Solution of Navier-Stokes Equations. Part Two

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Mechanical Engineering 692

Computational Fluid Dynamics

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California State University Northridge

Outline

- Review basics of integrating Navier-Stokes and continuity
- Pressure and the staggered grid
- Finite-volume momentum equations
  - Momentum equation coefficients
- Finite-volume continuity
- Finite-volume momentum and continuity combine into an equation for pressure
- Solving the equations

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Review False Diffusion

- Upwind differencing causes errors similar to having a "diffusion" coefficient that is too large
- Causes smearing of results
- Especially noticeable in flows with sharp gradients and shock waves
- Effect is reduced if flow is aligned with grid (not always possible to do this)
- Different from artifical diffusion

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Review Navier-Stokes

- Continuity and momentum equations
- Apply previous work for general variable, ϕ, to finding u, v, and w
- Must consider nonlinearity (e.g., $u\phi$ can be uu, uv, or uw for momentum)
  - Use "outer iteration process"
    - Assume values for u, v, and w
    - Use these values to compute the convection/diffusion coefficients a_E, a_N, *etc*.
    - Use new u, v, w values to update a_E, a_N, *etc*.

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Review Navier-Stokes Approach

- Compressible flows
  - Solve continuity and momentum for three velocity components and density
  - Get pressure from equation of state
- Incompressible flows
  - Mach number is low
  - Density is a problem input, often related to temperature (may or may not be constant)
  - Solve continuity and momentum for three velocity components and pressure

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Review Incompressible Flows

- Mach number is low (< ~0.3)
- Density (e.g., $\rho = p/RT$) may depend on mean, but not local pressure
- Can have equations like $\rho = \rho_0(1 + \beta T)$ for where $\beta = -(1/\rho)(\partial\rho/\partial T)_P$
- Density may be constant, but need not be for incompressible flows
  - Furnace flows a good example of this
- Basic idea is that density does not depend on local pressure

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Review Steady 2D Problem

- Continuity and momentun equations
  - Have x and y direction convection-diffusion
  - Now have source term and pressure gradient

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

$$\frac{\partial \rho uu}{\partial x} + \frac{\partial \rho vu}{\partial y} = -\frac{\partial P}{\partial x} + \frac{\partial}{\partial x}\mu\frac{\partial u}{\partial x} + \frac{\partial}{\partial y}\mu\frac{\partial u}{\partial y} + S^{(u)}$$

$$\frac{\partial \rho uv}{\partial x} + \frac{\partial \rho vv}{\partial y} = -\frac{\partial P}{\partial y} + \frac{\partial}{\partial x}\mu\frac{\partial v}{\partial x} + \frac{\partial}{\partial y}\mu\frac{\partial v}{\partial y} + S^{(v)}$$

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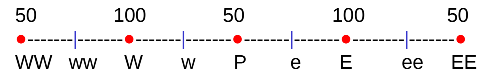
Review Problem with Pressure

- Consider the x momentum equation for the u velocity component at point P



- Second-order expression for pressure gradient at P $\left.\frac{\partial p}{\partial x}\right|_P = \frac{p_E - p_W}{2\delta x}$
- With this expression the velocity at P is not affected by the pressure at P
  - Also a checkerboard pattern of pressure would compute as zero pressure gradient

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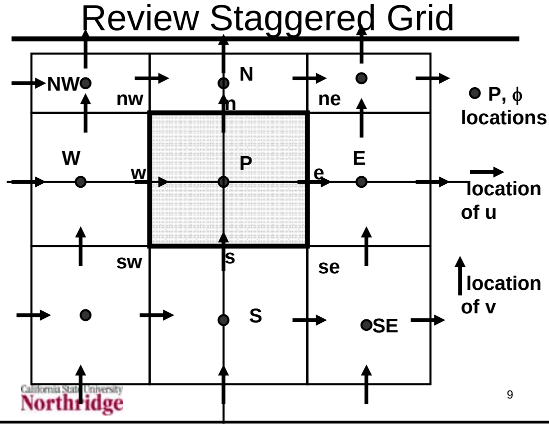
Review Staggered Grid



