

1D-FEM in Fortran: Steady State Heat Conduction

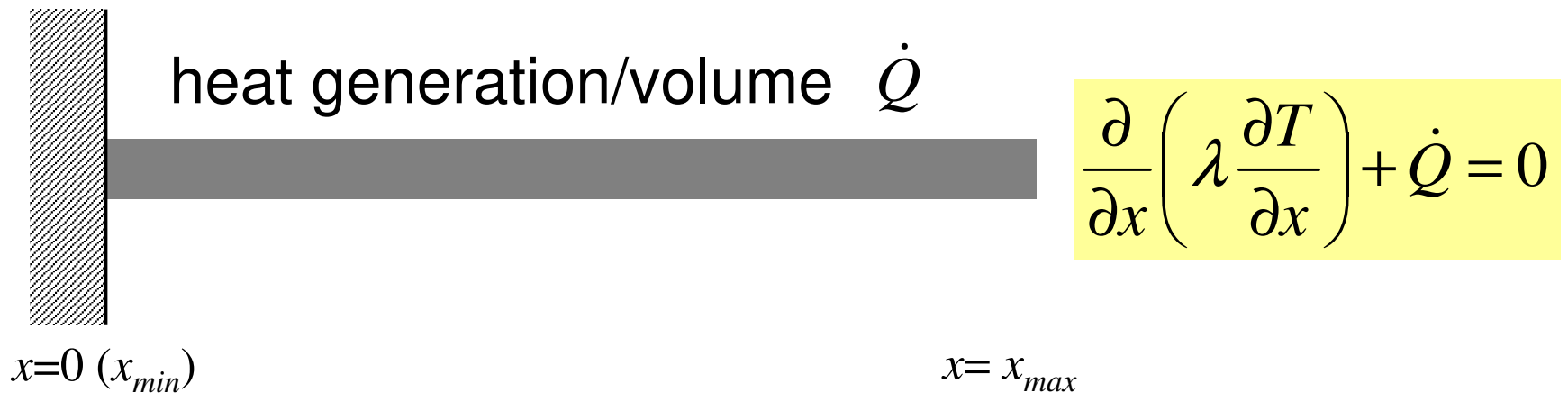
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RIKEN R-CCS

- 1D-code for Steady State Heat Conduction Problems by Galerkin FEM
- Sparse Linear Solver
 - Conjugate Gradient Method
 - Preconditioning
- Storage of Sparse Matrices
- Program

Keywords

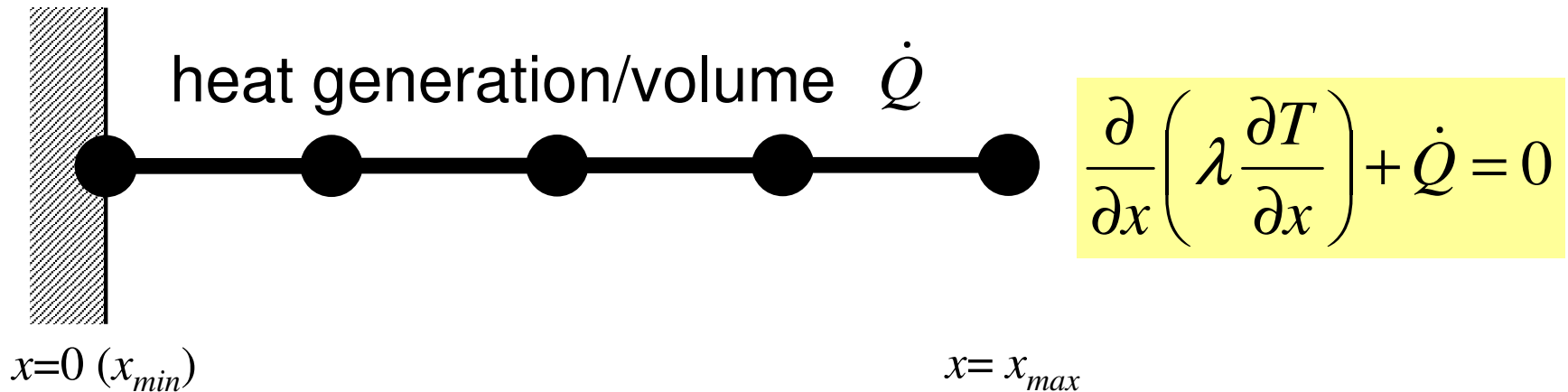
- 1D Steady State Heat Conduction Problems
- Galerkin Method
- Linear Element
- Preconditioned Conjugate Gradient Method

1D Steady State Heat Conduction



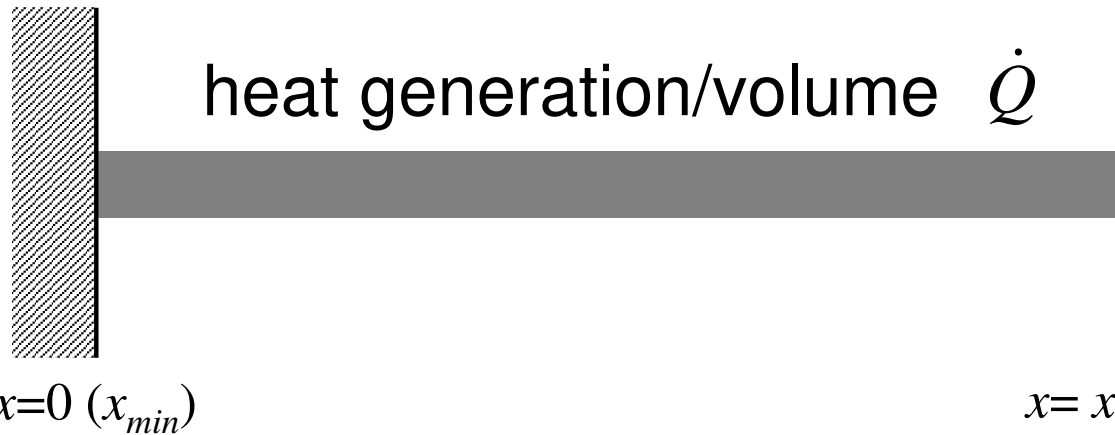
- **Uniform: Sectional Area: A , Thermal Conductivity: λ**
- Heat Generation Rate/Volume/Time [$QL^{-3}T^{-1}$] \dot{Q}
- Boundary Conditions
 - $x=0$: $T=0$ (Fixed Temperature)
 - $x=x_{max}$: $\frac{\partial T}{\partial x} = 0$ (Insulated)

1D Steady State Heat Conduction



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Analytical Solution



$$\frac{\partial}{\partial x} \left(\lambda \frac{\partial T}{\partial x} \right) + \dot{Q} = 0$$

$$T = 0 @ x = 0$$

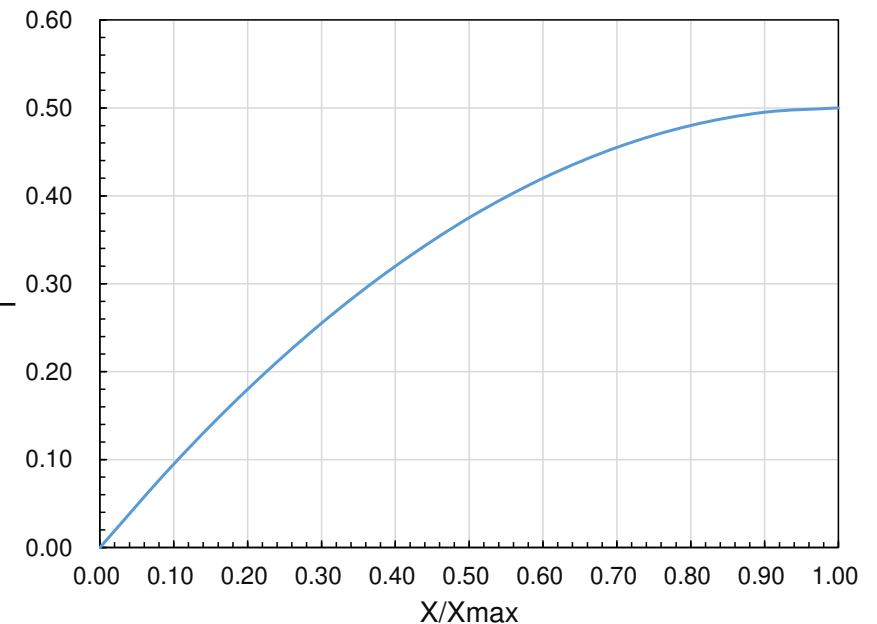
$$\frac{\partial T}{\partial x} = 0 @ x = x_{max}$$

$$\lambda T'' = -\dot{Q}$$

$$\lambda T' = -\dot{Q}x + C_1 \Rightarrow C_1 = \dot{Q}x_{max}, \quad T' = 0 @ x = x_{max}$$

$$\lambda T = -\frac{1}{2}\dot{Q}x^2 + C_1x + C_2 \Rightarrow C_2 = 0, \quad T = 0 @ x = 0$$

$$\therefore T = -\frac{1}{2\lambda}\dot{Q}x^2 + \frac{\dot{Q}x_{max}}{\lambda}x$$



1D Linear Element (1/4)

一次元線形要素

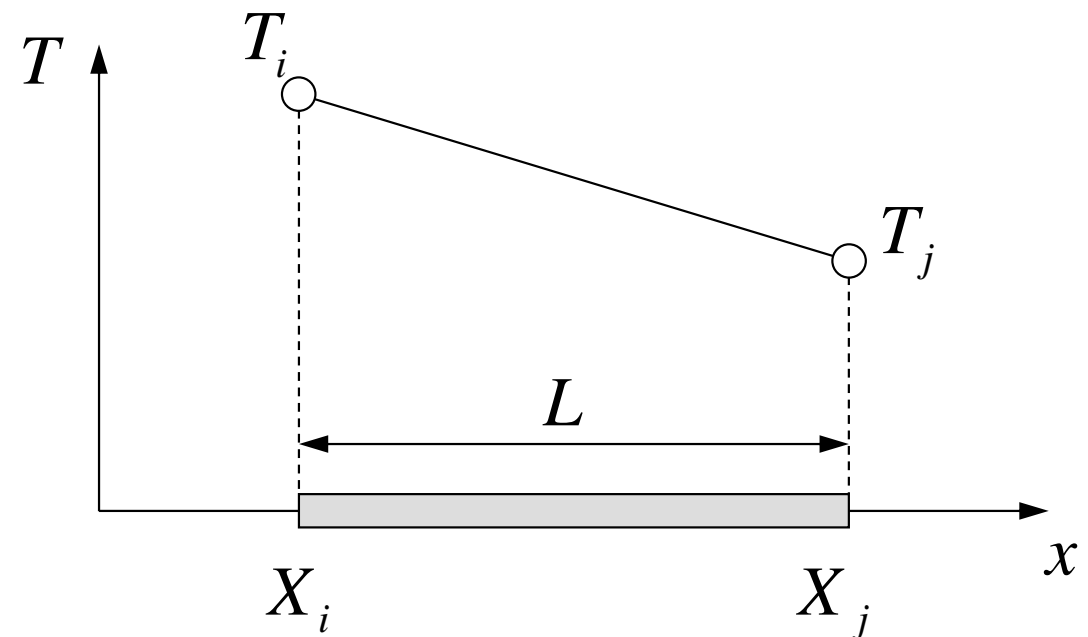
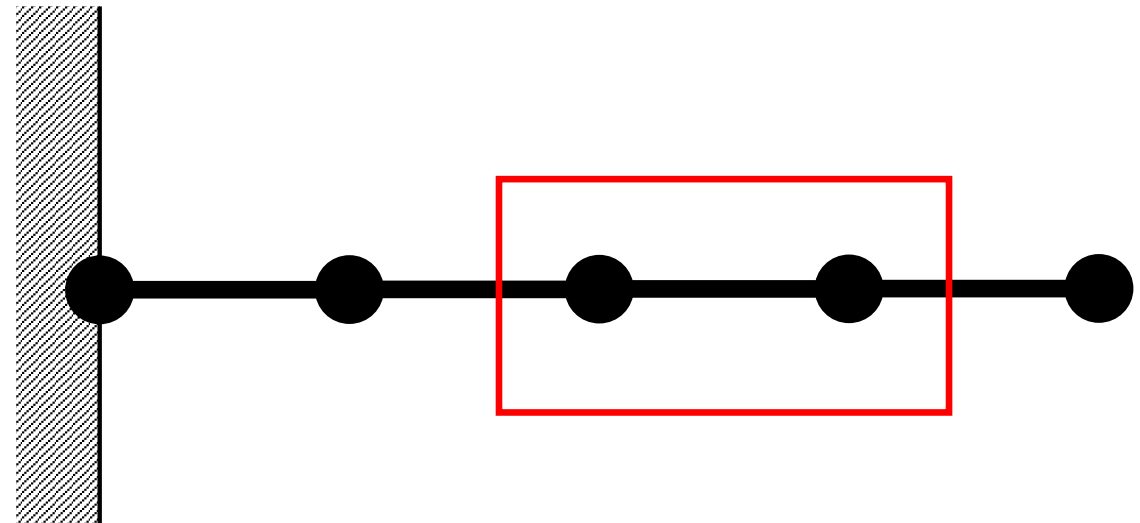
- 1D Linear Element

- Length = L

- Node (Vertex) (節点)
- Element (要素)

- T_i Temperature at i
- T_j Temperature at j
- Temperature T on each element is linear function of x (Piecewise Linear):

$$T = \alpha_1 + \alpha_2 x$$



1D Linear Element (1/4)

一次元線形要素

- 1D Linear Element

- Length = L

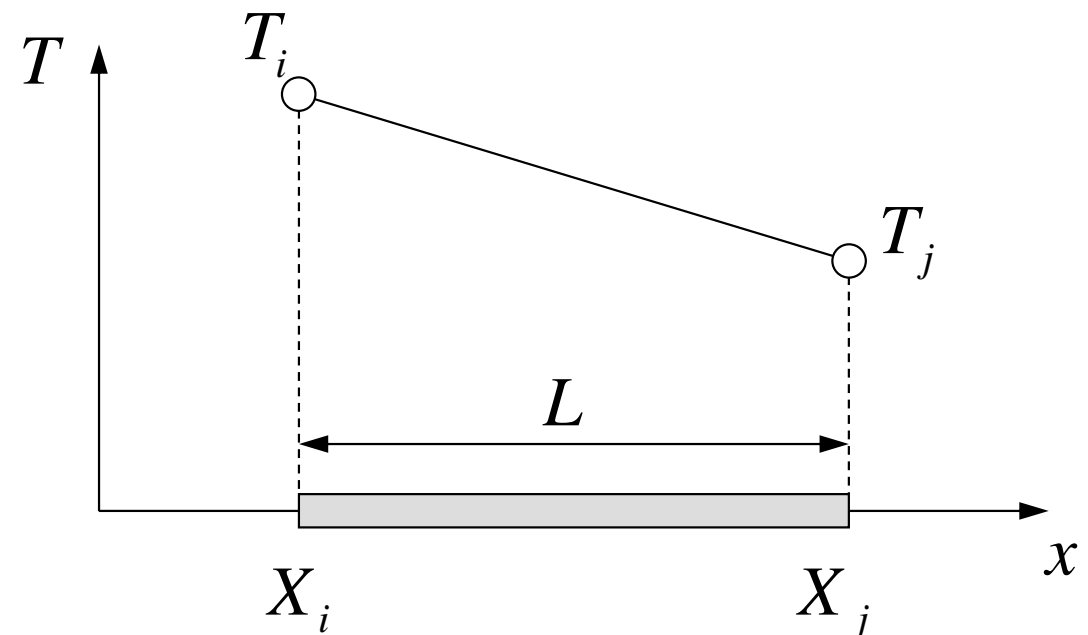
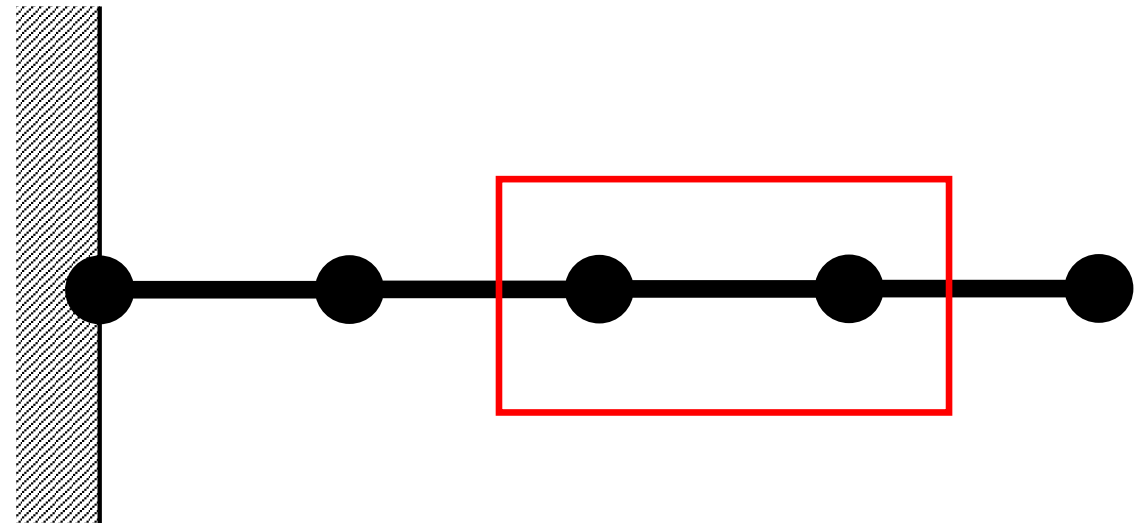
- Node (Vertex)
- Element

- T_i Temperature at i

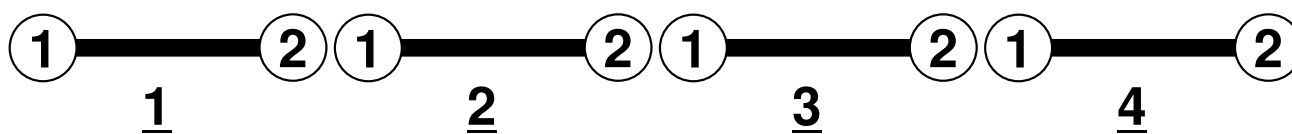
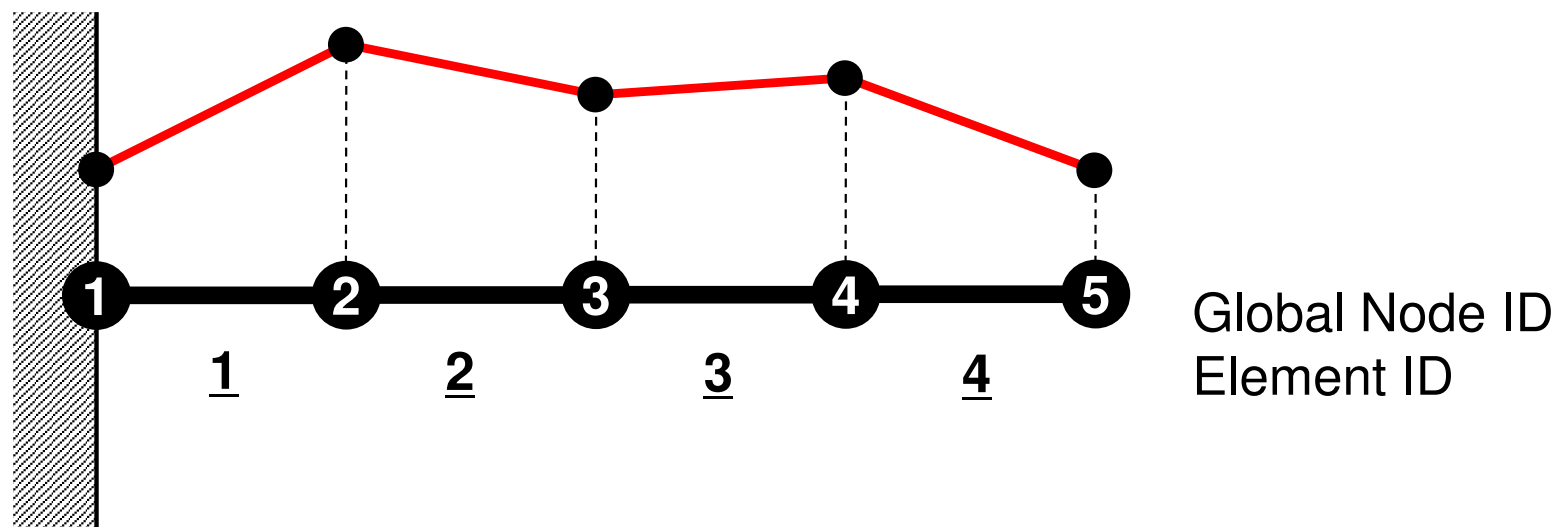
- T_j Temperature at j

- Temperature T on each element is linear function of x (Piecewise Linear):

$$T = \alpha_1 + \alpha_2 x$$



Piecewise Linear



Local Node ID
for each elem.

Gradient of temperature is constant in each element (might be discontinuous at each "node")

1D Linear Elem.: Shape Function (2/4)

- Coef's are calculated based on info. at each node

$$T = T_i @ x = X_i, \quad T = T_j @ x = X_j$$

$$T_i = \alpha_1 + \alpha_2 X_i, \quad T_j = \alpha_1 + \alpha_2 X_j$$

- Coefficients:

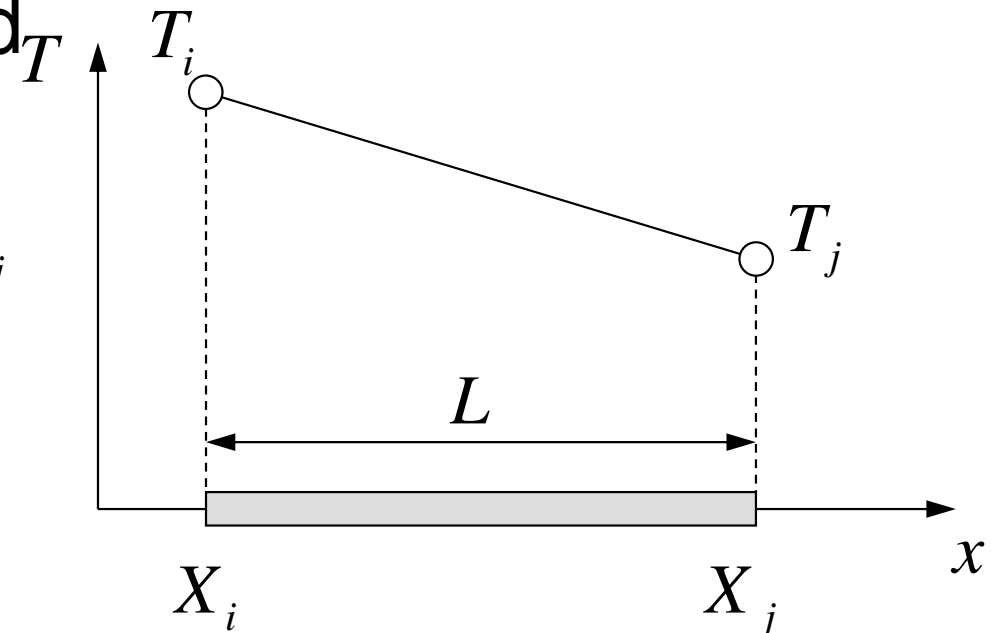
$$\alpha_1 = \frac{T_i X_j - T_j X_i}{L}, \quad \alpha_2 = \frac{T_j - T_i}{L}$$

- T can be written as follows, according to T_i and T_j :

$$T = \underbrace{\left(\frac{X_j - x}{L} \right)}_{N_i} T_i + \underbrace{\left(\frac{x - X_i}{L} \right)}_{N_j} T_j$$

N_i, N_j

Shape Function (形状関数) or
Interpolation Function (内挿関数), function of x (only)

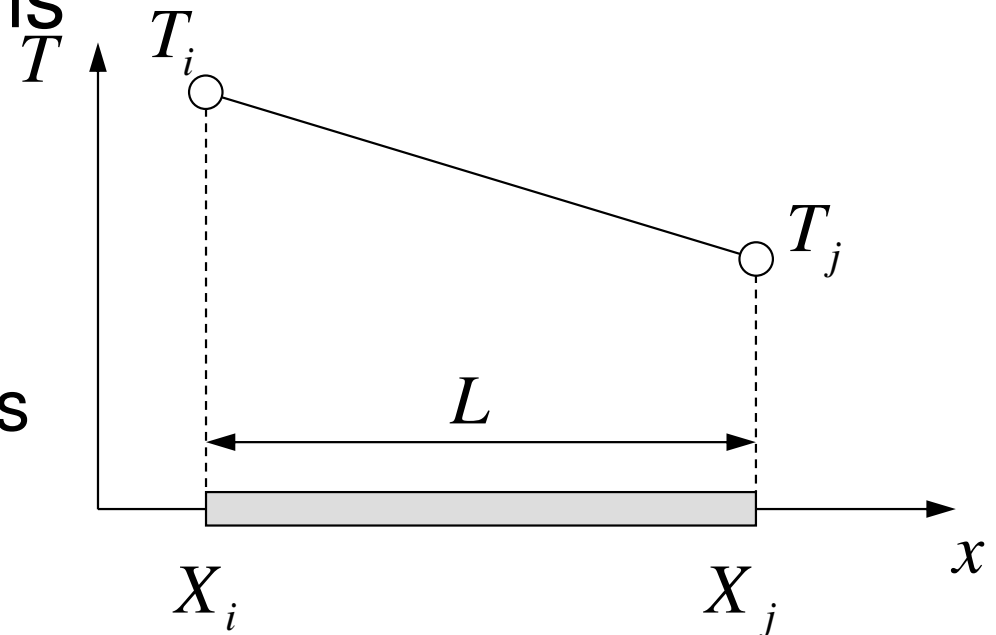


1D Linear Elem.: Shape Function (3/4)

