

- Conservative IVP:  $\frac{\partial u}{\partial t} = \frac{\partial F}{\partial x}$  in 1-D;  $\frac{\partial u}{\partial t} = \nabla \cdot \mathbf{F}$  in multi-D

- Conservative IVP:  $\frac{\partial u}{\partial t} = \frac{\partial F}{\partial x}$  in 1-D;  $\frac{\partial u}{\partial t} = \nabla \cdot \mathbf{F}$  in multi-D
- integrating over domain;  
$$\frac{d}{dt} \int u dV = \int \nabla \cdot \mathbf{F} dV = \oint \mathbf{F} \cdot d\mathbf{S}$$
- change in  $\int u dV$  is due to flux leaving boundaries

- Conservative IVP:  $\frac{\partial u}{\partial t} = \frac{\partial F}{\partial x}$  in 1-D;  $\frac{\partial u}{\partial t} = \nabla \cdot \mathbf{F}$  in multi-D
- integrating over domain;  
$$\frac{d}{dt} \int u dV = \int \nabla \cdot \mathbf{F} dV = \oint \mathbf{F} \cdot d\mathbf{S}$$
- change in  $\int u dV$  is due to flux leaving boundaries
- Examples: wave equation, diffusion equation

- Conservative IVP:  $\frac{\partial u}{\partial t} = \frac{\partial F}{\partial x}$  in 1-D;  $\frac{\partial u}{\partial t} = \nabla \cdot \mathbf{F}$  in multi-D
- integrating over domain;  
$$\frac{d}{dt} \int u dV = \int \nabla \cdot \mathbf{F} dV = \oint \mathbf{F} \cdot d\mathbf{S}$$
- change in  $\int u dV$  is due to flux leaving boundaries
- Examples: wave equation, diffusion equation
- Wave equation:  $\frac{\partial^2 u}{\partial t^2} = c^2 \frac{\partial^2 u}{\partial x^2}$ ,  $(\frac{\partial}{\partial t} - c \frac{\partial}{\partial x})(\frac{\partial}{\partial t} + c \frac{\partial}{\partial x})u = 0$
- advection eq.  $\frac{\partial u}{\partial t} + c \frac{\partial u}{\partial x} = 0$ ; solution a function  $u(x - ct)$

- Conservative IVP:  $\frac{\partial u}{\partial t} = \frac{\partial F}{\partial x}$  in 1-D;  $\frac{\partial u}{\partial t} = \nabla \cdot \mathbf{F}$  in multi-D
- integrating over domain;  
$$\frac{d}{dt} \int u dV = \int \nabla \cdot \mathbf{F} dV = \oint \mathbf{F} \cdot d\mathbf{S}$$
- change in  $\int u dV$  is due to flux leaving boundaries
- Examples: wave equation, diffusion equation
- Wave equation:  $\frac{\partial^2 u}{\partial t^2} = c^2 \frac{\partial^2 u}{\partial x^2}$ ,  $(\frac{\partial}{\partial t} - c \frac{\partial}{\partial x})(\frac{\partial}{\partial t} + c \frac{\partial}{\partial x})u = 0$
- advection eq.  $\frac{\partial u}{\partial t} + c \frac{\partial u}{\partial x} = 0$ ; solution a function  $u(x - ct)$
- diffusion eq.  $\frac{\partial u}{\partial t} = D \frac{\partial^2 u}{\partial x^2}$

- diffusion eq.  $\frac{\partial u}{\partial t} = \frac{\partial}{\partial x} \left( D \frac{\partial u}{\partial x} \right); F = -D \frac{\partial u}{\partial x}$

- diffusion eq.  $\frac{\partial u}{\partial t} = \frac{\partial}{\partial x} \left( D \frac{\partial u}{\partial x} \right); F = -D \frac{\partial u}{\partial x}$
- FTCS:  $\frac{u_j^{n+1} - u_j^n}{\Delta t} = D \left( \frac{u_{j+1}^n - 2u_j^n + u_{j-1}^n}{\Delta x^2} \right)$

- diffusion eq.  $\frac{\partial u}{\partial t} = \frac{\partial}{\partial x} \left( D \frac{\partial u}{\partial x} \right); F = -D \frac{\partial u}{\partial x}$
- FTCS:  $\frac{u_j^{n+1} - u_j^n}{\Delta t} = D \left( \frac{u_{j+1}^n - 2u_j^n + u_{j-1}^n}{\Delta x^2} \right)$
- von Neumann stability analysis (VNSA): assume  $u \sim u(t)e^{ikx} \sim u(t)e^{ikj\Delta x}$



