation representation of the inner or dot product. You cannot, however, repeat an index in any product more than once. $$x_i y_i \equiv \underset{\sim}{x} \bullet \underset{\sim}{y} = \sum_i x_i y_i$$ e.g., $x_i y_i = x_1 y_1 + x_2 y_2 + x_3 y_3$
Scalars	Point values, numbers with no direction. u_1 is a scalar, u_i is a vector! (e.g., u_1 is one component of u_i)
Surface Integral	The generalization of multiple integrals to integration over surfaces. $$\int_{\partial D} \underset{\sim}{f}\, dA \quad or \quad \int_{\partial D} \phi\, \underset{\sim}{u} \bullet \underset{\sim}{n}\, dA$$

Symmetric Tensor	It is a tensor that is invariant under a permutation of its vector arguments. In other words, a matrix A is the same as its transpose. $$A_{ij} = A_{ji}, \text{ or } \underset{\approx}{A} = \underset{\approx}{A}^T$$ Any second order tensor can be broken 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 other pairs, e.g., $A_{ijk} = p_i p_j n_k$ is symmetric with respect to *i* and *j*, but not *i* and *k*.
Tensor	A tensor can 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: $$\varepsilon_{123} = \varepsilon_{312} = \varepsilon_{231} = 1 \quad ; \quad \varepsilon_{321} = \varepsilon_{213} = \varepsilon_{132} = -1$$ ε_{ijk} is +1 if *i*, *j*, and *k* are cyclic, and -1 if they are counter-cyclic.
Time Averaging	Used to average out fluctuations over some small interval of time in turbulent flow. This is used to develop a set of time-averaged equations for turbulent flow, e.g., $$\bar{\underset{\sim}{u}} \equiv \frac{1}{\partial t} \int_t^{t+\partial t} \underset{\sim}{u} \, \partial t$$
Trace	The trace of a **n** by **n** square matrix A is defined to be the sum of the elements on the main diagonal of A such that, for example: $$\underset{\approx}{A} = \begin{bmatrix} a & b & c \\ d & e & f \\ g & h & i \end{bmatrix}$$

	$tr(\underset{\approx}{A}) = a + e + i$ $tr\left(\delta_{ij}\right) = \delta_{ii} = 3$ $tr(\underset{\approx}{A}) = A_{ij}\delta_{ij} = A_{ii} = A_{jj}$
Transpose	Notation: A' or A^T Switches the rows and columns of a matrix. Example: $\underset{\approx}{A} = \begin{bmatrix} 2 & 4 \\ 5 & 6 \end{bmatrix}, \ \underset{\approx}{A}' = \begin{bmatrix} 2 & 5 \\ 4 & 6 \end{bmatrix}$
Vector Notation	Example: $\underset{\sim}{u}$ The single underbar (squiggle) indicates a single vector consisting of the elements of $\underset{\sim}{u}$. For example: $\underset{\sim}{u} = \begin{bmatrix} 0 \\ 2 \\ 4 \end{bmatrix}$
Volume Integral	An integral over a three-dimensional domain, such as: $\iiint_D f\left(x,y,z\right)\partial x \partial y \partial z = \int_D f\, dV$

Equations and Derivations

Bernoulli's Equation	$$p_1 + \frac{1}{2}\rho U_1^2 + \rho g h_1 = p_2 + \frac{1}{2}\rho U_2^2 + \rho g h_2$$ p: local (static) pressure ρ: density of the fluid U: the average velocity of the fluid g: acceleration due to gravity h: the height above a reference plane Conservation of mechanical energy in fluid flow (ignoring all frictional losses!).
Biharmonic Equation	$$\nabla^4 \psi = 0$$ The equation governing the stream function for 2-D Stokes Flow.
Blasius Equation	$$f''' + f\,f'' = 0$$ subject to $f = f' = 0$ on $\eta = 0$ and $f' \to 1$ as $\eta \to \infty$ $$f = f(\eta)$$ $$\eta = \frac{y}{\left(\frac{2\nu x}{U}\right)^{1/2}}$$ The Blasius equation is used to describe the stream function in a steady two-dimensional boundary layer that forms on a semi-infinite plate held parallel to a constant unidirectional flow of magnitude U. The velocity in the x-direction is just: $$u_x = f'(\eta)$$
Body Force	The force on each fluid element in the interior of a domain. Example: $$\underset{\sim}{F} = \int_D \rho\, \underset{\sim}{g}\, dV$$ is the force due to gravity where the dV denotes 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. $$\underset{\sim}{F} = -\rho_f \underset{\sim}{g} V_f$$
Cauchy Stress Equations	$$\rho \frac{D\underset{\sim}{u}}{Dt} = \underset{\sim}{\nabla} \bullet \underset{\approx}{\sigma} + \rho \underset{\sim}{g}$$ or in index notation: $$\rho\left(\frac{\partial u_i}{\partial t} + u_j \frac{\partial u_i}{\partial x_j}\right) = \frac{\partial \sigma_{ij}}{\partial x_j} + \rho g_i$$ These equations are the stress balances that describe the relation between accumulation and convection of momentum and sources of momentum: gradients in the total stress and body forces due to gravity.
Continuity Equation (Divergence of the mass flux vector)	Definition: $\frac{\partial \rho}{\partial t} = -\left(\frac{\partial(\rho u_x)}{\partial x} + \frac{\partial(\rho u_y)}{\partial y} + \frac{\partial(\rho u_z)}{\partial z}\right)$ Or, condensed: $\frac{\partial \rho}{\partial t} = -\underset{\sim}{\nabla} \bullet (\rho \underset{\sim}{u})$ The time rate of change of the density is the negative of the divergence of the mass flux vector. (Or density changes over time in a control volume based on the net mass flux into or out of the control volume.) If the fluid is *incompressible*, the density of the fluid is *constant* and the equation simplifies to: $$\underset{\sim}{\nabla} \bullet \underset{\sim}{u} = 0$$ In index notation, the CE is written as: $$\frac{\partial \rho}{\partial t} + \frac{\partial(\rho u_i)}{\partial x_i} = 0$$ or: $$\frac{\partial \rho}{\partial t} + u_i \frac{\partial \rho}{\partial x_i} = -\rho \frac{\partial u_i}{\partial x_i}$$