- Number of Shape Functions = Number of Vertices of Each Element

- N_i : Function of Position
- A kind of Test/Trial Functions

$$N_i = \left(\frac{X_j - x}{L} \right), \quad N_j = \left(\frac{x - X_i}{L} \right)$$



- Linear combination of shape functions provides temperature “in” each element
 - Coef’s (unknowns): Temperature at each node

$$T = N_i T_i + N_j T_j \longleftrightarrow$$

$$T_M = \sum_{i=1}^M a_i \Psi_i$$

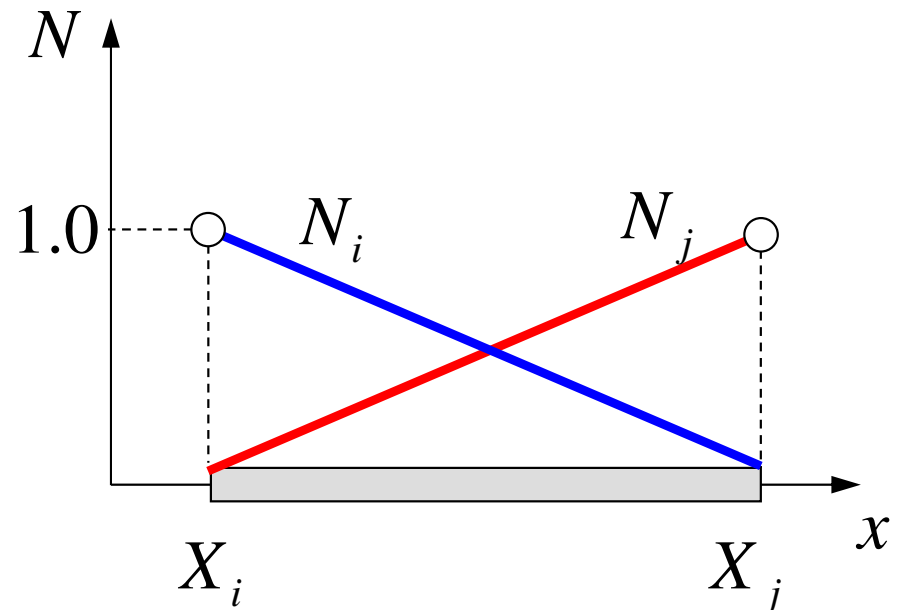
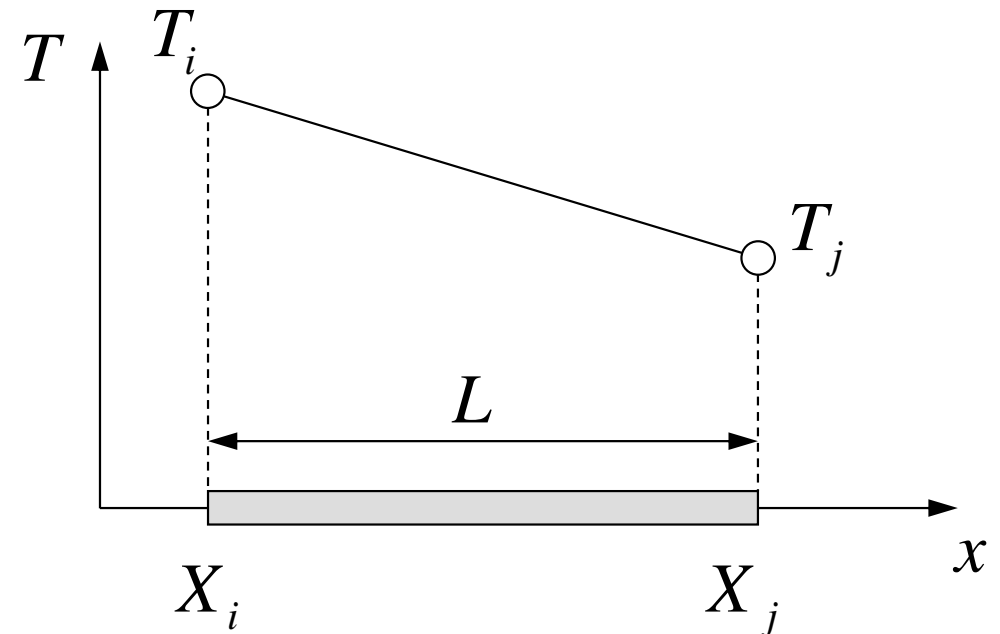
Ψ_i Trial/Test Function (known function of position, defined in domain and at boundary. “Basis” in linear algebra.

a_i Coefficients (unknown)

1D Linear Elem.: Shape Function (4/4)

- Value of N_i
 - =1 at one of the nodes in element
 - =0 on other nodes

$$N_i = \left(\frac{X_j - x}{L} \right), \quad N_j = \left(\frac{x - X_i}{L} \right)$$

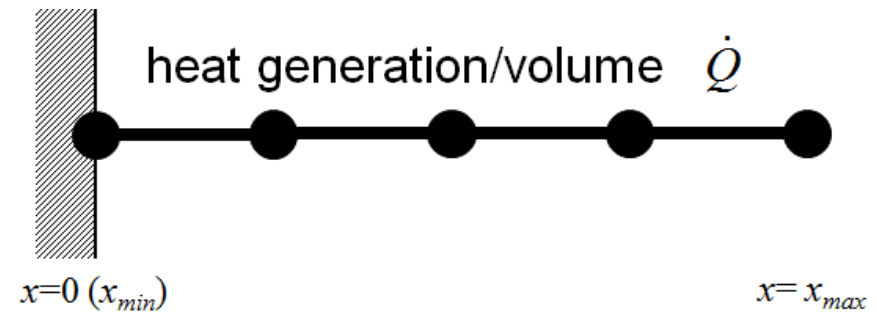


Galerkin Method (1/4)

- Governing Equation for 1D Steady State Heat Conduction Problems (Uniform λ):

$$\lambda \left(\frac{d^2 T}{dx^2} \right) + \dot{Q} = 0$$

$T = [N]\{\phi\}$ Distribution of temperature in each element (matrix form), ϕ : Temperature at each node



- Following integral equation is obtained at each element by Galerkin method, where $[N]$'s are also weighting functions:

$$\int_V [N]^T \left\{ \lambda \left(\frac{d^2 T}{dx^2} \right) + \dot{Q} \right\} dV = 0$$

Galerkin Method (2/4)

- Green's Theorem (1D)

$$\int_V A \left(\frac{d^2 B}{dx^2} \right) dV = \int_S A \frac{dB}{dx} dS - \int_V \left(\frac{dA}{dx} \frac{dB}{dx} \right) dV$$

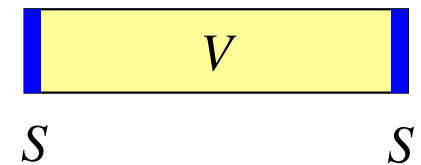
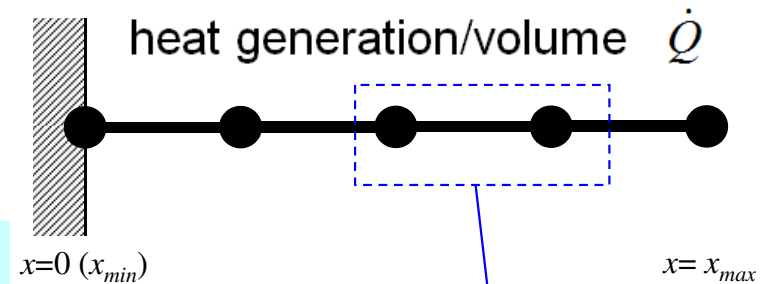
- Apply this to the 1st part of eqn with 2nd-order diff.:

$$\int_V \lambda [N]^T \left(\frac{d^2 T}{dx^2} \right) dV = - \int_V \lambda \left(\frac{d[N]^T}{dx} \frac{dT}{dx} \right) dV + \int_S \lambda [N]^T \frac{dT}{dx} dS$$

- Consider the following terms:

$$T = [N] \{ \phi \}, \quad \frac{dT}{dx} = \frac{d[N]}{dx} \{ \phi \} \quad \bar{q} = -\lambda \frac{dT}{dx}$$

: Heat flux at element surface [QL⁻²T⁻¹]

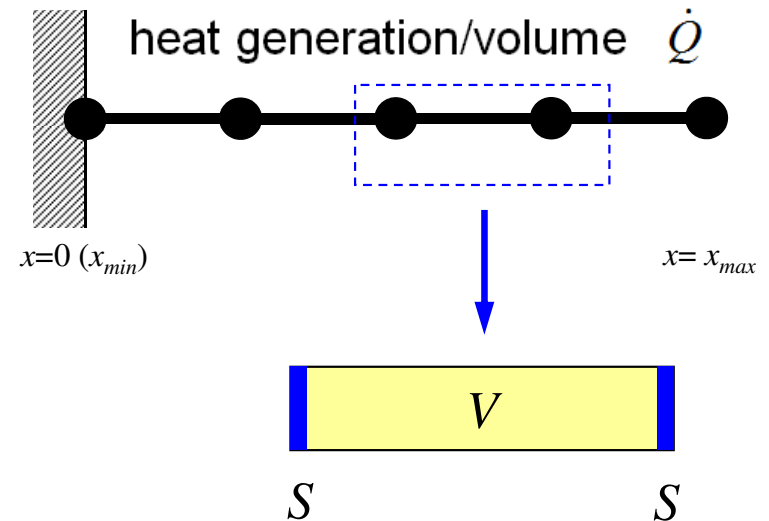


Galerkin Method (3/4)

- Finally, following eqn is obtained by considering heat generation term \dot{Q} :

$$-\int_V \lambda \left(\frac{d[N]^T}{dx} \frac{d[N]}{dx} \right) dV \cdot \{\phi\}$$

$$-\int_S \bar{q} [N]^T dS + \int_V \dot{Q} [N]^T dV = 0$$

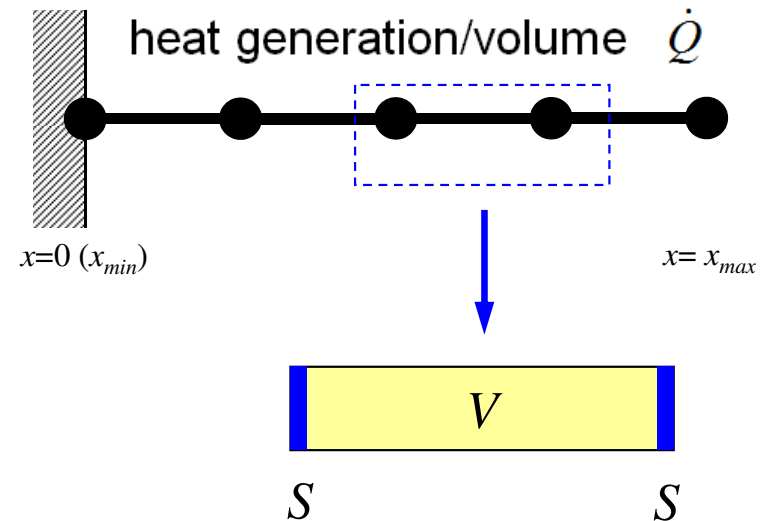


- This is called “weak form (弱形式)”. Original PDE consists of terms with 2nd-order diff., but this “weak form” only includes 1st-order diff by Green’s theorem.
 - Requirements for shape functions are “weaker” in “weak form”. Linear functions can describe effects of 2nd-order differentiation.

Galerkin Method (4/4)

$$-\int_V \lambda \left(\frac{d[N]^T}{dx} \frac{d[N]}{dx} \right) dV \cdot \{\phi\}$$

$$-\int_S \bar{q} [N]^T dS + \int_V \dot{Q} [N]^T dV = 0$$



- These terms coincide at element boundaries and disappear. Finally, only terms on the domain boundaries remain.

Weak Form and Boundary Conditions

- Value of dependent variable is defined (Dirichlet)

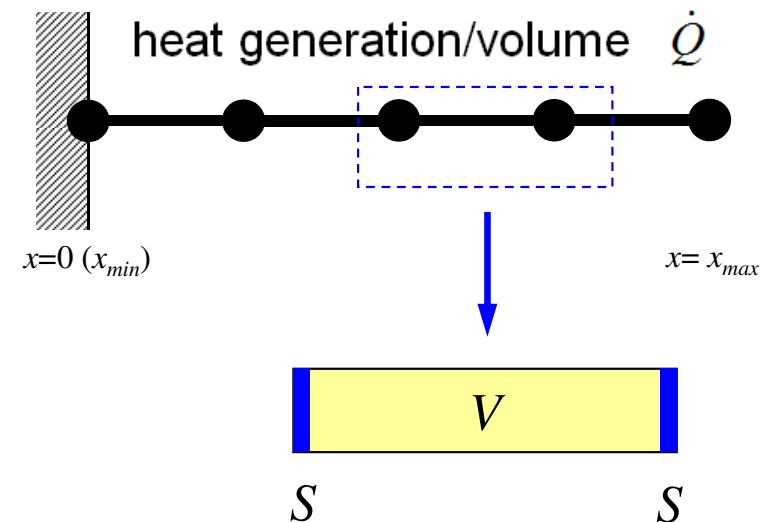
- Weighting Function = 0
- Principal B.C. (Boundary Condition) (第一種境界条件)
- Essential B.C. (基本境界条件)

- Derivatives of Unknowns (Neumann)

- Naturally satisfied in weak form
- Secondary B.C. (第二種境界条件)
- Natural B.C (自然境界条件)

- (Robin)

- Linear Combination of Dirichlet & Neumann
- Third Kind B.C. (第三種境界条件)
- Electromagnetics



$$-\int_V \lambda \left(\frac{d[N]^T}{dx} \frac{d[N]}{dx} \right) dV \cdot \{\phi\}$$

$$-\int_S \bar{q} [N]^T dS + \int_V \dot{Q} [N]^T dV = 0$$

$$\text{where } \bar{q} = -\lambda \frac{dT}{dx}$$

Weak Form with B.C.: on each elem.

$$[k]^{(e)} \{\phi\}^{(e)} = \{f\}^{(e)}$$

$$[k]^{(e)} = \int_V \lambda \left(\frac{d[N]^T}{dx} \frac{d[N]}{dx} \right) dV$$

$$\{f\}^{(e)} = \int_V \dot{Q} [N]^T dV - \int_S \bar{q} [N]^T dS$$

Integration over Each Element: $[k]$

$$N_i = \left(\frac{X_j - x}{L} \right), \quad N_j = \left(\frac{x - X_i}{L} \right)$$

$$\frac{dN_i}{dx} = \left(\frac{-1}{L} \right), \quad \frac{dN_j}{dx} = \left(\frac{1}{L} \right)$$

$$\int_V \lambda \left(\frac{d[N]^T}{dx} \frac{d[N]}{dx} \right) dV$$

$$= \lambda \int_0^L \begin{bmatrix} -1/L \\ 1/L \end{bmatrix} [-1/L, 1/L] A dx$$

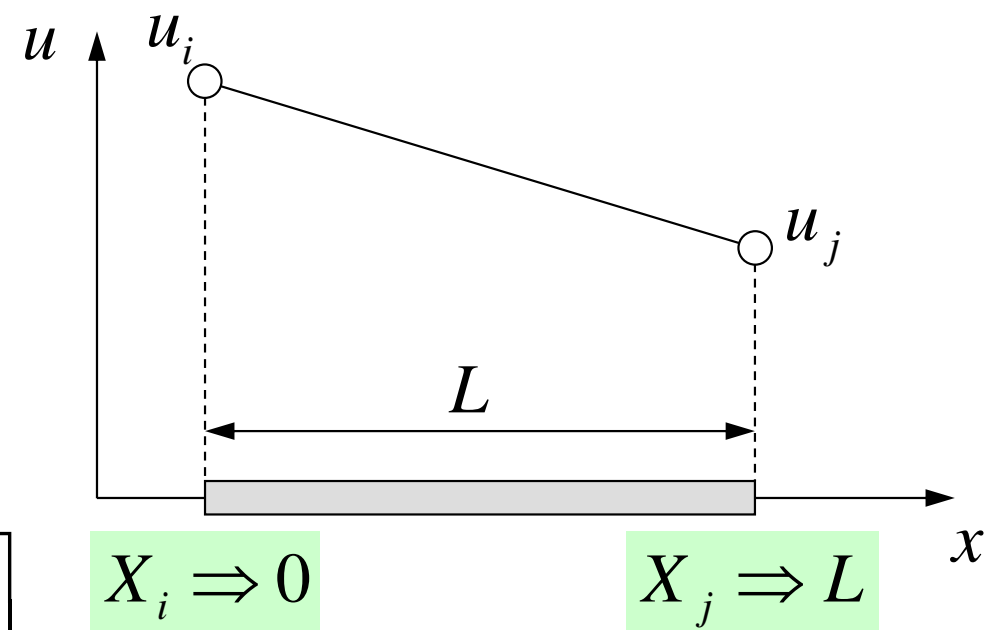
2x1 matrix

1x2 matrix

$$= \frac{\lambda A}{L^2} \int_0^L \begin{bmatrix} +1 & -1 \\ -1 & +1 \end{bmatrix} dx = \frac{\lambda A}{L} \begin{bmatrix} +1 & -1 \\ -1 & +1 \end{bmatrix}$$

A: Sectional Area

L: Length



$$N_i = \left(1 - \frac{x}{L} \right), \quad N_j = \left(\frac{x}{L} \right)$$

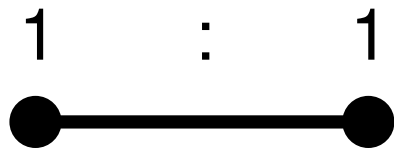
Integration over Each Element: $\{f\}$ (1/2)

$$N_i = \left(\frac{X_j - x}{L} \right), \quad N_j = \left(\frac{x - X_i}{L} \right) \quad \frac{dN_i}{dx} = \left(\frac{-1}{L} \right), \quad \frac{dN_j}{dx} = \left(\frac{1}{L} \right)$$

$$N_i = \left(1 - \frac{x}{L} \right), \quad N_j = \left(\frac{x}{L} \right)$$

$$\int_V \dot{Q} [N]^T dV = \dot{Q} A \int_0^L \begin{bmatrix} 1 - x/L \\ x/L \end{bmatrix} dx = \frac{\dot{Q} A L}{2} \begin{Bmatrix} 1 \\ 1 \end{Bmatrix}$$

Heat Generation
(Volume)



A : Sectional Area
 L : Length

Integration over Each Element: $\{f\}$ (2/2)

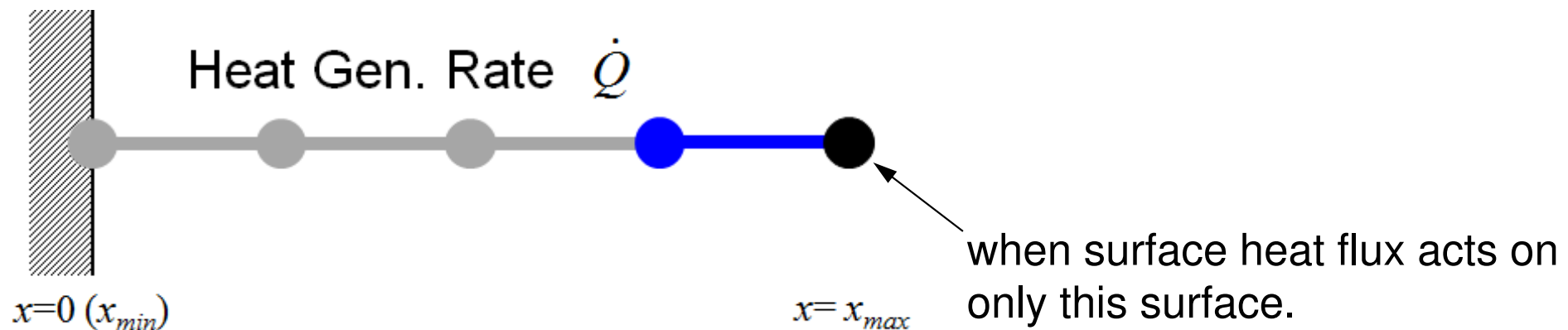
$$N_i = \left(\frac{X_j - x}{L} \right), \quad N_j = \left(\frac{x - X_i}{L} \right) \quad \frac{dN_i}{dx} = \left(\frac{-1}{L} \right), \quad \frac{dN_j}{dx} = \left(\frac{1}{L} \right)$$

$$\int_V \dot{Q} [N]^T dV = \dot{Q} A \int_0^L \begin{bmatrix} 1 - x/L \\ x/L \end{bmatrix} dx = \frac{\dot{Q} A L}{2} \begin{Bmatrix} 1 \\ 1 \end{Bmatrix}$$

Heat Generation
(Volume)

$$\int_S \bar{q} [N]^T dS = \bar{q} A \Big|_{x=L} = \bar{q} A \begin{Bmatrix} 0 \\ 1 \end{Bmatrix}, \quad \bar{q} = -\lambda \frac{dT}{dx}$$

Surface Heat Flux



Global Equations

- Accumulate Element Equations:

$$[k]^{(e)} \{\phi\}^{(e)} = \{f\}^{(e)} \quad \text{Element Matrix, Element Equations}$$



$$[K] \cdot \{\Phi\} = \{F\} \quad \text{Global Matrix, Global Equations}$$

$$[K] = \sum [k], \quad \{F\} = \sum \{f\}$$

$$\{\Phi\}: \text{global vector of } \{\phi\}$$

This is the final linear equations (global equations) to be solved.