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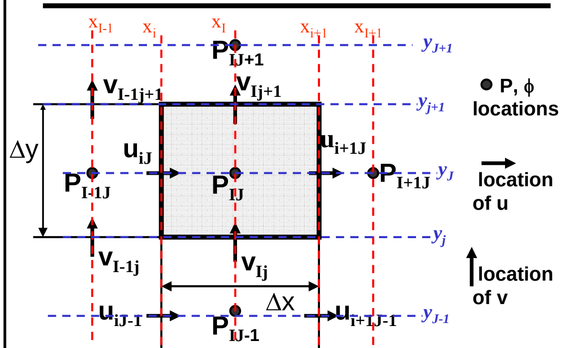
Review Staggered Grid II



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Finite Volume Equations

- Extend previous results for one dimension to two dimensions
- Can use any of the difference methods discussed for convection and diffusion
  - Have four faces, n, e, s, w, in 2D
  - Apply same relations to get coefficients a_N, a_S, a_E, and a_W, using F = ρu and D = Γ/δ for each face
  - As before $a_P = (a_N + a_S + a_E + a_W + \Delta F)$
    - Here $\Delta F = (F_n - F_s) + (F_e - F_w)$

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Finite Volume Equations II

- Integration of pressure terms

$$\left(\int_{\Delta V}\frac{\partial p}{\partial x}dV\right)_{iJ} \approx \frac{p_{IJ} - p_{I-1J}}{x_I - x_{I-1}}\left(x_I - x_{I-1}\right)A_{iJ}$$
$$= \left(p_{IJ} - p_{I-1J}\right)A_{iJ} = \left(p_{IJ} - p_{I-1J}\right)\left(y_{j+1} - y_j\right)\Delta z$$

$$\left(\int_{\Delta V}\frac{\partial p}{\partial y}dV\right)_{Ij} \approx \frac{p_{IJ} - p_{IJ-1}}{y_J - y_{J-1}}\left(y_J - y_{J-1}\right)A_{Ij}$$
$$= \left(p_{IJ} - p_{IJ-1}\right)A_{Ij} = \left(p_{IJ} - p_{I-1J}\right)\left(x_{i+1} - x_i\right)\Delta z$$

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Finite Volume Equations III

- Have similar equations for u and v
- b represents integrated source term
- Note that a_K coefficients vary from node to node and are different for u and v

$$a_N u_{iJ+1} + a_S u_{iJ-1} + a_E u_{i+1J} + a_W u_{i-1J} - a_P u_{iJ}$$
$$a_{N_{iJ}}^{(u)} u_{iJ+1} = (p_{IJ} - p_{I-1J})A_{iJ} + b_{iJ}^{(u)}$$
$$a_N v_{Ij+1} + a_S v_{iJ-1} + a_E v_{I+1j} + a_W v_{I-1j} - a_P v_{Ij}$$
$$a_{N_{Ij}}^{(v)} v_{Ij+1} = (p_{IJ} - p_{IJ-1})A_{Ij} + b_{Ij}^{(v)}$$

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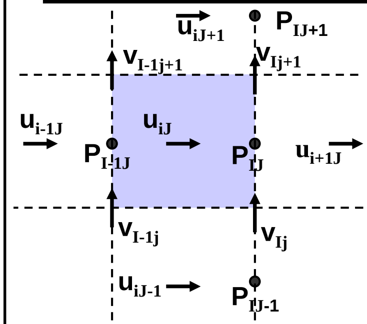
Control Volume for u (e face)



equations for e face at IJ

$$F_e = \frac{F_{i+1J} + F_{iJ}}{2} = \frac{1}{2}\left[\left(\frac{\rho_{IJ} + \rho_{I+1J}}{2}\right)u_{i+1J} + \left(\frac{\rho_{I-1J} + \rho_{IJ}}{2}\right)u_{iJ}\right]$$
$$D_e = \frac{\Gamma_{IJ}}{x_{i+1} - x_i}$$

