Compressible Flow - TME085

Lecture 13

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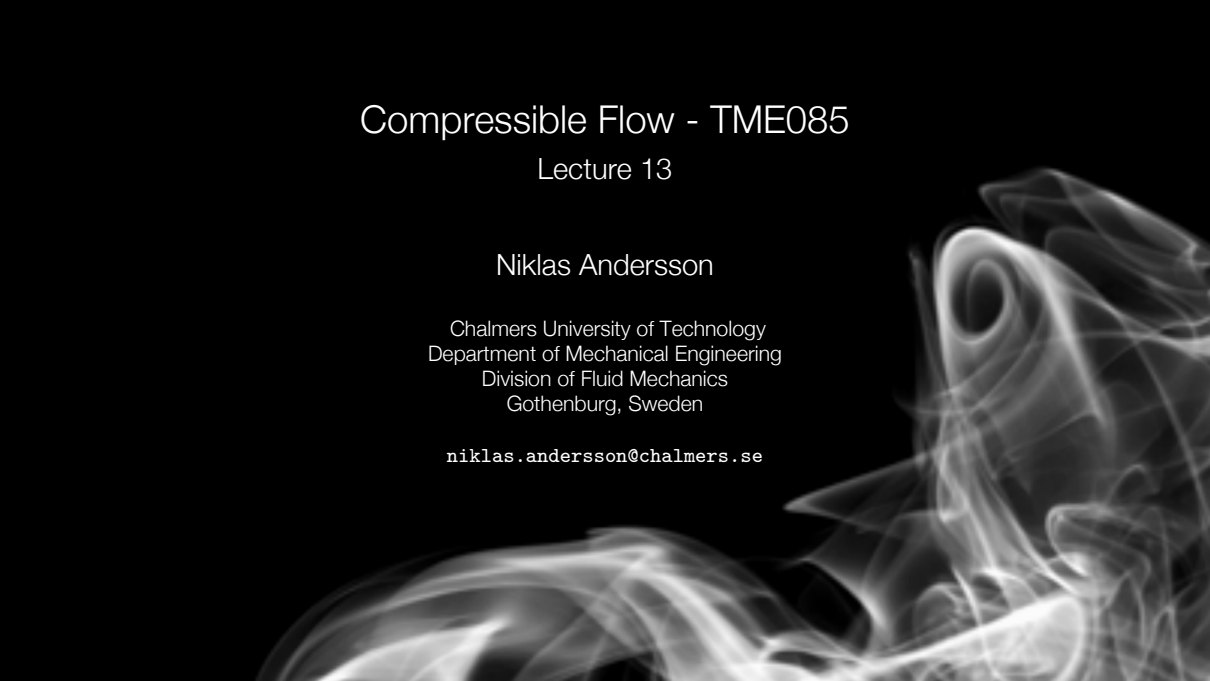
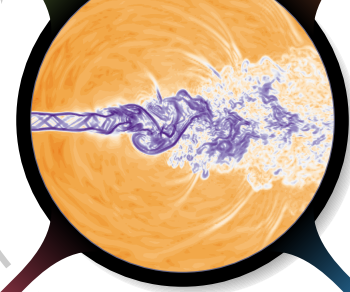


```
#undef __FUNCT__
#define __FUNCT__ "RungeKutta::fwd"
PetscErrorCode RungeKutta::fwd(Domain *dom){
    PetscErrorCode ierr=0;

    ierr=G3DCopy(dom->cons,cons0);CHKERRQ(ierr);

    /* RK1 */

    dom->update();

    dcons->evaluate(dom);

    ierr=G3DWAXPY(dom->cons,1.0,dcons,cons0);CHKERRQ(ierr);
    ierr=G3DAXPBY(cons0,0.5,0.5,dom->cons);CHKERRQ(ierr);

    /* RK2 */

    dom->update();
    dcons->evaluate(dom);

    ierr=G3DWAXPY(dom->cons,0.5,dcons,cons0);CHKERRQ(ierr);

    /* RK3 */
```

Overview



CFD

Basic concepts

Boundary conditions

Shock handling

Spatial dis-cretization

Time integration

Numerical schemes

High tem-perature effects

equilibrium gas

Boltzmann

method of char-acteristics

finite non-linear waves

Learning Outcomes

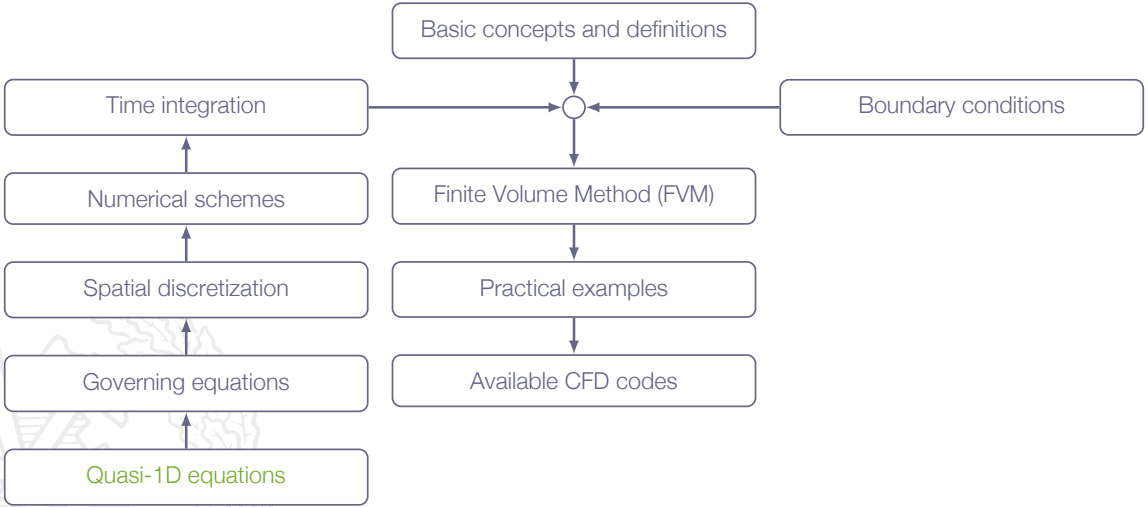
12 **Explain** the main principles behind a modern Finite Volume CFD code and such concepts as explicit/implicit time stepping, CFL number, conservation, handling of compression shocks, and boundary conditions