Your PC

Download the Files

(download <http://nkl.cc.u-tokyo.ac.jp/files/fem-f.tar>)

Copy to ¥Cygwin¥home¥YourName Directory on Windows

1D Code for Steady-State Heat Conduction Problems

```
>$ cd  
>$ tar xvf fem-f.tar  
>$ cd fem-f/1d
```

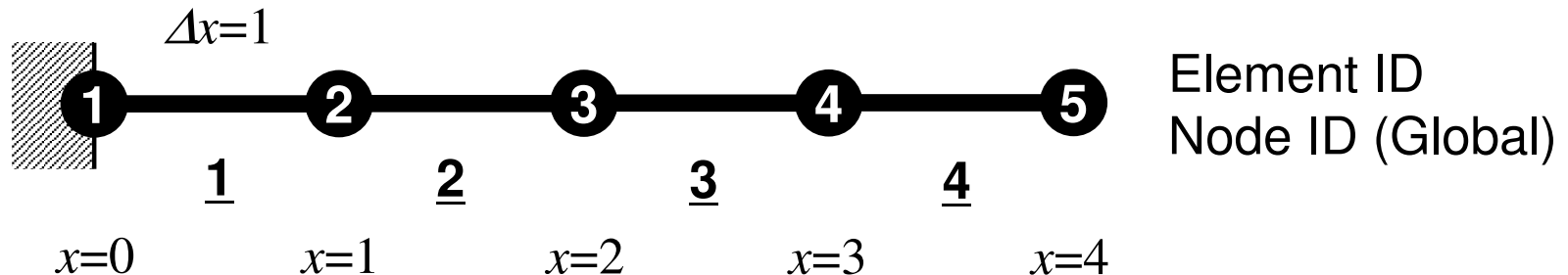
Compile & GO !

```
>$ cd
>$ cd fem-f/1d
>$ gfortran -O 1d.f
>$ ./a.exe
```

Control Data input.dat

```
4
1.0 1.0 1.0 1.0
100
1.e-8
```

NE (Number of Elements)
 Δx (Length of Each Elem.: L), Q , A , λ
 Number of MAX. Iterations for CG Solver
 Convergence Criteria for CG Solver



Results

```
>$ ./a.exe (or ./a.out)
```

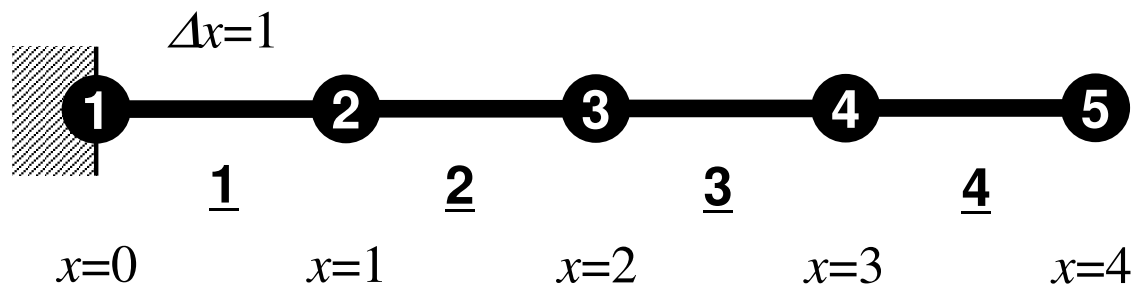
```
4 iters, RESID= 4.154074e-17
```

```
### TEMPERATURE
```

1	0.000000E+00	0.000000E+00
2	3.500000E+00	3.500000E+00
3	6.000000E+00	6.000000E+00
4	7.500000E+00	7.500000E+00
5	8.000000E+00	8.000000E+00

Computational

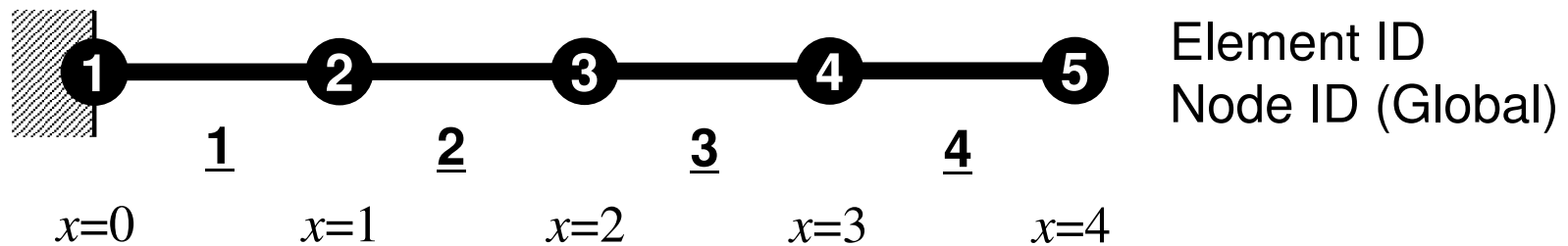
Analytical



Element ID
Node ID (Global)

Element Eqn's/Accumulation (1/3)

- 4 elements, 5 nodes



- $[k]$ and $\{f\}$ of Element-1:

$$[k]^{(1)} = \frac{\lambda A}{L} \begin{bmatrix} +1 & -1 \\ -1 & +1 \end{bmatrix} \quad \{f\}^{(1)} = \frac{\dot{Q}AL}{2} \begin{Bmatrix} 1 \\ 1 \end{Bmatrix}$$

- As for Element-4:

$$[k]^{(4)} = \frac{\lambda A}{L} \begin{bmatrix} +1 & -1 \\ -1 & +1 \end{bmatrix} \quad \{f\}^{(4)} = \frac{\dot{Q}AL}{2} \begin{Bmatrix} 1 \\ 1 \end{Bmatrix}$$

Element Eqn's/Accumulation (2/3)

- Element-by-Element Accumulation:

$$[K] = \sum_{e=1}^4 [k]^{(e)} =$$

$$\{F\} = \sum_{e=1}^4 \{f\}^{(e)} =$$

Element Eqn's/Accumulation (3/3)

- Relations to FDM

$$[k]^{(e)} = \frac{\lambda A}{L} \begin{bmatrix} +1 & -1 \\ -1 & +1 \end{bmatrix}$$

$$[K] = \sum_{e=1}^4 [k]^{(e)} = \left[\begin{array}{c|c|c|c} \begin{matrix} +1 & -1 \\ -1 & +1 \end{matrix} & & & \\ \hline & \begin{matrix} +1 & -1 \\ -1 & +1 \end{matrix} & & \\ \hline & & \begin{matrix} +1 & -1 \\ -1 & +1 \end{matrix} & \\ \hline & & & \begin{matrix} +1 & -1 \\ -1 & +1 \end{matrix} \end{array} \right] \times \frac{\lambda A}{L}$$

三重对角行列
Tri-Diagonal Matrix

$$= \begin{bmatrix} +1 & -1 & & & \\ -1 & +2 & -1 & & \\ & -1 & +2 & -1 & \\ & & -1 & +2 & -1 \\ & & & -1 & +1 \end{bmatrix} \times \frac{\lambda A}{L}$$

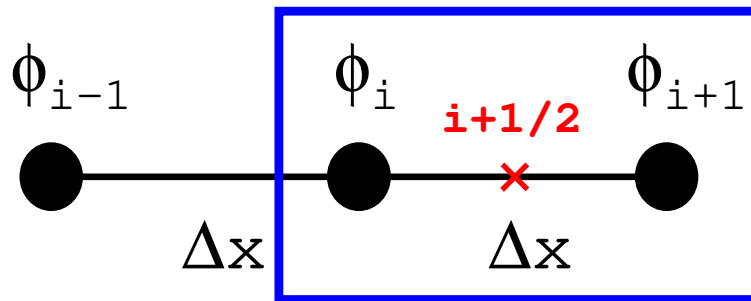
$$\begin{aligned} -\int_V \left(\frac{d^2 T}{dx^2} \right) dV &= -\int_V \left(\frac{T_{i+1} - 2T_i + T_{i-1}}{L^2} \right) dV \\ &= -\left(\frac{T_{i+1} - 2T_i + T_{i-1}}{L^2} \right) \cdot AL = -(T_{i+1} - 2T_i + T_{i-1}) \cdot \frac{A}{L} \end{aligned}$$

Something familiar ...

FEM: Coefficient Matrices are generally sparse
(many ZERO's)

2nd –Order Differentiation in FDM

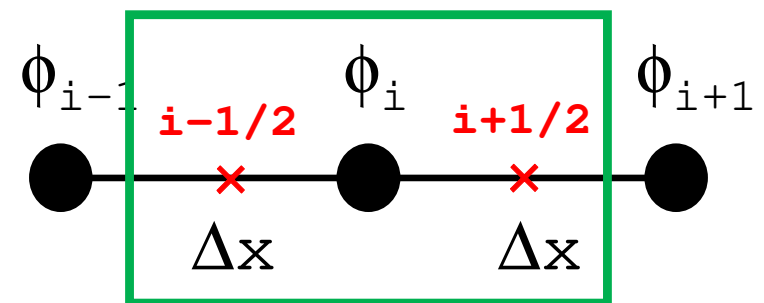
- Approximate Derivative at x (center of i and $i+1$)



$$\left(\frac{d\phi}{dx} \right)_{i+1/2} \approx \frac{\phi_{i+1} - \phi_i}{\Delta x}$$

$\Delta x \rightarrow 0$: Real Derivative

- 2nd-Order Diff. at i



$$\left(\frac{d^2\phi}{dx^2} \right)_i \approx \frac{\left(\frac{d\phi}{dx} \right)_{i+1/2} - \left(\frac{d\phi}{dx} \right)_{i-1/2}}{\Delta x} = \frac{\frac{\phi_{i+1} - \phi_i}{\Delta x} - \frac{\phi_i - \phi_{i-1}}{\Delta x}}{\Delta x} = \frac{\phi_{i+1} - 2\phi_i + \phi_{i-1}}{\Delta x^2}$$

Element-by-Element Operation

very flexible if each element has different material property, size, etc.

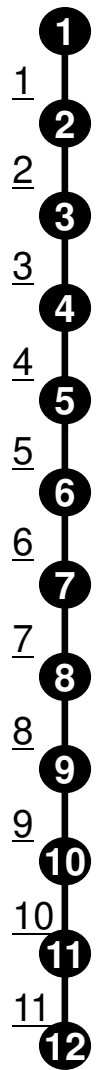
$$[k]^{(e)} = \frac{\lambda^{(e)} A^{(e)}}{L^{(e)}} \begin{bmatrix} +1 & -1 \\ -1 & +1 \end{bmatrix}$$

$$[K] = \sum_{e=1}^4 [k]^{(e)} =$$

$$\begin{matrix} \begin{matrix} +1 & -1 \\ -1 & +1 \end{matrix} & \times \frac{\lambda^{(1)} A^{(1)}}{L^{(1)}} & + & \begin{matrix} & & & \\ & +1 & -1 & \\ & -1 & +1 & \\ & & & \end{matrix} & \times \frac{\lambda^{(2)} A^{(2)}}{L^{(2)}} \\ \\ \\ \begin{matrix} & & & \\ & & +1 & -1 \\ & & -1 & +1 \\ & & & \end{matrix} & \times \frac{\lambda^{(3)} A^{(3)}}{L^{(3)}} & + & \begin{matrix} & & & \\ & & & \\ & & & \\ & & +1 & -1 \\ & & -1 & +1 \end{matrix} & \times \frac{\lambda^{(4)} A^{(4)}}{L^{(4)}} \end{matrix}$$

1D FEM: 12 nodes/11 elem's

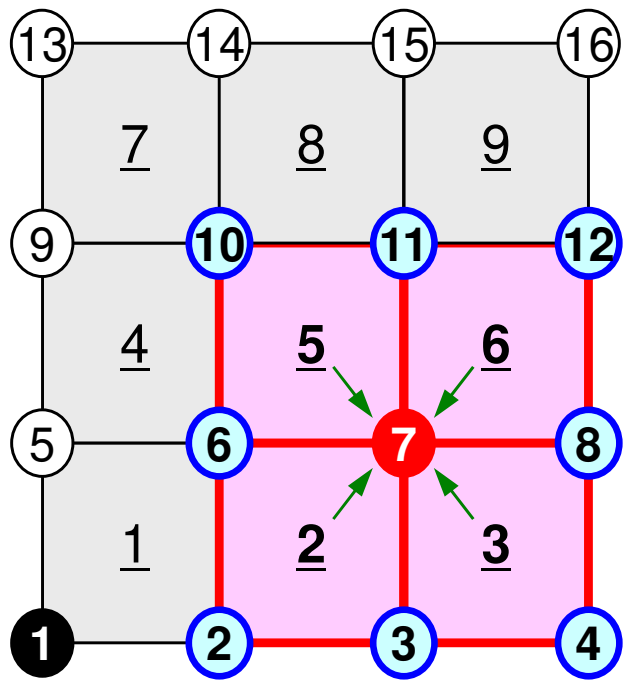
三重对角行列: Tri-Diagonal Matrix



1											
	2										
		3									
			4								
				5							
					6						
						7					
							8				
								9			
									10		
										11	
											12

1
2
3
4
5
6
7
8
9
10
11
12

Accumulation to Global/overall Matrix



$[K]\{\Phi\} = \{F\}$

D	X		X	X														Φ_1	F_1
X	D	X		X	X	X												Φ_2	F_2
	X	D	X		X	X	X											Φ_3	F_3
			X	D			X	X										Φ_4	F_4
X	X			D	X			X	X									Φ_5	F_5
X	X	X		X	D	X		X	X	X								Φ_6	F_6
X	X	X		X	D	X		X	X	X								Φ_7	F_7
			X	X			X	D			X	X						Φ_8	F_8
				X	X			D	X			X	X					Φ_9	F_9
				X	X	X		X	D	X		X	X	X				Φ_{10}	F_{10}
					X	X	X		X	D	X		X	X	X			Φ_{11}	F_{11}
						X	X			D			X	X				Φ_{12}	F_{12}
							X	X			D	X						Φ_{13}	F_{13}
								X	X	X		X	D	X				Φ_{14}	F_{14}
									X	X	X		X	D	X			Φ_{15}	F_{15}
											X	X			X	D		Φ_{16}	F_{16}

- 1D-code for Static Linear-Elastic Problems by Galerkin FEM
- Sparse Linear Solver
 - Conjugate Gradient Method
 - Preconditioning
- Storage of Sparse Matrices
- Program

Large-Scale Linear Equations in Scientific Applications

- Solving large-scale linear equations $\mathbf{Ax}=\mathbf{b}$ is the most important and **expensive** part of various types of scientific computing.
 - for both linear and nonlinear applications
- Various types of methods proposed & developed.
 - for dense and sparse matrices
 - classified into **direct** and **iterative** methods
- Dense Matrices: 密行列: Globally Coupled Problems
 - BEM, Spectral Methods, MO/MD (gas, liquid)
- Sparse Matrices: 疎行列: Locally Defined Problems
 - **FEM**, FDM, DEM, MD (solid), BEM w/FMM

Direct Method

直接法

- Gaussian Elimination/LU Factorization.
 - compute \mathbf{A}^{-1} directly (or equivalent operations)

Good

- Robust for wide range of applications.
- Good for both dense and sparse matrices

Bad

- More expensive than iterative methods (memory, CPU)
 - not scalable

What is Iterative Method ?

反復法

Linear Equations
連立一次方程式

$$\begin{pmatrix} a_{11} & a_{12} & \cdots & a_{1n} \\ a_{21} & a_{22} & \cdots & a_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ a_{n1} & a_{n2} & \cdots & a_{nn} \end{pmatrix} \begin{pmatrix} x_1 \\ x_2 \\ \vdots \\ x_n \end{pmatrix} = \begin{pmatrix} b_1 \\ b_2 \\ \vdots \\ b_n \end{pmatrix}$$

A **x** **b**

Initial Solution
初期解

$$\mathbf{x}^{(0)} = \begin{pmatrix} x_1^{(0)} \\ x_2^{(0)} \\ \vdots \\ x_n^{(0)} \end{pmatrix}$$

Starting from a initial vector $\mathbf{x}^{(0)}$, iterative method obtains the final converged solutions by iterations

$$\mathbf{X}^{(1)}, \mathbf{X}^{(2)}, \cdots$$

Iterative Method

反復法

- Stationary Method

- Only \mathbf{x} (solution vector) changes during iterations.
- SOR, Gauss-Seidel, Jacobi
- Generally slow, impractical

$$\mathbf{Ax} = \mathbf{b} \Rightarrow$$
$$\mathbf{x}^{(k+1)} = \mathbf{M}\mathbf{x}^{(k)} + \mathbf{N}\mathbf{b}$$

- Non-Stationary Method

- With restriction/optimization conditions
- Krylov-Subspace
- CG: Conjugate Gradient
- BiCGSTAB: Bi-Conjugate Gradient Stabilized
- GMRES: Generalized Minimal Residual

Iterative Method (cont.)

Good

- Less expensive than direct methods, especially in memory.
- Suitable for parallel and vector computing.

Bad

- Convergence strongly depends on problems, boundary conditions (condition number etc.)
- Preconditioning is required : Key Technology for Parallel FEM

Non-Stationary/Krylov Subspace Method (1/2)

非定常法・クリロフ部分空間法

$$\mathbf{Ax} = \mathbf{b} \Rightarrow \mathbf{x} = \mathbf{b} + (\mathbf{I} - \mathbf{A})\mathbf{x}$$

Compute $\mathbf{x}_0, \mathbf{x}_1, \mathbf{x}_2, \dots, \mathbf{x}_k$ by the following iterative procedures:

$$\begin{aligned}\mathbf{x}_k &= \mathbf{b} + (\mathbf{I} - \mathbf{A})\mathbf{x}_{k-1} \\ &= (\mathbf{b} - \mathbf{Ax}_{k-1}) + \mathbf{x}_{k-1}\end{aligned}$$

$$= \mathbf{r}_{k-1} + \mathbf{x}_{k-1} \quad \text{where } \mathbf{r}_k = \mathbf{b} - \mathbf{Ax}_k : \text{residual}$$



$$\mathbf{x}_k = \mathbf{x}_0 + \sum_{i=0}^{k-1} \mathbf{r}_i$$

$$\begin{aligned}\mathbf{r}_k &= \mathbf{b} - \mathbf{Ax}_k = \mathbf{b} - \mathbf{A}(\mathbf{r}_{k-1} + \mathbf{x}_{k-1}) \\ &= (\mathbf{b} - \mathbf{Ax}_{k-1}) - \mathbf{Ar}_{k-1} = \mathbf{r}_{k-1} - \mathbf{Ar}_{k-1} = (\mathbf{I} - \mathbf{A})\mathbf{r}_{k-1}\end{aligned}$$

Non-Stationary/Krylov Subspace Method (2/2)

非定常法・クリロフ部分空間法

$$\mathbf{x}_k = \mathbf{x}_0 + \sum_{i=0}^{k-1} \mathbf{r}_i = \mathbf{x}_0 + \mathbf{r}_0 + \sum_{i=0}^{k-2} (\mathbf{I} - \mathbf{A})\mathbf{r}_i = \mathbf{x}_0 + \mathbf{r}_0 + \sum_{i=1}^{k-1} (\mathbf{I} - \mathbf{A})^i \mathbf{r}_0$$

$$\mathbf{z}_k = \mathbf{r}_0 + \sum_{i=1}^{k-1} (\mathbf{I} - \mathbf{A})^i \mathbf{r}_0 = \left[\mathbf{I} + \sum_{i=1}^{k-1} (\mathbf{I} - \mathbf{A})^i \right] \mathbf{r}_0$$



\mathbf{z}_k is a vector which belongs to k^{th} Krylov Subspace (クリロフ部分空間), approximate solution vector \mathbf{x}_k is derived by the Krylov Subspace:

$$\left[\mathbf{r}_0, \mathbf{A}\mathbf{r}_0, \mathbf{A}^2\mathbf{r}_0, \dots, \mathbf{A}^{k-1}\mathbf{r}_0 \right]$$

Conjugate Gradient Method

共役勾配法

- Conjugate Gradient: CG
 - Most popular “non-stationary” iterative method
- for Symmetric Positive Definite (SPD) Matrices
 - 対称正定
 - $\{x\}^T[A]\{x\} > 0$ for arbitrary $\{x\}$
 - All of diagonal components, eigenvalues and leading principal minors > 0 (主小行列式・首座行列式)
 - Matrices of Galerkin-based FEM: heat conduction, Poisson, static linear elastic problems

- Algorithm

- “Steepest Descent Method”

- $\mathbf{x}^{(i)} = \mathbf{x}^{(i-1)} + \alpha_i \mathbf{p}^{(i)}$

- $\mathbf{x}^{(i)}$: solution, $\mathbf{p}^{(i)}$: search direction, α_i : coefficient

- Solution $\{x\}$ minimizes $\{x-y\}^T[A]\{x-y\}$, where $\{y\}$ is exact solution.

$$\det \begin{bmatrix} a_{11} & a_{12} & a_{13} & a_{14} & \cdots & a_{1n} \\ a_{21} & a_{22} & a_{23} & a_{24} & \cdots & a_{2n} \\ a_{31} & a_{32} & a_{33} & a_{34} & \cdots & a_{3n} \\ a_{41} & a_{42} & a_{43} & a_{44} & \cdots & a_{4n} \\ \vdots & \vdots & \vdots & \vdots & \ddots & \vdots \\ a_{n1} & a_{n2} & a_{n3} & a_{n4} & \cdots & a_{nn} \end{bmatrix}$$

Procedures of Conjugate Gradient

```

Compute  $r^{(0)} = b - [A]x^{(0)}$ 
for  $i = 1, 2, \dots$ 
   $z^{(i-1)} = r^{(i-1)}$ 
   $\rho_{i-1} = r^{(i-1)} \cdot z^{(i-1)}$ 
  if  $i = 1$ 
     $p^{(1)} = z^{(0)}$ 
  else
     $\beta_{i-1} = \rho_{i-1} / \rho_{i-2}$ 
     $p^{(i)} = z^{(i-1)} + \beta_{i-1} p^{(i-1)}$ 
  endif
   $q^{(i)} = [A]p^{(i)}$ 
   $\alpha_i = \rho_{i-1} / p^{(i)} \cdot q^{(i)}$ 
   $x^{(i)} = x^{(i-1)} + \alpha_i p^{(i)}$ 
   $r^{(i)} = r^{(i-1)} - \alpha_i q^{(i)}$ 
  check convergence  $|r|$ 
end

```

- Mat-Vec. Multiplication
- Dot Products
- DAXPY (Double Precision: $a\{X\} + \{Y\}$)

$x^{(i)}$: Vector

α_i : Scalar

Procedures of Conjugate Gradient

```

Compute  $r^{(0)} = b - [A]x^{(0)}$ 
for  $i = 1, 2, \dots$ 
   $z^{(i-1)} = r^{(i-1)}$ 
   $\rho_{i-1} = r^{(i-1)} z^{(i-1)}$ 
  if  $i = 1$ 
     $p^{(1)} = z^{(0)}$ 
  else
     $\beta_{i-1} = \rho_{i-1} / \rho_{i-2}$ 
     $p^{(i)} = z^{(i-1)} + \beta_{i-1} p^{(i-1)}$ 
  endif
   $q^{(i)} = [A]p^{(i)}$ 
   $\alpha_i = \rho_{i-1} / p^{(i)} q^{(i)}$ 
   $x^{(i)} = x^{(i-1)} + \alpha_i p^{(i)}$ 
   $r^{(i)} = r^{(i-1)} - \alpha_i q^{(i)}$ 
  check convergence  $|r|$ 
end

```

- Mat-Vec. Multiplication
- Dot Products
- DAXPY

$x^{(i)}$: Vector

α_i : Scalar

Procedures of Conjugate Gradient

```

Compute  $r^{(0)} = b - [A]x^{(0)}$ 
for  $i = 1, 2, \dots$ 
   $z^{(i-1)} = r^{(i-1)}$ 
   $\rho_{i-1} = r^{(i-1)} \cdot z^{(i-1)}$ 
  if  $i = 1$ 
     $p^{(1)} = z^{(0)}$ 
  else
     $\beta_{i-1} = \rho_{i-1} / \rho_{i-2}$ 
     $p^{(i)} = z^{(i-1)} + \beta_{i-1} p^{(i-1)}$ 
  endif
   $q^{(i)} = [A]p^{(i)}$ 
   $\alpha_i = \rho_{i-1} / (p^{(i)} \cdot q^{(i)})$ 
   $x^{(i)} = x^{(i-1)} + \alpha_i p^{(i)}$ 
   $r^{(i)} = r^{(i-1)} - \alpha_i q^{(i)}$ 
  check convergence  $|r|$ 
end

```

- Mat-Vec. Multiplication
- Dot Products
- DAXPY

$x^{(i)}$: Vector

α_i : Scalar

Procedures of Conjugate Gradient

```

Compute  $r^{(0)} = b - [A]x^{(0)}$ 
for  $i = 1, 2, \dots$ 
   $z^{(i-1)} = r^{(i-1)}$ 
   $\rho_{i-1} = r^{(i-1)} \cdot z^{(i-1)}$ 
  if  $i = 1$ 
     $p^{(1)} = z^{(0)}$ 
  else
     $\beta_{i-1} = \rho_{i-1} / \rho_{i-2}$ 
     $p^{(i)} = z^{(i-1)} + \beta_{i-1} p^{(i-1)}$ 
  endif
   $q^{(i)} = [A]p^{(i)}$ 
   $\alpha_i = \rho_{i-1} / p^{(i)} \cdot q^{(i)}$ 
   $x^{(i)} = x^{(i-1)} + \alpha_i p^{(i)}$ 
   $r^{(i)} = r^{(i-1)} - \alpha_i q^{(i)}$ 
  check convergence  $|r|$ 
end

```

- Mat-Vec. Multiplication
- Dot Products
- DAXPY
 - Double
 - $a\{x\} + \{y\}$

$x^{(i)}$: Vector

α_i : Scalar

Procedures of Conjugate Gradient

```

Compute  $r^{(0)} = b - [A]x^{(0)}$ 
for  $i = 1, 2, \dots$ 
     $z^{(i-1)} = r^{(i-1)}$ 
     $\rho_{i-1} = r^{(i-1)} z^{(i-1)}$ 
    if  $i = 1$ 
         $p^{(1)} = z^{(0)}$ 
    else
         $\beta_{i-1} = \rho_{i-1} / \rho_{i-2}$ 
         $p^{(i)} = z^{(i-1)} + \beta_{i-1} p^{(i-1)}$ 
    endif
     $q^{(i)} = [A]p^{(i)}$ 
     $\alpha_i = \rho_{i-1} / p^{(i)} q^{(i)}$ 
     $x^{(i)} = x^{(i-1)} + \alpha_i p^{(i)}$ 
     $r^{(i)} = r^{(i-1)} - \alpha_i q^{(i)}$ 
    check convergence  $|r|$ 
end

```

$x^{(i)}$: Vector

α_i : Scalar

Derivation of CG Algorithm (1/5)

Solution x minimizes the following equation if y is the exact solution ($Ay=b$)

$$(x - y)^T [A](x - y)$$

$$\begin{aligned} (x - y)^T [A](x - y) &= (x, Ax) - (y, Ax) - (x, Ay) + (y, Ay) \\ &= (x, Ax) - 2(x, Ay) + (y, Ay) = (x, Ax) - 2(x, b) + \underline{(y, b)} \quad \text{Const.} \end{aligned}$$

Therefore, the solution x minimizes the following $f(x)$:

$$f(x) = \frac{1}{2}(x, Ax) - (x, b)$$

$$f(x + h) = f(x) + (h, Ax - b) + \frac{1}{2}(h, Ah)$$

Arbitrary vector h

$$f(x) = \frac{1}{2}(x, Ax) - (x, b)$$

$$f(x+h) = f(x) + (h, Ax - b) + \frac{1}{2}(h, Ah) \quad \text{Arbitrary vector } h$$

$$\begin{aligned} f(x+h) &= \frac{1}{2}(x+h, A(x+h)) - (x+h, b) \\ &= \frac{1}{2}(x+h, Ax) + \frac{1}{2}(x+h, Ah) - (x, b) - (h, b) \\ &= \frac{1}{2}(x, Ax) + \frac{1}{2}(h, Ax) + \frac{1}{2}(x, Ah) + \frac{1}{2}(h, Ah) - (x, b) - (h, b) \\ &= \frac{1}{2}(x, Ax) - (x, b) + (h, Ax) - (h, b) + \frac{1}{2}(h, Ah) \\ &= f(x) + (h, Ax - b) + \frac{1}{2}(h, Ah) \end{aligned}$$

Derivation of CG Algorithm (2/5)

CG method minimizes $f(x)$ at each iteration. Assume that approximate solution: $x^{(0)}$, and search direction vector $p^{(k)}$ is defined at k -th iteration.

$$x^{(k+1)} = x^{(k)} + \alpha_k p^{(k)}$$

Minimization of $f(x^{(k+1)})$ is done as follows:

$$f(x^{(k)} + \alpha_k p^{(k)}) = \frac{1}{2} \alpha_k^2 (p^{(k)}, Ap^{(k)}) - \alpha_k (p^{(k)}, b - Ax^{(k)}) + f(x^{(k)})$$

$$\frac{\partial f(x^{(k)} + \alpha_k p^{(k)})}{\partial \alpha_k} = 0 \Rightarrow \alpha_k = \frac{(p^{(k)}, b - Ax^{(k)})}{(p^{(k)}, Ap^{(k)})} = \frac{(p^{(k)}, r^{(k)})}{(p^{(k)}, Ap^{(k)})} \quad \underline{\underline{(1)}}$$

$$r^{(k)} = b - Ax^{(k)} \text{ residual vector}$$

Derivation of CG Algorithm (3/5)