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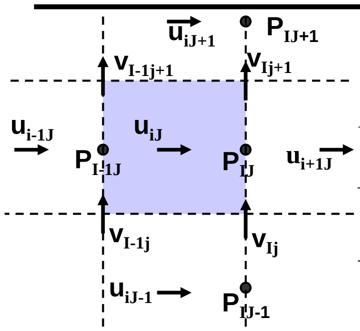
Control Volume for u (w face)



equations for w face at I-1J

$$F_w = \frac{F_{i-1J} + F_{iJ}}{2} = \frac{1}{2}\left[\left(\frac{\rho_{I-2J} + \rho_{I-1J}}{2}\right)u_{i-1J} + \left(\frac{\rho_{I-1J} + \rho_{IJ}}{2}\right)u_{iJ}\right]$$
$$D_w = \frac{\Gamma_{I-1J}}{x_i - x_{i-1}}$$

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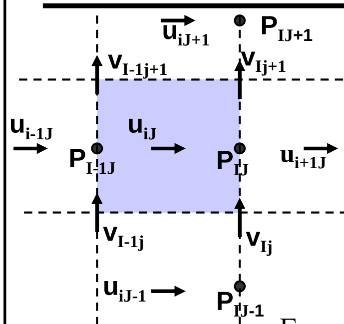
Control Volume for u (n face)



equations for n face at y_{j+1}

$$F_n = \frac{F_{Ij+1} + F_{I-1j+1}}{2} = \frac{1}{2}\left[\left(\frac{\rho_{IJ} + \rho_{IJ+1}}{2}\right)v_{Ij+1} + \left(\frac{\rho_{I-1J} + \rho_{I-1J+1}}{2}\right)v_{I-1j+1}\right]$$
$$D_n = \frac{\Gamma_{I-1J} + \Gamma_{I-1J+1} + \Gamma_{IJ+1} + \Gamma_{IJ}}{4(y_{J+1} - y_J)}$$

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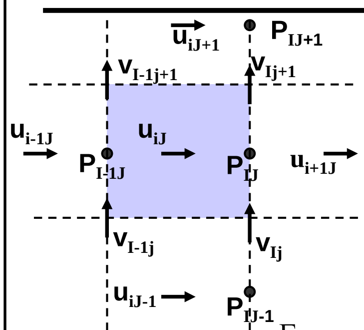
Control Volume for u (s face)



equations for s face at y_j

$$F_s = \frac{F_{Ij} + F_{I-1j}}{2} = \frac{1}{2}\left[\left(\frac{\rho_{IJ} + \rho_{IJ-1}}{2}\right)v_{Ij} + \left(\frac{\rho_{I-1J} + \rho_{I-1J-1}}{2}\right)v_{I-1}\right]$$
$$D_s = \frac{\Gamma_{I-1J-1} + \Gamma_{I-1J} + \Gamma_{IJ} + \Gamma_{IJ-1}}{4(y_J - y_{J-1})}$$

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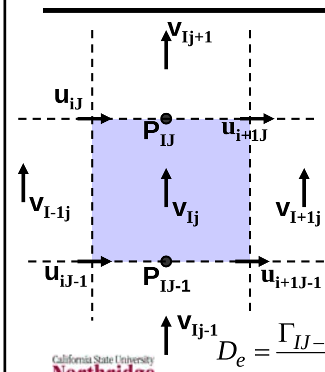
Control Volume for v (e face)



equations for e face at x_{i+1}

$$F_e = \frac{F_{I+1J} + F_{I+1J-1}}{2} = \frac{1}{2}\left[\left(\frac{\rho_{IJ} + \rho_{I+1J}}{2}\right)u_{i+1J} + \left(\frac{\rho_{IJ-1} + \rho_{I+1J-1}}{2}\right)u_{i+1J-1}\right]$$
$$D_e = \frac{\Gamma_{IJ-1} + \Gamma_{IJ} + \Gamma_{I+1J} + \Gamma_{I+1J-1}}{4(x_{I+1} - x_I)}$$