14 **Analyze** and **verify** the quality of the numerical solution

15 **Explain** the limitations in fluid flow simulation software

time for CFD!

Roadmap - The Time-Marching Technique



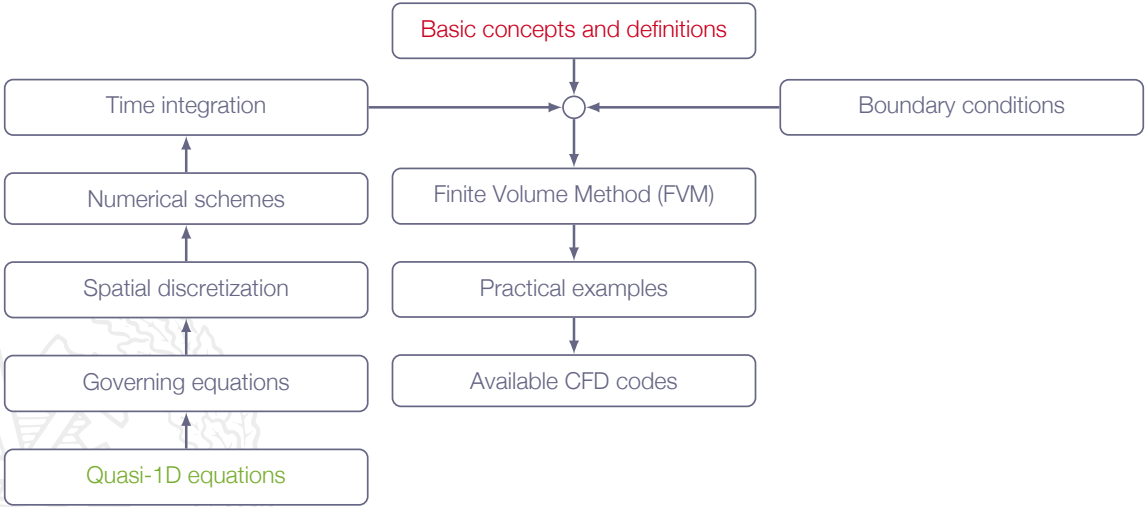
Motivation

Computational Fluid Dynamics (CFD) is the backbone of all practical engineering compressible flow analysis

As an engineer doing numerical compressible flow analyzes it is extremely important to have knowledge about the fundamental numerical principles and their **limitations**

Going through the material covered in this section will not make you understand all the details but you will get a feeling, which is a good start

Roadmap - The Time-Marching Technique



The Time-Marching Technique

The problems that we like to investigate numerically within the field of compressible flows can be categorized as

steady-state compressible flows

unsteady compressible flows

The **Time-marching technique** is a solver framework that addresses both problem categories

The Time-Marching Technique

Steady-state problems:

1. define simple initial solution
2. apply specified boundary conditions
3. march in time until steady-state solution is reached

Unsteady problems:

1. apply specified initial solution
2. apply specified boundary conditions
3. march in time for specified total time to reach a desired unsteady solution

establish fully developed flow before initiating data sampling

The Time-Marching Technique

The time-marching approach is a good alternative for simulating flows where there are both supersonic and subsonic regions

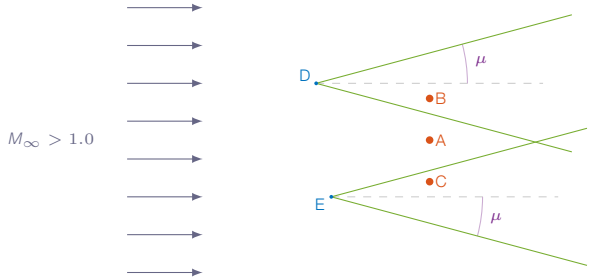
supersonic/hyperbolic:

- perturbations propagate in preferred directions
- zone of influence/zone of dependence
- PDEs can be transformed into ODEs

subsonic/elliptic:

- perturbations propagate in all directions

Zone of Influence and Zone of Dependence



A, B and C at the same axial position in the flow

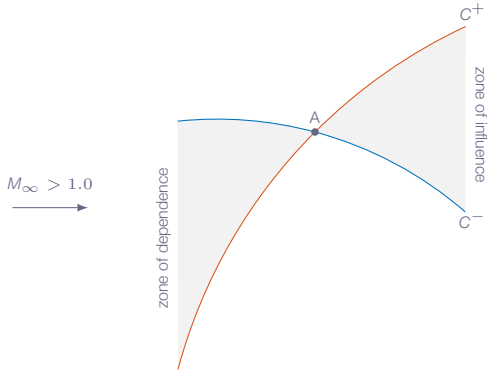
D and E are located upstream of A, B and C

