EECE 571F: Advanced Topics in Deep Learning

Lecture 4: Graph Neural Networks II
Graph Convolution Models

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Outline

- **Laplacian, Fourier Transforms, and Convolution**
- Graph Laplacian, Graph Fourier Transforms, and Graph Convolution
- Spectral Filtering and Chebyshev Polynomials
- Graph Convolutional Networks (GCNs)
- Relation between GCNs and Message Passing Neural Networks (MPNNs)
- Spectral Graph Neural Networks

Convolution on Graphs?

- Let us review Fourier Transform and Convolution Theorem

Fourier Transform

Given signal $f(t)$, the classical Fourier transform is:

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i.e., expansion in terms of complex exponentials

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$e^{-2\pi i \xi t}$ **is the eigenfunction of Laplacian operator!**

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where $\hat{f}(\xi) = \int_{\mathbb{R}} f(t)e^{-2\pi i\xi t}dt$ and $\hat{h}(\xi) = \int_{\mathbb{R}} h(t)e^{-2\pi i\xi t}dt$

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How can we generalize them to graphs?

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Convolution on Graphs?

- Let us review Fourier Transform and Convolution Theorem

1. Based on the *eigenfunction of Laplacian operator*, we define Fourier transform
2. Based on the convolution theorem, we can define convolution in Fourier domain

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  2. Based on the convolution theorem, we can define convolution in Fourier domain

- How can we generalize convolution to graphs?

  1. What is the Laplacian operator on graph?
  2. How can we define convolution in (graph) Fourier domain?

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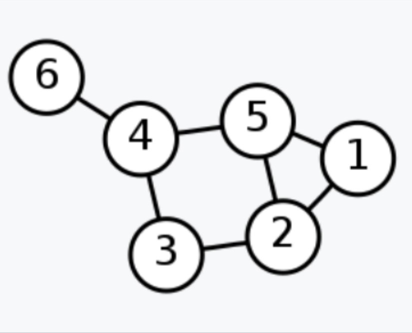
Graph Signal

Graph G = (V, E), graph signal (node feature) X

G

Labelled graph



A

Adjacency matrix

$$\begin{pmatrix} 0 & 1 & 0 & 0 & 1 & 0 \\ 1 & 0 & 1 & 0 & 1 & 0 \\ 0 & 1 & 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 & 1 & 1 \\ 1 & 1 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \end{pmatrix}$$

Image Credit: https://en.wikipedia.org/wiki/Laplacian_matrix

Graph Laplacian

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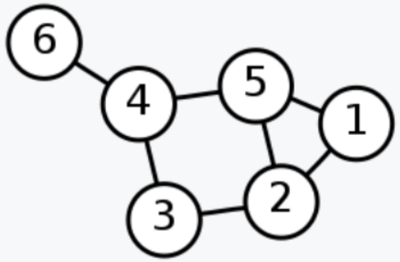
Degree matrix: $D_{ii} = \sum_{j=1}^{N} A_{ij}$

G Labelled graph	D Degree matrix	A Adjacency matrix
	$\begin{pmatrix} 2 & 0 & 0 & 0 & 0 & 0 \\ 0 & 3 & 0 & 0 & 0 & 0 \\ 0 & 0 & 2 & 0 & 0 & 0 \\ 0 & 0 & 0 & 3 & 0 & 0 \\ 0 & 0 & 0 & 0 & 3 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{pmatrix}$	$\begin{pmatrix} 0 & 1 & 0 & 0 & 1 & 0 \\ 1 & 0 & 1 & 0 & 1 & 0 \\ 0 & 1 & 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 & 1 & 1 \\ 1 & 1 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \end{pmatrix}$

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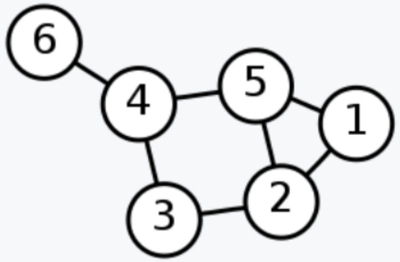
(Combinatorial) Graph Laplacian: $L = D - A$

G	D	A	$L = D - A$
Labelled graph	**Degree matrix**	**Adjacency matrix**	**Laplacian matrix**
	$\begin{pmatrix} 2 & 0 & 0 & 0 & 0 & 0 \\ 0 & 3 & 0 & 0 & 0 & 0 \\ 0 & 0 & 2 & 0 & 0 & 0 \\ 0 & 0 & 0 & 3 & 0 & 0 \\ 0 & 0 & 0 & 0 & 3 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{pmatrix}$	$\begin{pmatrix} 0 & 1 & 0 & 0 & 1 & 0 \\ 1 & 0 & 1 & 0 & 1 & 0 \\ 0 & 1 & 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 & 1 & 1 \\ 1 & 1 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \end{pmatrix}$	$\begin{pmatrix} 2 & -1 & 0 & 0 & -1 & 0 \\ -1 & 3 & -1 & 0 & -1 & 0 \\ 0 & -1 & 2 & -1 & 0 & 0 \\ 0 & 0 & -1 & 3 & -1 & -1 \\ -1 & -1 & 0 & -1 & 3 & 0 \\ 0 & 0 & 0 & -1 & 0 & 1 \end{pmatrix}$

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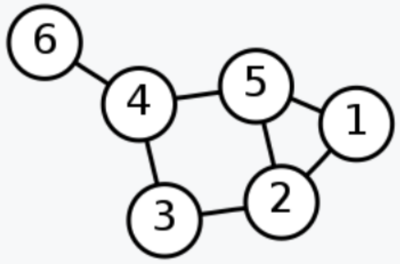
(Combinatorial) Graph Laplacian: $L = D - A$

Compute difference between current node and its neighbors!