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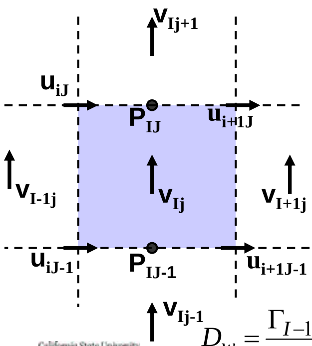
Control Volume for v (w face)



equations for w face at x_i

$$F_w = \frac{F_{iJ} + F_{iJ-1}}{2} = \frac{1}{2}\left[\left(\frac{\rho_{I-1J} + \rho_{IJ}}{2}\right)u_{iJ} + \left(\frac{\rho_{I-1J-1} + \rho_{IJ-1}}{2}\right)u_{iJ-1}\right]$$

$$D_w = \frac{\Gamma_{I-1J-1} + \Gamma_{I-1J} + \Gamma_{IJ} + \Gamma_{IJ-1}}{4\left(x_I - x_{I-1}\right)}$$

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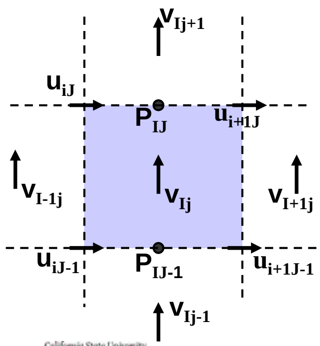
Control Volume for v (n face)



equations for n face at y_J

$$F_n = \frac{F_{Ij+1} + F_{Ij}}{2} = \frac{1}{2}\left[\left(\frac{\rho_{IJ+1} + \rho_{IJ}}{2}\right)v_{Ij+1} + \left(\frac{\rho_{IJ} + \rho_{IJ-1}}{2}\right)u_{IJ}\right]$$

$$D_n = \frac{\Gamma_{IJ}}{y_{j+1} - y_j}$$

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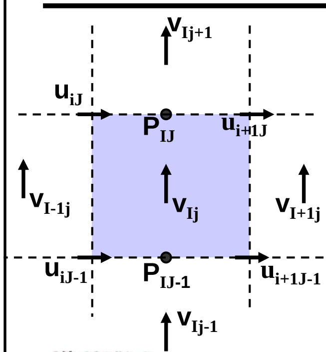
Control Volume for v (s face)



equations for s face at y_{J-1}

$$F_n = \frac{F_{Ij} + F_{Ij-1}}{2} = \frac{1}{2}\left[\left(\frac{\rho_{IJ} + \rho_{IJ-1}}{2}\right)v_{Ij} + \left(\frac{\rho_{IJ-1} + \rho_{IJ-2}}{2}\right)v_{Ij-1}\right]$$

$$D_s = \frac{\Gamma_{IJ-1}}{y_j - y_{j-1}}$$

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Rest Stop

- Now have F and D terms for momentum
  - Can use any method (central, upwind, *etc.*) to compute a_E, a_N, *etc.*
- Get finite volume representation of continuity by integration over control volume centered about p_{IJ}
- Substitute finite difference momentum equations into finite difference continuity equation to get finite difference equation for pressure