Mach waves generated at D will affect the flow in B but not in A and C

Mach waves generated at E will affect the flow in C but not in A and B

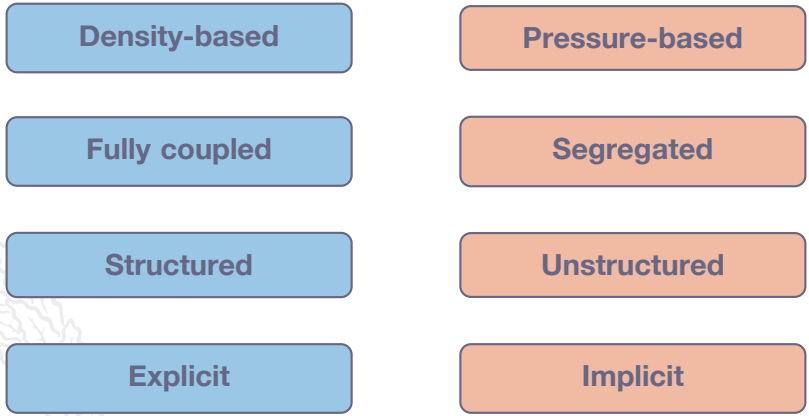
The flow in A is unaffected by the both D and E

Zone of Influence and Zone of Dependence



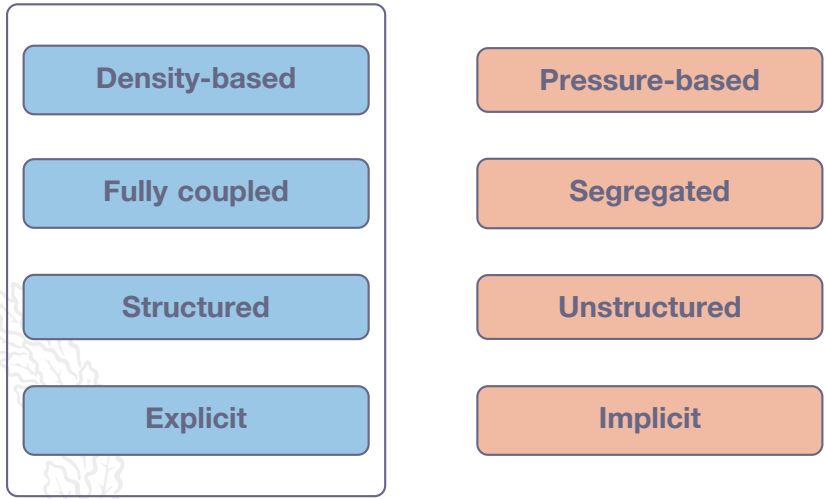
The **zone of dependence** for point A and the **zone of influence** of point A are defined by C^+ and C^- characteristic lines

Characterization of CFD Methods



Characterization of CFD Methods

Approach taken in this presentation



Characterization of CFD Methods - Equations

Density-based

solve for density in the continuity equation

suitable for transonic/supersonic flows

Pressure-based

the continuity and momentum equations are combined to form a pressure correction equation

suitable for subsonic/transonic flows

Characterization of CFD Methods - Solver Approach

Fully coupled

all equations (continuity, momentum, energy, ...) are solved simultaneously

suitable for transonic/supersonic flows

Segregated

the governing equations are solved in sequence

suitable for subsonic flows

Characterization of CFD Methods - Time Stepping

Explicit

- short time steps
+ very stable

Implicit

+ longer time steps possible

Characterization of CFD Methods - Time Stepping

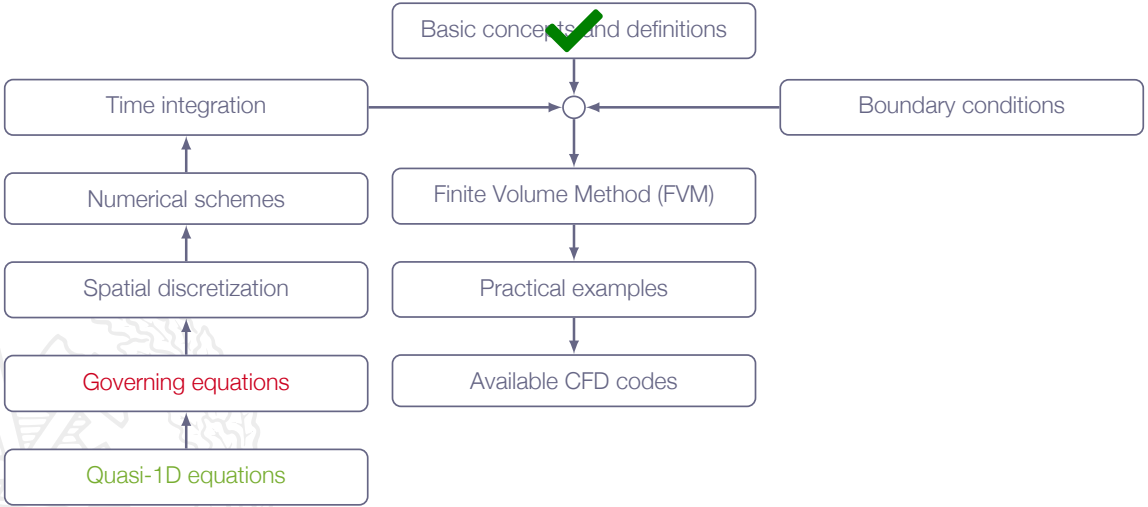
Explicit Time Stepping

Implicit Time Stepping

In general implicit solvers are more efficient than explicit solvers

For high-supersonic flows, explicit solvers may very well outperform implicit solvers