Residual vector at $(k+1)$ -th iteration:

$$r^{(k+1)} = r^{(k)} - \alpha_k Ap^{(k)} \quad \underline{(2)}$$

$$r^{(k+1)} = b - Ax^{(k+1)}, r^{(k)} = b - Ax^{(k)}$$

$$r^{(k+1)} - r^{(k)} = -Ax^{(k+1)} + Ax^{(k)} = -\alpha_k Ap^{(k)}$$

Search direction vector p is defined by the following recurrence formula:

$$p^{(k+1)} = r^{(k+1)} + \beta_k p^{(k)}, p^{(0)} = r^{(0)} \quad \underline{(3)}$$

It's lucky if we can get exact solution y at $(k+1)$ -th iteration:

$$y = x^{(k+1)} + \alpha_{k+1} p^{(k+1)}$$

Derivation of CG Algorithm (4/5)

BTW, we have the following (convenient) orthogonality relation:

$$\left(Ap^{(k)}, y - x^{(k+1)} \right) = 0$$

$$\begin{aligned} \left(Ap^{(k)}, y - x^{(k+1)} \right) &= \left(p^{(k)}, Ay - Ax^{(k+1)} \right) = \left(p^{(k)}, b - Ax^{(k+1)} \right) \\ &= \left(p^{(k)}, b - A[x^{(k)} + \alpha_k p^{(k)}] \right) = \left(p^{(k)}, b - Ax^{(k)} - \alpha_k Ap^{(k)} \right) \\ &= \left(p^{(k)}, r^{(k)} - \alpha_k Ap^{(k)} \right) = \left(p^{(k)}, r^{(k)} \right) - \alpha_k \left(p^{(k)}, Ap^{(k)} \right) = 0 \end{aligned}$$

$$\therefore \alpha_k = \frac{\left(p^{(k)}, r^{(k)} \right)}{\left(p^{(k)}, Ap^{(k)} \right)}$$

Thus, following relation is obtained:

$$\left(Ap^{(k)}, y - x^{(k+1)} \right) = \left(Ap^{(k)}, \alpha_{k+1} p^{(k+1)} \right) = 0 \Rightarrow \left(p^{(k+1)}, Ap^{(k)} \right) = 0$$

Derivation of CG Algorithm (5/5)

$$\begin{aligned} (p^{(k+1)}, Ap^{(k)}) &= (r^{(k+1)} + \beta_k p^{(k)}, Ap^{(k)}) = (r^{(k+1)}, Ap^{(k)}) + \beta_k (p^{(k)}, Ap^{(k)}) = 0 \\ \Rightarrow \beta_k &= \frac{-(r^{(k+1)}, Ap^{(k)})}{(p^{(k)}, Ap^{(k)})} \quad (4) \end{aligned}$$

$(p^{(k+1)}, Ap^{(k)}) = 0$ $p^{(k)}$ and $p^{(k+1)}$ are “conjugate (共役)” for matrix A

```

Compute  $p^{(0)} = r^{(0)} = b - [A]x^{(0)}$ 
for  $i = 1, 2, \dots$ 
  calc.  $\alpha_{i-1}$ 
   $x^{(i)} = x^{(i-1)} + \alpha_{i-1}p^{(i-1)}$ 
   $r^{(i)} = r^{(i-1)} - \alpha_{i-1}[A]p^{(i-1)}$ 

  check convergence  $|r|$ 
  (if not converged)
  calc.  $\beta_{i-1}$ 
   $p^{(i)} = r^{(i)} + \beta_{i-1}p^{(i-1)}$ 
end

```

$$\alpha_{i-1} = \frac{(p^{(i-1)}, r^{(i-1)})}{(p^{(i-1)}, Ap^{(i-1)})}$$

$$\beta_{i-1} = \frac{-(r^{(i)}, Ap^{(i-1)})}{(p^{(i-1)}, Ap^{(i-1)})}$$

Properties of CG Algorithm

Following “conjugate (共役)” relationship is obtained for arbitrary (i, j) :

$$\left(p^{(i)}, Ap^{(j)} \right) = 0 \quad (i \neq j)$$

Following relationships are also obtained for $p^{(k)}$ and $r^{(k)}$:

$$\left(r^{(i)}, r^{(j)} \right) = 0 \quad (i \neq j), \quad \left(p^{(k)}, r^{(k)} \right) = \left(r^{(k)}, r^{(k)} \right)$$

In N-dimensional space, only N sets of orthogonal and linearly independent residual vector $r^{(k)}$. This means CG method converges after N iterations if number of unknowns is N. Actually, round-off error sometimes affects convergence.

Proof (1/3)

Mathematical Induction

数学的帰納法

$$\begin{aligned} (r^{(i)}, r^{(j)}) &= 0 \quad (i \neq j) \\ (p^{(i)}, Ap^{(j)}) &= 0 \quad (i \neq j) \end{aligned}$$

$$(1) \quad \alpha_k = \frac{(p^{(k)}, r^{(k)})}{(p^{(k)}, Ap^{(k)})}$$

$$(2) \quad r^{(k+1)} = r^{(k)} - \alpha_k Ap^{(k)}$$

$$(3) \quad p^{(k+1)} = r^{(k+1)} + \beta_k p^{(k)}, \quad r^{(0)} = p^{(0)}$$

$$(4) \quad \beta_k = \frac{-(r^{(k+1)}, Ap^{(k)})}{(p^{(k)}, Ap^{(k)})}$$

Proof (2/3)

Mathematical Induction 数学的帰納法

$$\begin{aligned} (r^{(i)}, r^{(j)}) &= 0 \quad (i \neq j) \\ (p^{(i)}, Ap^{(j)}) &= 0 \quad (i \neq j) \end{aligned} \quad (*)$$

(*) is satisfied for $i \leq k, j \leq k$ where $i \neq j$

$$\begin{aligned} \text{if } i < k \quad (r^{(k+1)}, r^{(i)}) &= (r^{(i)}, r^{(k+1)}) \stackrel{(2)}{=} (r^{(i)}, r^{(k)} - \alpha_k Ap^{(k)}) \\ &\stackrel{(*)}{=} -\alpha_k (r^{(i)}, Ap^{(k)}) \stackrel{(3)}{=} -\alpha_k (p^{(i)} - \beta_{i-1} p^{(i-1)}, Ap^{(k)}) \\ &= -\alpha_k (p^{(i)}, Ap^{(k)}) + \alpha_k \beta_{i-1} (p^{(i-1)}, Ap^{(k)}) \stackrel{(*)}{=} 0 \end{aligned}$$

$$\begin{aligned} \text{if } i = k \quad (r^{(k+1)}, r^{(k)}) &\stackrel{(2)}{=} (r^{(k)}, r^{(k)}) - (r^{(k)}, \alpha_k Ap^{(k)}) \\ &\stackrel{(3)}{=} (r^{(k)}, r^{(k)}) - (p^{(k)} - \beta_{k-1} p^{(k-1)}, \alpha_k Ap^{(k)}) \\ \text{(1) } \alpha_k &= \frac{(p^{(k)}, r^{(k)})}{(p^{(k)}, Ap^{(k)})} \quad \stackrel{(*)}{=} (r^{(k)}, r^{(k)}) - \alpha_k (p^{(k)}, Ap^{(k)}) \stackrel{(1)}{=} (r^{(k)}, r^{(k)}) - (p^{(k)}, r^{(k)}) \\ \text{(2) } r^{(k+1)} &= r^{(k)} - \alpha_k Ap^{(k)} \quad \stackrel{(3)}{=} (r^{(k)}, r^{(k)}) - (\beta_{k-1} p^{(k-1)} + r^{(k)}, r^{(k)}) \\ \text{(3) } p^{(k+1)} &= r^{(k+1)} + \beta_k p^{(k)} \\ &= -\beta_{k-1} (p^{(k-1)}, r^{(k)}) \stackrel{(2)}{=} -\beta_{k-1} (p^{(k-1)}, r^{(k-1)} - \alpha_{k-1} Ap^{(k-1)}) \\ \text{(4) } \beta_k &= \frac{-(r^{(k+1)}, Ap^{(k)})}{(p^{(k)}, Ap^{(k)})} \\ &= -\beta_{k-1} \left\{ (p^{(k-1)}, r^{(k-1)}) - \alpha_{k-1} (p^{(k-1)}, Ap^{(k-1)}) \right\} \stackrel{(1)}{=} 0 \end{aligned}$$

Proof (3/3)

Mathematical Induction 数学的帰納法

$$\begin{aligned} (r^{(i)}, r^{(j)}) &= 0 \quad (i \neq j) \\ (p^{(i)}, Ap^{(j)}) &= 0 \quad (i \neq j) \end{aligned} \quad (*)$$

$(*)$ is satisfied for $i \leq k, j \leq k$ where $i \neq j$

$$\begin{aligned} \text{if } i < k \quad (p^{(k+1)}, Ap^{(i)}) &\stackrel{(3)}{=} (r^{(k+1)} + \beta_k p^{(k)}, Ap^{(i)}) \\ &\stackrel{(*)}{=} (r^{(k+1)}, Ap^{(i)}) \\ &\stackrel{(2)}{=} \frac{1}{\alpha_i} (r^{(k+1)}, r^{(i)} - r^{(i+1)}) = 0 \end{aligned}$$

$$\begin{aligned} \text{if } i = k \quad (p^{(k+1)}, Ap^{(k)}) &\stackrel{(3)}{=} (r^{(k+1)}, Ap^{(k)}) + \beta_k (p^{(k)}, Ap^{(k)}) \\ &\stackrel{(4)}{=} 0 \end{aligned}$$

$$(1) \alpha_k = \frac{(p^{(k)}, r^{(k)})}{(p^{(k)}, Ap^{(k)})}$$

$$(2) r^{(k+1)} = r^{(k)} - \alpha_k Ap^{(k)}$$

$$(3) p^{(k+1)} = r^{(k+1)} + \beta_k p^{(k)}$$

$$(4) \beta_k = \frac{-(r^{(k+1)}, Ap^{(k)})}{(p^{(k)}, Ap^{(k)})}$$

$$\left(r^{(k+1)}, r^{(k)} \right) = 0$$

$$\left(r^{(k+1)}, r^{(k)} \right) \stackrel{(2)}{=} \left(r^{(k)}, r^{(k)} \right) - \left(r^{(k)}, \alpha_k A p^{(k)} \right)$$

$$\stackrel{(3)}{=} \left(r^{(k)}, r^{(k)} \right) - \left(p^{(k)} - \beta_{k-1} p^{(k-1)}, \alpha_k A p^{(k)} \right)$$

$$\stackrel{(*)}{=} \left(r^{(k)}, r^{(k)} \right) - \alpha_k \left(p^{(k)}, A p^{(k)} \right) \stackrel{(1)}{=} \left(r^{(k)}, r^{(k)} \right) - \left(p^{(k)}, r^{(k)} \right) = 0$$

$$\therefore \left(r^{(k)}, r^{(k)} \right) = \left(p^{(k)}, r^{(k)} \right)$$

$$(1) \alpha_k = \frac{\left(p^{(k)}, r^{(k)} \right)}{\left(p^{(k)}, A p^{(k)} \right)}$$

$$(2) r^{(k+1)} = r^{(k)} - \alpha_k A p^{(k)}$$

$$(3) p^{(k+1)} = r^{(k+1)} + \beta_k p^{(k)}$$

$$(4) \beta_k = \frac{-\left(r^{(k+1)}, A p^{(k)} \right)}{\left(p^{(k)}, A p^{(k)} \right)}$$

$$\alpha_k, \beta_k$$

Usually, we use simpler definitions of α_k, β_k as follows:

$$\alpha_k = \frac{\left(p^{(k)}, b - Ax^{(k)} \right)}{\left(p^{(k)}, Ap^{(k)} \right)} = \frac{\left(p^{(k)}, r^{(k)} \right)}{\left(p^{(k)}, Ap^{(k)} \right)} = \frac{\left(r^{(k)}, r^{(k)} \right)}{\left(p^{(k)}, Ap^{(k)} \right)}$$

$$\because \left(p^{(k)}, r^{(k)} \right) = \left(r^{(k)}, r^{(k)} \right)$$

$$\beta_k = \frac{-\left(r^{(k+1)}, Ap^{(k)} \right)}{\left(p^{(k)}, Ap^{(k)} \right)} = \frac{\left(r^{(k+1)}, r^{(k+1)} \right)}{\left(r^{(k)}, r^{(k)} \right)}$$

$$\because \left(r^{(k+1)}, Ap^{(k)} \right) = \frac{\left(r^{(k+1)}, r^{(k)} - r^{(k+1)} \right)}{\alpha_k} = -\frac{\left(r^{(k+1)}, r^{(k+1)} \right)}{\alpha_k}$$

Procedures of Conjugate Gradient

```

Compute  $r^{(0)} = b - [A]x^{(0)}$ 
for  $i = 1, 2, \dots$ 
   $z^{(i-1)} = r^{(i-1)}$ 
   $\rho_{i-1} = r^{(i-1)} \cdot z^{(i-1)}$ 
  if  $i = 1$ 
     $p^{(1)} = z^{(0)}$ 
  else
     $\beta_{i-1} = \rho_{i-1} / \rho_{i-2}$ 
     $p^{(i)} = z^{(i-1)} + \beta_{i-1} p^{(i-1)}$ 
  endif
   $q^{(i)} = [A]p^{(i)}$ 
   $\alpha_i = \rho_{i-1} / p^{(i)} \cdot q^{(i)}$ 
   $x^{(i)} = x^{(i-1)} + \alpha_i p^{(i)}$ 
   $r^{(i)} = r^{(i-1)} - \alpha_i q^{(i)}$ 
  check convergence  $|r|$ 
end

```

$x^{(i)}$: Vector

α_i : Scalar

$$\beta_{i-1} = \frac{(r^{(i-1)}, r^{(i-1)})}{(r^{(i-2)}, r^{(i-2)})} \quad (= \rho_{i-1})$$

$$\alpha_i = \frac{(r^{(i-1)}, r^{(i-1)})}{(p^{(i)}, Ap^{(i)})} \quad (= \rho_{i-1})$$

Preconditioning for Iterative Solvers

- Convergence rate of iterative solvers strongly depends on the spectral properties (eigenvalue distribution) of the coefficient matrix \mathbf{A} .
 - Eigenvalue distribution is small, eigenvalues are close to 1
 - In “ill-conditioned” problems, “condition number” (ratio of max/min eigenvalue if \mathbf{A} is symmetric) is large (条件数).
- A preconditioner \mathbf{M} (whose properties are similar to those of \mathbf{A}) transforms the linear system into one with more favorable spectral properties (前处理)
 - \mathbf{M} transforms $\mathbf{Ax}=\mathbf{b}$ into $\mathbf{A}'\mathbf{x}=\mathbf{b}'$ where $\mathbf{A}'=\mathbf{M}^{-1}\mathbf{A}$, $\mathbf{b}'=\mathbf{M}^{-1}\mathbf{b}$
 - If $\mathbf{M}\sim\mathbf{A}$, $\mathbf{M}^{-1}\mathbf{A}$ is close to identity matrix.
 - If $\mathbf{M}^{-1}=\mathbf{A}^{-1}$, this is the best preconditioner (Gaussian Elim.)
 - Generally, $\mathbf{A}'\mathbf{x}'=\mathbf{b}'$ where $\mathbf{A}'=\mathbf{M}_L^{-1}\mathbf{A}\mathbf{M}_R^{-1}$, $\mathbf{b}'=\mathbf{M}_L^{-1}\mathbf{b}$, $\mathbf{x}'=\mathbf{M}_R\mathbf{x}$
 - $\mathbf{M}_L/\mathbf{M}_R$: Left/Right Preconditioning (左/右前处理)

Preconditioned CG Solver

```

Compute  $r^{(0)} = b - [A]x^{(0)}$ 
for  $i = 1, 2, \dots$ 
  solve  $[M]z^{(i-1)} = r^{(i-1)}$ 
   $\rho_{i-1} = r^{(i-1)} \cdot z^{(i-1)}$ 
  if  $i = 1$ 
     $p^{(1)} = z^{(0)}$ 
  else
     $\beta_{i-1} = \rho_{i-1} / \rho_{i-2}$ 
     $p^{(i)} = z^{(i-1)} + \beta_{i-1} p^{(i-1)}$ 
  endif
   $q^{(i)} = [A]p^{(i)}$ 
   $\alpha_i = \rho_{i-1} / p^{(i)} \cdot q^{(i)}$ 
   $x^{(i)} = x^{(i-1)} + \alpha_i p^{(i)}$ 
   $r^{(i)} = r^{(i-1)} - \alpha_i q^{(i)}$ 
  check convergence  $|r|$ 
end

```

$$[M] = [M_1][M_2]$$

$$[A']x' = b'$$

$$[A'] = [M_1]^{-1}[A][M_2]^{-1}$$

$$x' = [M_2]x, \quad b' = [M_1]^{-1}b$$

$$p' \Rightarrow [M_2]p, \quad r' \Rightarrow [M_1]^{-1}r$$

$$p'^{(i)} = r'^{(i-1)} + \beta'_{i-1} p'^{(i-1)}$$

$$[M_2]p^{(i)} = [M_1]^{-1}r^{(i-1)} + \beta'_{i-1} [M_2]p^{(i-1)}$$

$$p^{(i)} = [M_2]^{-1}[M_1]^{-1}r^{(i-1)} + \beta'_{i-1} p^{(i-1)}$$

$$p^{(i)} = [M]^{-1}r^{(i-1)} + \beta'_{i-1} p^{(i-1)}$$

$$\beta'_{i-1} = \frac{([M]^{-1}r^{(i-1)}, r^{(i-1)})}{([M]^{-1}r^{(i-2)}, r^{(i-2)})}$$

$$\alpha'_{i-1} = \frac{([M]^{-1}r^{(i-1)}, r^{(i-1)})}{(p^{(i-1)}, [A]p^{(i-1)})}$$

In CG method, preconditioner usually satisfies $[M_2] = [M_1]^T$, such as Incomplete Cholesky/Incomplete Modified Cholesky Factorizations. In this problem, let us define $[M_1]$ and $[M_2]$ as follows:

$$[M_1] = [X]^T, [M_2] = [X], [M] = [M_1][M_2]$$

$$[A']x' = b'$$

$$[A'] = [M_1]^{-1}[A][M_2]^{-1} = [[X]^T]^{-1}[A][X]^{-1} = [X]^{-T}[A][X]^{-1}$$

$$x' = [X]x, \quad b' = [X]^{-T}b, \quad r' = [X]^{-T}r$$

$$\begin{aligned} \alpha'_{i-1} &= \frac{\left(r^{(i-1)}, r^{(i-1)} \right)}{\left(p^{(i-1)}, A' p^{(i-1)} \right)} = \frac{\left([X]^{-T} r^{(i-1)}, [X]^{-T} r^{(i-1)} \right)}{\left([X] p^{(i-1)}, [X]^{-T} [A][X]^{-1} [X] p^{(i-1)} \right)} \\ &= \frac{\left(\left([X]^{-T} r^{(i-1)} \right)^T, [X]^{-T} r^{(i-1)} \right)}{\left(\left([X]^{-T} r^{(i-1)} \right)^T, [X]^{-T} r^{(i-1)} \right)} = \frac{\left(\left(r^{(i-1)} \right)^T [X]^{-1}, [X^T]^{-1} r^{(i-1)} \right)}{\left(\left(r^{(i-1)} \right)^T [X]^{-1}, [X^T]^{-1} r^{(i-1)} \right)} \\ &= \frac{\left(\left([X] p^{(i-1)} \right)^T, [X]^{-T} [A] p^{(i-1)} \right)}{\left(\left(p^{(i-1)} \right)^T [X]^T, [X]^{-T} [A] p^{(i-1)} \right)} \\ &= \frac{\left(r^{(i-1)}, [[X^T][X]]^{-1} r^{(i-1)} \right)}{\left(r^{(i-1)}, [M]^{-1} r^{(i-1)} \right)} = \frac{\left(r^{(i-1)}, z^{(i-1)} \right)}{\left(r^{(i-1)}, [A] p^{(i-1)} \right)} \\ &= \frac{\left(p^{(i-1)}, [A] p^{(i-1)} \right)}{\left(p^{(i-1)}, [A] p^{(i-1)} \right)} = \frac{\left(p^{(i-1)}, [A] p^{(i-1)} \right)}{\left(p^{(i-1)}, [A] p^{(i-1)} \right)} \end{aligned}$$

$$\begin{aligned}
\beta'_{i-1} &= \frac{\left(r^{(i-1)}, r^{(i-1)} \right)}{\left(r^{(i-2)}, r^{(i-2)} \right)} = \frac{\left([\mathbf{X}]^{-T} r^{(i-1)}, [\mathbf{X}]^{-T} r^{(i-1)} \right)}{\left([\mathbf{X}]^{-T} r^{(i-2)}, [\mathbf{X}]^{-T} r^{(i-2)} \right)} \\
&= \frac{\left(\left([\mathbf{X}]^{-T} r^{(i-1)} \right)^T, [\mathbf{X}]^{-T} r^{(i-1)} \right)}{\left(\left([\mathbf{X}]^{-T} r^{(i-2)} \right)^T, [\mathbf{X}]^{-T} r^{(i-2)} \right)} = \frac{\left(\left(r^{(i-1)} \right)^T [\mathbf{X}]^{-1}, [\mathbf{X}^T]^{-1} r^{(i-1)} \right)}{\left(\left(r^{(i-2)} \right)^T [\mathbf{X}]^{-1}, [\mathbf{X}^T]^{-1} r^{(i-2)} \right)} \\
&= \frac{\left(r^{(i-1)}, \left[[\mathbf{X}^T] [\mathbf{X}] \right]^{-1} r^{(i-1)} \right)}{\left(r^{(i-2)}, \left[[\mathbf{X}^T] [\mathbf{X}] \right]^{-1} r^{(i-2)} \right)} = \frac{\left(r^{(i-1)}, [\mathbf{M}]^{-1} r^{(i-1)} \right)}{\left(r^{(i-2)}, [\mathbf{M}]^{-1} r^{(i-2)} \right)} = \frac{\left(r^{(i-1)}, \mathcal{Z}^{(i-1)} \right)}{\left(r^{(i-2)}, \mathcal{Z}^{(i-2)} \right)}
\end{aligned}$$

Preconditioning in PCG

```

Compute  $r^{(0)} = b - [A]x^{(0)}$ 
for  $i = 1, 2, \dots$ 
  solve  $[M]z^{(i-1)} = r^{(i-1)}$ 
   $\rho_{i-1} = r^{(i-1)} \cdot z^{(i-1)}$ 
  if  $i = 1$ 
     $p^{(1)} = z^{(0)}$ 
  else
     $\beta_{i-1} = \rho_{i-1} / \rho_{i-2}$ 
     $p^{(i)} = z^{(i-1)} + \beta_{i-1} p^{(i-1)}$ 
  endif
   $q^{(i)} = [A]p^{(i)}$ 
   $\alpha_i = \rho_{i-1} / p^{(i)} \cdot q^{(i)}$ 
   $x^{(i)} = x^{(i-1)} + \alpha_i p^{(i)}$ 
   $r^{(i)} = r^{(i-1)} - \alpha_i q^{(i)}$ 
  check convergence  $|r|$ 
end

```

Solving the following equation:

$$\{z\} = [M]^{-1} \{r\}$$

“Approximate Inverse Matrix”

$$[M]^{-1} \approx [A]^{-1}, \quad [M] \approx [A]$$

Ultimate Preconditioning:

Inverse Matrix

$$[M]^{-1} = [A]^{-1}, \quad [M] = [A]$$

Diagonal Scaling: Simple but weak

$$[M]^{-1} = [D]^{-1}, \quad [M] = [D]$$

ILU(0), IC(0)

- Widely used Preconditioners for Sparse Matrices
 - Incomplete LU Factorization (不完全LU分解)
 - Incomplete Cholesky Factorization (for Symmetric Matrices) (不完全コレスキー分解)
- Incomplete Direct Method
 - Even if original matrix is sparse, inverse matrix is not necessarily sparse.
 - fill-in
 - ILU(0)/IC(0) without fill-in have same non-zero pattern with the original (sparse) matrices

Diagonal Scaling, Point-Jacobi

$$[M] = \begin{bmatrix} D_1 & 0 & \dots & 0 & 0 \\ 0 & D_2 & & 0 & 0 \\ \dots & & \dots & & \dots \\ 0 & 0 & & D_{N-1} & 0 \\ 0 & 0 & \dots & 0 & D_N \end{bmatrix}$$

- **solve** $[M] \mathbf{z}^{(i-1)} = \mathbf{r}^{(i-1)}$ is very easy.
- Provides fast convergence for simple problems.
- 1d.f, 1d.c

- 1D-code for Static Linear-Elastic Problems by Galerkin FEM
- Sparse Linear Solver
 - Conjugate Gradient Method
 - Preconditioning
- **Storage of Sparse Matrices**
- Program

Variables/Arrays in 1d.f, 1d.c related to coefficient matrix

name	type	size	description
N	I	–	# Unknowns
NPLU	I	–	# Non-Zero Off-Diagonal Components
Diag (:)	R	N	Diagonal Components
PHI (:)	R	N	Unknown Vector
Rhs (:)	R	N	RHS Vector
Index (:)	I	0:N N+1	Off-Diagonal Components (Number of Non-Zero Off-Diagonals at Each ROW)
Item (:)	I	NPLU	Off-Diagonal Components (Corresponding Column ID)
AMat (:)	R	NPLU	Off-Diagonal Components (Value)

Only non-zero components are stored according to “Compressed Row Storage”.