G Labelled graph	D Degree matrix	A Adjacency matrix	$L = D - A$ Laplacian matrix
	$\begin{pmatrix} 2 & 0 & 0 & 0 & 0 & 0 \\ 0 & 3 & 0 & 0 & 0 & 0 \\ 0 & 0 & 2 & 0 & 0 & 0 \\ 0 & 0 & 0 & 3 & 0 & 0 \\ 0 & 0 & 0 & 0 & 3 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{pmatrix}$	$\begin{pmatrix} 0 & 1 & 0 & 0 & 1 & 0 \\ 1 & 0 & 1 & 0 & 1 & 0 \\ 0 & 1 & 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 & 1 & 1 \\ 1 & 1 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \end{pmatrix}$	$\begin{pmatrix} 2 & -1 & 0 & 0 & -1 & 0 \\ -1 & 3 & -1 & 0 & -1 & 0 \\ 0 & -1 & 2 & -1 & 0 & 0 \\ 0 & 0 & -1 & 3 & -1 & -1 \\ -1 & -1 & 0 & -1 & 3 & 0 \\ 0 & 0 & 0 & -1 & 0 & 1 \end{pmatrix}$

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Graph Laplacian

For undirected graphs, (Combinatorial) Graph Laplacian:

- Symmetric
- Diagonally dominant
- Positive semi-definite (PSD)
- The number of connected components in the graph is the algebraic multiplicity of the eigenvalue 0.

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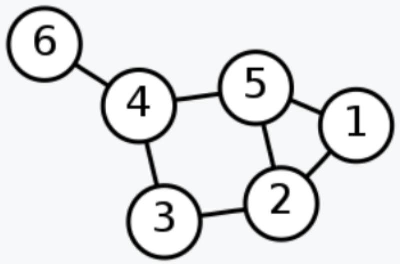
Labelled graph	**Degree matrix**	**Adjacency matrix**	**Laplacian matrix**
	$\begin{pmatrix} 2 & 0 & 0 & 0 & 0 & 0 \\ 0 & 3 & 0 & 0 & 0 & 0 \\ 0 & 0 & 2 & 0 & 0 & 0 \\ 0 & 0 & 0 & 3 & 0 & 0 \\ 0 & 0 & 0 & 0 & 3 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{pmatrix}$	$\begin{pmatrix} 0 & 1 & 0 & 0 & 1 & 0 \\ 1 & 0 & 1 & 0 & 1 & 0 \\ 0 & 1 & 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 & 1 & 1 \\ 1 & 1 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \end{pmatrix}$	$\begin{pmatrix} 2 & -1 & 0 & 0 & -1 & 0 \\ -1 & 3 & -1 & 0 & -1 & 0 \\ 0 & -1 & 2 & -1 & 0 & 0 \\ 0 & 0 & -1 & 3 & -1 & -1 \\ -1 & -1 & 0 & -1 & 3 & 0 \\ 0 & 0 & 0 & -1 & 0 & 1 \end{pmatrix}$

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Graph Laplacian

Symmetrically Normalized Graph Laplacian:

$$L = D^{-\frac{1}{2}}(D - A)D^{-\frac{1}{2}} = I - D^{-\frac{1}{2}}AD^{-\frac{1}{2}}$$

Eigenvalues lie in [0, 2], why? (Try to show it by yourself!)

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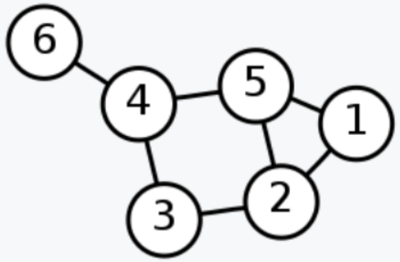	$\begin{pmatrix} 2&0&0&0&0&0\\ 0&3&0&0&0&0\\ 0&0&2&0&0&0\\ 0&0&0&3&0&0\\ 0&0&0&0&3&0\\ 0&0&0&0&0&1 \end{pmatrix}$	$\begin{pmatrix} 0&1&0&0&1&0\\ 1&0&1&0&1&0\\ 0&1&0&1&0&0\\ 0&0&1&0&1&1\\ 1&1&0&1&0&0\\ 0&0&0&1&0&0 \end{pmatrix}$	$\begin{pmatrix} 2&-1&0&0&-1&0\\ -1&3&-1&0&-1&0\\ 0&-1&2&-1&0&0\\ 0&0&-1&3&-1&-1\\ -1&-1&0&-1&3&0\\ 0&0&0&-1&0&1 \end{pmatrix}$