Roadmap - The Time-Marching Technique

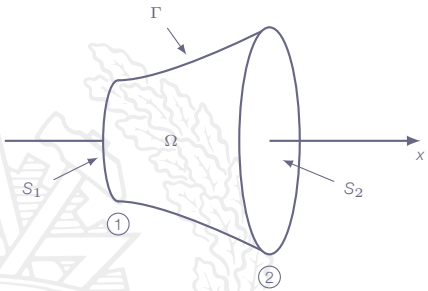


Governing Equations

Quasi-One-Dimensional Flow - Conceptual Idea

Introduce **cross-section-averaged flow quantities** $\Rightarrow$
all quantities depend on x only

$$A = A(x),\ \rho = \rho(x),\ u = u(x),\ p = p(x),\ \ldots$$



Ω	control volume
S_1	left boundary (area A_1)
S_2	right boundary (area A_2)
Γ	perimeter boundary

$$\partial\Omega = S_1 \cup \Gamma \cup S_2$$

Quasi-One-Dimensional Flow - Governing Equations

Governing equations (general form):

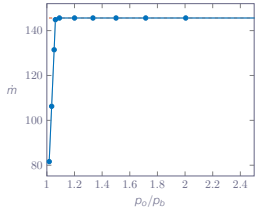
$$\frac{d}{dt}\iiint_{\Omega} \rho d\mathscr{V} + \oiint_{\partial\Omega} \rho \mathbf{v}\cdot\mathbf{n} dS = 0$$

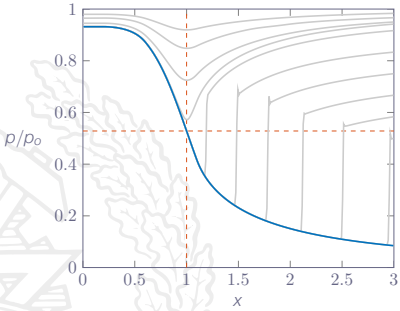
$$\frac{d}{dt}\iiint_{\Omega} \rho u d\mathscr{V} + \oiint_{\partial\Omega} \left[\rho(\mathbf{v}\cdot\mathbf{n})u + p(\mathbf{n}\cdot\mathbf{e}_x)\right] dS = 0$$

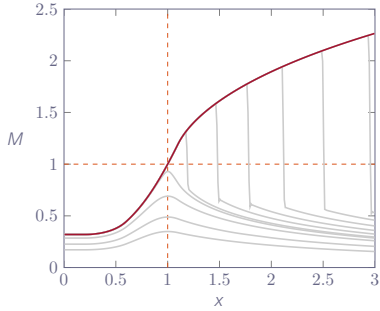
$$\frac{d}{dt}\iiint_{\Omega} \rho e_o d\mathscr{V} + \oiint_{\partial\Omega} \rho h_o(\mathbf{v}\cdot\mathbf{n}) dS = 0$$

Quasi-One-Dimensional Flow - Example: Nozzle Flow

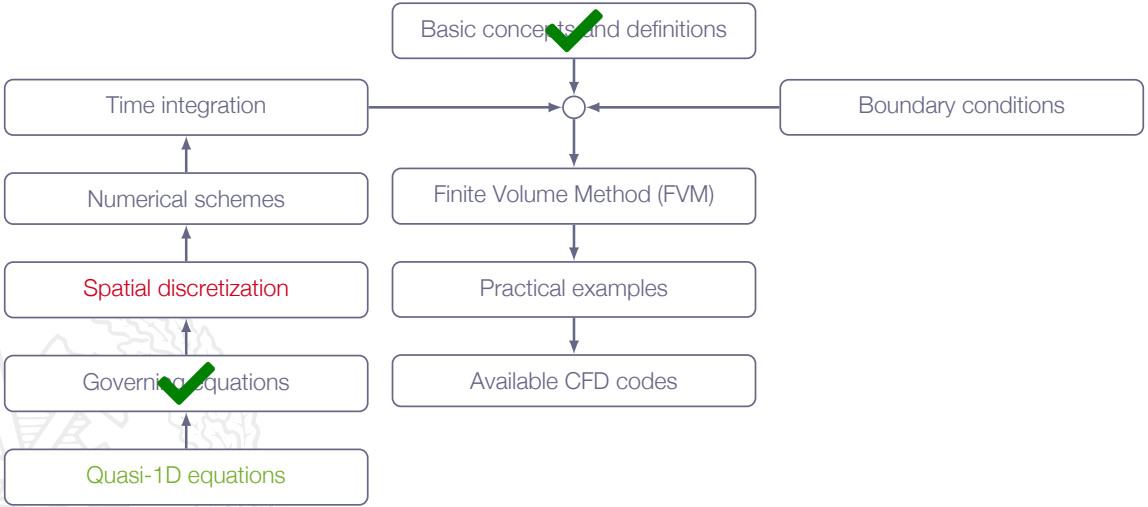
p_o	1.20 [bar]
p_b	0.50 [bar]
p_o/p_b	11.8
$\dot{m}$	145.6 [kg/s]
M_{max}	2.26







Roadmap - The Time-Marching Technique



Spatial Discretization

Spatial Discretization

CFLOW

Discretization in space and time:

Method of Lines (a very common approach):

1. discretize in space $\Rightarrow$ system of ordinary differential equations (ODEs)
2. discretize in time $\Rightarrow$ time-stepping scheme for system of ODEs