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Rest Stop II

- Solve u momentum equation for u_{iJ}
  - Define a_P for this equation as a_{iJ}

$$a_N u_{iJ+1} + a_S u_{iJ-1} + a_E u_{i+1J} + a_W u_{i-1J} - a_P u_{iJ} = \left(p_{IJ} - p_{I-1J}\right)A_{iJ} + b_{iJ}^{(u)}$$

$$a_{iJ} u_{iJ} = a_N u_{iJ+1} + a_S u_{iJ-1} + a_E u_{i+1J} + a_W u_{i-1J} - \left(p_{IJ} - p_{I-1J}\right)A_{iJ} - b_{iJ}^{(u)}$$

$$\boxed{d_{iJ} = \frac{A_{iJ}}{a_{iJ}}}$$

$$u_{iJ} = \frac{\sum_{nb} a_{nb}u_{nb}}{a_{iJ}} + \left(p_{I-1J} - p_{IJ}\right)\boxed{\frac{A_{iJ}}{a_{iJ}}} - \frac{b_{iJ}^{(u)}}{a_{iJ}}$$

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Rest Stop III

- Solve v momentum equation for v_{Ij}
  - Define a_P for this equation as a_{iJ}

$$a_N v_{Ij+1} + a_S v_{iJ-1} + a_E v_{I+1j} + a_W v_{I-1j} - a_P v_{Ij} = \left(p_{IJ} - p_{IJ-1}\right)A_{Ij} + b_{Ij}^{(v)}$$

$$a_P v_{Ij} = a_N v_{Ij+1} + a_S v_{iJ-1} + a_E v_{I+1j} + a_W v_{I-1j} - \left(p_{IJ} - p_{IJ-1}\right)A_{Ij} - b_{Ij}^{(v)}$$

$$\boxed{d_{Ij} = \frac{A_{Ij}}{a_{Ij}}}$$

$$v_{Ij} = \frac{\sum_{nb} a_{nb}u_{nb}}{a_{Ij}} + \left(p_{IJ-1} - p_{IJ}\right)\boxed{\frac{A_{Ij}}{a_{Ij}}} - \frac{b_{iJ}^{(u)}}{a_{Ij}}$$

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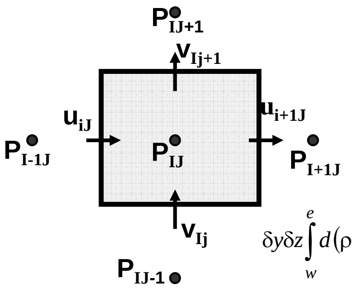
Integrated Continuity Equation



$$\int_{\Delta V}\left(\frac{\partial \rho u}{\partial x}+\frac{\partial \rho v}{\partial y}\right)dV=0$$

$$\int_{\Delta V}\frac{\partial \rho u}{\partial x}dxdydz+\int_{\Delta V}\frac{\partial \rho v}{\partial y}dxdydz=0$$

$$\delta y\delta z\int_{w}^{e}d(\rho u)+\delta x\delta z\int_{s}^{n}d(\rho v)=0$$

$$\delta y\delta z\left[(\rho u)_e-(\rho u)_w\right]+\delta x\delta z\left[(\rho v)_n-(\rho v)_s\right]=0$$

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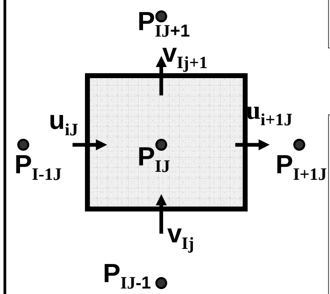
Integrated Continuity Equation II



$$\boxed{\begin{aligned}&\delta y\delta z\left[(\rho u)_e-(\rho u)_w\right]+\\&\delta x\delta z\left[(\rho v)_n-(\rho v)_s\right]=0\end{aligned}}$$

$$\boxed{\begin{aligned}&\left[(\rho uA)_{i+1J}-(\rho uA)_{iJ}\right]+\\&\left[(\rho vA)_{Ij+1}-(\rho vA)_{Ij}\right]=0\end{aligned}}$$

$$\boxed{\begin{aligned}&\frac{\rho_{I+1J}+\rho_{IJ}}{2}(uA)_{i+1J}-\\&\frac{\rho_{IJ}+\rho_{I-1J}}{2}(uA)_{iJ}+\\&\frac{\rho_{IJ+1}+\rho_{IJ}}{2}(vA)_{Ij+1}-\\&\frac{\rho_{IJ}+\rho_{IJ-1}}{2}(vA)_{Ij}=0\end{aligned}}$$