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Spectral Theorem

If L is a symmetric matrix, we have

$$L = U \Lambda U^\top = \sum_{i=1}^N \lambda_i \mathbf{u}_i \mathbf{u}_i^\top$$

where $U = [\mathbf{u}_1, \mathbf{u}_2, \cdots, \mathbf{u}_N]$ contains eigenvectors of L and is orthogonal $UU^\top = U^\top U = I$

$$\Lambda = \begin{bmatrix} \lambda_1 & & & \\ & \lambda_2 & & \\ & & \ddots & \\ & & & \lambda_N \end{bmatrix}$$

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Spectral Decomposition

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Given graph signal $X \in \mathbb{R}^{N \times 1}$, the *Graph Fourier Transform* is:

$$\hat{X}[i] = \sum_{j=1}^{N} U[j, i] X[j]$$

$$\hat{X} = U^{\top} X$$

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Eigenvalue corresponds to frequency!

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Graph Convolution (Spectral Filtering)

Convolution:

$$(f * h)(t) = \int_{\mathbb{R}} f(\tau)h(t-\tau)d\tau = \int_{\mathbb{R}} \hat{f}(\xi)\hat{h}(\xi)e^{2\pi i\xi t}d\xi$$

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Graph Convolution in Fourier domain (Spectral Filtering):

$$h_\theta * X = U h_\theta(\Lambda) U^\top X$$

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Can we find some efficient construction of h?

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Graph Convolution in Fourier domain (Spectral Filtering):

$$h_\theta * X = U h_\theta(\Lambda) U^\top X$$

Directly construct h requires spectral decomposition which is O(N^3)!

Can we find some efficient construction of h?

- Chebyshev polynomials [7]
- Graph wavelets [7]

Chebyshev Polynomials

Chebyshev polynomials of the first kind:

$$T_0(x) = 1$$
$$T_1(x) = x$$
$$T_{n+1}(x) = 2xT_n(x) - T_{n-1}(x)$$

Image Credit: https://en.wikipedia.org/wiki/Chebyshev_polynomials

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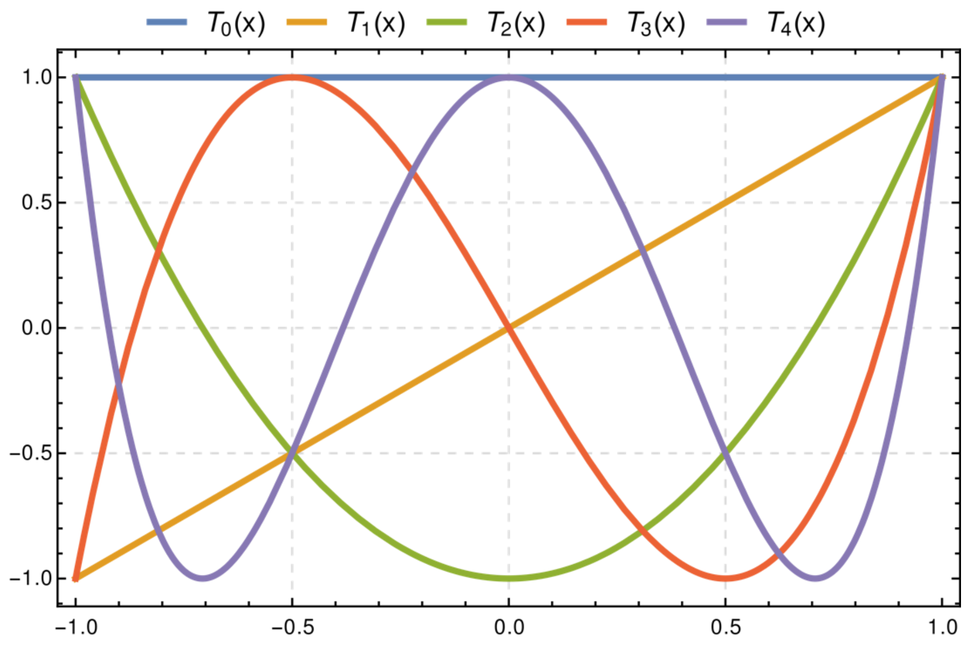

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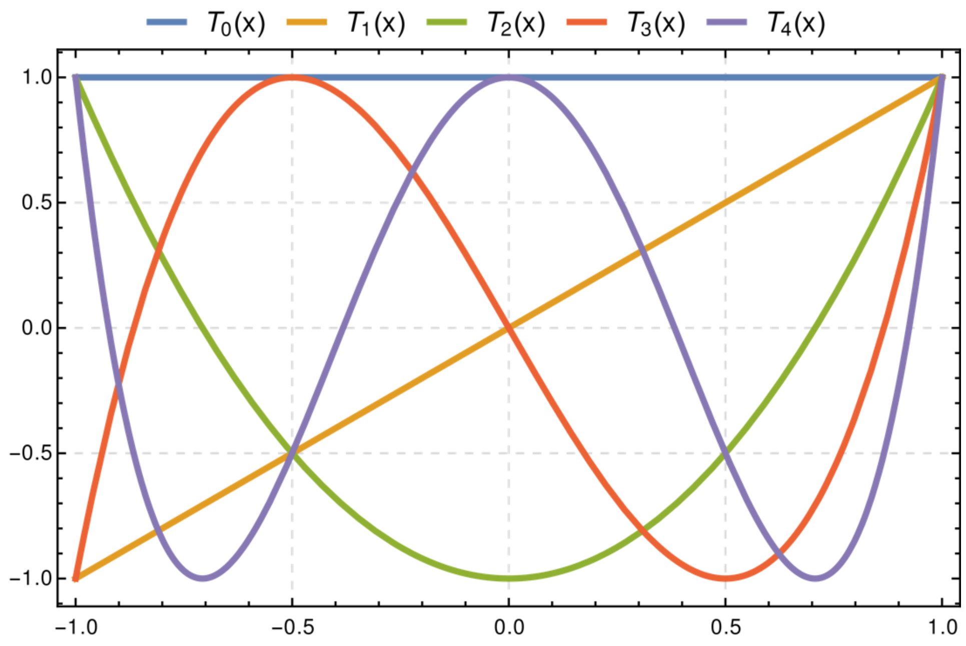