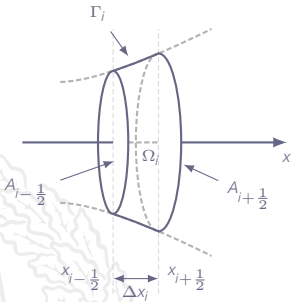
Spatial discretization techniques:

FDM Finite-Difference Method

FVM **Finite-Volume Method**

FEM Finite-Element Method

Let's look at a small tube segment with length Δx



Streamtube with area $A(x)$

$$A_{i-\frac{1}{2}} = A(x_{i-\frac{1}{2}})$$

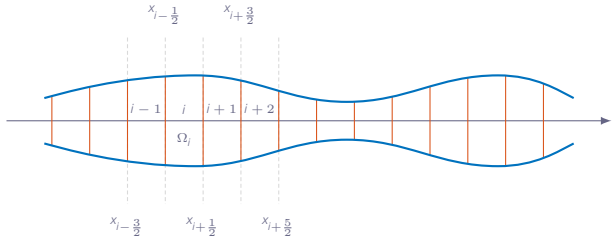
$$A_{i+\frac{1}{2}} = A(x_{i+\frac{1}{2}})$$

$$\Delta x_i = x_{i+\frac{1}{2}} - x_{i-\frac{1}{2}}$$

Ω_i - control volume enclosed by $A_{i-\frac{1}{2}}$, $A_{i+\frac{1}{2}}$, and Γ_i

$\Rightarrow$ **spatial discretization**

Quasi-One-Dimensional Flow - Spatial Discretization

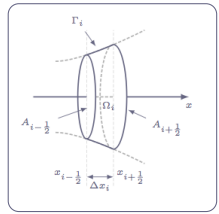


Integer indices: control volumes or **cells**

Fractional indices: interfaces between control volumes or **cell faces**

Apply control volume formulations for mass, momentum, energy to control volume Ω_i

Quasi-One-Dimensional Flow - Spatial Discretization



cell-averaged quantity

face-averaged quantity

Conservation of mass:

$$\underbrace{\frac{d}{dt}\iiint_{\Omega_i}\rho d\mathscr{V}}_{VOL_i\frac{d}{dt}\bar{\rho}_i}+\underbrace{\iint_{x_{i-\frac{1}{2}}}\rho\mathbf{v}\cdot\mathbf{n}dS}_{-\overline{(\rho u)}_{i-\frac{1}{2}}A_{i-\frac{1}{2}}}+\underbrace{\iint_{x_{i+\frac{1}{2}}}\rho\mathbf{v}\cdot\mathbf{n}dS}_{\overline{(\rho u)}_{i+\frac{1}{2}}A_{i+\frac{1}{2}}}+\underbrace{\iint_{\Gamma_i}\rho\mathbf{v}\cdot\mathbf{n}dS}_{0}=0$$

where

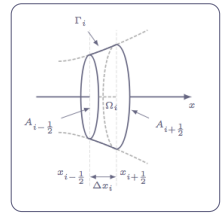
$$VOL_i=\iiint_{\Omega_i}d\mathscr{V}$$

$$\overline{(\rho u)}_{i-\frac{1}{2}}=\frac{1}{A_{i-\frac{1}{2}}}\iint_{x_{i-\frac{1}{2}}}\rho u dS$$

$$\bar{\rho}_i=\frac{1}{VOL_i}\iiint_{\Omega_i}\rho d\mathscr{V}$$

$$\overline{(\rho u)}_{i+\frac{1}{2}}=\frac{1}{A_{i+\frac{1}{2}}}\iint_{x_{i+\frac{1}{2}}}\rho u dS$$

Quasi-One-Dimensional Flow - Spatial Discretization



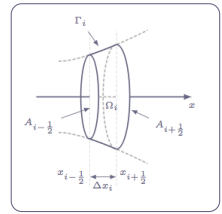
cell-averaged quantity
face-averaged quantity
source term

Conservation of momentum:

$$\underbrace{\frac{d}{dt}\iiint_{\Omega_i}\rho u d\mathscr{V}}_{VOL_i\,\frac{d}{dt}\overline{(\rho u)}_i} + \underbrace{\iint_{x_{i-\frac{1}{2}}}\left[\rho(\mathbf{v}\cdot\mathbf{n})u + p(\mathbf{n}\cdot\mathbf{e}_x)\right]dS}_{-\overline{(\rho u^2+p)}_{i-\frac{1}{2}}A_{i-\frac{1}{2}}} +$$

$$+\underbrace{\iint_{x_{i+\frac{1}{2}}}\left[\rho(\mathbf{v}\cdot\mathbf{n})u + p(\mathbf{n}\cdot\mathbf{e}_x)\right]dS}_{\overline{(\rho u^2+p)}_{i+\frac{1}{2}}A_{i+\frac{1}{2}}} + \underbrace{\iint_{\Gamma_i}\left[\rho(\mathbf{v}\cdot\mathbf{n})u + p(\mathbf{n}\cdot\mathbf{e}_x)\right]dS}_{-\iint_{\Gamma_i}pdA} = 0$$