Darcy's Law	$$Q = \frac{-kA}{\mu}\frac{(P_b - P_a)}{L}$$ k is the intrinsic permeability of the medium A is the cross-sectional area ΔP is the total pressure drop L is the length over which the pressure drop is taking place μ is the viscosity It describes flow through a porous medium, and is valid when the Reynolds number based on the pore radius is small (the usual case). In vector form: $$u_i = \frac{-k}{\mu}\frac{\partial p}{\partial x_i}$$
Displacement thickness	$$\delta^* = \int_0^\infty \left(1 - \frac{u}{U}\right) dy$$ A measure of the thickness of a boundary layer. It is also the distance streamlines far from a wall are displaced by the wedge of slow moving fluid in a boundary layer.
$E^4 \psi = 0$	The equivalent to the biharmonic equation for axi-symmetric flows (e.g. flow past a sphere). Valid for Stokes Flow (zero Re flows) only.
Euler Flow Equations	$$\rho \frac{D\underset{\sim}{u}}{Dt} = -\underset{\sim}{\nabla} P$$ $$\underset{\sim}{\nabla} \bullet \underset{\sim}{u} = 0$$ Inviscid flow equations, valid at high Reynolds numbers. The assumption of inviscid flow eliminates the no-slip boundary condition, leading to discontinuities in the velocity at the surface that must be resolved by the boundary layer equations.
Falkner-Skan Equation	Occurs when the Blasius boundary layer equation is generalized by considering high Re flow into a wedge with internal angle πβ with some uniform velocity U_o. $$\frac{\partial^3 f}{\partial \eta^3} + f\frac{\partial^2 f}{\partial \eta^2} + \beta\left[1 - \left(\frac{df}{d\eta}\right)^2\right] = 0$$

	where $$\eta = y\sqrt{\frac{U_0(m+1)}{2\nu L}}\left(\frac{x}{L}\right)^{(m-1)/2}$$ $$\beta = \frac{2m}{m+1}$$ m is a dimensionless constant $\beta = 0$ yields the Blasius problem (m = 0), $\beta = 1$ is stagnation flow (m=1).
Fick's Law	$$J = -D\frac{\partial \phi}{\partial x}$$ 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.
Fourier's Law of Heat Conduction	$$\underset{\sim}{q} = -k\underset{\sim}{\nabla} T$$ $\underset{\sim}{q}$ is the local heat flux (energy/(area*time)) k is the material's thermal conductivity T is the temperature The law states that the heat flux via conduction through a material is proportional to the temperature gradient. If the material is not isotropic, this is generalized to: $$q_i = -k_{ij}\frac{\partial T}{\partial x_j}$$ where k_{ij} is a second order tensor.
Integrable Singularity	A function that goes to infinity within a domain, but its integral over the domain is finite (e.g. f (x) = $x^{-1/2}$ is infinite at x = 0, but is integrable over a domain including zero).
Invariant	Does not change.
Laplace's Equation	$$\nabla^2\varphi = 0,$$ or

	$$\nabla^2 f = \frac{\partial^2 f}{\partial x^2} + \frac{\partial^2 f}{\partial y^2} + \frac{\partial^2 f}{\partial z^2} = 0$$ The solutions to these equations are called the harmonic functions. The equation (among many, many applications) describes the velocity potential for inviscid, irrotational, incompressible flow.
Material Derivative	Definition: $$\frac{D\phi}{Dt} \equiv \frac{\partial \phi}{\partial t} + \underset{\sim}{u} \bullet \underset{\sim}{\nabla} \phi$$ The time rate change of any property ϕ experienced by a fluid *element*. (Lagrangian perspective)
Momentum thickness	$$\theta = \int_0^\infty \frac{u}{U}\left(1 - \frac{u}{U}\right) dy$$ A measure of the momentum removed from a boundary layer due to viscous diffusion to a surface. Used in the von Karman Momentum Balance to determine the stress on a flat plate.
Navier-Stokes Equations	In index notation: $$\rho\left(\frac{\partial u_i}{\partial t} + u_j \frac{\partial u_i}{\partial x_j}\right) = -\frac{\partial p}{\partial x_i} + \mu \frac{\partial^2 u_i}{\partial x_j^{\,2}} + \rho g_i$$ Or in vector notation: $$\rho\left(\frac{\partial \underset{\sim}{u}}{\partial t} + \underset{\sim}{u} \bullet \underset{\sim}{\nabla} \underset{\sim}{u}\right) = -\underset{\sim}{\nabla} p + \mu \nabla^2 \underset{\sim}{u} + \rho \underset{\sim}{g}$$ What each part of the equation represents: $\rho \frac{\partial \underset{\sim}{u}}{\partial t}$: time dependent accumulation of momentum (fluid acceleration) $\rho \underset{\sim}{u} \bullet \underset{\sim}{\nabla} u$: convection of momentum associated with fluid inertia (fluid velocity) $-\underset{\sim}{\nabla} p$: gradients in the pressure acting as a source or sink of momentum

	$\mu \nabla^2 \underset{\sim}{u}$: viscous diffusion of momentum $\rho \underset{\sim}{g}$: gravitational source of momentum (Note: for constant density, it may be combined with the pressure gradient to form an augmented pressure, removing pressure variation due to hydrostatics.) The key equation governing conservation of momentum for an incompressible, isotropic (Newtonian) fluid with constant viscosity.
Net convection of momentum out of a control volume	Definition: $$\int_{\partial D} \left(\rho \underset{\sim}{u}\right) \underset{\sim}{u} \bullet \underset{\sim}{n}\, dA$$
Newton's Law of Viscosity	$$\tau_{yx} = \mu \left(\frac{\partial u_x}{\partial y} + \frac{\partial u_y}{\partial x} \right)$$ Flux of x-momentum in the y direction, or y-momentum in the x direction due to velocity gradients. In general for an incompressible, isotropic fluid: $$\tau_{ij} = \mu \left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right)$$
Normal Equations	$$\underset{\approx}{A}^T \underset{\approx}{A} \underset{\sim}{x} = \underset{\approx}{A}^T \underset{\sim}{b}$$ The equations from linear regression. The solution vector $\underset{\sim}{x}$ minimizes the 2-norm of the residual $\underset{\sim}{r} = \underset{\approx}{A} \underset{\sim}{x} - \underset{\sim}{b}$
Poiseuille's Law	$$Q = \frac{-\pi}{8} \frac{\Delta P}{L} \frac{R^4}{\mu}$$ Flow rate resulting from a pressure drop through a circular tube of radius R and length L. Valid for steady, well-developed laminar flow (Poiseuille flow).
Prandtl Boundary Layer Equations	$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0$$