- diffusion eq.  $\frac{\partial u}{\partial t} = \frac{\partial}{\partial x} \left( D \frac{\partial u}{\partial x} \right); F = -D \frac{\partial u}{\partial x}$
- FTCS:  $\frac{u_j^{n+1} - u_j^n}{\Delta t} = D \left( \frac{u_{j+1}^n - 2u_j^n + u_{j-1}^n}{\Delta x^2} \right)$
- von Neumann stability analysis (VNSA): assume  $u \sim u(t)e^{ikx} \sim u(t)e^{ikj\Delta x}$
- substituting in FTCS eq.  $\xi \equiv \frac{u^{n+1}}{u^n}$  amplification factor,  
 $\xi - 1 = \frac{D\Delta t}{\Delta x^2} (e^{ik\Delta x} - 2 + e^{-ik\Delta x})$
- $\xi = 1 - \frac{4D\Delta t}{\Delta x^2} \sin^2 \left( \frac{k\Delta x}{2} \right)$

- diffusion eq.  $\frac{\partial u}{\partial t} = \frac{\partial}{\partial x} \left( D \frac{\partial u}{\partial x} \right); F = -D \frac{\partial u}{\partial x}$
- FTCS:  $\frac{u_j^{n+1} - u_j^n}{\Delta t} = D \left( \frac{u_{j+1}^n - 2u_j^n + u_{j-1}^n}{\Delta x^2} \right)$
- von Neumann stability analysis (VNSA): assume  $u \sim u(t)e^{ikx} \sim u(t)e^{ikj\Delta x}$
- substituting in FTCS eq.  $\xi \equiv \frac{u^{n+1}}{u^n}$  amplification factor,  
 $\xi - 1 = \frac{D\Delta t}{\Delta x^2} (e^{ik\Delta x} - 2 + e^{-ik\Delta x})$
- $\xi = 1 - \frac{4D\Delta t}{\Delta x^2} \sin^2 \left( \frac{k\Delta x}{2} \right)$
- numerical stability demands  $|\xi| \leq 1$ , or  $\Delta t \leq \frac{\Delta x^2}{2D}$

- diffusion eq.  $\frac{\partial u}{\partial t} = \frac{\partial}{\partial x} \left( D \frac{\partial u}{\partial x} \right); F = -D \frac{\partial u}{\partial x}$
- FTCS:  $\frac{u_j^{n+1} - u_j^n}{\Delta t} = D \left( \frac{u_{j+1}^n - 2u_j^n + u_{j-1}^n}{\Delta x^2} \right)$
- von Neumann stability analysis (VNSA): assume  $u \sim u(t)e^{ikx} \sim u(t)e^{ikj\Delta x}$
- substituting in FTCS eq.  $\xi \equiv \frac{u^{n+1}}{u^n}$  amplification factor,  
 $\xi - 1 = \frac{D\Delta t}{\Delta x^2} (e^{ik\Delta x} - 2 + e^{-ik\Delta x})$
- $\xi = 1 - \frac{4D\Delta t}{\Delta x^2} \sin^2 \left( \frac{k\Delta x}{2} \right)$
- numerical stability demands  $|\xi| \leq 1$ , or  $\Delta t \leq \frac{\Delta x^2}{2D}$
- on  $L$ ,  $\tau \sim L^2/2D$ ; requires  $(L/\Delta x)^2 \sim N^2$  timesteps

- diffusion eq.  $\frac{\partial u}{\partial t} = \frac{\partial}{\partial x} \left( D \frac{\partial u}{\partial x} \right); F = -D \frac{\partial u}{\partial x}$
- FTCS:  $\frac{u_j^{n+1} - u_j^n}{\Delta t} = D \left( \frac{u_{j+1}^n - 2u_j^n + u_{j-1}^n}{\Delta x^2} \right)$
- von Neumann stability analysis (VNSA): assume  $u \sim u(t)e^{ikx} \sim u(t)e^{ikj\Delta x}$
- substituting in FTCS eq.  $\xi \equiv \frac{u^{n+1}}{u^n}$  amplification factor,  
 $\xi - 1 = \frac{D\Delta t}{\Delta x^2} (e^{ik\Delta x} - 2 + e^{-ik\Delta x})$
- $\xi = 1 - \frac{4D\Delta t}{\Delta x^2} \sin^2 \left( \frac{k\Delta x}{2} \right)$
- numerical stability demands  $|\xi| \leq 1$ , or  $\Delta t \leq \frac{\Delta x^2}{2D}$
- on  $L$ ,  $\tau \sim L^2/2D$ ; requires  $(L/\Delta x)^2 \sim N^2$  timesteps
- can do better implicitly

■ fully implicit: 
$$\frac{u_j^{n+1} - u_j^n}{\Delta t} = D \left( \frac{u_{j+1}^{n+1} - 2u_j^{n+1} + u_{j-1}^{n+1}}{\Delta x^2} \right)$$