Quasi-One-Dimensional Flow - Spatial Discretization



cell-averaged quantity

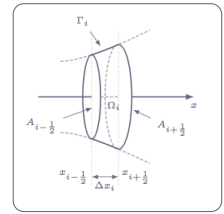
face-averaged quantity

Conservation of energy:

$$\underbrace{\frac{d}{dt}\iiint_{\Omega_i}\rho e_o d\mathcal{V}}_{VOL_i\frac{d}{dt}\overline{(\rho e_o)}_i}+\underbrace{\iint_{x_{i-\frac{1}{2}}}\rho h_o(\mathbf{v}\cdot\mathbf{n})dS}_{-\overline{(\rho u h_o)}_{i-\frac{1}{2}}A_{i-\frac{1}{2}}}+$$

$$+\underbrace{\iint_{x_{i+\frac{1}{2}}}\rho h_o(\mathbf{v}\cdot\mathbf{n})dS}_{\overline{(\rho u h_o)}_{i+\frac{1}{2}}A_{i+\frac{1}{2}}}+\underbrace{\iint_{\Gamma_i}\rho h_o(\mathbf{v}\cdot\mathbf{n})dS}_{0}=0$$

Quasi-One-Dimensional Flow - Spatial Discretization



Lower order term due to varying stream tube area:

$$\iint_{\Gamma_i} p dA \approx \bar{p}_i \left(A_{i+\frac{1}{2}} - A_{i-\frac{1}{2}} \right)$$

where $\bar{p}_i$ is **calculated from cell-averaged quantities** (DOFs) $\left\{ \bar{\rho}, \overline{(\rho u)}, \overline{(\rho e_o)} \right\}_i$ as

$$\bar{p}_i = (\gamma - 1) \left(\overline{(\rho e_o)}_i - \frac{1}{2} \bar{\rho}_i \bar{u}_i^2 \right), \; \bar{u}_i = \frac{\overline{(\rho u)}_i}{\bar{\rho}_i}$$

Quasi-One-Dimensional Flow - Spatial Discretization

cell-averaged quantity
face-averaged quantity
source term

$$VOL_i \frac{d}{dt} \bar{\rho}_i - \overline{(\rho u)}_{i-\frac{1}{2}} A_{i-\frac{1}{2}} + \overline{(\rho u)}_{i+\frac{1}{2}} A_{i+\frac{1}{2}} = 0$$

$$VOL_i \frac{d}{dt} \overline{(\rho u)}_i - \overline{(\rho u^2 + p)}_{i-\frac{1}{2}} A_{i-\frac{1}{2}} + \overline{(\rho u^2 + p)}_{i+\frac{1}{2}} A_{i+\frac{1}{2}} = \bar{p}_i \left(A_{i+\frac{1}{2}} - A_{i-\frac{1}{2}} \right)$$

$$VOL_i \frac{d}{dt} \overline{(\rho e_o)}_i - \overline{(\rho u h_o)}_{i-\frac{1}{2}} A_{i-\frac{1}{2}} + \overline{(\rho u h_o)}_{i+\frac{1}{2}} A_{i+\frac{1}{2}} = 0$$

Application of these equations to all cells $i \in \{1, 2, ..., N\}$ of the computational domain results in a system of ODEs

Spatial Discretization - Summary

Steps to achieve spatial discretization:

1. Choose primary variables (degrees of freedom)
2. Approximate all other quantities in terms of the primary variables

$\Rightarrow$ **System of ordinary differential equations** (ODEs)

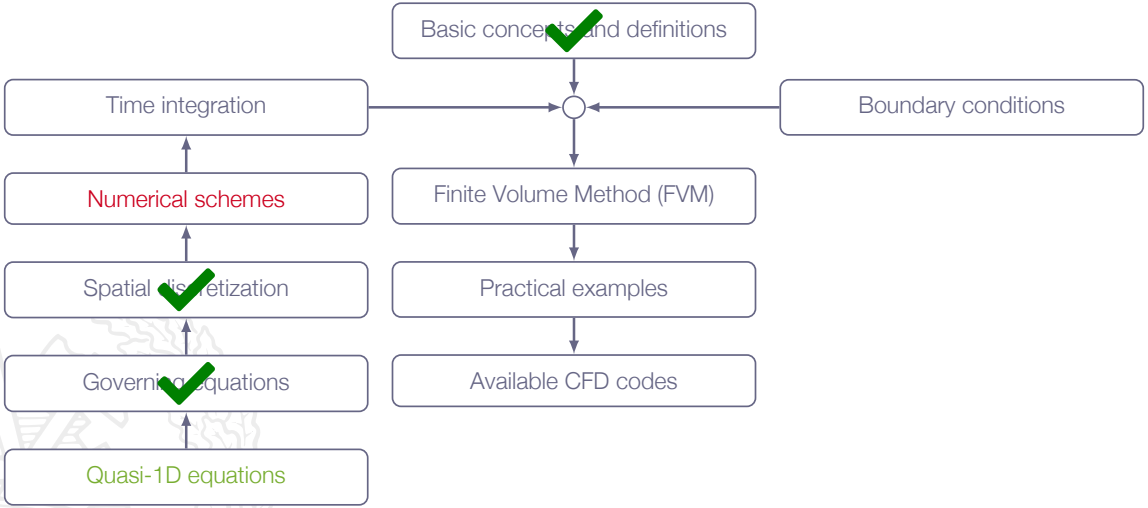
Degrees of freedom:

Choose $\left\{ \bar{\rho}, \overline{(\rho u)}, \overline{(\rho e_o)} \right\}_i$ in all control volumes Ω_i, $i \in \{1, 2, ..., N\}$ as degrees of freedom, or primary variables

Note that these are **cell-averaged quantities**

What about the face values?