They provide orthonormal basis in some Sobolev space on [-1, 1]:

$$h(x) = \sum_{n=0}^{\infty} a_n T_n(x)$$

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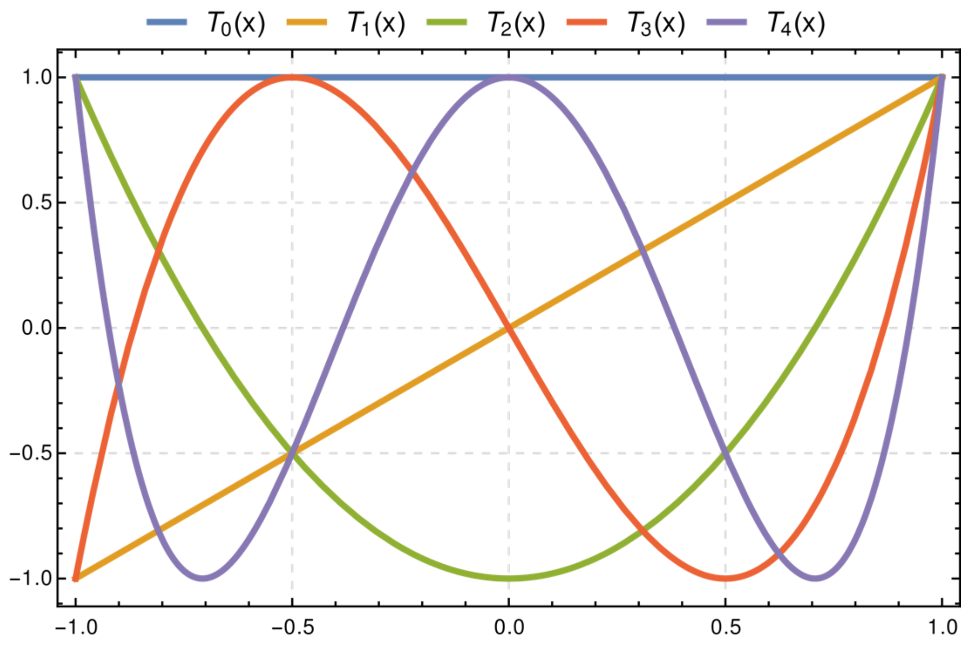

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$$h(x) = \sum_{n=0}^{\infty} a_n T_n(x)$$

$$\int_{-1}^{1} T_n(x)T_m(x)\frac{dx}{\sqrt{1-x^2}} = \begin{cases} 0 & \text{if } n \neq m \\ \pi & \text{if } n = m = 0 \\ \frac{\pi}{2} & \text{if } n = m \neq 0 \end{cases}$$

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Spectral Filters

Chebyshev expansion:

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Spectral Filters

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$$h_\theta * X = U h_\theta(\Lambda) U^\top X$$

Spectral Filters

Chebyshev expansion:

$$h(x) = \sum_{n=0}^{\infty} a_n T_n(x)$$

Spectral filtering:

$$h_\theta * X = U h_\theta(\Lambda) U^\top X$$

Truncated Chebyshev polynomials approximation:

$$h_\theta(\Lambda) \approx \sum_{n=0}^{K} \theta_n T_n(\tilde{\Lambda}) = \sum_{n=0}^{K} \theta_n T_n(\frac{2\Lambda}{\lambda_{\max}} - I)$$

Spectral Filters

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Spectral Filters

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Graph Convolution:

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Truncated Chebyshev polynomials based Graph Convolution:

$$\begin{aligned} h_\theta * X &= U h_\theta(\Lambda) U^\top X \\ &\approx U \left(\sum_{n=0}^{K} \theta_n T_n(\frac{2\Lambda}{\lambda_{\max}} - I) \right) U^\top X \end{aligned}$$

Spectral Filters

Recall we do not want explicit spectral decomposition since it is expensive!

$$h_\theta * X \approx U \left(\sum_{n=0}^{K} \theta_n T_n(\frac{2\Lambda}{\lambda_{\max}} - I) \right) U^\top X$$

Spectral Filters

Recall we do not want explicit spectral decomposition since it is expensive!

$$h_\theta * X \approx U\left(\sum_{n=0}^{K}\theta_n T_n(\frac{2\Lambda}{\lambda_{\max}} - I)\right)U^\top X$$

Are Chebyshev polynomials efficient?