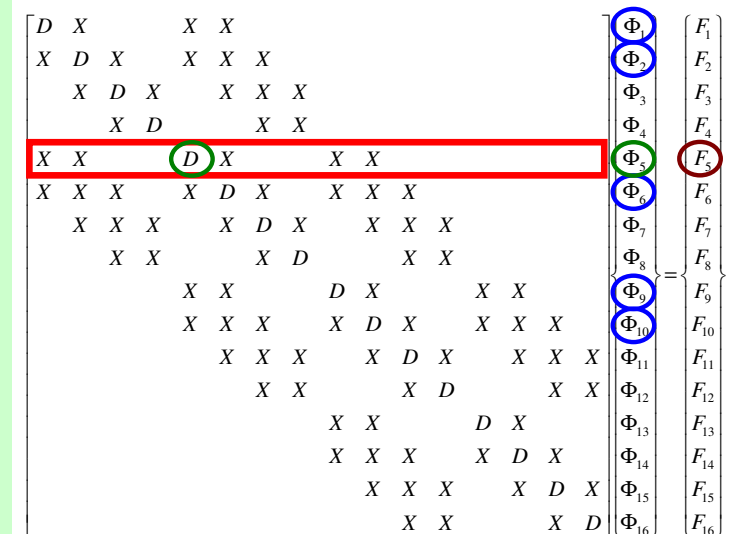
Mat-Vec. Multiplication for Sparse Matrix

Compressed Row Storage (CRS)

Diag (i) Diagonal Components (REAL, i=1~N)
Index (i) Number of Non-Zero Off-Diagonals at Each ROW (INT, i=0~N)
Item (k) Off-Diagonal Components (Corresponding Column ID)
 (INT, k=1, index(N))
AMat (k) Off-Diagonal Components (Value)
 (REAL, k=1, index(N))

$$\{Y\} = [A] \{X\}$$

```
do i= 1, N
  Y(i)= Diag(i)*X(i)
  do k= Index(i-1)+1, Index(i)
    Y(i)= Y(i) + Amat(k)*X(Item(k))
  enddo
enddo
```



Mat-Vec. Multiplication for Dense Matrix

Very Easy, Straightforward

$$\begin{bmatrix} a_{11} & a_{12} & \cdots & a_{1,N-1} & a_{1,N} \\ a_{21} & a_{22} & & a_{2,N-1} & a_{2,N} \\ \cdots & & \cdots & & \cdots \\ a_{N-1,1} & a_{N-1,2} & & a_{N-1,N-1} & a_{N-1,N} \\ a_{N,1} & a_{N,2} & \cdots & a_{N,N-1} & a_{N,N} \end{bmatrix} \begin{Bmatrix} x_1 \\ x_2 \\ \vdots \\ x_{N-1} \\ x_N \end{Bmatrix} = \begin{Bmatrix} y_1 \\ y_2 \\ \vdots \\ y_{N-1} \\ y_N \end{Bmatrix}$$

$$\{Y\} = [A] \{X\}$$

```

do j= 1, N
  Y(j) = 0. d0
  do i= 1, N
    Y(j) = Y(j) + A(i, j)*X(i)
  enddo
enddo

```


Compressed Row Storage (CRS)

	①	②	③	④	⑤	⑥	⑦	⑧
①	1.1	2.4	0	0	3.2	0	0	0
②	4.3	3.6	0	2.5	0	3.7	0	9.1
③	0	0	5.7	0	1.5	0	3.1	0
④	0	4.1	0	9.8	2.5	2.7	0	0
⑤	3.1	9.5	10.4	0	11.5	0	4.3	0
⑥	0	0	6.5	0	0	12.4	9.5	0
⑦	0	6.4	2.5	0	0	1.4	23.1	13.1
⑧	0	9.5	1.3	9.6	0	3.1	0	51.3

Compressed Row Storage (CRS): Fortran

	①	②	③	④	⑤	⑥	⑦	⑧
①	1.1 ①	2.4 ②			3.2 ⑤			
②	4.3 ①	3.6 ②		2.5 ④		3.7 ⑥		9.1 ⑧
③			5.7 ③		1.5 ⑤		3.1 ⑦	
④		4.1 ②		9.8 ④	2.5 ⑤	2.7 ⑥		
⑤	3.1 ①	9.5 ②	10.4 ③		11.5 ⑤		4.3 ⑦	
⑥			6.5 ③			12.4 ⑥	9.5 ⑦	
⑦		6.4 ②	2.5 ③			1.4 ⑥	23.1 ⑦	13.1 ⑧
⑧		9.5 ②	1.3 ③	9.6 ④		3.1 ⑥		51.3 ⑧

N= 8

対角成分

$$\text{Diag}(1) = 1.1$$

$$\text{Diag}(2) = 3.6$$

$$\text{Diag}(3) = 5.7$$

$$\text{Diag}(4) = 9.8$$

$$\text{Diag}(5) = 11.5$$

$$\text{Diag}(6) = 12.4$$

$$\text{Diag}(7) = 23.1$$

$$\text{Diag}(8) = 51.3$$

Compressed Row Storage (CRS)

	①	②	③	④	⑤	⑥	⑦	⑧
①	1.1 ①		2.4 ②			3.2 ⑤		
②	3.6 ②	4.3 ①			2.5 ④		3.7 ⑥	9.1 ⑧
③	5.7 ③					1.5 ⑤		3.1 ⑦
④	9.8 ④		4.1 ②			2.5 ⑤	2.7 ⑥	
⑤	11.5 ⑤	3.1 ①	9.5 ②	10.4 ③				4.3 ⑦
⑥	12.4 ⑥			6.5 ③				9.5 ⑦
⑦	23.1 ⑦		6.4 ②	2.5 ③			1.4 ⑥	13.1 ⑧
⑧	51.3 ⑧		9.5 ②	1.3 ③	9.6 ④		3.1 ⑥	

Compressed Row Storage (CRS)

		# Non-Zero Off-Diag.						
1	<table border="1"> <tr> <td>1.1 ①</td> <td>2.4 ②</td> <td>3.2 ⑤</td> <td></td> <td></td> </tr> </table>	1.1 ①	2.4 ②	3.2 ⑤			2	$\text{index}(0) = 0$
1.1 ①	2.4 ②	3.2 ⑤						
2	<table border="1"> <tr> <td>3.6 ②</td> <td>4.3 ①</td> <td>2.5 ④</td> <td>3.7 ⑥</td> <td>9.1 ⑧</td> </tr> </table>	3.6 ②	4.3 ①	2.5 ④	3.7 ⑥	9.1 ⑧	4	$\text{index}(1) = 2$
3.6 ②	4.3 ①	2.5 ④	3.7 ⑥	9.1 ⑧				
3	<table border="1"> <tr> <td>5.7 ③</td> <td>1.5 ⑤</td> <td>3.1 ⑦</td> <td></td> <td></td> </tr> </table>	5.7 ③	1.5 ⑤	3.1 ⑦			2	$\text{index}(2) = 6$
5.7 ③	1.5 ⑤	3.1 ⑦						
4	<table border="1"> <tr> <td>9.8 ④</td> <td>4.1 ②</td> <td>2.5 ⑤</td> <td>2.7 ⑥</td> <td></td> </tr> </table>	9.8 ④	4.1 ②	2.5 ⑤	2.7 ⑥		3	$\text{index}(3) = 8$
9.8 ④	4.1 ②	2.5 ⑤	2.7 ⑥					
5	<table border="1"> <tr> <td>11.5 ⑤</td> <td>3.1 ①</td> <td>9.5 ②</td> <td>10.4 ③</td> <td>4.3 ⑦</td> </tr> </table>	11.5 ⑤	3.1 ①	9.5 ②	10.4 ③	4.3 ⑦	4	$\text{index}(4) = 11$
11.5 ⑤	3.1 ①	9.5 ②	10.4 ③	4.3 ⑦				
6	<table border="1"> <tr> <td>12.4 ⑥</td> <td>6.5 ③</td> <td>9.5 ⑦</td> <td></td> <td></td> </tr> </table>	12.4 ⑥	6.5 ③	9.5 ⑦			2	$\text{index}(5) = 15$
12.4 ⑥	6.5 ③	9.5 ⑦						
7	<table border="1"> <tr> <td>23.1 ⑦</td> <td>6.4 ②</td> <td>2.5 ③</td> <td>1.4 ⑥</td> <td>13.1 ⑧</td> </tr> </table>	23.1 ⑦	6.4 ②	2.5 ③	1.4 ⑥	13.1 ⑧	4	$\text{index}(6) = 17$
23.1 ⑦	6.4 ②	2.5 ③	1.4 ⑥	13.1 ⑧				
8	<table border="1"> <tr> <td>51.3 ⑧</td> <td>9.5 ②</td> <td>1.3 ③</td> <td>9.6 ④</td> <td>3.1 ⑥</td> </tr> </table>	51.3 ⑧	9.5 ②	1.3 ③	9.6 ④	3.1 ⑥	4	$\text{index}(7) = 21$
51.3 ⑧	9.5 ②	1.3 ③	9.6 ④	3.1 ⑥				
					4	$\text{index}(8) = 25$		

NPLU= 25
(=index(N))

$\text{index}(i-1) + 1^{\text{th}} \sim \text{index}(i)^{\text{th}}$
Non-Zero Off-Diag. Components corresponding to i -th row

Compressed Row Storage (CRS)

		# Non-Zero Off-Diag.					
1	1.1 ①	2.4 ②,1	3.2 ⑤,2	2	$\text{index}(0) = 0$		
2	3.6 ②	4.3 ①,3	2.5 ④,4	3.7 ⑥,5	9.1 ⑧,6	4	$\text{index}(1) = 2$
3	5.7 ③	1.5 ⑤,7	3.1 ⑦,8			2	<u>$\text{index}(2) = 6$</u>
4	9.8 ④	4.1 ②,9	2.5 ⑤,10	2.7 ⑥,11		3	<u>$\text{index}(3) = 8$</u>
5	11.5 ⑤	3.1 ①,12	9.5 ②,13	10.4 ③,14	4.3 ⑦,15	4	<u>$\text{index}(4) = 11$</u>
6	12.4 ⑥	6.5 ③,16	9.5 ⑦,17			2	$\text{index}(5) = 15$
7	23.1 ⑦	6.4 ②,18	2.5 ③,19	1.4 ⑥,20	13.1 ⑧,21	4	$\text{index}(6) = 17$
8	51.3 ⑧	9.5 ②,22	1.3 ③,23	9.6 ④,24	3.1 ⑥,25	4	$\text{index}(7) = 21$
							$\text{index}(8) = 25$

NPLU= 25
(=index(N))

$\text{index}(i-1) + 1^{\text{th}} \sim \text{index}(i)^{\text{th}}$
Non-Zero Off-Diag. Components corresponding to i -th row

Compressed Row Storage (CRS)

1	1.1 ①	2.4 ②,1	3.2 ⑤,2		
2	3.6 ②	4.3 ①,3	2.5 ④,4	3.7 ⑥,5	9.1 ⑧,6
3	5.7 ③	1.5 ⑤,7	3.1 ⑦,8		
4	9.8 ④	4.1 ②,9	2.5 ⑤,10	2.7 ⑥,11	
5	11.5 ⑤	3.1 ①,12	9.5 ②,13	10.4 ③,14	4.3 ⑦,15
6	12.4 ⑥	6.5 ③,16	9.5 ⑦,17		
7	23.1 ⑦	6.4 ②,18	2.5 ③,19	1.4 ⑥,20	13.1 ⑧,21
8	51.3 ⑧	9.5 ②,22	1.3 ③,23	9.6 ④,24	3.1 ⑥,25

Example:

`item(7) = 5, AMAT(7) = 1.5`

`item(19) = 3, AMAT(19) = 2.5`

Compressed Row Storage (CRS)

1	1.1 ①	2.4 ②,1	3.2 ⑤,2		
2	3.6 ②	4.3 ①,3	2.5 ④,4	3.7 ⑥,5	9.1 ⑧,6
3	5.7 ③	1.5 ⑤,7	3.1 ⑦,8		
4	9.8 ④	4.1 ②,9	2.5 ⑤,10	2.7 ⑥,11	
5	11.5 ⑤	3.1 ①,12	9.5 ②,13	10.4 ③,14	4.3 ⑦,15
6	12.4 ⑥	6.5 ③,16	9.5 ⑦,17		
7	23.1 ⑦	6.4 ②,18	2.5 ③,19	1.4 ⑥,20	13.1 ⑧,21
8	51.3 ⑧	9.5 ②,22	1.3 ③,23	9.6 ④,24	3.1 ⑥,25

Diag (i) Diagonal Components (REAL, i=1~N)
Index (i) Number of Non-Zero Off-Diagonals at Each ROW (INT, i=0~N)
Item (k) Off-Diagonal Components (Corresponding Column ID) (INT, k=1, index(N))
AMat (k) Off-Diagonal Components (Value) (REAL, k=1, index(N))

$$\{Y\} = [A] \{X\}$$

```
do i= 1, N
  Y(i)= D(i)*X(i)
  do k= index(i-1)+1, index(i)
    Y(i)= Y(i) + AMAT(k)*X(item(k))
  enddo
enddo
```

- 1D-code for Static Linear-Elastic Problems by Galerkin FEM
- Sparse Linear Solver
 - Conjugate Gradient Method
 - Preconditioning
- Storage of Sparse Matrices
- Program

Finite Element Procedures

- Initialization
 - Control Data
 - Node, Connectivity of Elements (N: Node#, NE: Elem#)
 - Initialization of Arrays (Global/Element Matrices)
 - Element-Global Matrix Mapping (Index, Item)
- Generation of Matrix
 - Element-by-Element Operations (do icel= 1, NE)
 - Element matrices
 - Accumulation to global matrix
 - Boundary Conditions
- Linear Solver
 - Conjugate Gradient Method

Program: 1d.f (1/6)

variables and arrays

```
!C
!C 1D Steady-State Heat Transfer
!C FEM with Piece-wise Linear Elements
!C CG (Conjugate Gradient) Method
!C
!C  $d/dx(CdT/dx) + Q = 0$ 
!C  $T=0@x=0$ 
!C
program heat1D
implicit REAL*8 (A-H, O-Z)

integer :: N, NPLU, ITERmax
integer :: R, Z, P, Q, DD

real(kind=8) :: dX, RESID, EPS
real(kind=8) :: AREA, QV, COND
real(kind=8), dimension(:), allocatable :: PHI, RHS, X
real(kind=8), dimension(:), allocatable :: DIAG, AMAT
real(kind=8), dimension(:, :), allocatable :: W

real(kind=8), dimension(2, 2) :: KMAT, EMAT

integer, dimension(:), allocatable :: ICELNOD
integer, dimension(:), allocatable :: INDEX, ITEM
```

Variable/Arrays (1/2)

Name	Type	Size	I/O	Definition
NE	I		I	# Element
N	I		O	# Node
NPLU	I		O	# Non-Zero Off-Diag. Components
IterMax	I		I	MAX Iteration Number for CG
errno	I		O	ERROR flag
R, Z, Q, P, DD	I		O	Name of Vectors in CG
dX	R		I	Length of Each Element
Resid	R		O	Residual for CG
Eps	R		I	Convergence Criteria for CG
Area	R		I	Sectional Area of Element
QV	R		I	Heat Generation Rate/Volume/Time \dot{Q}
COND	R		I	Thermal Conductivity

Variable/Arrays (2/2)

Name	Type	Size	I/O	Definition
X	R	N	○	Location of Each Node
PHI	R	N	○	Temperature of Each Node
Rhs	R	N	○	RHS Vector
Diag	R	N	○	Diagonal Components
W	R	(N, 4)	○	Work Array for CG
Amat	R	NPLU	○	Off-Diagonal Components (Value)
Index	I	0:N	○	Number of Non-Zero Off-Diagonals at Each ROW
Item	I	NPLU	○	Off-Diagonal Components (Corresponding Column ID)
Icelnod	I	2*NE	○	Node ID for Each Element
Kmat	R	(2, 2)	○	Element Matrix [k]
Emat	R	(2, 2)	○	Element Matrix

Program: 1d.f (2/6)

Initialization, Allocation of Arrays

```
!C
!C +-----+
!C | INIT. |
!C +-----+
!C===
```

```
open (11, file='input.dat', status='unknown')
read (11,*) NE
read (11,*) dX, QV, AREA, COND
read (11,*) ITERmax
read (11,*) EPS
close (11)
```

Control Data input.dat

4	NE (Number of Elements)
1.0 1.0 1.0 1.0	Δx (Length of Each Elem.: L), Q , A , λ
100	Number of MAX. Iterations for CG Solver
1.e-8	Convergence Criteria for CG Solver

```
N= NE + 1
allocate (PHI(N), DIAG(N), AMAT(2*N-2), RHS(N))
allocate (ICELNOD(2*NE), X(N))
allocate (INDEX(0:N), ITEM(2*N-2), W(N,4))
```

```
PHI = 0. d0
AMAT= 0. d0
DIAG= 0. d0
RHS= 0. d0
X= 0. d0
```



NE: # Element
N : # Node (NE+1)

Program: 1d.f (2/6)

Initialization, Allocation of Arrays

```

!C
!C +-----+
!C | INIT. |
!C +-----+
!C===
      open (11, file='input.dat', status='unknown')
      read (11,*) NE
      read (11,*) dX, QV, AREA, COND
      read (11,*) ITERmax
      read (11,*) EPS
      close (11)

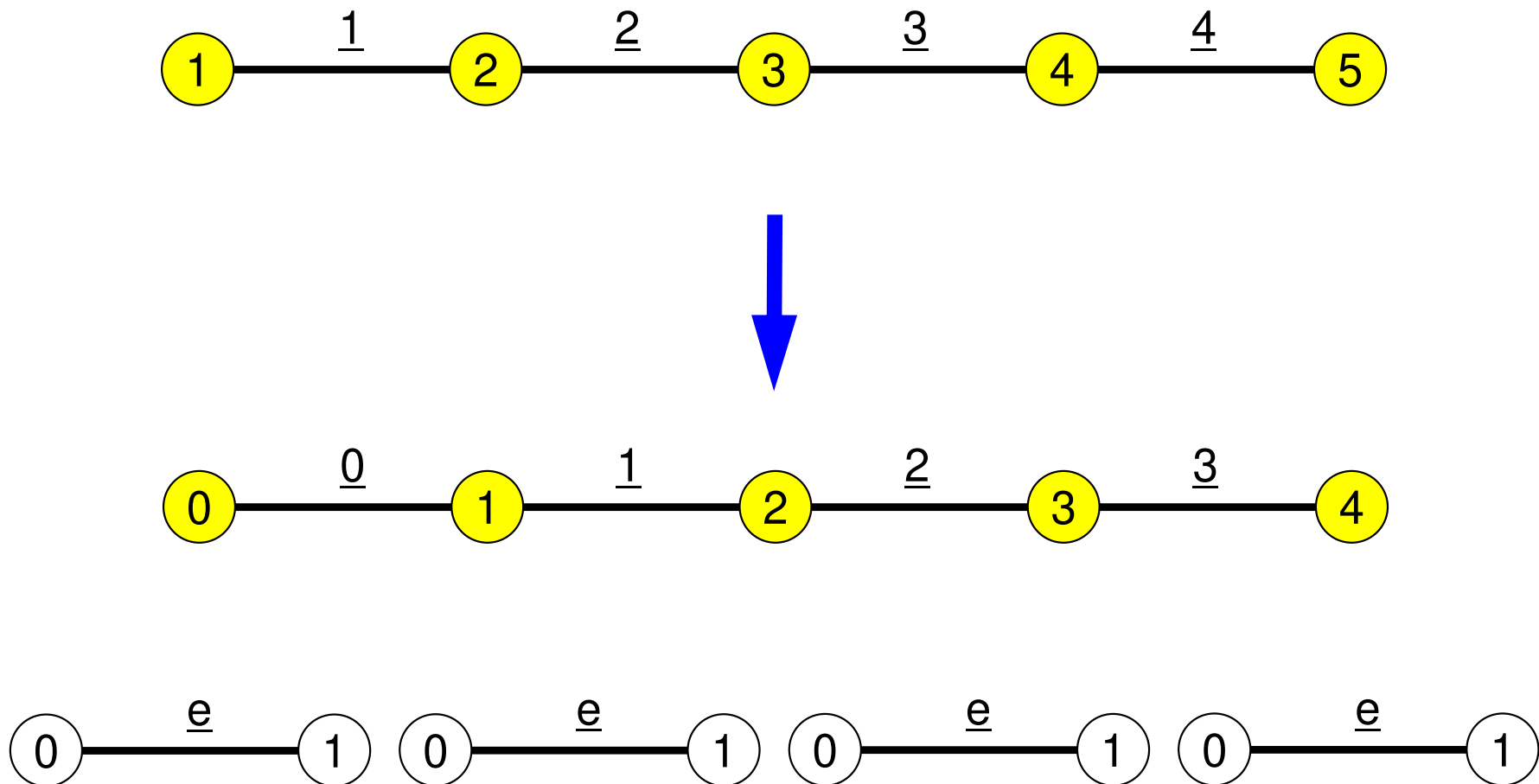
      N= NE + 1
      allocate (PHI(N), DIAG(N), AMAT(2*N-2), RHS(N))
      allocate (ICELNOD(2*NE), X(N))
      allocate (INDEX(0:N), ITEM(2*N-2), W(N,4))

      PHI = 0. d0
      AMAT= 0. d0
      DIAG= 0. d0
      RHS= 0. d0
      X= 0. d0

```

Amat: Non-Zero Off-Diag. Comp.
Item: Corresponding Column ID

Attention: In C program, node and element ID's start from 0.



Program: 1d.f (2/6)

Initialization, Allocation of Array

```

!C
!C +-----+
!C | INIT. |
!C +-----+
!C===
open (11, file='input.dat', status='unknown')
read (11,*) NE
read (11,*) dX, QV, AREA, COND
read (11,*) ITERmax
read (11,*) EPS
close (11)

```

```

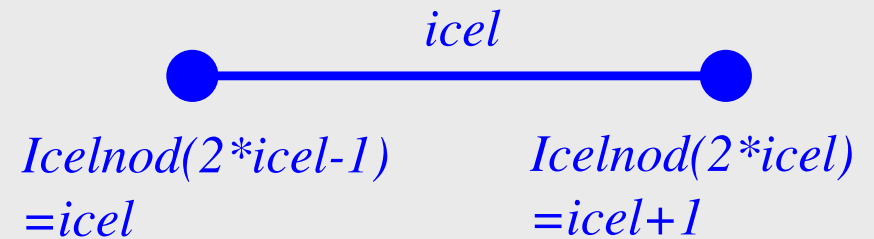
N= NE + 1
allocate (PHI(N), DIAG(N), AMAT(2*N-2), RHS(N))
allocate (ICELNOD(2*NE), X(N))
allocate (INDEX(0:N), ITEM(2*N-2), W(N,4))

```

```

PHI = 0. d0
AMAT= 0. d0
DIAG= 0. d0
RHS= 0. d0
X= 0. d0

```



Amat: Non-Zero Off-Diag. Comp.
Item: Corresponding Column ID

Number of non-zero off-diag. components is 2 for each node. This number is 1 at boundary nodes).

Total Number of Non-Zero Off-Diag. Components:

$$2 * (N-2) + 1 + 1 = 2 * N - 2$$

Program: 1d.f (3/6)

Initialization, Allocation of Arrays (cont.)

```
do i= 1, N
  X(i)= dfloat(i-1)*dX
enddo

do icel= 1, NE
  ICELNOD(2*icel-1)= icel
  ICELNOD(2*icel )= icel + 1
enddo

KMAT (1, 1)= +1. d0
KMAT (1, 2)= -1. d0
KMAT (2, 1)= -1. d0
KMAT (2, 2)= +1. d0
```

x: X-coordinate
component of each node

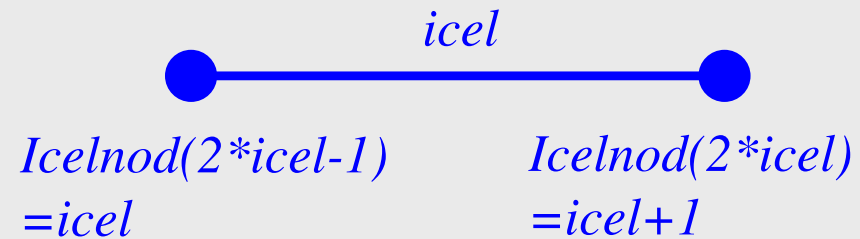
Program: 1d.f (3/6)

Initialization, Allocation of Arrays (cont.)

```
do i= 1, N
  X(i)= dfloat(i-1)*dX
enddo
```

```
do icel= 1, NE
  ICELNOD(2*icel-1)= icel
  ICELNOD(2*icel )= icel + 1
enddo
```

```
KMAT (1, 1)= +1. d0
KMAT (1, 2)= -1. d0
KMAT (2, 1)= -1. d0
KMAT (2, 2)= +1. d0
```



Program: 1d.f (3/6)

Initialization, Allocation of Arrays (cont.)

```
do i= 1, N
  X(i)= dfloat(i-1)*dX
enddo

do icel= 1, NE
  ICELNOD(2*icel-1)= icel
  ICELNOD(2*icel )= icel + 1
enddo
```

```
KMAT (1, 1)= +1. d0
KMAT (1, 2)= -1. d0
KMAT (2, 1)= -1. d0
KMAT (2, 2)= +1. d0
```

$$[k]^{(e)} = \int_V \lambda \left(\frac{d[N]^T}{dx} \frac{d[N]}{dx} \right) dV = \frac{\lambda A}{L} \begin{bmatrix} +1 & -1 \\ -1 & +1 \end{bmatrix}$$

[Kmat]

Program: 1d.f (4/6)

Global Matrix: Column ID for Non-Zero Off-Diag's

```
!C
!C +-----+
!C | CONNECTIVITY |
!C +-----+
!C===
```

INDEX = 2

INDEX(0) = 0

INDEX(1) = 1

INDEX(N) = 1

```
do i= 1, N
  INDEX(i)= INDEX(i) + INDEX(i-1)
enddo
```

NPLU= INDEX(N)

```
do i= 1, N
  jS= INDEX(i-1)
  if (i.eq.1) then
    ITEM(jS+1)= i+1
  else if
& (i.eq.N) then
    ITEM(jS+1)= i-1
  else
    ITEM(jS+1)= i-1
    ITEM(jS+2)= i+1
  endif
enddo
```

```
!C===
```

Number of non-zero off-diag. components is 2 for each node. This number is 1 at boundary nodes).