Roadmap - The Time-Marching Technique



Numerical Schemes

Flux Term Approximation

$$\begin{Bmatrix} \overline{(\rho u)} \\ \overline{(\rho u^2 + p)} \\ \overline{(\rho u h_o)} \end{Bmatrix}_{i+\frac{1}{2}} = f\left(\begin{Bmatrix} \overline{\rho} \\ \overline{(\rho u)} \\ \overline{(\rho e_o)} \end{Bmatrix}_i , \begin{Bmatrix} \overline{\rho} \\ \overline{(\rho u)} \\ \overline{(\rho e_o)} \end{Bmatrix}_{i+1} , \ldots \right)$$

cell face values

cell-averaged values

Simple example:

$$\overline{(\rho u)}_{i+\frac{1}{2}} \approx \frac{1}{2}\left[\overline{(\rho u)}_i + \overline{(\rho u)}_{i+1}\right]$$

Flux Term Approximation

CFLOW

More complex approximations usually needed

High-order schemes:

- increased accuracy
- more cell values involved (*wider flux molecule*)
- boundary conditions more difficult to implement

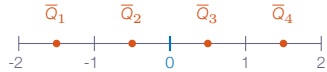
Optimized numerical dissipation:

- upwind type of flux scheme

Shock handling:

- non-linear treatment needed (*e.g.* TVD schemes)
- artificial damping

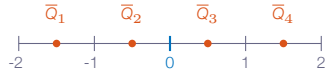
Flux Term Approximation



$$Q(x) = A + Bx + Cx^2 + Dx^3$$

Assume constant area: $A(x) = 1.0$

Flux Term Approximation

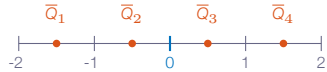


$$\overline{Q}_1 = \frac{1}{VOL_1} \int_{-2}^{-1} Q(x)dx$$

$$VOL_1 = A_1 \Delta x_1 = \{A_1 = 1.0,\ \Delta x_1 = 1.0\} = 1.0$$

$$\Rightarrow \overline{Q}_1 = \int_{-2}^{-1} Q(x)dx$$

Flux Term Approximation



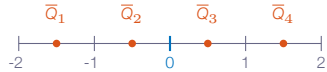
$$\overline{Q}_1 = \int_{-2}^{-1} Q(x)dx = \left[Ax + \frac{1}{2}Bx^2 + \frac{1}{3}Cx^3 + \frac{1}{4}Dx^4\right]_{-2}^{-1}$$

$$\overline{Q}_2 = \int_{-1}^{0} Q(x)dx = \left[Ax + \frac{1}{2}Bx^2 + \frac{1}{3}Cx^3 + \frac{1}{4}Dx^4\right]_{-1}^{0}$$

$$\overline{Q}_3 = \int_{0}^{1} Q(x)dx = \left[Ax + \frac{1}{2}Bx^2 + \frac{1}{3}Cx^3 + \frac{1}{4}Dx^4\right]_{0}^{1}$$

$$\overline{Q}_4 = \int_{1}^{2} Q(x)dx = \left[Ax + \frac{1}{2}Bx^2 + \frac{1}{3}Cx^3 + \frac{1}{4}Dx^4\right]_{1}^{2}$$

Flux Term Approximation



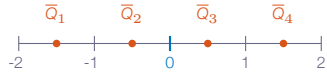
$$\overline{Q}_1 = A - \frac{3}{2}B + \frac{7}{3}C - \frac{15}{4}D$$

$$\overline{Q}_2 = A - \frac{1}{2}B + \frac{1}{3}C - \frac{1}{4}D$$

$$\overline{Q}_3 = A + \frac{1}{2}B + \frac{1}{3}C + \frac{1}{4}D$$

$$\overline{Q}_4 = A + \frac{3}{2}B + \frac{7}{3}C + \frac{15}{4}D$$

Flux Term Approximation



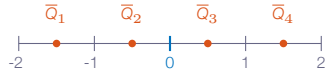
$$A = \frac{1}{12}\left[-\overline{Q}_1 + 7\overline{Q}_2 + 7\overline{Q}_3 - \overline{Q}_4\right]$$

$$B = \frac{1}{12}\left[\overline{Q}_1 - 15\overline{Q}_2 + 15\overline{Q}_3 - \overline{Q}_4\right]$$

$$C = \frac{1}{4}\left[\overline{Q}_1 - \overline{Q}_2 - \overline{Q}_3 + \overline{Q}_4\right]$$

$$D = \frac{1}{6}\left[-\overline{Q}_1 + 3\overline{Q}_2 - 3\overline{Q}_3 + \overline{Q}_4\right]$$

Flux Term Approximation



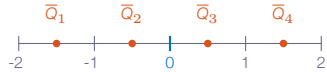
$$Q_0 = Q(0) + \delta Q'''(0) \Rightarrow Q_0 = A + 6\delta D$$

$\delta = 0 \Rightarrow$ fourth-order central scheme

$\delta = 1/12 \Rightarrow$ third-order upwind scheme

$\delta = 1/96 \Rightarrow$ third-order low-dissipation upwind scheme

Flux Term Approximation



$$Q_0 = A + 6\delta D = \{\delta = 1/12\} = -\frac{1}{6}\overline{Q}_1 + \frac{5}{6}\overline{Q}_2 + \frac{1}{3}\overline{Q}_3$$

$$Q_{0_{left}} = -\frac{1}{6}\overline{Q}_1 + \frac{5}{6}\overline{Q}_2 + \frac{1}{3}\overline{Q}_3$$

$$Q_{0_{right}} = -\frac{1}{6}\overline{Q}_4 + \frac{5}{6}\overline{Q}_3 + \frac{1}{3}\overline{Q}_2$$

method of characteristics used in order to decide whether left- or right-upwinded flow quantities should be used