	$$\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}=-\frac{1}{\rho}\frac{\partial p}{\partial x}+\nu\frac{\partial^2 u}{\partial y^2}$$ or in dimensionless form: $$\frac{\partial u^*}{\partial x^*}+\frac{\partial v^*}{\partial y^*}=0$$ $$\frac{\partial u^*}{\partial t^*}+u^*\frac{\partial u^*}{\partial x^*}+v^*\frac{\partial u^*}{\partial y^*}=-\frac{\partial p^*}{\partial x^*}+\frac{\partial^2 u^*}{\partial y^{*2}}+O\left(\frac{1}{\mathrm{Re}_L}\right)$$ Valid for $\mathrm{Re}_L >> 1$, this equation governs the velocity distribution in a laminar boundary layer next to a solid surface. Normal (y direction) distances are scaled with the boundary layer thickness: $$\delta=\left(\frac{\nu L}{U}\right)^{\frac{1}{2}}$$ while distances along the boundary layer (x direction) are scaled with L. Diffusion of momentum in the x direction scales out, and the pressure distribution from *outside* the boundary layer is *impressed* on the boundary layer.
Reynolds Lubrication Equation	$$\frac{\partial\left(h^{*3}\frac{\partial P^*}{\partial x^*}\right)}{\partial x^*}=6\left[h^*\frac{\partial u^*}{\partial x^*}-U^*\frac{\partial h^*}{\partial x^*}+2V^*\right]$$ Dimensionless equation relating the pressure gradient in the tangential direction between two surfaces to variations in the gap width h*, the upper surface velocity U*, or the approach velocity V*. Useful for problems when h/L << 1 (lubrication) and where you know P* at x*=0 and x*=1.
Stokes Flow Equations	$$\frac{\partial\sigma_{ij}}{\partial x_j}=0$$ Conservation of momentum for a fluid at zero Re (no inertia or gravity).
Stokes' Law	$$\underset{\sim}{F}=-6\pi\mu a U\,\underset{\sim}{\hat{e}_z}$$ The force on a sphere of radius a moving with velocity U at zero Re. It is of fundamental importance in the study of suspensions at low Re.

Stokes' Sedimentation Velocity	$$U_s = \frac{2}{9}\frac{\Delta\rho\, g\, a^2}{\mu}$$ The sedimentation velocity of a sphere of radius a and density difference $\Delta\rho$ in a fluid of viscosity μ at zero Re. Forces exerted on the surface of a body.
Surface Force	Forces exerted on the surface of a body. Examples: Integrated surface force on an object: $$\underset{\sim}{F} = \int_{\partial D} \underset{\approx}{\sigma} \bullet \underset{\sim}{n}\, dA$$ Integrated normal force on an object for the case where shear stresses are zero (e.g., hydrostatics): $$\underset{\sim}{F} = \int_{\partial D} -p\, \underset{\sim}{n}\, dA$$ The *dA* denotes a differential patch of the surface, and $\underset{\sim}{n}$ the unit normal.
Von Karman Momentum Balance	$$\frac{\tau_o}{\rho} = \frac{\partial\left(u_\infty^2\theta\right)}{\partial x} + \delta^* u_\infty \frac{\partial u_\infty}{\partial x}$$ The surface stress τ_o on a plate at high Re inside a boundary layer related to changes in the momentum and displacement thicknesses. Experimentally, it allows for the measurement of shear stresses by evaluating *integrals* of the tangential velocity u, which is much easier and more accurate than evaluating the *normal derivative* of the tangential velocity.

Symbol Definitions

Adverse Pressure Gradient	$$\frac{\partial p}{\partial x} > 0$$ In boundary layer flow, adverse (positive) pressure gradients cause rapid growth in boundary layer thickness, and lead to separation.
Angular Velocity	Symbol: ω or Ω Units: $\frac{\text{radians}}{\text{second}}$ It is defined as the rate of change of angular displacement and is a pseudovector which specifies the angular speed (rotational speed) of an object and (in vector form) the axis about which the object is rotating.
Augmented Pressure	Symbol: P In flows in a homogeneous system, it is convenient to define the augmented pressure: $$P = p - \rho \underset{\sim}{g} \bullet \underset{\sim}{x}$$ which subtracts off hydrostatic pressure variation. It is the *deviation* from hydrostatics that drives the flow.
Average Velocity	Symbol: U, Common units: $\frac{m}{s}$ Definition: $\frac{Q}{A}$ $\left(\frac{length}{time}\right)$ Q: the volumetric flowrate A: the cross-sectional area normal (perpendicular) to the flow
Boundary Layer Coordinates	x= distance along a surface from the leading point of stagnation y=distance normal to the surface For boundary layer flow, x scales with the size of the object (L) and y scales with the thickness of the boundary layer (δ). In the boundary layer limit δ/L << 1.

Centrifugal Force	$$-\rho \frac{u_\theta^2}{r}$$ A pseudoforce which arises from the coordinate transformation from Cartesian coordinates to cylindrical (polar) coordinates. Acts in the radial direction. It's why a satellite doesn't fall to Earth…
Coefficient of Thermal Expansion	$$\beta = \frac{-1}{\rho}\left(\frac{\partial \rho}{\partial T}\right)_P = \frac{1}{T} \text{ for an ideal gas}$$ Important Values: $H_2O = 2 \times 10^{-4}\ K^{-1}$ Metals $\approx O(5 \times 10^{-5})\ K^{-1}$ The amount that a material expands when it is heated, it is important in natural convection problems, such as the draft off of a window.
Coriolis Force	$$\rho \frac{v_r v_\theta}{r}$$ The apparent force in the theta direction due to theta and radial velocities. This force explains why low pressure systems (e.g., hurricanes) circulate counter-clockwise in the northern hemisphere, by combining the (small) inward radial velocity due to the pressure gradient with the much larger theta direction motion due to the rotation of the Earth.
Critical Surface Roughness	$$e^+ \geq 7$$ At this value, the wall roughness of magnitude *e* (normalized by the viscous length scale, e.g., in + units) sticks up outside the viscous sublayer in turbulent pipe flow, and leads to the friction factor depending on roughness rather than the implicit relationship obtained for smooth pipes.
Darcy Friction Factor	Four times the Fanning friction factor.
Density	Symbol: ρ, Common units: $\frac{g}{cm^3}$ Definition: $\frac{M}{V}$, $\frac{mass}{length^3}$

	Values you need to *know*: $H_2O \approx 1 \ \frac{g}{cm^3}$ Air $\approx 1.2 \times 10^{-3} \ \frac{g}{cm^3}$ Hg $\approx 13.6 \ \frac{g}{cm^3}$
Deviatoric Stress	Symbol: τ_{ij} $$\tau_{ij} = \mu\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right)$$ for an isotropic incompressible fluid What is left over from the total stress when you subtract off the isotropic contribution from the pressure -pδ_{ij}. Arises due to the deformation of a fluid. Identically zero for isotropic fluids at rest (hydrostatics, for example). It is symmetric, and also traceless for an incompressible fluid.
Drag Coefficient	$$C_D = \frac{F}{\frac{1}{2}\rho U^2 A}$$ The drag on an object normalized by the dynamic pressure and the cross-sectional area normal to flow, the appropriate scaling at high Re. For a flat plate, we can define a local drag coefficient: $$C_D^{(loc)} = \frac{\tau_w}{\frac{1}{2}\rho U^2}$$ where τ_w is the wall shear stress.
Eddy Viscosity	$$\tau_{yx}^{turb} = \left\{\rho \ell^2 \left\|\frac{\partial u}{\partial y}\right\|\right\} \frac{\partial u}{\partial y}$$ where the eddy viscosity is the quantity in brackets {}. Obtained from Prandtl mixing length theory. The quantity "ℓ" is the length scale of the eddies and the shear rate $\left\|\partial u / \partial y\right\|$ is the