Spectral Filters

Recall

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Let

$$T_n(\tilde{L}) = UT_n\left(\frac{2\Lambda}{\lambda_{\max}} - I\right)U^\top$$

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Let

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We have

$$\begin{aligned} T_0(\tilde{L}) &= I \\ T_1(\tilde{L}) &= U\left(\frac{2\Lambda}{\lambda_{\max}} - I\right)U^\top = 2L/\lambda_{\max} - I \\ T_{n+1}(\tilde{L}) &= U\left(2\left(\frac{2\Lambda}{\lambda_{\max}} - I\right)T_n\left(\frac{2\Lambda}{\lambda_{\max}} - I\right) - T_{n-1}\left(\frac{2\Lambda}{\lambda_{\max}} - I\right)\right)U^\top \\ &= 2U\left(\frac{2\Lambda}{\lambda_{\max}} - I\right)U^\top UT_n\left(\frac{2\Lambda}{\lambda_{\max}} - I\right)U^\top - UT_{n-1}\left(\frac{2\Lambda}{\lambda_{\max}} - I\right)U^\top \\ &= 2\left(\frac{2L}{\lambda_{\max}} - I\right)T_n(\tilde{L}) - T_{n-1}(\tilde{L}) \end{aligned}$$

Spectral Filters

Recall

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Spectral Filters

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We have
$$h_\theta * X \approx U\left(\sum_{n=0}^{K}\theta_n T_n(\frac{2\Lambda}{\lambda_{\max}} - I)\right)U^\top X$$
$$= \sum_{n=0}^{K}\theta_n T_n(\tilde{L})X$$

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$$h_\theta * X \approx U\left(\sum_{n=0}^{K}\theta_n T_n(\frac{2\Lambda}{\lambda_{\max}} - I)\right)U^\top X$$

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Let

$$T_0(\tilde{X}) = T_0(\tilde{L})X$$

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$$T_n(\tilde{L}) = UT_n\left(\frac{2\Lambda}{\lambda_{\max}} - I\right)U^\top$$

We have

$$h_\theta * X \approx U\left(\sum_{n=0}^{K}\theta_n T_n(\frac{2\Lambda}{\lambda_{\max}} - I)\right)U^\top X$$

$$= \sum_{n=0}^{K}\theta_n T_n(\tilde{L})X$$

Let

$$T_0(\tilde{X}) = T_0(\tilde{L})X$$

We have

$$T_0(\tilde{X}) = X$$

$$T_1(\tilde{X}) = 2LX/\lambda_{\max} - X$$

$$T_{n+1}(\tilde{X}) = 2\left(\frac{2L}{\lambda_{\max}} - I\right)T_n(\tilde{X}) - T_{n-1}(\tilde{X})$$

Spectral Filters

Truncated Chebyshev polynomials based Graph Convolution:

$$h_\theta * X \approx \sum_{n=0}^{K} \theta_n T_n(\tilde{X})$$

where

$$\begin{aligned} T_0(\tilde{X}) &= X \\ T_1(\tilde{X}) &= 2LX/\lambda_{\max} - X \\ T_{n+1}(\tilde{X}) &= 2\left(\frac{2L}{\lambda_{\max}} - I\right) T_n(\tilde{X}) - T_{n-1}(\tilde{X}) \end{aligned}$$

Spectral Filters

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What if we truncate to 1st order?

Spectral Filters

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What if we truncate to 1st order?

That is Graph Convolutional Networks (GCNs) [8] !

Outline

- Laplacian, Fourier Transforms, and Convolution
- Graph Laplacian, Graph Fourier Transforms, and Graph Convolution
- Spectral Filtering and Chebyshev Polynomials
- **Graph Convolutional Networks (GCNs)**
- Relation between GCNs and Message Passing Neural Networks (MPNNs)
- Spectral Graph Neural Networks

Graph Convolutional Networks (GCNs)

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Graph Convolutional Networks (GCNs)

Truncated Chebyshev polynomials based Graph Convolution:

$$h_\theta * X \approx \sum_{n=0}^{K} \theta_n T_n(\tilde{X})$$

$$h_\theta * X \approx \theta_0 X + \theta_1 T_1(\tilde{X})$$

$$T_0(\tilde{X}) = X$$

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We can use the normalize graph Laplacian so that its eigenvalues are in [0, 2]

$$L = I - D^{-\frac{1}{2}} A D^{-\frac{1}{2}}$$

Graph Convolutional Networks (GCNs)

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Assuming $\lambda_{\max} \approx 2$

$$\begin{aligned} h_\theta * X &\approx \theta_0 X + \theta_1 T_1(\tilde{X}) \\ &\approx \theta_0 X - \theta_1 D^{-\frac{1}{2}} A D^{-\frac{1}{2}} X \end{aligned}$$

Graph Convolutional Networks (GCNs)