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The Rest is SIMPLE

- Now need to find way to solve for pressures and velocity components
- Use SIMPLE algorithm due to Patankar and Spalding (1971)
  - Semi-Implicit Method for Pressure-Linked Equations
- Started with guessed pressures, p*
- Solve momentum equations for u* and v* based on p* pressures

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SIMPLE Two

$$u_{iJ}^{*}=\frac{\sum_{nb}a_{nb}u_{nb}^{*}}{a_{iJ}}+\left(p_{I-1J}^{*}-p_{IJ}^{*}\right)d_{iJ}-\frac{b_{iJ}^{(u)}}{a_{iJ}}$$

$$v_{Ij}^{*}=\frac{\sum_{nb}a_{nb}u_{nb}^{*}}{a_{Ij}}+\left(p_{IJ-1}^{*}-p_{IJ}^{*}\right)d_{Ij}-\frac{b_{iJ}^{(u)}}{a_{Ij}}$$

- Define correction terms: u', v', p'
  - u = u* + u'
  - v = v* + v'
  - p = p* + p'

Now subtract the momentum equations with u* and v* from the momentum equations with u and v

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SIMPLE Three

$$u_{iJ}=\frac{\sum_{nb}a_{nb}u_{nb}}{a_{iJ}}+\left(p_{I-1J}-p_{IJ}\right)d_{iJ}-\frac{b_{iJ}^{(u)}}{a_{iJ}}$$

$$u_{iJ}^{*}=\frac{\sum_{nb}a_{nb}u_{nb}^{*}}{a_{iJ}}+\left(p_{I-1J}^{*}-p_{IJ}^{*}\right)d_{iJ}-\frac{b_{iJ}^{(u)}}{a_{iJ}}$$

$$u_{iJ}-u_{iJ}^{*}=\frac{\sum_{nb}a_{nb}\left(u_{nb}-u_{nb}^{*}\right)}{a_{iJ}}+\left[\left(p_{I-1J}-p_{IJ}\right)-\left(p_{I-1J}^{*}-p_{IJ}^{*}\right)\right]d_{iJ}$$

$$u_{iJ}'=\frac{\sum_{nb}a_{nb}u_{nb}'}{a_{iJ}}+\left(p_{I-1J}'-p_{IJ}'\right)d_{iJ}$$

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SIMPLE Four

$$v_{Ij}=\frac{\sum_{nb}a_{nb}u_{nb}}{a_{Ij}}+\left(p_{IJ-1}-p_{IJ}\right)d_{Ij}-\frac{b_{iJ}^{(u)}}{a_{Ij}}$$

$$v_{Ij}^{*}=\frac{\sum_{nb}a_{nb}u_{nb}^{*}}{a_{Ij}}+\left(p_{IJ-1}^{*}-p_{IJ}^{*}\right)d_{Ij}-\frac{b_{iJ}^{(u)}}{a_{Ij}}$$

$$v_{Ij}-v_{Ij}^{*}=\frac{\sum_{nb}a_{nb}\left(u_{nb}-u_{nb}^{*}\right)}{a_{Ij}}+\left[\left(p_{IJ-1}-p_{IJ}\right)-\left(p_{IJ-1}^{*}-p_{IJ}^{*}\right)\right]d_{Ij}$$

$$v_{Ij}'=\frac{\sum_{nb}a_{nb}u_{Inb}'}{a_{Ij}}+\left(p_{IJ-1}'-p_{IJ}'\right)d_{Ij}$$