	rate with which eddy exchanges take place in turbulent flow.
Euler's Constant	Symbol: γ $\gamma = 0.5772\ldots$ The Euler constant 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 Re (see Stokes' Paradox).
Fanning Friction Factor	Symbol: 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	$\frac{\partial p}{\partial x} < 0$ Negative pressure gradients retard boundary layer growth and delay boundary layer separation.
Fluctuation Velocity	The instantaneous deviation from the average velocity in turbulent flow.
Friction Velocity	The appropriate velocity scaling in turbulent flow near a wall. $v_* = \left(\frac{\tau_o}{\rho}\right)^{1/2}$
Head Loss	Loss in hydrostatic head due to flow (useful for pipe flow calculations at high Re). For pipes: $h_L = \frac{\Delta P}{\rho g} = 4 f_f \frac{L}{D} \frac{<u>^2}{2g}$ and for fittings: $h_L = \frac{\Delta P}{\rho g} = K \frac{<u>^2}{2g}$ where K values are determined empirically.
Kinematic Viscosity (Momentum diffusivity)	Symbol: ν Common units: $\frac{cm^2}{s}$ (stokes) , $\frac{length^2}{time}$

	Definition: $\dfrac{\mu}{\rho}$ μ: viscosity of the fluid ρ: density of the fluid The diffusion coefficient for momentum. Values you need to *know*: $H_2O \approx 0.01$ stokes Air ≈ 0.15 stokes Hg ≈ 0.0011 stokes glycerine ≈ 11 stokes (*very* temperature dependent!)
Kinetic Energy/Volume (Dynamic Pressure)	$$\frac{1}{2}\rho u^2$$ The extra pressure that you would get if you stopped the motion of a flow.
Mass Flux	Definition: $\rho \underset{\sim}{u} \quad \left(\dfrac{mass}{area * time}\right)$ (Same as momentum/volume!)
Mean Free Path Length	In a gas, $\lambda \approx \dfrac{1}{\sqrt{2}\pi d^2 n}$, Where d is the molecular diameter and n is the number density (molecules/vol). The minimum length for the continuum hypothesis to hold true in a gas is a multiple of the mean free path length, which is the distance a molecule travels before hitting another.
Moment of Inertia	The mass property of a rigid body that determines the torque needed for a desired angular acceleration about an axis of rotation. $$I = \int_D \rho s^2 \, dV$$ s is the distance from the axis of rotation.

Momentum Flux (Stress tensor)	Symbol: σ_{ij} Definition: $\sigma_{ij} \equiv \frac{Force}{Area}$ The force per unit area exerted <u>by</u> fluid of greater i <u>on</u> fluid of lesser i in the j direction. Flux of momentum per area per time due to surface forces. Except for very weird systems (where you are imposing a body torque per unit volume) the stress tensor is symmetric.
$\mu \frac{\partial^2 u_x}{\partial y^2}$	The viscous diffusion of x-momentum in the y-direction
Normal Stress	Symbol: σ_{xx}, e.g. normal stress in the x-direction Definition: $\underset{\sim n}{f} = \left(\underset{\sim}{f} \bullet \underset{\sim}{n}\right)\underset{\sim}{n}$, where $\underset{\sim}{f}$ is $\frac{F}{A}$ arises from the force vector component perpendicular to the cross sectional area.
Plus Units	Dimensionless variables used in turbulent flow near a boundary. Usually given the superscript $^+$, they are the velocity normalized by the friction velocity, the distance from the wall normalized by the viscous length scale, and the time normalized by ν/v_*^2, e.g., a time scale created from the kinematic viscosity and the friction velocity.
Pressure	Symbol: p Common Unit: Pascal (Pa), $\frac{N}{m^2}$ or $\frac{\mathrm{kg}}{\mathrm{m \cdot s^2}}$ $p = -\frac{1}{3}\left(\sigma_{xx} + \sigma_{yy} + \sigma_{zz}\right)$, $P = \frac{F}{A}$ The average of the normal stresses on a fluid. Pressure is also the amount of force acting per unit area in the normal direction in a fluid at rest. One atmosphere is 1.013×10^5 Pa, or about 10.3m of water.

Reynolds Stress	$$\bar{\underset{\approx}{\tau}}' \equiv -<\rho \underset{\sim}{u}' \underset{\sim}{u}'>$$ The added momentum flux (stress) due to turbulent velocity fluctuations.
Shape Factor	$$H \equiv \frac{\delta^*}{\theta}$$ It is a dimensionless measure of the shape of the boundary layer velocity profile. H=2.59 for laminar flow past a flat plate, and is reduced in turbulent boundary layer flow.
Shear Stress	Symbol: τ_{yx} Definition: $\tau_{yx} = \mu\left(\frac{\partial u_x}{\partial y} + \frac{\partial u_y}{\partial x}\right)$ Shear stress arises from the force vector component parallel to a surface. Shear stresses are the off-diagonal elements of the deviatoric stress tensor. In all Newtonian fluids in laminar flow, the shear stress is proportional to the strain rate in the fluid.
Shear Rate (Rate of strain)	Symbol: $\dot{\gamma}$ Definition: $\frac{U}{D}$ (for simple shear flow) U: relative tangential velocity of two plates D: separation distance between the plates Rate with which a fluid element deforms. Units: $\frac{1}{time}$ For more complicated flows, it is the magnitude of the symmetric part of the rate of strain tensor.
Speed of sound	Symbol: V_s $V_s = \left(\frac{\partial P}{\partial \rho}\right)_T^{1/2} = \frac{RT}{M}$ (ideal gas),

	where P is pressure and T is temperature It is related to the compressibility of fluid: sound is a pressure wave traveling through a fluid. When $U \approx O(V_s)$ a flow is compressible (this means that the fluid density is affected by fluid motion) and shock waves develop.
Surface Tension	Symbol: σ or Γ, Units : $\frac{erg}{cm^2}$, $\frac{dyne}{cm}$, $\frac{energy}{length^2}$ The energy required to create the interfacial surface area between two dissimilar fluids. (Tends to be minimized as much as possible. This is why bubbles are spherical: the minimum surface area to volume ratio.) For a clean drop of water in air, Γ = 70 dyne/cm. Surfactants reduce this by orders of magnitude!
Thermal Diffusivity	Symbol: α $$\alpha = \frac{length^2}{time} = \frac{k}{\rho C_p}$$ k is the thermal conductivity ρ is the density C_p is the specific heat capacity The diffusion coefficient for thermal energy.
Torque (or Couple)	$$\underset{\sim}{M} = \underset{\sim}{R} \times \underset{\sim}{F}$$ Note that this has units force * length (same as energy!)
Unit Normal	The unit normal to a patch of surface dA is $\underset{\sim}{n}$, which by itself is a unit vector of length 1. To get the normal portion of a vector $\underset{\sim}{f}$, we calculate $\underset{\sim}{f}_n = \left(\underset{\sim}{f} \bullet \underset{\sim}{n}\right)\underset{\sim}{n}$
Viscosity	Symbol: μ Common unit: $\frac{g}{cm * s}$ (poise) , $\frac{mass}{length * time}$ Values you need to *know*:

	$H_2O \approx 0.01$ p = 1 cp (*centipoise)* Air ≈ 0.00018 p = 0.018 cp Glycerine ~ 14 p (*very* temperature sensitive!)
Viscous Length Scale	$$\frac{\nu}{v_*}$$ Ratio of kinematic viscosity to the friction velocity. The length scale over which viscous effects are important in turbulent flow.
Volumetric Flux	$$\underset{\sim}{u} = \frac{volume}{area \cdot time}$$ Same as velocity!
Von Karman Constant	$$\alpha = 0.36 \text{ (or 0.40)}$$ A fitting parameter used in determining the length scale of eddies in Prandtl Mixing Length Theory.
Vorticity	$$\underset{\sim}{\omega} = \underset{\sim}{\nabla} \times \underset{\sim}{u}, \text{ or}$$ $$\omega_{\mathrm{i}} \equiv \varepsilon_{ijk} \frac{\partial u_k}{\partial x_j}$$ ω_{i} is a pseudovector u_k is a physical vector The 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 $$E \equiv \frac{\text{shear stress}}{\text{strain}} = \frac{\tau}{\gamma}$$ Young's modulus, also known as the elastic modulus, is the measure of the stiffness of a linearly elastic material. It is defined as the ratio of the stress along an axis over the strain along the same axis.

Defining Terms and Phenomena

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	It is 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, Fr is preserved, while 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 convenient to remember, and is also important: it is what makes clearing bubbles from a syringe possible, for example. The convective effects of this ratio gave rise to the meniscus accumulation in squeeze flow demonstrated in the first class. Most importantly, this effect also 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. Mayo is a good example.
Boston Molasses Flood	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 Re 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 ~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. 2-D 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.
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 doesn't matter, and only the initial density of the air need 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 US atom 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 $< 10^2$ or so. Colloids contribute to the osmotic pressure of a suspension and are an important additive 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	It is a demonstration of the conservation of momentum, but *not* the momentum associated with light. Originally solved by Reynolds, and a demonstration of the phenomenon of thermal transpiration.
CSTR	A continuous flow stirred tank reactor, it is a common ideal reactor type in chemical engineering. The behavior in a CSTR is usually approximated by assuming perfect mixing, such that the output composition is identical to the composition of the materials 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 on the cylinder separates, leading to loss of pressure recovery and thus 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 modeling are usually divided into two types: independent and dependent. The dependent variable represents the output or effect of an equation (e.g., velocity, temperature, pressure, etc.). Its value is dependent on the independent variables such as position and time (e.g., x, y, t, etc.).
Diffusion Length	The distance a quantity diffuses during some time Δt. This applies equally to mass, momentum, and energy. The momentum diffusion length is given by $\left(\nu \Delta t\right)^{\frac{1}{2}}$ where ν is the kinematic viscosity (momentum diffusivity), and that of mass or energy would be the same with D (mass diffusivity) or α (thermal diffusivity) instead of ν.
Diffusion Time	The time required for a quantity to diffuse a length L. Again, this applies equally to mass, momentum, and energy. For momentum it is given by L^2/ν, for example. This would be the characteristic time for plane-Couette flow to reach steady-state if the upper plate is impulsively started from rest if the plates are separated by a distance L.
Dilatant	A fluid whose viscosity increases with increasing strain rate. Also called shear thickening. The viscosity effect is common in suspensions of colloidal particles such as corn starch/water mixtures, and is due to jamming caused by shearing motion. It is the basis of modern 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 away 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 be 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 to modeling fluids	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 Ordinary Differential Equation (ODE)	$$\frac{\partial y}{\partial x} + p(x)y = f(x)$$ First order linear ODEs take the form described above. Pretty much the *only* general class of differential equation for which you can always write down the solution. 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 (kinematic

	energy/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, and so on). The optimum choice is not always obvious, but is usually mass, length, and time.
Geometric Ratios	The ratio of length scales used in scaleup and dimensional modeling. In general, 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 fuel density unit conversion error, becoming a glider at 30,000ft. Amazingly, the pilots managed to land it in one piece at Gimli Airforce 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, as pressure (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	$$p+\rho gh$$ The potential energy or pressure available to drive fluid flow. This, plus the dynamic pressure (kinematic energy/volume), is 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. $$\rho \underset{\sim}{u} \bullet \underset{\sim}{\nabla} \underset{\sim}{u}$$ For unsteady problems, it also includes the acceleration term $$\rho \frac{\partial \underset{\sim}{u}}{\partial t}$$
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 Re 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 – It was the result of the catastrophic failure of the South Fork Dam, made worse by several days of heavy rainfall. The dam was located fourteen miles upriver and 400ft above the town. When it broke, the water's flow rate reportedly equaled that of the Mississippi River. A tragic demonstration of hydrostatics (the force on the dam prior to failure), the conversion of hydrostatic head to kinetic energy in driving the flow, and finally conversion back to pressure (F/A) when the flood flattened the town. The remnants of the dam are preserved as a national memorial.

Knudsen Diffusion	A means of diffusion that occurs when the length scale of a system is comparable to or smaller than the mean free path of the particles involved. In practice, Knudsen diffusion applies only to gases because the mean free path for liquid molecules is small, typically near the diameter of the molecule itself. Important in diffusion of gases into catalyst pores.
Lagrangian approach to modeling fluids	Description of properties such as velocity, density, pressure, etc., following a fluid element as it moves through a flow. This is done by keeping track of the position and velocity of the fluid elements starting initial position x_o for all time. Useful for celestial dynamics, particulate systems, and evaluating continuous pasteurization processes...
Laminar vs. Turbulent Flow	Laminar flow: layers of fluid slip smoothly over each other Turbulent flow: chaotic flow, time dependent, and very difficult to describe mathematically with precision At $Re \approx 2100$ (for circular pipes only!), turbulent flow disturbances will not decay back to laminar flow.
Law of the Wall	It states that the average velocity of a turbulent flow at a certain point is proportional to the logarithm of the distance from that point to the "wall", or the boundary of the fluid region. Arises naturally from the assumptions of Prandtl mixing length theory.
Lift and Drag	A fluid flowing past the surface of a body exerts a force on it. Lift is the component of this force that is perpendicular to the oncoming flow direction. The drag force is the component of the surface force parallel to the flow direction.
Lift/Drag Ratio	A plane stays in the air because the lift equals (pretty much exactly) the weight of the plane. The plane's engines are designed to overcome only the drag. A commercial airliner has an L/D ratio much greater than one (maximum of ~20). That's why you never see a Boeing jet go straight up...
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 $H << L$ flow length scale L. Due to the thin gap, the flow is quasi-parallel, and viscous effects usually dominate the forces.
Magneto-hydrodynamics	The study of the dynamics of electrically conducting fluids in