Simplified Truncated Chebyshev polynomials based Graph Convolution:

$$
\begin{aligned}
h_\theta * X &\approx \theta_0 X + \theta_1 T_1(\tilde{X}) \\
&\approx \theta_0 X - \theta_1 D^{-\frac{1}{2}} A D^{-\frac{1}{2}} X \\
&= \theta \left(I + D^{-\frac{1}{2}} A D^{-\frac{1}{2}} \right) X
\end{aligned}
$$

Graph Convolutional Networks (GCNs)

Simplified Truncated Chebyshev polynomials based Graph Convolution:

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Graph Convolutional Networks (GCNs)

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$$I + D^{-\frac{1}{2}} A D^{-\frac{1}{2}}$$

eigenvalues are in [0, 2]

⇨

$$\tilde{D}^{-\frac{1}{2}} (A + I) \tilde{D}^{-\frac{1}{2}}$$

$$\tilde{D}_{ii} = \sum_j (A + I)_{ij}$$

eigenvalues are in [-1, 1]

Graph Convolutional Networks (GCNs)

Simplified Truncated Chebyshev polynomials based Graph Convolution:

$$
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h_\theta * X &\approx \theta_0 X + \theta_1 T_1(\tilde{X}) \\
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&= \theta \left(I + D^{-\frac{1}{2}} A D^{-\frac{1}{2}} \right) X
\end{aligned}
$$

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⇨

$$\tilde{D}^{-\frac{1}{2}} (A + I) \tilde{D}^{-\frac{1}{2}}$$

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eigenvalues are in [-1, 1]

Final Form of Graph Convolution: $h_\theta * X \approx \theta \tilde{D}^{-\frac{1}{2}} (A + I) \tilde{D}^{-\frac{1}{2}} X$

Graph Convolutional Networks (GCNs)

Graph convolution in GCNs for 1D graph signal:

$$h_\theta * X \approx \theta \tilde{D}^{-\frac{1}{2}}(A+I)\tilde{D}^{-\frac{1}{2}}X$$

Graph Convolutional Networks (GCNs)

Graph convolution in GCNs for 1D graph signal:

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Generalize to multi-input and multi-output convolution:

$$\begin{aligned} h_W * X &\approx \tilde{D}^{-\frac{1}{2}}(A+I)\tilde{D}^{-\frac{1}{2}}XW \\ &= \tilde{L}XW \end{aligned}$$

Graph Convolutional Networks (GCNs)

Graph convolution in GCNs for 1D graph signal:

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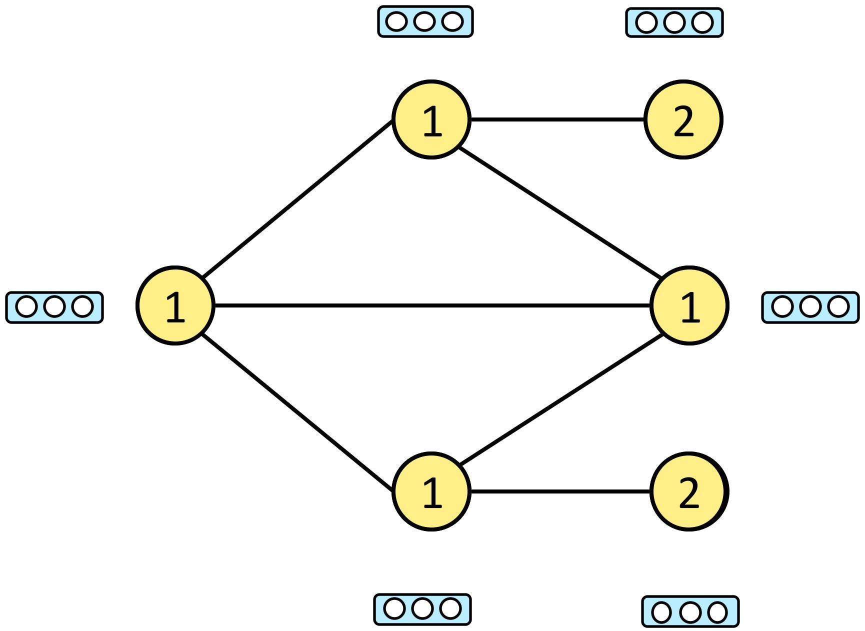
$$\begin{aligned} h_W * X &\approx \tilde{D}^{-\frac{1}{2}}(A+I)\tilde{D}^{-\frac{1}{2}}XW \\ &= \tilde{L}XW \end{aligned}$$

Add nonlinearity: $\sigma\left(h_W * X\right) \approx \sigma\left(\tilde{L}XW\right)$

Graph Convolutional Networks (GCNs)

Our Spectral Filters are Localized:

$$\tilde{L} = \tilde{D}^{-\frac{1}{2}}(A+I)\tilde{D}^{-\frac{1}{2}}$$



1-step Graph Convolution: $h_W * X \approx \tilde{L}XW$

2-step Graph Convolution: $h_{W_2} * h_{W_1} * X \approx \tilde{L}^2 X W_1 W_2$

$\vdots$

Exponent of matrix power indicates how far the propagation is!