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Make it Really SIMPLE

- Since correction terms will vanish as iterations converge, ignore such terms in sums over neighbors!

$$u'_{iJ} = \frac{\sum_{nb} a_{nb} u'_{nb}}{a_{iJ}} + \left(p'_{I-1J} - p'_{IJ}\right) d_{iJ} \approx \left(p'_{I-1J} - p'_{IJ}\right) d_{iJ}$$

$$v'_{Ij} = \frac{\sum_{nb} a_{nb} u'_{Inb}}{a_{Ij}} + \left(p'_{IJ-1} - p'_{IJ}\right) d_{Ij} \approx \left(p'_{IJ-1} - p'_{IJ}\right) d_{Ij}$$

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Get Ready for Continuity

- Replace u' and v' by u – u* and v – v*

$$u'_{iJ} = u_{iJ} - u^*_{iJ} = \left(p'_{I-1J} - p'_{IJ}\right) d_{iJ} \quad \Rightarrow$$

$$u_{iJ} = u^*_{iJ} + \left(p'_{I-1J} - p'_{IJ}\right) d_{iJ}$$

$$v'_{Ij} = v_{Ij} - v^*_{Ij} = \left(p'_{IJ-1} - p'_{IJ}\right) d_{Ij} \quad \Rightarrow$$

$$v_{Ij} = v^*_{Ij} + \left(p'_{IJ-1} - p'_{IJ}\right) d_{Ij} \quad \Rightarrow$$

- Substitute relations between u, v, and p' into finite-volume continuity

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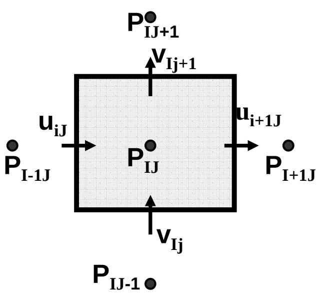
Finite Volume Continuity



$$\frac{\rho_{I+1J} + \rho_{IJ}}{2}(uA)_{i+1J} - \frac{\rho_{IJ} + \rho_{I-1J}}{2}(uA)_{iJ} + \frac{\rho_{IJ+1} + \rho_{IJ}}{2}(vA)_{Ij+1} - \frac{\rho_{IJ} + \rho_{IJ-1}}{2}(vA)_{Ij} = 0$$

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Substitute u, v into Continuity

$$u_{iJ} = u^*_{iJ} + \left(p'_{I-1J} - p'_{IJ}\right) d_{iJ}$$

$$u_{i+1J} = u^*_{i+1J} + \left(p'_{IJ} - p'_{I+1J}\right) d_{i+1J}$$

$$v_{Ij} = v^*_{Ij} + \left(p'_{IJ-1} - p'_{IJ}\right) d_{Ij}$$

$$v_{Ij+1} = v^*_{Ij+1} + \left(p'_{IJ} - p'_{IJ+1}\right) d_{Ij+1}$$

$$\frac{\rho_{I+1J} + \rho_{IJ}}{2}(uA)_{i+1J} - \frac{\rho_{IJ} + \rho_{I-1J}}{2}(uA)_{iJ} + \frac{\rho_{IJ+1} + \rho_{IJ}}{2}(vA)_{Ij+1} - \frac{\rho_{IJ} + \rho_{IJ-1}}{2}(vA)_{Ij} = 0$$

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Finite-Volume Equation for p'

$$\frac{\rho_{I+1J} + \rho_{IJ}}{2} A_{i+1J}\left[u^*_{i+1J} + \left(p'_{IJ} - p'_{I+1J}\right) d_{i+1J}\right] - \frac{\rho_{IJ} + \rho_{I-1J}}{2} A_{iJ}\left[u^*_{iJ} + \left(p'_{I-1J} - p'_{IJ}\right) d_{iJ}\right] + \frac{\rho_{IJ+1} + \rho_{IJ}}{2} A_{Ij+1}\left[v^*_{Ij+1} + \left(p'_{IJ} - p'_{IJ+1}\right) d_{Ij+1}\right] - \frac{\rho_{IJ} + \rho_{IJ-1}}{2} A_{Ij}\left[v^*_{Ij} + \left(p'_{IJ-1} - p'_{IJ}\right) d_{Ij}\right] = 0$$