(MHD)	magnetic fields. Examples of such fluids include plasmas, liquid metals, and salt water or electrolytes. The concept behind it is that magnetic fields can induce currents in a moving conductive fluid, which in turn creates forces on the fluid and also changes the magnetic field itself.
Manometer	An instrument that uses a column of liquid to measure pressure. Usually the liquid inside one is either mercury or water. The displacement of the fluid is used to calculate the pressure using hydrostatics.
Matched Asymptotic Expansions	A sophisticated approach to finding an accurate approximation to the solution of an equation or a system of equations. It involves finding solutions to two approximate equations, each of which is valid for part of the range of the independent variable (e.g., close to an object and far from an object). These solutions are then combined together to give a single approximate solution that is valid for the whole range. Boundary layer flow is an example of where matched asymptotic expansions are applied.
Matching Conditions	The procedure by which the solutions in matched asymptotic expansions are merged. In boundary layer flow, for example, the outer limit of the inner boundary layer solution has to match the inner limit of the outer Euler flow solution.
Minimum Dissipation Theorem	Of all solenoidal (divergence-free) vector fields satisfying a set of boundary conditions, the one which also satisfies the Stokes Flow Equations yields the minimum viscous dissipation (minimum drag). There are a couple of useful corollaries to this which you should look up and remember!
Momentum per unit volume	Definition: $\rho \underset{\sim}{u}$ (Same as 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	For a Newtonian fluid, in simple shear flow:

	$\frac{F}{A} = \frac{U}{D}\mu$, where μ is the viscosity and $\frac{U}{D}$ is the shear rate. Newtonian fluids are isotropic, and have a linear stress-strain relationship with no yield stress.
Normal Stress Differences	Occur when the normal stresses in a shear flow are different in the flow, gradient, or vorticity directions. Often found in polymers and concentrated suspensions. Normal stress differences lead to phenomena such as the rod climbing effect (where cookie batter or a polymer melt climbs up a rotating rod).
No-slip condition	At a solid surface in contact with a fluid, velocity is continuous. Thus the fluid layer adjacent to the solid surface moves with the velocity of the solid surface. This arises from finite viscosity, and thus is violated if the flow is inviscid. In such flows it is reestablished by solving the boundary layer equations in a thin region near the boundary.
NPSHR	The “net positive suction head required” at the inlet of a pump to prevent cavitation from occurring in the pump. Generally, you get 1 atm (less the vapor pressure of water, equivalent to 0.3m head at room temperature) for free, and this minus upstream losses must be greater than NPSHR.
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/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. It is very important in studying the biology of cells. In RO (reverse osmosis) systems, applying a pressure greater than this can produce pure water from salt water. Arises from the entropy of a solution or suspension.
Pathlines	Paths followed by fluid elements. Usually captured by time-lapsed photography.

Pelton Wheel	It is 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 is produced in the *narrow* gap (low Re 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 is a quadratic function of 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 the 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 Re flow reduces drag. Note that this only happens if the boundary layer is still attached to the object. You can often see trucks on the highway with modifications on the end of the trailer to delay separation and promote pressure recovery, reducing drag and improving fuel economy.
Pseudoplastic	Viscosity decreases with increased shear rate. This is also called shear thinning. It is very common in polymer melts because the shear causes the 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 are made to show the operating ranges of a specific type of pump. Typically, you identify the desired head gain and flow rate on the graph, and determine if it lies within the recommended operating range of the pump. It can also be used to easily calculate pump efficiency.
Pyroclastic Flows	The flow of a mixture of hot ash and air that results from a volcanic eruption. The resulting gravity driven flow down the mountain (even

	though very hot, the ash makes the mixture denser than unheated air) moves *extremely* fast. Probably the most dangerous part of the eruption, as lava is much easier to run away from!
Quasi-Parallel Flows	A case where the flow is predominately in one direction. This usually happens when there is a separation of length scales, with the velocity in the long direction being much greater than the velocity in the thin direction, leading to a great simplification of the flow equations.
Rate of strain tensor	Rate of deformation of a fluid (tensor): $\frac{\partial u_i}{\partial x_j}$ The symmetric part of the rate of strain tensor is usually given the symbol e_{ij}, and 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 the flow of surrounding fluid around the body. At high Re flow past a blunt object, the boundary layer separates and there is a reverse flow region where the flow is moving towards the body (e.g., upstream), causing recirculation. I use this effect in paddling my kayak upriver behind bridge pylons - it saves a lot of effort!
Reference Frame	A coordinate system used to represent and measure properties of objects, such as their position and orientation, at different moments of time. It can also refer to a set of axes used for such representation. In fluid mechanics it is usually a very, very good idea 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 is usually the result of thermal (Brownian) processes.
Residence Time	The average amount of time that a fluid element spends in a particular system: $$\tau = \frac{V}{Q}$$

	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, this is the disturbance velocity produced by a sphere rotating in a viscous fluid at zero Re. Also called a couplet.
Separation of Length Scales	This occurs when one dimension of the problem is much greater than another. In fluid mechanics, this leads to a great simplification: velocities in the long direction are much greater than those 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 the fluid flow. By looking at the forces on one small portion of a body, it is possible to integrate over the flow to see the larger picture of the flow as a whole. The balance is determining what goes into and out of the shell.
Similarity Transform	A powerful technique that allows one to reduce the number of *independent variables* that a problem depends on. For example, sometimes you can convert a 2-D partial differential equation into an ordinary differential equation, which is much simpler to solve.
Squeeze Flow	A lubrication flow that results from the normal motion between two surfaces (e.g., squeezing two plates together).
Stagnation Flow	The flow resulting from fluid being directed normal to a surface (e.g., a jet of water directed at a plate).
Stagnation Point	The point on a surface in a stagnation flow where the local velocity of the fluid is zero.
Stall	Stall occurs when the boundary layer over a wing separates from the plane, greatly increasing the drag. This slows the plane down and greatly reduces lift. Also, the wing control surfaces are on the trailing edges of the wing. If the flow separates, these surfaces are now in a separation bubble and can no longer control the motion of the plane, making stall hard to escape and a crash hard to avoid.
Static Pressure	The local pressure in a fluid flow.
Steady-State	If a system is in steady state, the observed behavior of the system will not change with time in an Eulerian reference frame.