Graph Convolutional Networks (GCNs)

- We start with Chebyshev Polynomials which can represent any spectral filters (eigenvalues in [-1, 1])

$$h(x) = \sum_{n=0}^{\infty} a_n T_n(x)$$

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- Further simplification/approximation

$$h_\theta * X \approx \theta \tilde{D}^{-\frac{1}{2}}(A+I)\tilde{D}^{-\frac{1}{2}} X$$
$$h_W * X \approx \tilde{L} X W$$

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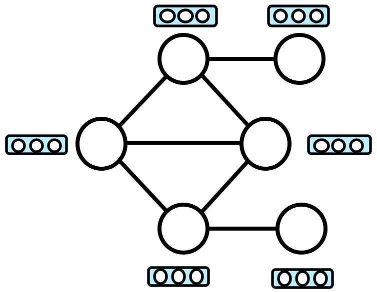
- Further simplification/approximation

$$h_\theta * X \approx \theta \tilde{D}^{-\frac{1}{2}}(A + I)\tilde{D}^{-\frac{1}{2}} X$$
$$h_W * X \approx \tilde{L} X W$$

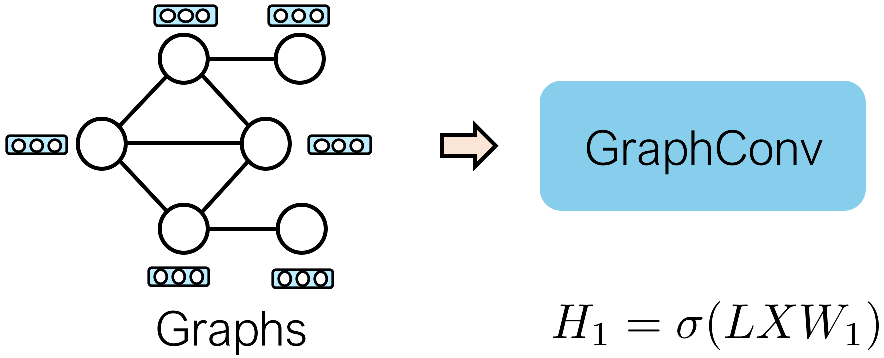
We can remedy the lost expressiveness by stacking multiple graph convolution layers!

Graph Convolutional Networks (GCNs)



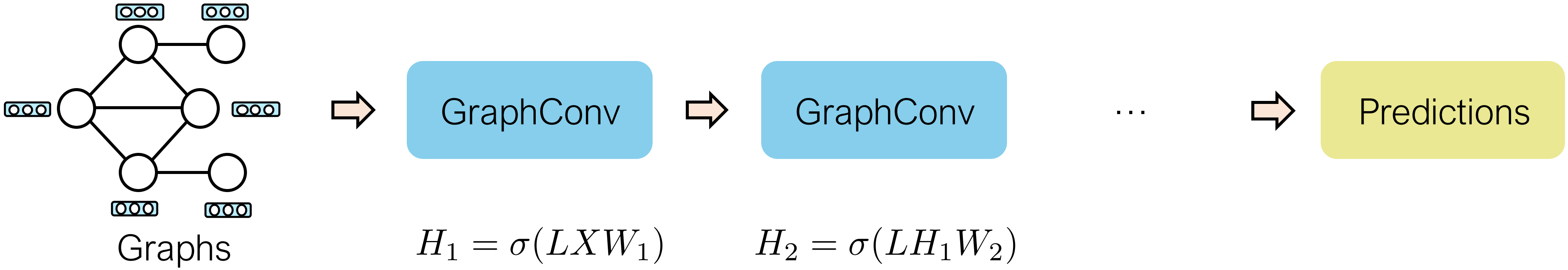
Graphs

Graph Convolutional Networks (GCNs)



$$H_1 = \sigma(LXW_1)$$

Graph Convolutional Networks (GCNs)