- fully implicit:  $\frac{u_j^{n+1} - u_j^n}{\Delta t} = D \left( \frac{u_{j+1}^{n+1} - 2u_j^{n+1} + u_{j-1}^{n+1}}{\Delta x^2} \right)$
- von Neumann stability analysis (VNSA): assume  $u \sim u(t)e^{ikx} \sim u(t)e^{ikj\Delta x}$

- fully implicit:  $\frac{u_j^{n+1} - u_j^n}{\Delta t} = D \left( \frac{u_{j+1}^{n+1} - 2u_j^{n+1} + u_{j-1}^{n+1}}{\Delta x^2} \right)$
- von Neumann stability analysis (VNSA): assume  $u \sim u(t)e^{ikx} \sim u(t)e^{ikj\Delta x}$
- substituting,  $\xi - 1 = \frac{D\Delta t}{\Delta x^2} \xi (e^{ik\Delta x} - 2 + e^{-ik\Delta x})$
- $\xi = \frac{1}{1 + \frac{4D\Delta t}{\Delta x^2} \sin^2\left(\frac{k\Delta x}{2}\right)} < 1$  for all  $\Delta t$ ; unconditionally stable

- fully implicit:  $\frac{u_j^{n+1} - u_j^n}{\Delta t} = D \left( \frac{u_{j+1}^{n+1} - 2u_j^{n+1} + u_{j-1}^{n+1}}{\Delta x^2} \right)$
- von Neumann stability analysis (VNSA): assume  $u \sim u(t)e^{ikx} \sim u(t)e^{ikj\Delta x}$
- substituting,  $\xi - 1 = \frac{D\Delta t}{\Delta x^2} \xi (e^{ik\Delta x} - 2 + e^{-ik\Delta x})$
- $\xi = \frac{1}{1 + \frac{4D\Delta t}{\Delta x^2} \sin^2\left(\frac{k\Delta x}{2}\right)} < 1$  for all  $\Delta t$ ; unconditionally stable
- tridiagonal equation, that is easy to solve



- fully implicit:  $\frac{u_j^{n+1} - u_j^n}{\Delta t} = D \left( \frac{u_{j+1}^{n+1} - 2u_j^{n+1} + u_{j-1}^{n+1}}{\Delta x^2} \right)$
- von Neumann stability analysis (VNSA): assume  $u \sim u(t)e^{ikx} \sim u(t)e^{ikj\Delta x}$
- substituting,  $\xi - 1 = \frac{D\Delta t}{\Delta x^2} \xi (e^{ik\Delta x} - 2 + e^{-ik\Delta x})$
- $\xi = \frac{1}{1 + \frac{4D\Delta t}{\Delta x^2} \sin^2\left(\frac{k\Delta x}{2}\right)} < 1$  for all  $\Delta t$ ; unconditionally stable
- tridiagonal equation, that is easy to solve
- like FTCS, first order accurate in time

- fully implicit:  $\frac{u_j^{n+1} - u_j^n}{\Delta t} = D \left( \frac{u_{j+1}^{n+1} - 2u_j^{n+1} + u_{j-1}^{n+1}}{\Delta x^2} \right)$
- von Neumann stability analysis (VNSA): assume  $u \sim u(t)e^{ikx} \sim u(t)e^{ikj\Delta x}$
- substituting,  $\xi - 1 = \frac{D\Delta t}{\Delta x^2} \xi (e^{ik\Delta x} - 2 + e^{-ik\Delta x})$
- $\xi = \frac{1}{1 + \frac{4D\Delta t}{\Delta x^2} \sin^2\left(\frac{k\Delta x}{2}\right)} < 1$  for all  $\Delta t$ ; unconditionally stable
- tridiagonal equation, that is easy to solve
- like FTCS, first order accurate in time
- equilibrium solution  $d^2u/dx^2 = 0$  as  $\Delta t \rightarrow \infty$

- CTCS : 
$$\frac{u_j^{n+1} - u_j^n}{\Delta t} = D \left( \frac{(u_{j+1}^{n+1} - 2u_j^{n+1} + u_{j-1}^{n+1}) + (u_{j+1}^n - 2u_j^n + u_{j-1}^n)}{2\Delta x^2} \right)$$

- CTCS :  $\frac{u_j^{n+1} - u_j^n}{\Delta t} = D \left( \frac{(u_{j+1}^{n+1} - 2u_j^{n+1} + u_{j-1}^{n+1}) + (u_{j+1}^n - 2u_j^n + u_{j-1}^n)}{2\Delta x^2} \right)$
- von Neumann stability analysis (VNSA): assume  
 $u \sim u(t)e^{ikx} \sim u(t)e^{ikj\Delta x}$