	$$\frac{\partial(properties)}{\partial t}=0$$
Stokes-Einstein Diffusivity	$$D_0=\frac{kT}{6\pi\mu a}$$ k is Boltzmann's constant T is the absolute temperature a is the radius of a sphere (or effective radius of a particle) Einstein showed that the diffusion coefficient of a colloidal particle (small particle or large molecule) in a fluid was the thermal energy divided by the Stokes flow resistance to motion. This can actually be used in modified form to estimate mass diffusivity of molecules in liquids.
Stokeslet	The disturbance velocity due to a point force in creeping flow. It is also the far field of the velocity distribution produced by any object with a net force applied to it (e.g., a sphere settling due to gravity). This is the fundamental singularity of Stokes flow.
Stokes Paradox	You can't solve creeping flow past a cylinder (2-D analog to flow past a sphere). Inertia, no matter how slow the flow, always comes into play. This is why a layer of hair plugs a drain even if the fraction of surface area occupied by the (very thin!) hair is rather small.
Strain	Symbol: ε or γ The ratio of deformation over initial length.
Streaklines	Streaks of dye originating from a fixed point in a flow. Usual method of flow visualization.
Stream Function	A mathematical function whose value is constant along a streamline.
Streamlines	Curves which are everywhere tangent to the velocity at an instant in time. For unsteady flows, they cannot be visualized and must be calculated from the velocity field. For steady flows, pathlines, streaklines, and streamlines are identical!
Stresslet	The far field of the disturbance velocity of a force free and torque free particle in creeping flow (e.g., a freely suspended sphere in a simple shear flow at zero Re). One of the fundamental singularities in Stokes flow.

Strict Dynamic Similarity	All dimensionless groups in dimensional scaling are preserved exactly. Very difficult to do for scale-up in fluid mechanics!
Taylor-Couette Vortices	In Couette flow, when the angular velocity of the inner cylinder is increased above a certain threshold, the flow becomes unstable and a secondary steady state characterized by axisymmetrical toroidal vortices, known as Taylor vortex flow, emerges. As more angular speed is added, the system becomes more unstable, eventually leading to turbulent flow.
Taylor Dispersion	Important in chromatography, this is the dispersion (spread of a solute slug) in the flow direction that arises due to solute molecules being convected with different velocities. In Poiseuille flow through a circular tube the centerline velocity is twice the average velocity. This means that molecules traveling along the centerline move faster than the average at any instant. As a result a plug of solute in Poiseuille flow will spread out (disperse) in the flow direction, with the dispersion ultimately limited by solute molecules diffusing across all the streamlines. This yields a dimensionless Taylor dispersivity for a tube of radius a: $$\frac{K}{D} = 1 + \frac{1}{48}\left(\frac{U\,a}{D}\right)^2$$
Tollmein-Schlicting Waves	Unstable laminar flow past a flat plate at high Re exhibits 2-D Tollmein-Schlicting waves. These “roll waves” can be predicted via an instability analysis from the Navier-Stokes equations.
Total Pressure (Stagnation Pressure)	The sum of the static and dynamic pressure.
Turbulent Core	The region in turbulent flow where the momentum transfer is dominated by turbulent velocity fluctuations, e.g., the Reynolds Stress.
Unidirectional Flow	The flow is in only one direction (as opposed to quasi-parallel flow where it is *mostly* in one direction!). For an incompressible fluid, application of the continuity equation leads to a tremendous simplification in the flow equations, including elimination of the non-linear inertial terms.
Venturi Meter	A venturi meter constricts the flow in a smooth throat and pressure sensors measure the differential pressure before and within the constriction. The reduction in pressure due to the increased velocity in the constriction allows calculation of the velocity and flow rate from Bernoulli’s Equation.

Viscous Forces	The viscous forces in a fluid flow. $$\mu\nabla^2 \underset{\sim}{u}$$
Viscous Sublayer	The region next to the wall in turbulent flow where momentum transfer is dominated by viscous effects rather than turbulent velocity fluctuations.
Von Karman Vortex Street	It is a repeating pattern of swirling vortices caused by the unsteady separation of flow of a fluid around blunt bodies. It is responsible for such things like the "singing" of suspended telephone or power lines and the vibration of a car antenna at certain speeds. It is closely related to aeroelastic flutter.
Yield Stress	For some fluids no motion occurs until a critical shear stress is exceeded. Mayonnaise and frozen orange juice are two examples of this. Yield stresses are also designed into many food products such as 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).

Biot Number (Bi)	Definition: $Bi = \frac{hL}{k}$ h is the surface heat transfer coefficient k is the thermal conductivity L is the length scale of the object This is the ratio of external to internal heat transfer in a solid, and a number you will encounter next term in the thermal quenching of a block. For small Bi external heat transfer resistance dominates, and an object will be at a uniform temperature (but different from the surroundings). For large Bi external heat transfer is fast, and the surface temperature will be close to that of the surroundings, but there will be significant internal gradients.
Bond Number (Bo)	Definition: $Bo = \frac{\rho g a^2}{\Gamma}$ a is the radius of curvature or radius of an object Γ is the surface tension This is the ratio of gravitational forces to surface tension forces. As an example, the dynamics of waves or ripples depend on the Bond number. If Bo is large, wave speed is the result of the interaction of gravity and fluid inertia. If Bo is small, you get capillary waves where the speed is due to the interaction of surface tension and inertia.
Brownian Peclet Number (Pe)	Definition: $Pe = \frac{\dot{\gamma} \mu a^3}{\kappa T}$ a is the radius of a sphere κ is Boltzmann's constant T is the absolute temperature

	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 ~ 1. Thus, in modern body armor the low shear rate associated with normal motion is at low Pe and this permits an 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: $\frac{\mu\dot{\gamma}a}{\Gamma}$ Γ is the surface tension $\dot{\gamma}$ is the shear rate a is a drop radius or curvature length scale The ratio of viscous forces to capillary forces, and 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 a bunch of tiny satellite drops) when you exceed a critical Ca of O(1), depending on the internal to external viscosity ratio.
Deborah Number (De)	Definition: $\frac{\lambda}{t_p}$ λ is the stress relaxation time t_p is the time scale of observation In a viscoelastic fluid, any structure created by applied shear or strain will eventually relax to equilibrium values (e.g., stretched out rubber bands will relax once shearing stops). In a non-steady flow, such a viscoelastic fluid would behave like a Newtonian fluid when oscillated at low De (relaxation is fast relative to the oscillation frequency), but like an elastic solid at high De. The Deborah number is very similar to the Weissenberg number (measuring a similar transition for steady flows), and both are zero for Newtonian fluids.
Drag Coefficient (C_D)	Definition: $C_D = \frac{F_{(drag)}}{\frac{1}{2}\rho U^2 A}$ A is the projected area normal to the flow. This is the dimensionless drag on an object, scaled with the inertial forces in a system. For high Re, this is an O(1) function of an

	object's shape.
Froude Number (Fr)	Definition: $\frac{U^2}{Lg}$ The ratio of inertial forces to gravitational forces. Used along with the Reynolds number in preserving strict dynamic similarity in scaling models where gravity is important. For ship modeling, you preserve Fr and keep Re "high" to achieve approximate dynamic similarity.
Grashof Number (Gr)	Definition: $\frac{g\beta\Delta T H^3}{\nu^2}$ β is the coefficient of thermal expansion ΔT is the temperature difference H is a vertical length scale ν is the kinematic viscosity This is the ratio of buoyancy due to thermal expansion to viscous dissipation. It plays a role in natural convection problems where there is a temperature difference of DT between an object and its surroundings. If the Grashof number is sufficiently high, for example, a natural convection flow will become turbulent, much like exceeding a critical Re.
Leighton Number (Le)	Definition: $\frac{\mu_0 \dot{\gamma} b}{N\varepsilon}$ => $\frac{\text{viscous stress}}{\text{frictional stress}}$ or: $\frac{\mu_0 \dot{\gamma}}{\sigma}$ => $\frac{\text{viscous stress}}{\text{total stress}}$ N = particulate normal stresses b = particle length scale ε = particle roughness length scale Originally coined by Coussot & Ancey (PRE 1999), Le governs the transition from frictional to lubricated interactions in suspensions and wet granular flows. The alternate definition is from Huang *et al*. PRL 2005, *Flow of Wet Granular Materials*.
Lift Coefficient (C_l)	Definition: $C_L = \frac{L}{\frac{1}{2}\rho U^2 S}$