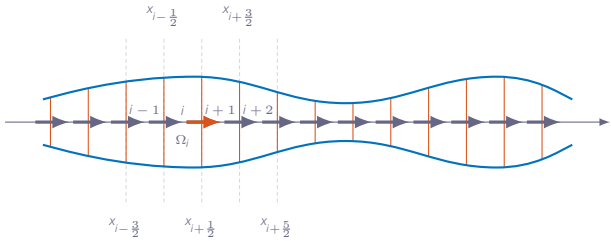
Flux Term Approximation

CFLOW

High-order numerical schemes:

- low numerical dissipation (smearing due to amplitudes errors)
- low dispersion errors (wiggles due to phase errors)

Conservative Scheme



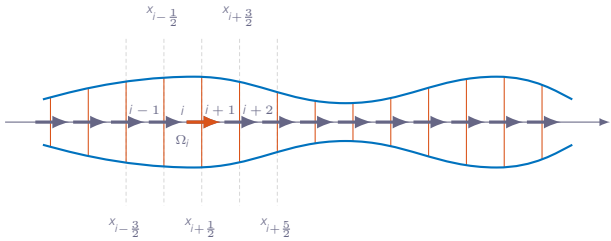
mass conservation:

cell (i): $$VOL_i \frac{d}{dt}\bar{\rho}_i + \overline{(\rho u)}_{i+\frac{1}{2}} A_{i+\frac{1}{2}} - \overline{(\rho u)}_{i-\frac{1}{2}} A_{i-\frac{1}{2}} = 0$$

cell $(i+1)$: $$VOL_{i+1} \frac{d}{dt}\bar{\rho}_{i+1} + \overline{(\rho u)}_{i+\frac{3}{2}} A_{i+\frac{3}{2}} - \overline{(\rho u)}_{i+\frac{1}{2}} A_{i+\frac{1}{2}} = 0$$

(similarly for momentum and energy conservation)

Conservative Scheme



mass conservation:

cell (i):

$$VOL_i \frac{d}{dt}\bar{\rho}_i + \overline{(\rho u)}_{i+\frac{1}{2}} A_{i+\frac{1}{2}} - \overline{(\rho u)}_{i-\frac{1}{2}} A_{i-\frac{1}{2}} = 0$$

cell $(i+1)$:

$$VOL_{i+1} \frac{d}{dt}\bar{\rho}_{i+1} + \overline{(\rho u)}_{i+\frac{3}{2}} A_{i+\frac{3}{2}} - \overline{(\rho u)}_{i+\frac{1}{2}} A_{i+\frac{1}{2}} = 0$$

(similarly for momentum and energy conservation)

Conservative scheme

"The flux leaving one control volume equals the flux entering neighbouring control volume"

Conservation of for mass, momentum and energy is crucial for the correct prediction of shocks*

* correct prediction of shocks:
  strength
  position
  velocity

Jameson shock detector:

$$\nu_{i+\frac{1}{2}} = max\left\{\nu_i, \nu_{i+1}\right\}$$

where ν_i is a scaled pressure derivative

$$\nu_i = \frac{|p_{i+1} - 2p_i + p_{i-1}|}{p_{i+1} + 2p_i + p_{i-1}}$$

For a smooth pressure field $\nu\ \mathcal{O}(\Delta x^2)$ and near a shock $\nu\ \mathcal{O}(1)$

Artificial damping term (α is a user-defined constant):

$$\alpha\left(|u| + c\right)_{i+\frac{1}{2}} \nu_{i+\frac{1}{2}} A_{i+\frac{1}{2}} \left(Q_{i+1} - Q_i\right)$$

Density Discontinuities

CFLOW

Jameson-type detector:

$$\nu_{i+\frac{1}{2}} = max\left\{\nu_i, \nu_{i+1}\right\}$$

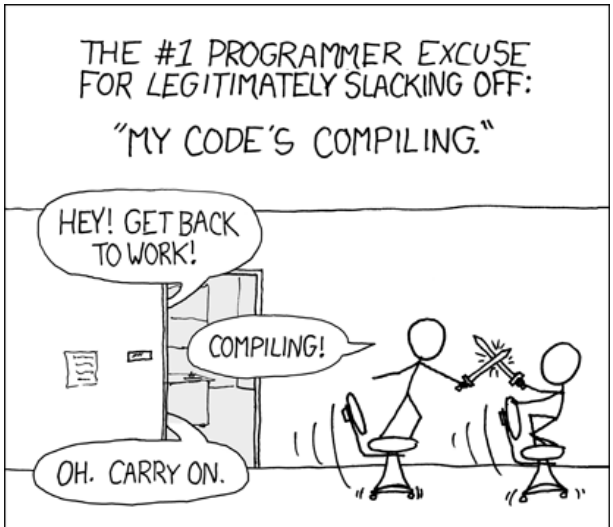
where ν_i is a scaled density derivative

$$\nu_i = \frac{|\rho_{i+1} - 2\rho_i + \rho_{i-1}|}{\rho_{i+1} + 2\rho_i + \rho_{i-1}}$$

For a smooth density field $\nu\ \mathcal{O}(\Delta x^2)$ and near a density discontinuity $\nu\ \mathcal{O}(1)$

Artificial damping term (β is a user-defined constant):

$$\beta\,|u|_{i+\frac{1}{2}}\,\nu_{i+\frac{1}{2}} A_{i+\frac{1}{2}}\,(Q_{i+1} - Q_i)$$


THE #1 PROGRAMMER EXCUSE FOR LEGITIMATELY SLACKING OFF:
"MY CODE'S COMPILING."
HEY! GET BACK TO WORK!
COMPILING!
OH. CARRY ON.