- CTCS :  $\frac{u_j^{n+1} - u_j^n}{\Delta t} = D \left( \frac{(u_{j+1}^{n+1} - 2u_j^{n+1} + u_{j-1}^{n+1}) + (u_{j+1}^n - 2u_j^n + u_{j-1}^n)}{2\Delta x^2} \right)$
- von Neumann stability analysis (VNSA): assume  $u \sim u(t)e^{ikx} \sim u(t)e^{ikj\Delta x}$
- $\xi = \frac{1 - 2\frac{D\Delta t}{\Delta x^2} \sin^2\left(\frac{k\Delta x}{2}\right)}{1 + \frac{2D\Delta t}{\Delta x^2} \sin^2\left(\frac{k\Delta x}{2}\right)} \leq 1$  for all  $\Delta t$ ; unconditionally stable

- CTCS :  $\frac{u_j^{n+1} - u_j^n}{\Delta t} = D \left( \frac{(u_{j+1}^{n+1} - 2u_j^{n+1} + u_{j-1}^{n+1}) + (u_{j+1}^n - 2u_j^n + u_{j-1}^n)}{2\Delta x^2} \right)$
- von Neumann stability analysis (VNSA): assume  $u \sim u(t)e^{ikx} \sim u(t)e^{ikj\Delta x}$
- $\xi = \frac{1 - 2\frac{D\Delta t}{\Delta x^2} \sin^2\left(\frac{k\Delta x}{2}\right)}{1 + \frac{2D\Delta t}{\Delta x^2} \sin^2\left(\frac{k\Delta x}{2}\right)} \leq 1$  for all  $\Delta t$ ; unconditionally stable
- again tridiagonal equation, that is easy to solve

- CTCS :  $\frac{u_j^{n+1} - u_j^n}{\Delta t} = D \left( \frac{(u_{j+1}^{n+1} - 2u_j^{n+1} + u_{j-1}^{n+1}) + (u_{j+1}^n - 2u_j^n + u_{j-1}^n)}{2\Delta x^2} \right)$
- von Neumann stability analysis (VNSA): assume  $u \sim u(t)e^{ikx} \sim u(t)e^{ikj\Delta x}$
- $\xi = \frac{1 - 2\frac{D\Delta t}{\Delta x^2} \sin^2\left(\frac{k\Delta x}{2}\right)}{1 + \frac{2D\Delta t}{\Delta x^2} \sin^2\left(\frac{k\Delta x}{2}\right)} \leq 1$  for all  $\Delta t$ ; unconditionally stable
- again tridiagonal equation, that is easy to solve
- second order accurate in time

- CTCS :  $\frac{u_j^{n+1} - u_j^n}{\Delta t} = D \left( \frac{(u_{j+1}^{n+1} - 2u_j^{n+1} + u_{j-1}^{n+1}) + (u_{j+1}^n - 2u_j^n + u_{j-1}^n)}{2\Delta x^2} \right)$
- von Neumann stability analysis (VNSA): assume  $u \sim u(t)e^{ikx} \sim u(t)e^{ikj\Delta x}$
- $\xi = \frac{1 - 2\frac{D\Delta t}{\Delta x^2} \sin^2\left(\frac{k\Delta x}{2}\right)}{1 + \frac{2D\Delta t}{\Delta x^2} \sin^2\left(\frac{k\Delta x}{2}\right)} \leq 1$  for all  $\Delta t$ ; unconditionally stable
- again tridiagonal equation, that is easy to solve
- second order accurate in time
- equilibrium solution  $(d^2u/dx^2)^{n+1} = -(d^2u/dx^2)^n$  as  $\Delta t \rightarrow \infty$ , esp. for large  $k$  modes



# Diffusion equation: $D(u,x)$

- $u_j^{n+1} = \frac{\Delta t}{\Delta x^2} \left[ D(u_{i+1/2}^n, x_{i+1/2})(u_{i+1}^{n+1} - u_i^{n+1}) - D(u_{i-1/2}^n, x_{i-1/2})(u_i^{n+1} - u_{i-1}^{n+1}) \right]$
- $D(u_{i+1/2}^n, x_{i+1/2}) = \mathcal{M} [D(u_i^n, x_i), D(u_{i+1}^n, x_{i+1})]$
- $\mathcal{M}$  harmonic mean, weighted toward the lower value

# Diffusion equation: $D(u,x)$

- $u_j^{n+1} = \frac{\Delta t}{\Delta x^2} \left[ D(u_{i+1/2}^n, x_{i+1/2})(u_{i+1}^{n+1} - u_i^{n+1}) - D(u_{i-1/2}^n, x_{i-1/2})(u_i^{n+1} - u_{i-1}^{n+1}) \right]$
- $D(u_{i+1/2}^n, x_{i+1/2}) = \mathcal{M} [D(u_i^n, x_i), D(u_{i+1}^n, x_{i+1})]$
- $\mathcal{M}$  harmonic mean, weighted toward the lower value
- a tridiagonal matrix equation, unconditionally stable