	S is the planoform area (e.g., the surface area of a wing, area of a surface aligned with the flow).
Mach Number (M)	Definition: $M = \frac{U}{V_s}$ The speed of an object divided by the speed of sound in the fluid is called the Mach number. If M<<1, the fluid can be regarded as incompressible (even air) as the flow cannot lead to compression of the fluid.
Nusselt Number (Nu)	Definition: $\frac{hL}{k}$ h is the heat transfer coefficient k is the thermal conductivity L is the length scale of the object This is the ratio of total heat transfer to conductive heat transfer, and is regarded as a dimensionless heat transfer coefficient. For a heated sphere in a fluid, if the fluid is at rest (pure conduction), the Nusselt number is 1 (with L as the radius). If the fluid is flowing, the convective heat transfer increases Nu from this pure conduction limit. It's not the same thing as a Biot number, even though it looks that way!
Peclet Number (Pe)	Definition (mass transfer): $\frac{LU}{D} = Re\,Sc$ Definition (heat transfer): $\frac{LU}{\alpha} = Re\,Pr$ This is the ratio of convection to diffusion in mass transfer or in heat transfer, and plays the same role as Re in momentum transfer: the relative importance of the convective terms to the diffusive terms. Because Pr and Sc are large for a viscous fluid, it is possible for Pe to be O(1) or larger even when Re <<1.
Prandtl Number (Pr)	Definition: $\frac{\nu}{\alpha}$ ν: the kinematic viscosity (momentum diffusivity) α: the thermal diffusivity The ratio of ν/α indicates the relative rate of momentum and energy diffusion in fluids. This is O(1) for gases, ~7 for water, and

	very high for viscous liquids. It governs the relative thickness of momentum and thermal boundary layers (length ratio scales as $Pr^{1/2}$).
Rayleigh Number (Ra)	Definition: $\dfrac{g\beta \Delta T H^3}{\nu \alpha} = Gr\,Pr$ β is the coefficient of thermal expansion ΔT is the temperature difference H is a vertical length scale ν is the kinematic viscosity This is the ratio of buoyancy due to thermal expansion to viscous dissipation. It is closely related to the Grashof number, and governs some buoyancy-induced instabilities. For example, a thin layer of liquid heated from below will become unstable (convective roll cells will form) when the critical Rayleigh number is exceeded.
Reynolds Number (Re)	Definition: $\dfrac{UD}{\nu}$ U: average velocity of the fluid D: the length scale *perpendicular* to the flow (the diameter of a pipe, *not* the length for example) ν: the kinematic viscosity (momentum diffusivity) It is the ratio of inertial forces to viscous forces. For large Re flow past an object of projected area A and width D, for example, drag scales with inertial forces (e.g., $F \sim \frac{1}{2}\rho U^2 A$), while for low Re flow it scales with the viscous forces (e.g., $F \sim (U/D)\,\mu A$). The Reynolds number also governs transition to turbulence, as turbulence is promoted by inertial effects (eddies crossing streamlines) and dissipated by viscous diffusion of momentum. This is by far the most important dimensionless group in fluid mechanics.
Richardson Number (Ri)	Definition: $\dfrac{\Delta\rho\, g H}{\rho_0 U^2}$ $\Delta\rho$ 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. If you are trying to mix two fluids with a density difference $\Delta\rho$ in a tank of

	height H, the vertical mixing velocities should be sufficiently large that Ri<<1, otherwise density stratification will greatly impede the mixing process.
Schmidt Number (Sc)	Definition: $\frac{\nu}{D}$ 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 $Sc^{1/2}$). For gases it is O(1), but for liquids it is very large (O(500) or greater).
Strouhal Number (Sr)	Definition: $\frac{f\,L}{U}$ 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 the 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: $\frac{\Omega^2 \overline{R} \Delta R^3}{\nu^2}$ ΔR is the gap width $\overline{R}$ is the average radius of the two cylinders 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)	Definition: $\dot{\gamma}\,\lambda$ λ is the relaxation time (time for fluid structure to relax to isotropic equilibrium distribution) It is a dimensionless number used in the study of viscoelastic flows. In steady shear flows, it is defined as the shear rate times the

	relaxation time of the fluid. For Wi >> 1, polymer molecules are stretched out in the shear flow leading to normal stress differences and phenomena such as the rod climbing effect for rotating rods or die swell in extrusion.
Womersley Number (α)	Definition: $\alpha = \left(\frac{\omega a^2}{\nu}\right)^{1/2} = \frac{a}{\left(\nu/\omega\right)^{1/2}}$ ω is the angular frequency of oscillation a is the tube radius ν is the kinematic viscosity It is a dimensionless number that is important in oscillatory flows in tubes and channels. If α << 1 the radius of the tube is much less than the diffusion length $(\nu/\omega)^{1/2}$, and the flow will look like a time-varying Poiseuille flow (parabolic). If α >> 1 then the flow profile will be flat with a rapidly decaying shear wave near the tube walls.

Some Important Historical Fluid Mechanics

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!).

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	~120 B.C.	Studied hydrostatics "Pneumatics" Hero's Fountain example in class
Isaac Newton	1642-1727	Studied friction, viscosity, and orifices "Principia" in 1713
Leonhard Euler	1707-1783	Equation of motion for frictionless fluids (and lots of other things!)
Claude Louis Navier and George Gabriel Stokes	1785-1836 1819-1903	Incorporation of viscous terms into the equation describing fluid motion, The Navier-Stokes Equations
William Froude	1810-1879	Model testing and scaling laws for ship design
Osbourne Reynolds	1842-1919	Transition to turbulence
Ludwig Prandtl	1875-1953	Viscous Boundary Layers
Theodore von Karman	1881-1963	Turbulence, vortex shedding
Sir Geoffrey Taylor	1883-1975	Many, many problems. Widely considered the preeminent fluid mechanic of the 20th century.
George Batchelor	1920-2000	Turbulence, particle dynamics