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Finite-Volume Equation for p' II

$$\underbrace{\frac{\rho_{I+1J} + \rho_{IJ}}{2} A_{i+1J} u^*_{i+1J} - \frac{\rho_{IJ} + \rho_{I-1J}}{2} A_{iJ} u^*_{iJ} + \frac{\rho_{IJ+1} + \rho_{IJ}}{2} A_{Ij+1} v^*_{Ij+1} - \frac{\rho_{IJ} + \rho_{IJ-1}}{2} A_{Ij} v^*_{Ij}}_{-b'_{IJ}} + \underbrace{\frac{\rho_{I+1J} + \rho_{IJ}}{2} A_{i+1J} d_{i+1J}}_{a_{I+1J}}\left(p'_{IJ} - p'_{I+1J}\right) + \underbrace{\frac{\rho_{IJ} + \rho_{I-1J}}{2} A_{iJ} d_{iJ}}_{a_{I-1J}}\left(p'_{IJ} - p'_{I-1J}\right) + \underbrace{\frac{\rho_{IJ+1} + \rho_{IJ}}{2} A_{Ij+1} d_{Ij+1}}_{a_{IJ+1}}\left(p'_{IJ} - p'_{IJ+1}\right) + \underbrace{\frac{\rho_{IJ} + \rho_{IJ-1}}{2} A_{Ij} d_{Ij}}_{a_{IJ-1}}\left(p'_{IJ} - p'_{IJ-1}\right) = 0$$

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Final Equation for p'

$$a_{I+1J}(p'_{IJ} - p'_{I+1J}) + a_{I-1J}(p'_{IJ} - p'_{I-1J}) + a_{IJ+1}(p'_{IJ} - p'_{IJ+1}) + a_{IJ-1}(p'_{IJ} - p'_{IJ+1}) = b'_{IJ}$$

$$a_{IJ} = a_{I+1J} + a_{I-1J} + a_{IJ+1} + a_{IJ-1}$$

$$\boxed{a_{I+1J}p'_{I+1J} + a_{I-1J}p'_{I-1J} + a_{IJ+1}p'_{IJ+1} + a_{IJ-1}p'_{IJ+1} - a_{IJ}p'_{IJ} = b'_{IJ}}$$

- Solve final equation for p'

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Using Corrections

- Use of p = p* + p' can lead to divergence
  - Use underrelaxation: p = p* + α_pp', where α_p is the underrelaxation factor (0 < α_p < 1)
- Similar underrelaxation factors (between 0 and 1) for velocity correction

$$u_{iJ} = u^*_{iJ} + \alpha_u\left(p'_{I-1J} - p'_{IJ}\right)d_{iJ}$$

$$v_{Ij} = v^*_{Ij} + \alpha_v\left(p'_{IJ-1} - p'_{IJ}\right)d_{Ij}$$

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Putting it All Together

0. Start with initial guesses for p*, u*, v*
1. Start iterations
2. Compute coefficients in finite volume equations for momentum and pressure
3. Do an iteration on u* and v* equations
4. Get p' source term
5. Do an iteration on p' equation
6. Use p' to correct p*, u*, and v
7. Check convergence; if not converged return to step 1

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Conclusion

- Wasn't that simple?
- Next week we will look at another method called SIMPLER (for SIMPLE Revised)
  - It is more complex than SIMPLE
- Will also look at other methods for solving continuity and momentum
  - SIMPLEC
  - PISO

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