Total Number of Non-Zero Off-Diag. Components:
 $2*(N-2)+1+1= 2*N-2= NPLU= \text{Index}[N]$

						# Non-Zero Off-Diag.	index (0) = 0
①	1.1 ①	2.4 ②	3.2 ⑤			2	index (1) = 2
②	3.6 ②	4.3 ①	2.5 ④	3.7 ⑥	9.1 ⑧	4	index (2) = 6
③	5.7 ③	1.5 ⑤	3.1 ⑦			2	index (3) = 8
④	9.8 ④	4.1 ②	2.5 ⑤	2.7 ⑥		3	index (4) = 11
⑤	11.5 ⑤	3.1 ①	9.5 ②	10.4 ③	4.3 ⑦	4	index (5) = 15
⑥	12.4 ⑥	6.5 ③	9.5 ⑦			2	index (6) = 17
⑦	23.1 ⑦	6.4 ②	2.5 ③	1.4 ⑥	13.1 ⑧	4	index (7) = 21
⑧	51.3 ⑧	9.5 ②	1.3 ③	9.6 ④	3.1 ⑥	4	index (8) = 25

$\text{index}(i-1) + 1^{\text{th}} \sim \text{index}(i)^{\text{th}}$
 Non-Zero Off-Diag. Components corresponding to i -th row

Program: 1d.f (4/6)

Global Matrix: Column ID for Non-Zero Off-Diag's

```
!C
!C +-----+
!C | CONNECTIVITY |
!C +-----+
!C===
```

```
INDEX = 2
```

```
INDEX(0) = 0
```

```
INDEX(1) = 1
```

```
INDEX(N) = 1
```

```
do i= 1, N
```

```
  INDEX(i) = INDEX(i) + INDEX(i-1)
```

```
enddo
```

```
NPLU = INDEX(N)
```

```
do i= 1, N
```

```
  jS = INDEX(i-1)
```

```
  if (i.eq.1) then
```

```
    ITEM(jS+1) = i+1
```

```
  else if
```

```
& (i.eq.N) then
```

```
  ITEM(jS+1) = i-1
```

```
  else
```

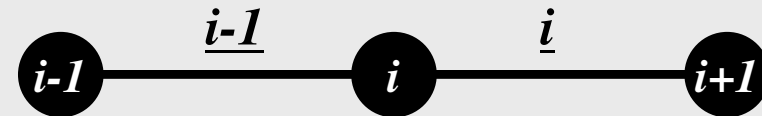
```
    ITEM(jS+1) = i-1
```

```
    ITEM(jS+2) = i+1
```

```
  endif
```

```
enddo
```

```
!C===
```



						# Non-Zero Off-Diag.	index(0) = 0
1	1.1 ①	2.4 ②	3.2 ⑤			2	index(1) = 2
2	3.6 ②	4.3 ①	2.5 ④	3.7 ⑥	9.1 ⑧	4	index(2) = 6
3	5.7 ③	1.5 ⑤	3.1 ⑦			2	index(3) = 8
4	9.8 ④	4.1 ②	2.5 ⑤	2.7 ⑥		3	index(4) = 11
5	11.5 ⑤	3.1 ①	9.5 ②	10.4 ③	4.3 ⑦	4	index(5) = 15
6	12.4 ⑥	6.5 ③	9.5 ⑦			2	index(6) = 17
7	23.1 ⑦	6.4 ②	2.5 ③	1.4 ⑥	13.1 ⑧	4	index(7) = 21
8	51.3 ⑧	9.5 ②	1.3 ③	9.6 ④	3.1 ⑥	4	index(8) = 25

$\text{index}(i-1) + 1^{\text{th}} \sim \text{index}(i)^{\text{th}}$
Non-Zero Off-Diag. Components corresponding to i -th row

Program: 1d.f (5/6)

Element Matrix ~ Global Matrix

```

!C +-----+
!C | MATRIX ASSEMBLE |
!C +-----+
!C===
do icel= 1, NE
  in1= ICELNOD(2*icel-1)
  in2= ICELNOD(2*icel )
  X1 = X(in1)
  X2 = X(in2)
  DL = dabs(X2-X1)

  cK= AREA*COND/DL
  EMAT(1,1)= Ck*KMAT(1,1)
  EMAT(1,2)= Ck*KMAT(1,2)
  EMAT(2,1)= Ck*KMAT(2,1)
  EMAT(2,2)= Ck*KMAT(2,2)

  DIAG(in1)= DIAG(in1) + EMAT(1,1)
  DIAG(in2)= DIAG(in2) + EMAT(2,2)

  if (icel.eq.1) then
    k1= INDEX(in1-1) + 1
  else
    k1= INDEX(in1-1) + 2
  endif
  k2= INDEX(in2-1) + 1

  AMAT(k1)= AMAT(k1) + EMAT(1,2)
  AMAT(k2)= AMAT(k2) + EMAT(2,1)

  QN= 0.50d0*QV*AREA*DL
  RHS(in1)= RHS(in1) + QN
  RHS(in2)= RHS(in2) + QN
enddo
!C===

```



Program: 1d.f (5/6)

Element Matrix ~ Global Matrix

```
!C +-----+
!C | MATRIX ASSEMBLE |
!C +-----+
!C===
```

```
do icel= 1, NE
  in1= ICELNOD(2*icel-1)
  in2= ICELNOD(2*icel )
  X1 = X(in1)
  X2 = X(in2)
  DL = dabs(X2-X1)
```

```
cK= AREA*COND/DL
EMAT(1,1)= Ck*KMAT(1,1)
EMAT(1,2)= Ck*KMAT(1,2)
EMAT(2,1)= Ck*KMAT(2,1)
EMAT(2,2)= Ck*KMAT(2,2)
```

```
DIAG(in1)= DIAG(in1) + EMAT(1,1)
DIAG(in2)= DIAG(in2) + EMAT(2,2)
```

```
if (icel.eq.1) then
  k1= INDEX(in1-1) + 1
else
  k1= INDEX(in1-1) + 2
endif
k2= INDEX(in2-1) + 1
```

```
AMAT(k1)= AMAT(k1) + EMAT(1,2)
AMAT(k2)= AMAT(k2) + EMAT(2,1)
```

```
QN= 0.50d0*QV*AREA*DL
RHS(in1)= RHS(in1) + QN
RHS(in2)= RHS(in2) + QN
```

```
enddo
```

```
!C===
```



$$[Emat] = [k]^{(e)} = \frac{\lambda A}{L} \begin{bmatrix} +1 & -1 \\ -1 & +1 \end{bmatrix} = \frac{\lambda A}{L} [Kmat]$$

Program: 1d.f (5/6)

Element Matrix ~ Global Matrix

```

!C +-----+
!C | MATRIX ASSEMBLE |
!C +-----+
!C===
do icel= 1, NE
  in1= ICELNOD(2*icel-1)
  in2= ICELNOD(2*icel )
  X1 = X(in1)
  X2 = X(in2)
  DL = dabs(X2-X1)

  cK= AREA*COND/DL
  EMAT (1, 1)= Ck*KMAT (1, 1)
  EMAT (1, 2)= Ck*KMAT (1, 2)
  EMAT (2, 1)= Ck*KMAT (2, 1)
  EMAT (2, 2)= Ck*KMAT (2, 2)

  DIAG(in1)= DIAG(in1) + EMAT (1, 1)
  DIAG(in2)= DIAG(in2) + EMAT (2, 2)

  if (icel.eq.1) then
    k1= INDEX(in1-1) + 1
  else
    k1= INDEX(in1-1) + 2
  endif
  k2= INDEX(in2-1) + 1

  AMAT (k1)= AMAT (k1) + EMAT (1, 2)
  AMAT (k2)= AMAT (k2) + EMAT (2, 1)

  QN= 0.50d0*QV*AREA*DL
  RHS(in1)= RHS(in1) + QN
  RHS(in2)= RHS(in2) + QN
enddo
!C===

```



$$[Emat] = [k]^{(e)} = \frac{EA}{L} \begin{bmatrix} +1 & -1 \\ -1 & +1 \end{bmatrix}$$

Program: 1d.f (5/6)

Element Matrix ~ Global Matrix

```

!C +-----+
!C | MATRIX ASSEMBLE |
!C +-----+
!C===
do icel= 1, NE
  in1= ICELNOD(2*icel-1)
  in2= ICELNOD(2*icel )
  X1 = X(in1)
  X2 = X(in2)
  DL = dabs(X2-X1)

  cK= AREA*COND/DL
  EMAT(1,1)= Ck*KMAT(1,1)
  EMAT(1,2)= Ck*KMAT(1,2)
  EMAT(2,1)= Ck*KMAT(2,1)
  EMAT(2,2)= Ck*KMAT(2,2)

  DIAG(in1)= DIAG(in1) + EMAT(1,1)
  DIAG(in2)= DIAG(in2) + EMAT(2,2)

  if (icel.eq.1) then
    k1= INDEX(in1-1) + 1
  else
    k1= INDEX(in1-1) + 2
  endif
  k2= INDEX(in2-1) + 1

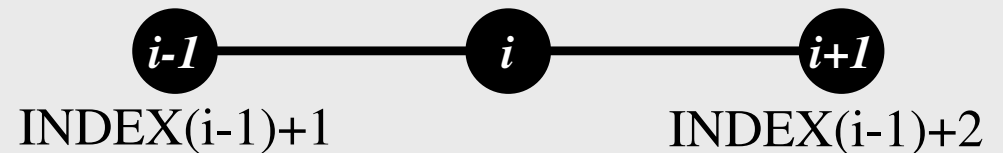
  AMAT(k1)= AMAT(k1) + EMAT(1,2)
  AMAT(k2)= AMAT(k2) + EMAT(2,1)

  QN= 0.50d0*QV*AREA*DL
  RHS(in1)= RHS(in1) + QN
  RHS(in2)= RHS(in2) + QN
enddo
!C===

```



Non-zero Off-Diag. at i -th row:
Index($i-1$)+1, Index($i-1$)+2



$$[Emat] = [k]^{(e)} = \frac{\lambda A}{L} \begin{bmatrix} +1 & \ominus -1 \\ \ominus -1 & +1 \end{bmatrix} \begin{matrix} k1 \\ k2 \end{matrix}$$

General Elements: k1

“in2” as a off-diag. component of “in1”

```

!C +-----+
!C | MATRIX ASSEMBLE |
!C +-----+
!C===
do icel= 1, NE
  in1= ICELNOD(2*icel-1)
  in2= ICELNOD(2*icel )
  X1 = X(in1)
  X2 = X(in2)
  DL = dabs(X2-X1)

  cK= AREA*COND/DL
  EMAT(1, 1)= Ck*KMAT(1, 1)
  EMAT(1, 2)= Ck*KMAT(1, 2)
  EMAT(2, 1)= Ck*KMAT(2, 1)
  EMAT(2, 2)= Ck*KMAT(2, 2)

  DIAG(in1)= DIAG(in1) + EMAT(1, 1)
  DIAG(in2)= DIAG(in2) + EMAT(2, 2)

  if (icel.eq.1) then
    k1= INDEX(in1-1) + 1
  else
    k1= INDEX(in1-1) + 2
  endif
  k2= INDEX(in2-1) + 1

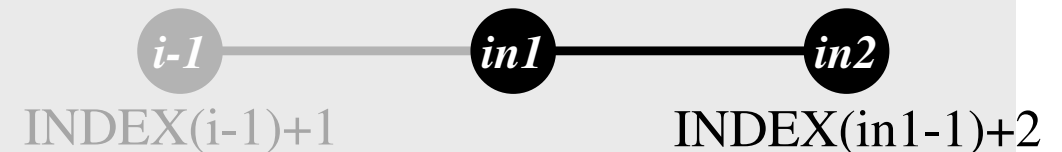
  AMAT(k1)= AMAT(k1) + EMAT(1, 2)
  AMAT(k2)= AMAT(k2) + EMAT(2, 1)

  QN= 0.50d0*QV*AREA*DL
  RHS(in1)= RHS(in1) + QN
  RHS(in2)= RHS(in2) + QN
enddo
!C===

```



Non-zero Off-Diag. at i -th row:
Index($i-1$)+1, Index($i-1$)+2



$$[Emat] = [k]^{(e)} = \frac{\lambda A}{L} \begin{bmatrix} +1 & \ominus -1 \\ -1 & +1 \end{bmatrix} \quad k1$$

General Elements: k2

“in1” as a off-diag. component of “in2”

```

!C +-----+
!C | MATRIX ASSEMBLE |
!C +-----+
!C===
do icel= 1, NE
  in1= ICELNOD(2*icel-1)
  in2= ICELNOD(2*icel )
  X1 = X(in1)
  X2 = X(in2)
  DL = dabs(X2-X1)

  cK= AREA*COND/DL
  EMAT(1,1)= Ck*KMAT(1,1)
  EMAT(1,2)= Ck*KMAT(1,2)
  EMAT(2,1)= Ck*KMAT(2,1)
  EMAT(2,2)= Ck*KMAT(2,2)

  DIAG(in1)= DIAG(in1) + EMAT(1,1)
  DIAG(in2)= DIAG(in2) + EMAT(2,2)

  if (icel.eq.1) then
    k1= INDEX(in1-1) + 1
  else
    k1= INDEX(in1-1) + 2
  endif
  k2= INDEX(in2-1) + 1

  AMAT(k1)= AMAT(k1) + EMAT(1,2)
  AMAT(k2)= AMAT(k2) + EMAT(2,1)

  QN= 0.50d0*QV*AREA*DL
  RHS(in1)= RHS(in1) + QN
  RHS(in2)= RHS(in2) + QN
enddo
!C===

```



Non-zero Off-Diag. at i -th row:
Index $(i-1)+1$, Index $(i-1)+2$



$$[Emat] = [k]^{(e)} = \frac{\lambda A}{L} \begin{bmatrix} +1 & -1 \\ \ominus 1 & +1 \end{bmatrix}$$

k2

0-th Element: k1

“in2” as a off-diag. component of “in1”

```

!C +-----+
!C | MATRIX ASSEMBLE |
!C +-----+
!C===
do icel= 1, NE
  in1= ICELNOD(2*icel-1)
  in2= ICELNOD(2*icel )
  X1 = X(in1)
  X2 = X(in2)
  DL = dabs(X2-X1)

  cK= AREA*COND/DL
  EMAT(1, 1)= Ck*KMAT(1, 1)
  EMAT(1, 2)= Ck*KMAT(1, 2)
  EMAT(2, 1)= Ck*KMAT(2, 1)
  EMAT(2, 2)= Ck*KMAT(2, 2)

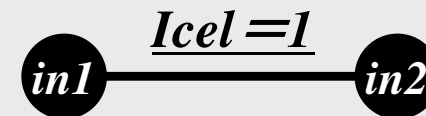
  DIAG(in1)= DIAG(in1) + EMAT(1, 1)
  DIAG(in2)= DIAG(in2) + EMAT(2, 2)

  if (icel.eq.1) then
    k1= INDEX(in1-1) + 1
  else
    k1= INDEX(in1-1) + 2
  endif
  k2= INDEX(in2-1) + 1

  AMAT(k1)= AMAT(k1) + EMAT(1, 2)
  AMAT(k2)= AMAT(k2) + EMAT(2, 1)

  QN= 0.50d0*QV*AREA*DL
  RHS(in1)= RHS(in1) + QN
  RHS(in2)= RHS(in2) + QN
enddo
!C===

```



Non-zero Off-Diag. at i -th row:
INDEX($i-1$)+1 only



$$[Emat] = [k]^{(e)} = \frac{\lambda A}{L} \begin{bmatrix} +1 & \ominus 1 \\ -1 & +1 \end{bmatrix} \quad k1$$

Program: 1d.f (5/6)

RHS: Heat Generation Term

```

!C +-----+
!C | MATRIX ASSEMBLE |
!C +-----+
!C===
do icel= 1, NE
  in1= ICELNOD(2*icel-1)
  in2= ICELNOD(2*icel )
  X1 = X(in1)
  X2 = X(in2)
  DL = dabs(X2-X1)

  cK= AREA*COND/DL
  EMAT(1,1)= Ck*KMAT(1,1)
  EMAT(1,2)= Ck*KMAT(1,2)
  EMAT(2,1)= Ck*KMAT(2,1)
  EMAT(2,2)= Ck*KMAT(2,2)

  DIAG(in1)= DIAG(in1) + EMAT(1,1)
  DIAG(in2)= DIAG(in2) + EMAT(2,2)

  if (icel.eq.1) then
    k1= INDEX(in1-1) + 1
  else
    k1= INDEX(in1-1) + 2
  endif
  k2= INDEX(in2-1) + 1

  AMAT(k1)= AMAT(k1) + EMAT(1,2)
  AMAT(k2)= AMAT(k2) + EMAT(2,1)

  QN= 0.50d0*QV*AREA*DL
  RHS(in1)= RHS(in1) + QN
  RHS(in2)= RHS(in2) + QN
enddo
!C===

```



$$\int_V \dot{Q}[N]^T dV = \dot{Q}A \int_0^L \begin{bmatrix} 1-x/L \\ x/L \end{bmatrix} dx = \frac{\dot{Q}AL}{2} \begin{Bmatrix} 1 \\ 1 \end{Bmatrix}$$

Program: 1d.f (6/6)

Dirichlet B.C. @ X=0

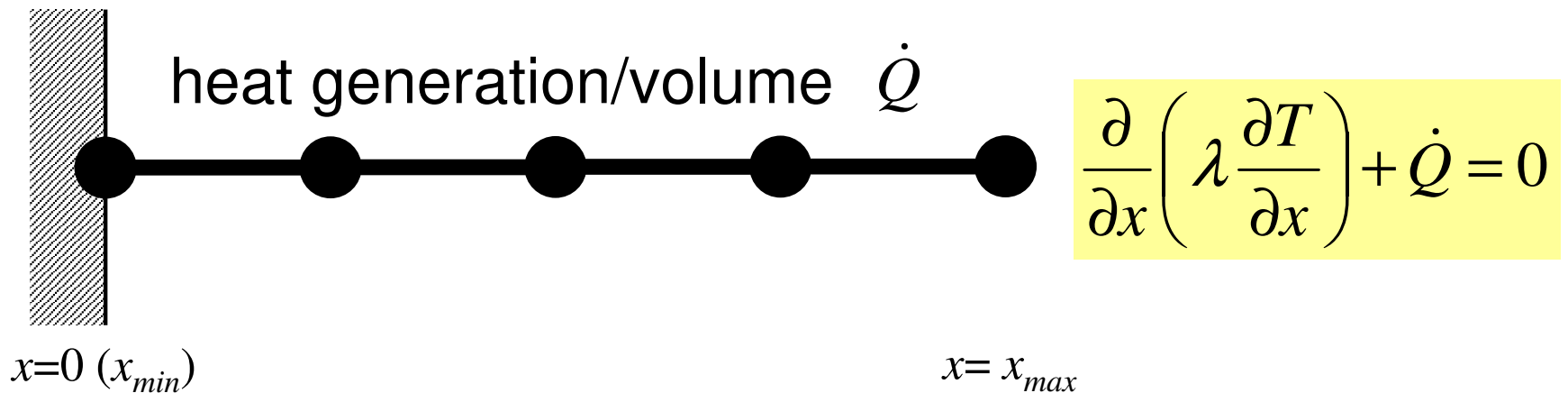
```
!C
!C +-----+
!C | BOUNDARY CONDITIONS |
!C +-----+
!C===

!C
!C-- X=Xmin
      i= 1
      jS= INDEX(i-1)

      AMAT(jS+1)= 0. d0
      DIAG(i)= 1. d0
      RHS (i)= 0. d0

      do k= 1, NPLU
        if (ITEM(k).eq. 1) AMAT(k)= 0. d0
      enddo
!C===
```

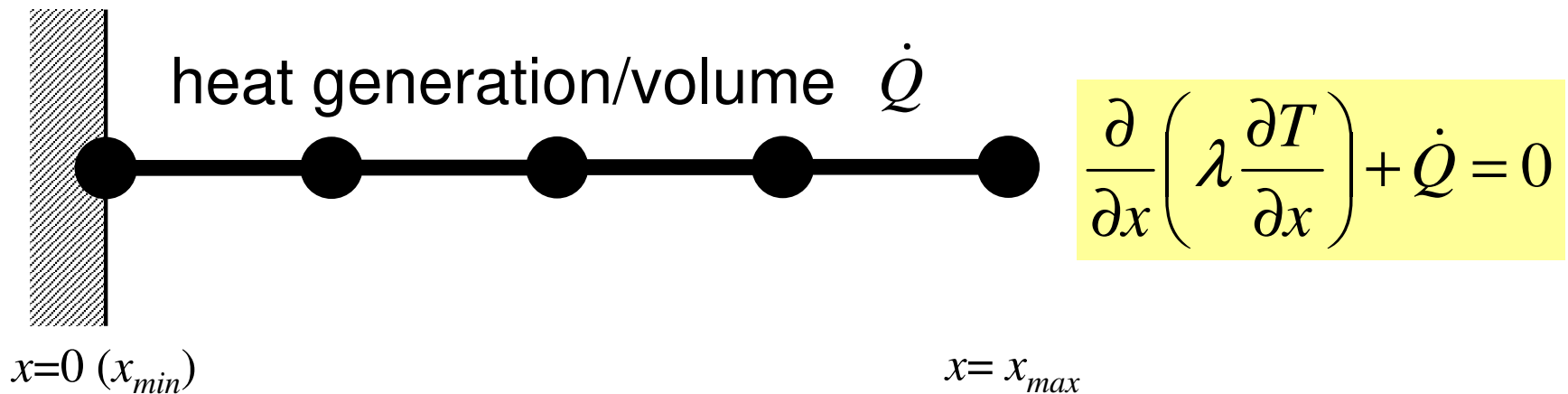

1D Steady State Heat Conduction



- **Uniform: Sectional Area: A , Thermal Conductivity: λ**
- Heat Generation Rate/Volume/Time [$QL^{-3}T^{-1}$] \dot{Q}
- Boundary Conditions
 - $x=0$: $T=0$ (Fixed Temperature)
 - $x=x_{max}$: $\frac{\partial T}{\partial x} = 0$ (Insulated)

(Linear) Equation at $x=0$

$$T_I = 0 \text{ (or } T_o = 0)$$



- **Uniform: Sectional Area: A , Thermal Conductivity: λ**
- Heat Generation Rate/Volume/Time [$QL^{-3}T^{-1}$] \dot{Q}
- Boundary Conditions
 - $x=0$: $T=0$ (Fixed Temperature)
 - $x=x_{max}$: $\frac{\partial T}{\partial x} = 0$ (Insulated)

Program: 1d.f (6/6)

Dirichlet B.C. @ X=0

```

!C
!C +-----+
!C | BOUNDARY CONDITIONS |
!C +-----+
!C===

!C
!C-- X=Xmin
  i= 1
  js= INDEX(i-1)

  AMAT(js+1)= 0. d0
  DIAG(i)= 1. d0
  RHS (i)= 0. d0

  do k= 1, NPLU
    if (ITEM(k).eq. 1) AMAT(k)= 0. d0
  enddo
!C===

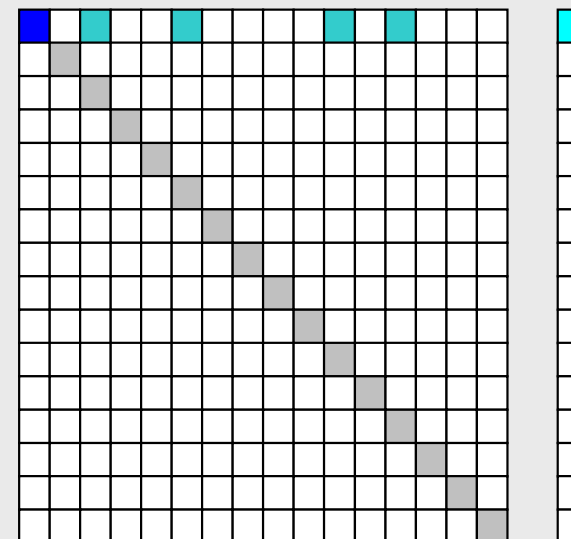
```

$$T_1=0$$

Diagonal Component=1

RHS=0

Off-Diagonal Components= 0.



Program: 1d.f (6/6)

Dirichlet B.C. @ X=0

```

!C
!C +-----+
!C | BOUNDARY CONDITIONS |
!C +-----+
!C===

!C
!C-- X=Xmin
  i= 1
  js= INDEX(i-1)

  AMAT(js+1)= 0. d0
  DIAG(i)= 1. d0
  RHS (i)= 0. d0

  do k= 1, NPLU
    if (ITEM(k).eq. 1) AMAT(k)= 0. d0
  enddo
!C===

```

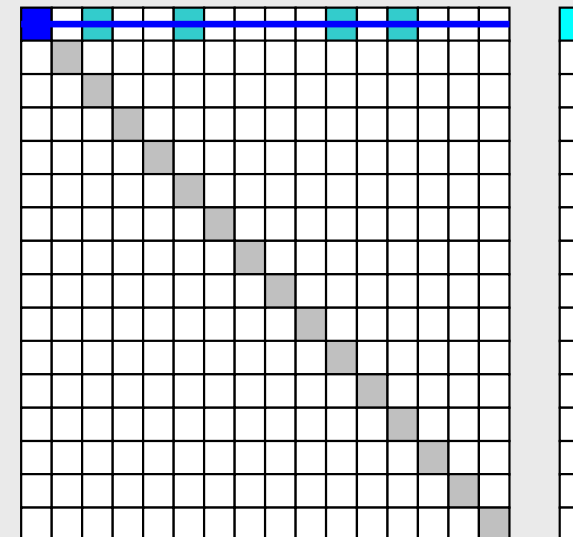
$$T_1=0$$

Diagonal Component=1

RHS=0

Off-Diagonal Components= 0.

Erase !



Program: 1d.f (6/6)

Dirichlet B.C. @ X=0

```

!C
!C +-----+
!C | BOUNDARY CONDITIONS |
!C +-----+
!C===

!C
!C-- X=Xmin
    i= 1
    jS= INDEX(i-1)

    AMAT(jS+1)= 0. d0
    DIAG(i)= 1. d0
    RHS (i)= 0. d0

    do k= 1, NPLU
      if (ITEM(k).eq. 1) AMAT(k)= 0. d0
    enddo
!C===

```

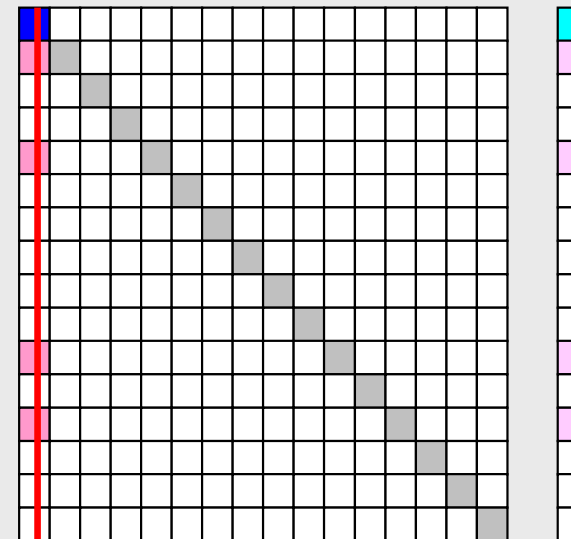
$$T_1=0$$

Diagonal Component=1

RHS=0

Off-Diagonal Components= 0.

Elimination and Erase



Column components of boundary nodes (Dirichlet B.C.) are moved to RHS and eliminated for keeping symmetrical feature of the matrix (in this case just erase off-diagonal components)

if $T_1 \neq 0$

```

!C
!C +-----+
!C | BOUNDARY CONDITIONS |
!C +-----+
!C===

!C
!C-- X=Xmin
      i= 1
      js= INDEX(i-1)

      AMAT(js+1)= 0. d0
      DIAG(i)= 1. d0
      RHS (i)= PHImin

      do i= 1, N
        do k= INDEX(i-1)+1, INDEX(i)
          if (ITEM(k).eq.1) then
            RHS (i)= RHS(i) - AMAT(k)*PHImin
            AMAT(k)= 0. d0
          endif
        enddo
      enddo
!C===

```

Column components of boundary nodes (Dirichlet B.C.) are moved to RHS and eliminated for keeping symmetrical feature of the matrix.

$$Diag_j \phi_j + \sum_{k=Index[j]}^{Index[j+1]-1} Amat_k \phi_{Item[k]} = Rhs_j$$

if $T_1 \neq 0$

```

!C
!C +-----+
!C | BOUNDARY CONDITIONS |
!C +-----+
!C===

!C
!C-- X=Xmin
      i= 1
      js= INDEX(i-1)

      AMAT(js+1)= 0. d0
      DIAG(i)= 1. d0
      RHS (i)= PHImin

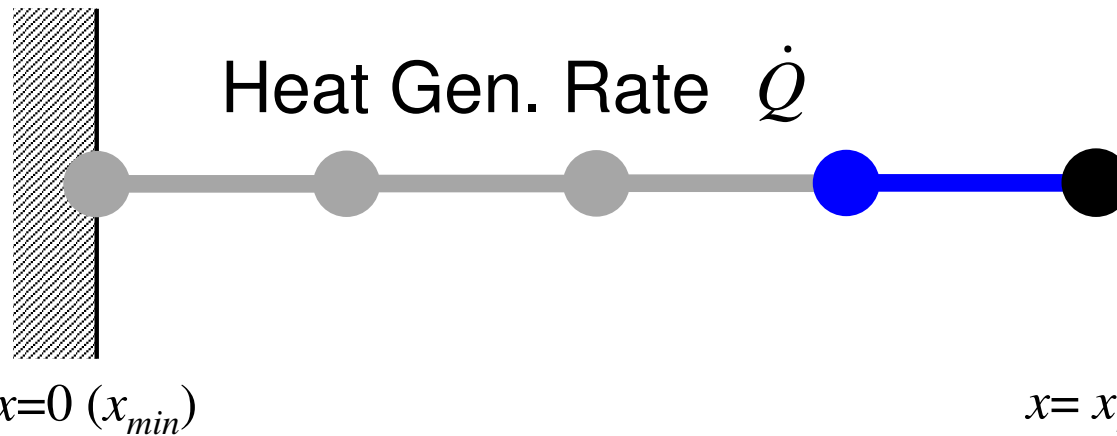
      do i= 1, N
        do k= INDEX(i-1)+1, INDEX(i)
          if (ITEM(k).eq.1) then
            RHS (i)= RHS(i) - AMAT(k)*PHImin
            AMAT(k)= 0. d0
          endif
        enddo
      enddo
!C===

```

$$\begin{aligned}
 & \text{Diag}_j \phi_j + \sum_{k=\text{Index}[j], k \neq k_s}^{\text{Index}[j+1]-1} \text{Amat}_k \phi_{\text{Item}[k]} \\
 &= \text{Rhs}_j - \text{Amat}_{k_s} \phi_{\text{Item}[k_s]} \\
 &= \text{Rhs}_j - \text{Amat}_{k_s} \phi_{\min} \quad \text{where } \text{Item}[k_s] = 1
 \end{aligned}$$

Column components of boundary nodes (Dirichlet B.C.) are moved to RHS and eliminated for keeping symmetrical feature of the matrix.

Secondary B.C. (Insulated)



$$\frac{\partial}{\partial x} \left(\lambda \frac{\partial T}{\partial x} \right) + \dot{Q} = 0$$

$$T = 0 @ x = 0$$

$$\frac{\partial T}{\partial x} = 0 @ x = x_{\max}$$

$$\int_S \bar{q} [N]^T dS = \bar{q} A \Big|_{x=L} = \bar{q} A \begin{Bmatrix} 0 \\ 1 \end{Bmatrix}, \quad \bar{q} = -\lambda \frac{dT}{dx}$$

Surface Flux



$$\frac{\partial T}{\partial x} = 0 @ x = x_{\max}$$

According to insulated B.C., $\bar{q} = 0$ is satisfied. No contribution by this term. Insulated B.C. is automatically satisfied without explicit operations -> Natural B.C.

Preconditioned CG Solver

```

Compute  $\mathbf{r}^{(0)} = \mathbf{b} - [\mathbf{A}]\mathbf{x}^{(0)}$ 
for i= 1, 2, ...
  solve  $[\mathbf{M}]\mathbf{z}^{(i-1)} = \mathbf{r}^{(i-1)}$ 
   $\rho_{i-1} = \mathbf{r}^{(i-1)} \mathbf{z}^{(i-1)}$ 
  if i=1
     $\mathbf{p}^{(1)} = \mathbf{z}^{(0)}$ 
  else
     $\beta_{i-1} = \rho_{i-1} / \rho_{i-2}$ 
     $\mathbf{p}^{(i)} = \mathbf{z}^{(i-1)} + \beta_{i-1} \mathbf{p}^{(i-1)}$ 
  endif
   $\mathbf{q}^{(i)} = [\mathbf{A}]\mathbf{p}^{(i)}$ 
   $\alpha_i = \rho_{i-1} / \mathbf{p}^{(i)} \mathbf{q}^{(i)}$ 
   $\mathbf{x}^{(i)} = \mathbf{x}^{(i-1)} + \alpha_i \mathbf{p}^{(i)}$ 
   $\mathbf{r}^{(i)} = \mathbf{r}^{(i-1)} - \alpha_i \mathbf{q}^{(i)}$ 
  check convergence  $|\mathbf{r}|$ 
end

```

$$[\mathbf{M}] = \begin{bmatrix} D_1 & 0 & \dots & 0 & 0 \\ 0 & D_2 & & 0 & 0 \\ \dots & & \dots & & \dots \\ 0 & 0 & & D_{N-1} & 0 \\ 0 & 0 & \dots & 0 & D_N \end{bmatrix}$$

Diagonal Scaling, Point-Jacobi

$$[M] = \begin{bmatrix} D_1 & 0 & \dots & 0 & 0 \\ 0 & D_2 & & 0 & 0 \\ \dots & & \dots & & \dots \\ 0 & 0 & & D_{N-1} & 0 \\ 0 & 0 & \dots & 0 & D_N \end{bmatrix}$$

- **solve** $[M] \mathbf{z}^{(i-1)} = \mathbf{r}^{(i-1)}$ is very easy.
- Provides fast convergence for simple problems.
- 1d.f, 1d.c

CG Solver (1/6)

```
!C
!C +-----+
!C | CG iterations |
!C +-----+
!C===
      R = 1
      Z = 2
      Q = 2
      P = 3
      DD= 4

      do i= 1, N
        W(i, DD)= 1.000 / DIAG(i)
      enddo
```

```
W(i, 1) = W(i, R)   ⇒ {r}
W(i, 2) = W(i, Z)   ⇒ {z}
W(i, 2) = W(i, Q)   ⇒ {q}
W(i, 3) = W(i, P)   ⇒ {p}
W(i, 4) = W(i, DD) ⇒ 1/{D}
```

```
Compute  $r^{(0)} = b - [A]x^{(0)}$ 
for i= 1, 2, ...
  solve  $[M]z^{(i-1)} = r^{(i-1)}$ 
   $\rho_{i-1} = r^{(i-1)} z^{(i-1)}$ 
  if i=1
     $p^{(1)} = z^{(0)}$ 
  else
     $\beta_{i-1} = \rho_{i-1} / \rho_{i-2}$ 
     $p^{(i)} = z^{(i-1)} + \beta_{i-1} p^{(i-1)}$ 
  endif
   $q^{(i)} = [A]p^{(i)}$ 
   $\alpha_i = \rho_{i-1} / p^{(i)} q^{(i)}$ 
   $x^{(i)} = x^{(i-1)} + \alpha_i p^{(i)}$ 
   $r^{(i)} = r^{(i-1)} - \alpha_i q^{(i)}$ 
  check convergence |r|
end
```

CG Solver (1/6)

```
!C
!C +-----+
!C | CG iterations |
!C +-----+
!C===
```

```
R = 1
Z = 2
Q = 2
P = 3
DD= 4
```

```
do i= 1, N
  W(i, DD)= 1.0D0 / DIAG(i)
enddo
```

Reciprocal numbers (倒数) of diagonal components are stored in $W[DD][i]$.

Computational cost for division is usually expensive.

Although it was said (division):(+, -, *) is 10:1 before, the difference is much smaller now. Generally, multiplying is still faster than division.

```
W(i, 1) = W(i, R)   => {r}
W(i, 2) = W(i, Z)   => {z}
W(i, 2) = W(i, Q)   => {q}
W(i, 3) = W(i, P)   => {p}
W(i, 4) = W(i, DD) => 1/{D}
```

CG Solver (2/6)

```
!C
!C-- {r0} = {b} - [A]{xini} |
```

!C 初期残差

```
do i = 1, N
  W(i, R) = DIAG(i)*PHI(i)
  do j = INDEX(i-1)+1, INDEX(i)
    W(i, R) = W(i, R) + AMAT(j)*PHI(ITEM(j))
  enddo
enddo
```

```
BNRM2 = 0.0D0
do i = 1, N
  BNRM2 = BNRM2 + RHS(i) **2
  W(i, R) = RHS(i) - W(i, R)
enddo
```

**$BNRM2 = |b|^2$
for convergence criteria
of CG solvers**

Compute $r^{(0)} = b - [A]x^{(0)}$

```
for i = 1, 2, ...
  solve [M]z(i-1) = r(i-1)
  ρi-1 = r(i-1) z(i-1)
  if i = 1
    p(1) = z(0)
  else
    βi-1 = ρi-1 / ρi-2
    p(i) = z(i-1) + βi-1 p(i-1)
  endif
  q(i) = [A]p(i)
  αi = ρi-1 / p(i) q(i)
  x(i) = x(i-1) + αi p(i)
  r(i) = r(i-1) - αi q(i)
  check convergence |r|
end
```

CG Solver (3/6)

```

do iter= 1, ITERmax

!C
!C-- {z}= [Minv]{r}

do i= 1, N
W(i, Z)= W(i, DD) * W(i, R)
enddo

!C
!C-- RHO= {r} {z}

RHO= 0. d0
do i= 1, N
RHO= RHO + W(i, R)*W(i, Z)
enddo

```

Compute $r^{(0)} = b - [A]x^{(0)}$
for $i = 1, 2, \dots$
solve $[M]z^{(i-1)} = r^{(i-1)}$
 $\rho_{i-1} = r^{(i-1)} z^{(i-1)}$
if $i = 1$
 $p^{(1)} = z^{(0)}$
else
 $\beta_{i-1} = \rho_{i-1} / \rho_{i-2}$
 $p^{(i)} = z^{(i-1)} + \beta_{i-1} p^{(i-1)}$
endif
 $q^{(i)} = [A]p^{(i)}$
 $\alpha_i = \rho_{i-1} / p^{(i)} q^{(i)}$
 $x^{(i)} = x^{(i-1)} + \alpha_i p^{(i)}$
 $r^{(i)} = r^{(i-1)} - \alpha_i q^{(i)}$
check convergence $|r|$
end

CG Solver (4/6)

```

!C
!C-- {p} = {z} if      ITER=1
!C  BETA= RHO / RH01  otherwise

      if ( iter.eq.1 ) then
        do i= 1, N
          W(i,P)= W(i,Z)
        enddo
      else
        BETA= RHO / RH01
        do i= 1, N
          W(i,P)= W(i,Z) + BETA*W(i,P)
        enddo
      endif

!C
!C-- {q}= [A] {p}

      do i= 1, N
        W(i,Q) = DIAG(i)*W(i,P)
        do j= INDEX(i-1)+1, INDEX(i)
          W(i,Q) = W(i,Q) + AMAT(j)*W(ITEM(j),P)
        enddo
      enddo

```

```

Compute  $r^{(0)} = b - [A]x^{(0)}$ 
for  $i = 1, 2, \dots$ 
  solve  $[M]z^{(i-1)} = r^{(i-1)}$ 
   $\rho_{i-1} = r^{(i-1)} z^{(i-1)}$ 
  if  $i=1$ 
     $p^{(1)} = z^{(0)}$ 
  else
     $\beta_{i-1} = \rho_{i-1} / \rho_{i-2}$ 
     $p^{(i)} = z^{(i-1)} + \beta_{i-1} p^{(i-1)}$ 
  endif
   $q^{(i)} = [A]p^{(i)}$ 
   $\alpha_i = \rho_{i-1} / p^{(i)} q^{(i)}$ 
   $x^{(i)} = x^{(i-1)} + \alpha_i p^{(i)}$ 
   $r^{(i)} = r^{(i-1)} - \alpha_i q^{(i)}$ 
  check convergence  $|r|$ 
end

```

CG Solver (5/6)

```

!C
!C-- ALPHA= RHO / {p} {q}

      C1= 0. d0
      do i= 1, N
        C1= C1 + W(i, P)*W(i, Q)
      enddo
      ALPHA= RHO / C1

!C
!C-- {x}= {x} + ALPHA*{p}
!C  {r}= {r} - ALPHA*{q}

      do i= 1, N
        PHI (i)= PHI (i) + ALPHA * W(i, P)
        W(i, R)= W(i, R) - ALPHA * W(i, Q)
      enddo

```

```

Compute  $r^{(0)} = b - [A]x^{(0)}$ 
for i= 1, 2, ...
  solve  $[M]z^{(i-1)} = r^{(i-1)}$ 
   $\rho_{i-1} = r^{(i-1)} z^{(i-1)}$ 
  if i=1
     $p^{(1)} = z^{(0)}$ 
  else
     $\beta_{i-1} = \rho_{i-1} / \rho_{i-2}$ 
     $p^{(i)} = z^{(i-1)} + \beta_{i-1} p^{(i-1)}$ 
  endif
   $q^{(i)} = [A]p^{(i)}$ 
   $\alpha_i = \rho_{i-1} / p^{(i)} q^{(i)}$ 
   $x^{(i)} = x^{(i-1)} + \alpha_i p^{(i)}$ 
   $r^{(i)} = r^{(i-1)} - \alpha_i q^{(i)}$ 
  check convergence  $|r|$ 
end

```


CG Solver (6/6)

```

DNRM2 = 0.0
do i= 1, N
  DNRM2= DNRM2 + W(i,R)**2
enddo

```

RESID= dsqrt(DNRM2/BNRM2)

```

if ( RESID. le. EPS) goto 900
RHO1 = RHO  ρi-2

```

```

enddo
900 continue

```

$$\text{Resid} = \sqrt{\frac{\text{DNorm2}}{\text{BNorm2}}} = \frac{|r|}{|b|} = \frac{|b - Ax|}{|b|} \leq \text{Eps}$$

$|r|, |b|$: 2 / L2 / Euclidean - norm $(\|r\|_2, \|b\|_2)$ end

Control Data input.dat

```

4          NE (Number of Elements)
1.0 1.0 1.0 1.0 Δx (Length of Each Elem.: L), Q, A, λ
100       Number of MAX. Iterations for CG Solver
1.e-8     Convergence Criteria for CG Solver

```

Compute $r^{(0)} = b - [A]x^{(0)}$

for $i = 1, 2, \dots$

solve $[M]z^{(i-1)} = r^{(i-1)}$

$\rho_{i-1} = r^{(i-1)} z^{(i-1)}$

if $i=1$

$p^{(1)} = z^{(0)}$

else

$\beta_{i-1} = \rho_{i-1} / \rho_{i-2}$

$p^{(i)} = z^{(i-1)} + \beta_{i-1} p^{(i-1)}$

endif

$q^{(i)} = [A]p^{(i)}$

$\alpha_i = \rho_{i-1} / p^{(i)} q^{(i)}$

$x^{(i)} = x^{(i-1)} + \alpha_i p^{(i)}$

$r^{(i)} = r^{(i-1)} - \alpha_i q^{(i)}$

check convergence $|r|$

end

$$Ax = b \Rightarrow \alpha Ax = \alpha b$$

$$r = b - Ax \Rightarrow R = \alpha b - \alpha Ax = \alpha r$$

Finite Element Procedures

- Initialization
 - Control Data
 - Node, Connectivity of Elements (N: Node#, NE: Elem#)
 - Initialization of Arrays (Global/Element Matrices)
 - Element-Global Matrix Mapping (Index, Item)
- Generation of Matrix
 - Element-by-Element Operations (do icel= 1, NE)
 - Element matrices
 - Accumulation to global matrix
 - Boundary Conditions
- Linear Solver
 - Conjugate Gradient Method

Remedies for Higher Accuracy

- Finer Meshes

NE=8, dx=12.5

8 iters, RESID= 2.822910E-16 PHI(N)= 1.953586E-01

Temperature

1	0.000000E+00	-0.000000E+00
2	1.101928E-02	1.103160E-02
3	2.348034E-02	2.351048E-02
4	3.781726E-02	3.787457E-02
5	5.469490E-02	5.479659E-02
6	7.520772E-02	7.538926E-02
7	1.013515E-01	1.016991E-01
8	1.373875E-01	1.381746E-01
9	1.953586E-01	1.980421E-01



NE=20, dx=5

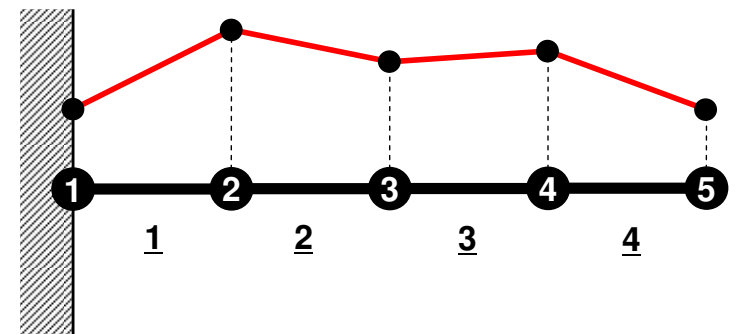
20 iters, RESID= 5.707508E-15 PHI(N)= 1.975734E-01

Temperature

1	0.000000E+00	-0.000000E+00
2	4.259851E-03	4.260561E-03
3	8.719160E-03	8.720685E-03
4	1.339752E-02	1.339999E-02

.....

17	1.145876E-01	1.146641E-01
18	1.295689E-01	1.296764E-01
19	1.473466E-01	1.475060E-01
20	1.692046E-01	1.694607E-01
21	1.975734E-01	1.980421E-01



$$u = \frac{F}{EA_1} \left[\log(A_1x + A_2) - \log(A_2) \right]$$

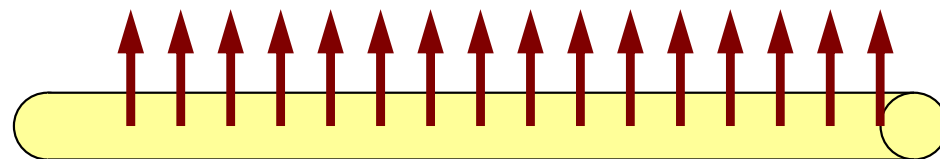
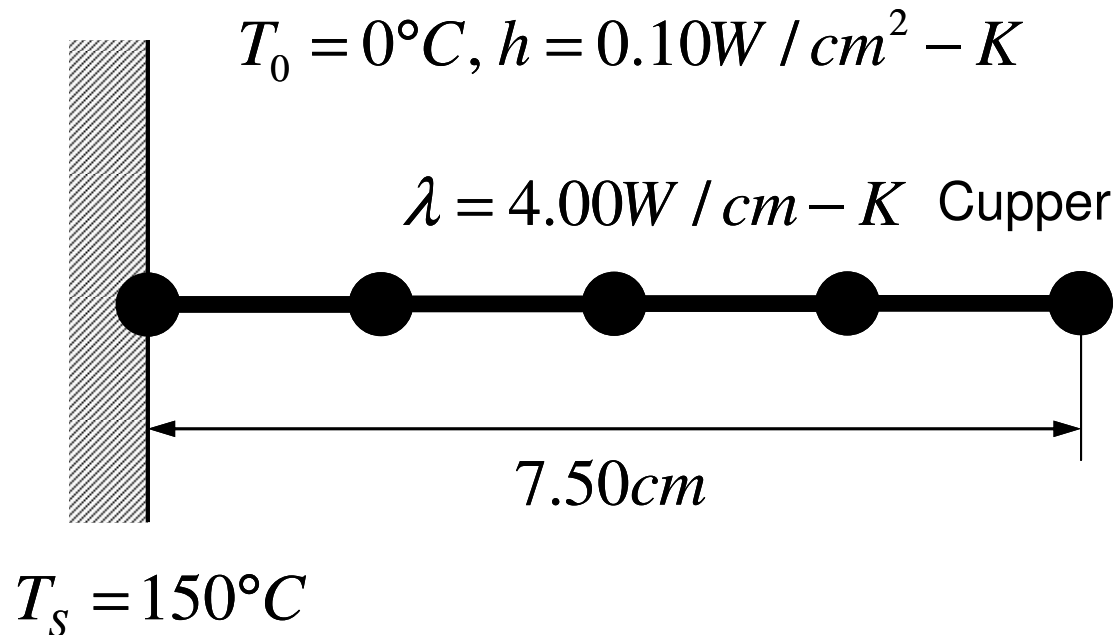
Remedies for Higher Accuracy

- Finer Meshes
- Higher Order Shape/Interpolation Function (高次補間関数・形状関数)
 - Higher-Order Element (高次要素)
 - Linear-Element, 1st-Order Element: Lower Order (低次要素)
- Formulation which assures continuity of n-th order derivatives
 - C^n Continuity (C^n 連続性)

Remedies for Higher Accuracy

- Finer Meshes
- Higher Order Shape/Interpolation Function (高次補間関数・形状関数)
 - Higher-Order Element (高次要素)
 - Linear-Element, 1st-Order Element: Lower Order (低次要素)
- Formulation which assures continuity of n-th order derivatives
 - C^n Continuity (C^n 連続性)
- **Linear Elements**
 - Piecewise Linear
 - C^0 Continuity
 - Only dependent variables are continuous at element boundary

Example: 1D Heat Transfer (1/2)



Convective Heat Transfer on
Cylindrical Surface

- Temp. Thermal Fins
- Circular Sectional Area,
 $r=1\text{cm}$
- Boundary Condition
 - $x=0$: Fixed Temperature
 - $x=7.5$: Insulated
- Convective Heat Transfer
on Cylindrical Surface
 - $q = h(T - T_0)$
 - q : Heat Flux
 - Heat Flow/Unit Surface
Area/sec.

Example: 1D Heat Transfer (2/2)

RESULTS (linear interpolation)

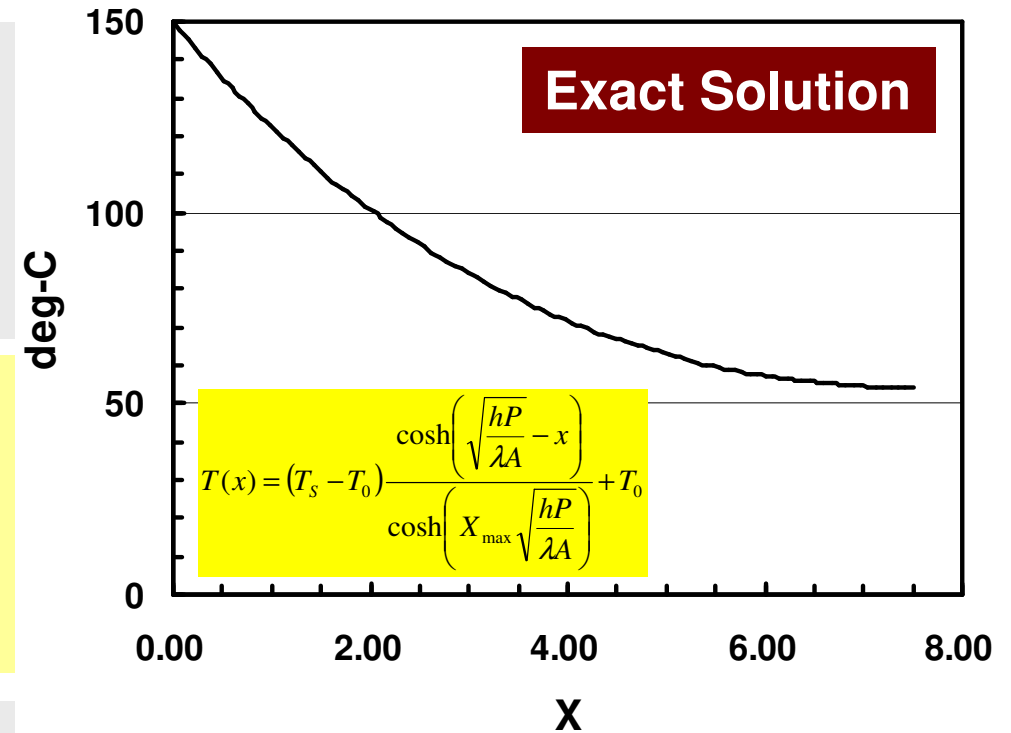
ID	X	FEM.	ANALYTICAL	ERR (%)
1	0.00000	150.00000	150.00000	0.00000
2	1.87500	102.62226	103.00165	0.25292
3	3.75000	73.82803	74.37583	0.36520
4	5.62500	58.40306	59.01653	0.40898
5	7.50000	53.55410	54.18409	0.41999

RESULTS (quadratic interpolation)

ID	X	FEM.	ANALYTICAL	ERR (%)
1	0.00000	150.00000	150.00000	0.00000
2	1.87500	102.98743	103.00165	0.00948
3	3.75000	74.40203	74.37583	0.01747
4	5.62500	59.02737	59.01653	0.00722
5	7.50000	54.21426	54.18409	0.02011

RESULTS (linear interpolation)

ID	X	FEM.	ANALYTICAL	ERR (%)
1	0.00000	150.00000	150.00000	0.00000
2	0.93750	123.71561	123.77127	0.03711
3	1.87500	102.90805	103.00165	0.06240
4	2.81250	86.65618	86.77507	0.07926
5	3.75000	74.24055	74.37583	0.09019
6	4.68750	65.11151	65.25705	0.09703
7	5.62500	58.86492	59.01653	0.10107
8	6.56250	55.22426	55.37903	0.10317
9	7.50000	54.02836	54.18409	0.10382

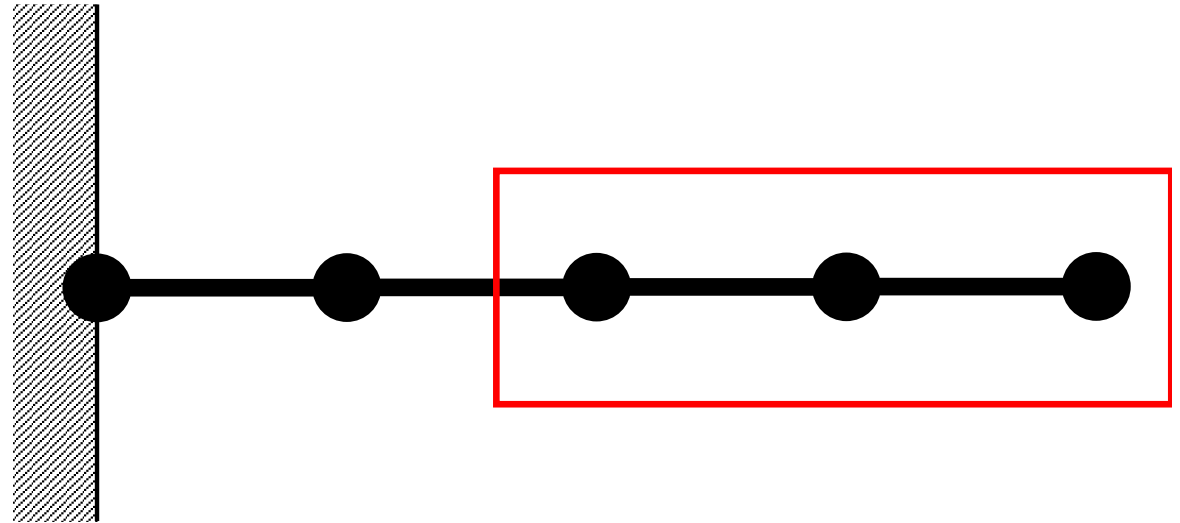


Quadratic interpolation provides more accurate solution, especially if X is close to 7.50cm.

1D Quadratic Element (1/2)

一次元二次要素

- Length= L
- (i,k): Both Ends
- (j): Intermediate Node
 - ✓ Mid-Point (中間節点)



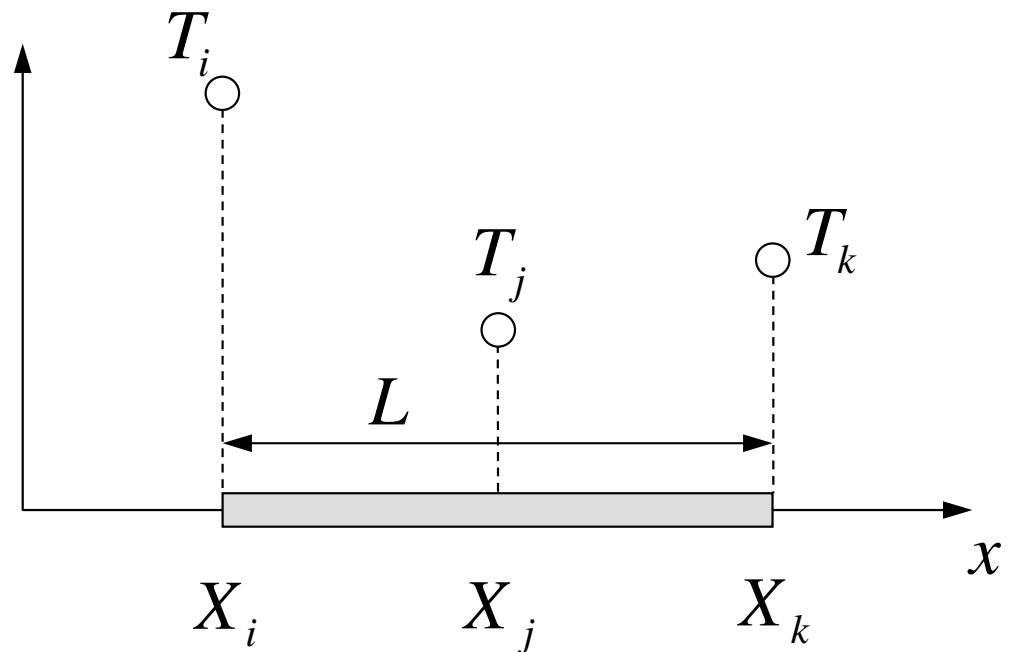
- Distribution of T in each element:

$$T = \alpha_1 + \alpha_2 x + \alpha_3 x^2$$

$$T_i = \alpha_1 + X_i \alpha_2 + X_i^2 \alpha_3$$

$$T_j = \alpha_1 + X_j \alpha_2 + X_j^2 \alpha_3$$

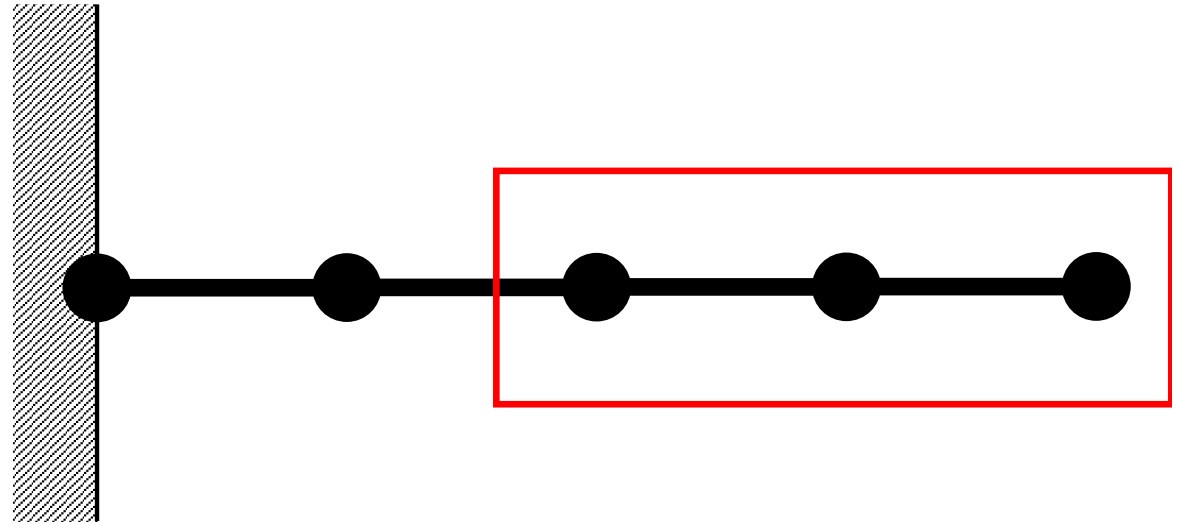
$$T_k = \alpha_1 + X_k \alpha_2 + X_k^2 \alpha_3$$



1D Quadratic Element (1/2)

一次元二次要素

- Length= L
- (i,k): Both Ends
- (j): Intermediate Node
 - ✓ Mid-Point (中間節点)

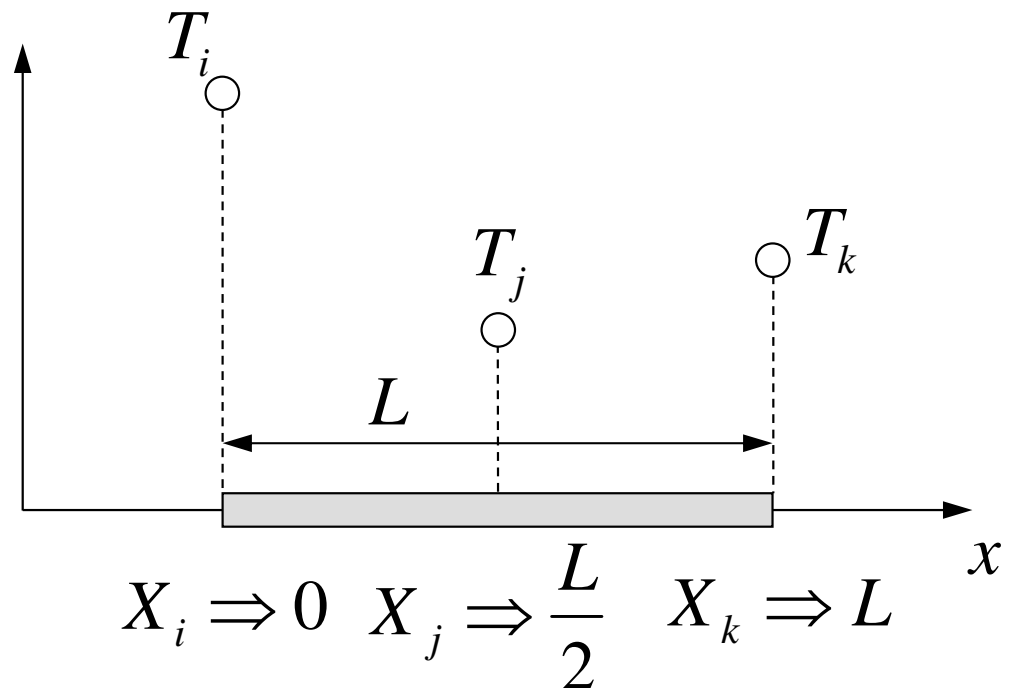


- Distribution of T in each element:

$$T = \alpha_1 + \alpha_2 x + \alpha_3 x^2$$

$$u_i = \alpha_1, \quad u_j = \alpha_1 + \frac{L}{2}\alpha_2 + \frac{L^2}{4}\alpha_3$$

$$u_k = \alpha_1 + L\alpha_2 + L^2\alpha_3$$



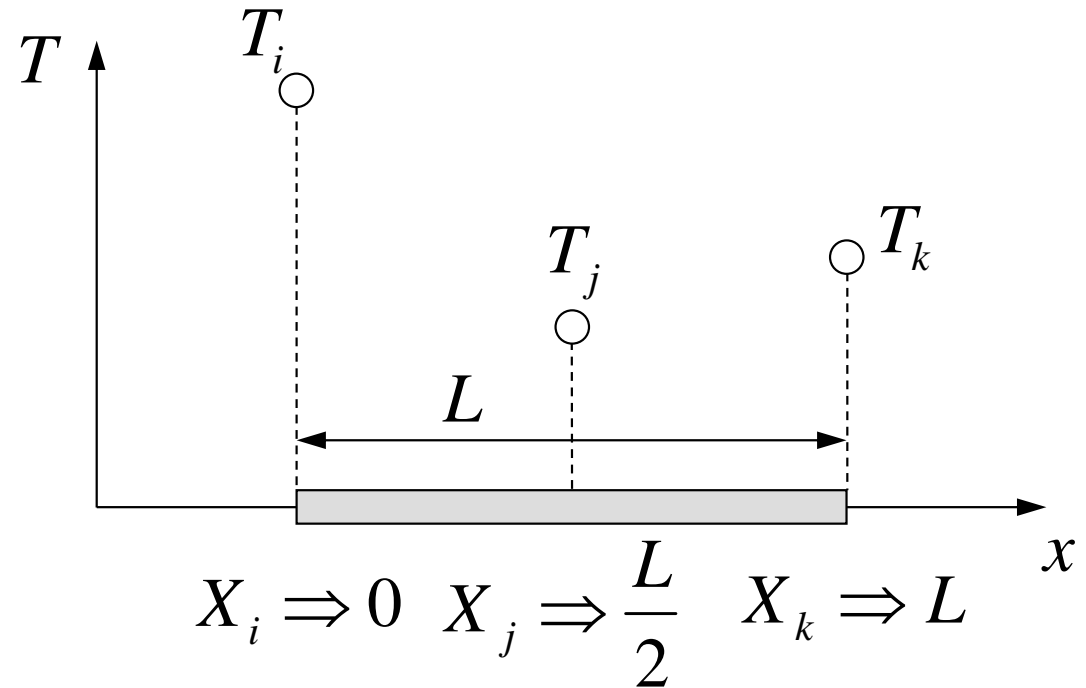
1D Quadratic Element (2/2)

一次元二次要素

- Coef's are calculated based on info. at each node:

$$\alpha_1 = T_i, \alpha_2 = \frac{4T_i - 3T_j - T_k}{L},$$

$$\alpha_3 = \frac{2}{L^2} (T_i - 2T_j + T_k)$$

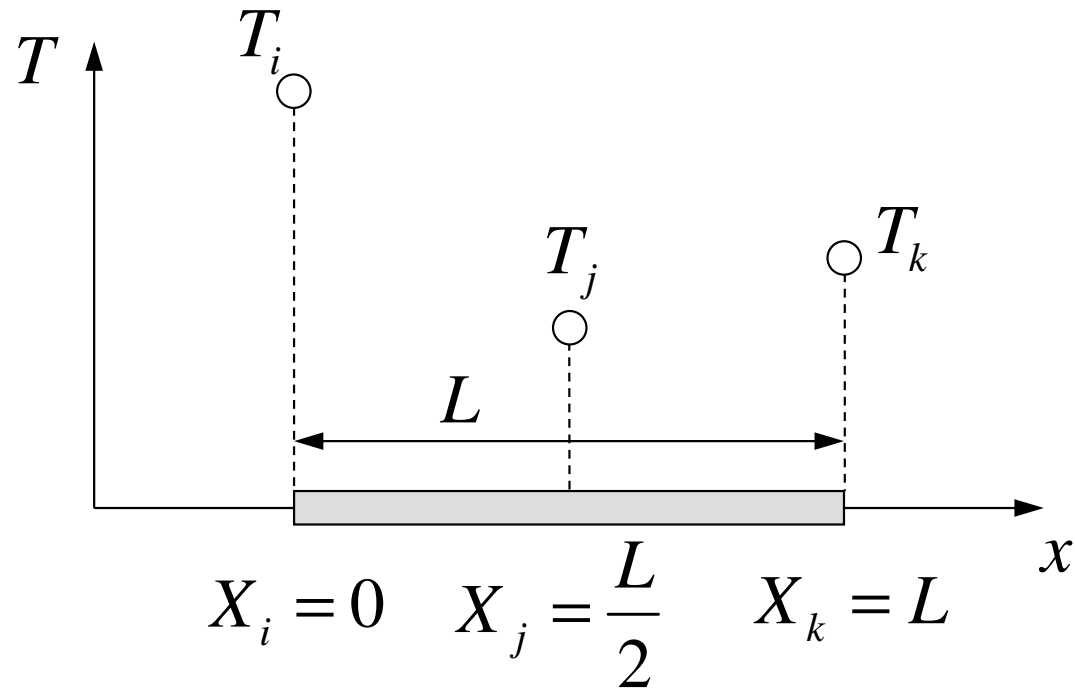


- Shape Functions: N_i , N_j , N_k

$$\begin{aligned} T &= N_i T_i + N_j T_j + N_k T_k \\ &= \left(1 - \frac{2x}{L}\right) \left(1 - \frac{x}{L}\right) T_i + \left(\frac{4x}{L}\right) \left(1 - \frac{x}{L}\right) T_j + \left(-\frac{x}{L}\right) \left(1 - \frac{2x}{L}\right) T_k \end{aligned}$$

1D Quadratic Element

一次元二次要素



Intermediate Node
Mid Point: j

Integration over Each Element: $[k]$ (1/2)

$$N_i = \left(1 - \frac{2x}{L}\right) \left(1 - \frac{x}{L}\right)$$

$$\frac{dN_i}{dx} = \left(\frac{4x}{L^2} - \frac{3}{L}\right)$$

$$N_j = \left(\frac{4x}{L}\right) \left(1 - \frac{x}{L}\right)$$

$$\frac{dN_j}{dx} = \left(\frac{4}{L} - \frac{8x}{L^2}\right)$$

$$N_k = \left(-\frac{x}{L}\right) \left(1 - \frac{2x}{L}\right)$$

$$\frac{dN_k}{dx} = \left(\frac{4x}{L^2} - \frac{1}{L}\right)$$


Integration over Each Element: $[k]$ (2/2)

$$\int_V \lambda \left(\frac{d[N]^T}{dx} \frac{d[N]}{dx} \right) dV = \int_0^L \begin{bmatrix} dN_i / dx \\ dN_j / dx \\ dN_k / dx \end{bmatrix} \lambda \left[\frac{dN_i}{dx}, \frac{dN_j}{dx}, \frac{dN_k}{dx} \right] A dx$$

$$= \lambda A \int_0^L \begin{bmatrix} \frac{dN_i}{dx} \frac{dN_i}{dx} & \frac{dN_i}{dx} \frac{dN_j}{dx} & \frac{dN_i}{dx} \frac{dN_k}{dx} \\ \frac{dN_j}{dx} \frac{dN_i}{dx} & \frac{dN_j}{dx} \frac{dN_j}{dx} & \frac{dN_j}{dx} \frac{dN_k}{dx} \\ \frac{dN_k}{dx} \frac{dN_i}{dx} & \frac{dN_k}{dx} \frac{dN_j}{dx} & \frac{dN_k}{dx} \frac{dN_k}{dx} \end{bmatrix} dx = \frac{\lambda A}{6L} \begin{bmatrix} +14 & -16 & +2 \\ -16 & +32 & -16 \\ +2 & -16 & +14 \end{bmatrix}$$

Integration over Each Element: $\{f\}$

$$\int_V \dot{Q} [N]^T dV = \dot{Q} A \int_0^L \begin{bmatrix} N_i \\ N_j \\ N_k \end{bmatrix} dx = \dot{Q} A \int_0^L \begin{bmatrix} 1 - \frac{3x}{L} + \frac{2x^2}{L^2} \\ \frac{4x}{L} - \frac{4x^2}{L^2} \\ -\frac{x}{L} + \frac{2x^2}{L^2} \end{bmatrix} dx = \frac{\dot{Q} A L}{6} \begin{Bmatrix} 1 \\ 4 \\ 1 \end{Bmatrix}$$

$1 : 4 : 1$


The Ratio was 1:1 in Linear Element

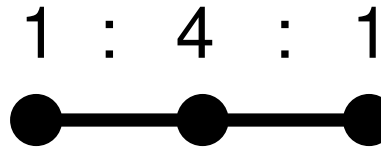
$$N_i = \left(\frac{X_j - x}{L} \right), \quad N_j = \left(\frac{x - X_i}{L} \right) \quad \frac{dN_i}{dx} = \left(\frac{-1}{L} \right), \quad \frac{dN_j}{dx} = \left(\frac{1}{L} \right)$$

$$\int_V \dot{Q} [N]^T dV = \dot{Q} A \int_0^L \begin{bmatrix} 1 - x/L \\ x/L \end{bmatrix} dx = \frac{\dot{Q} A L}{2} \begin{Bmatrix} 1 \\ 1 \end{Bmatrix}$$



Integration over Each Element: $\{f\}$

$$\int_V \dot{Q} [N]^T dV = \dot{Q} A \int_0^L \begin{bmatrix} N_i \\ N_j \\ N_k \end{bmatrix} dx = \dot{Q} A \int_0^L \begin{bmatrix} 1 - \frac{3x}{L} + \frac{2x^2}{L^2} \\ \frac{4x}{L} - \frac{4x^2}{L^2} \\ -\frac{x}{L} + \frac{2x^2}{L^2} \end{bmatrix} dx = \frac{\dot{Q} A L}{6} \begin{Bmatrix} 1 \\ 4 \\ 1 \end{Bmatrix}$$



Volume
Heat Flux

$$\int_S \bar{q} [N]^T dS = \bar{q} A \Big|_{x=L} = \bar{q} A \begin{Bmatrix} 0 \\ 0 \\ 1 \end{Bmatrix}$$

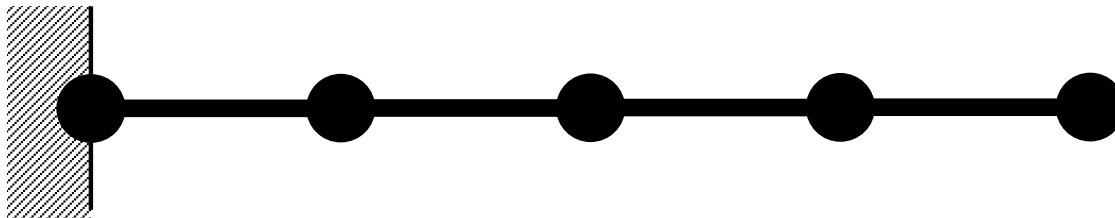
Surface
Heat Flux

Element Eqn's/Accumulation

1D Linear Element

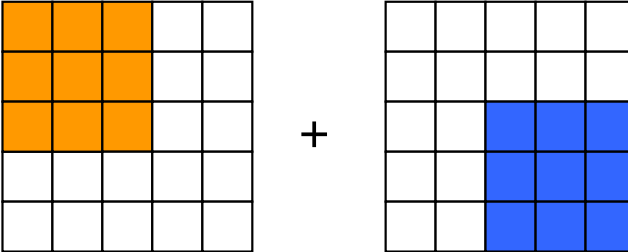
$$[K] = \sum_{i=1}^4 [k^{(i)}] =$$

$$\{F\} = \sum_{i=1}^4 \{f^{(i)}\} =$$



Element Eqn's/Accumulation

1D Quadratic Element, 2 Elements

$$[K] = \sum_{i=1}^2 [k^{(i)}] =$$


$$\{F\} = \sum_{i=1}^4 \{f^{(i)}\} =$$