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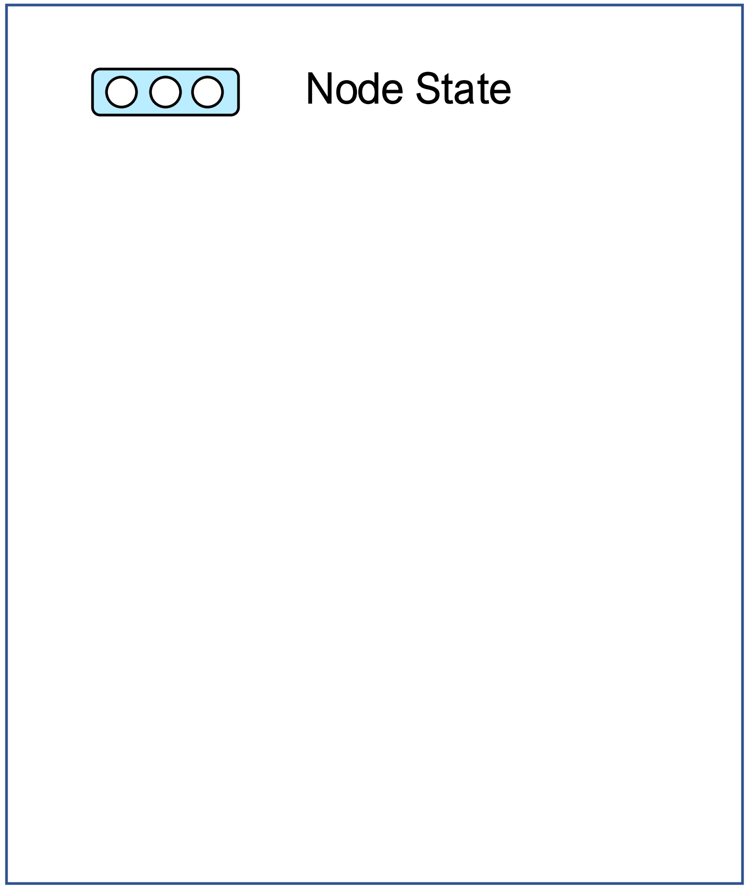
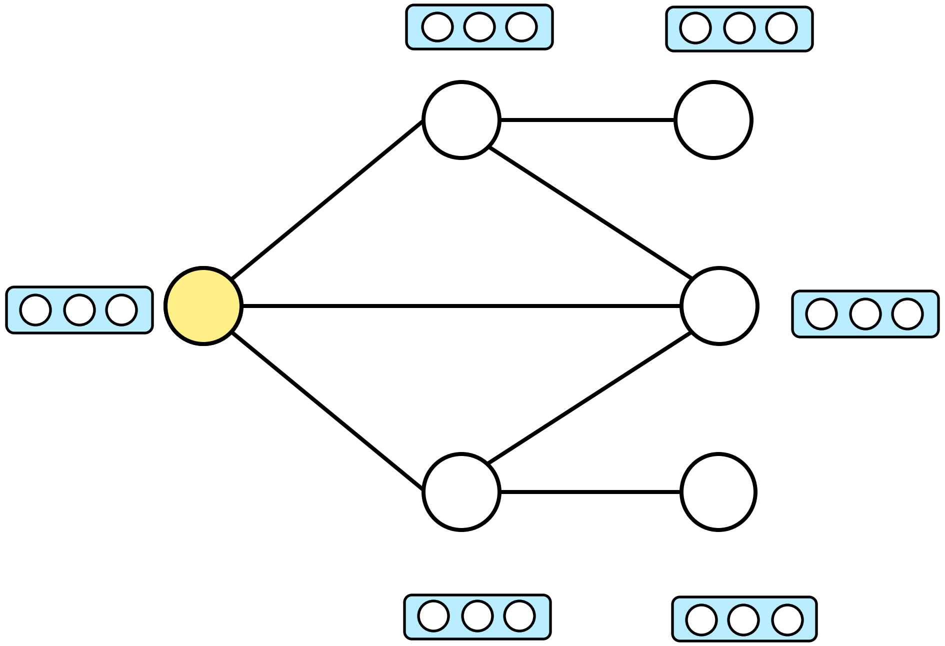
Message Passing GNNs

$\mathbf{h}_i^t$

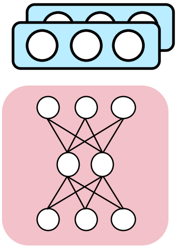


(t+1)-th message passing step/layer



Message Passing GNNs

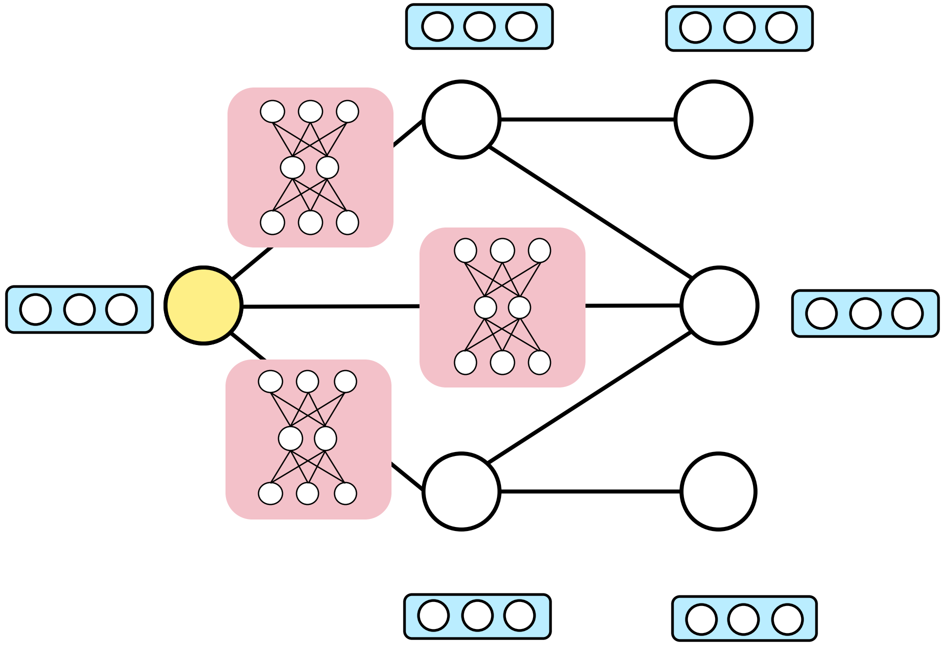
$\mathbf{h}_i^t \quad \mathbf{h}_j^t$



Node State

Message Network

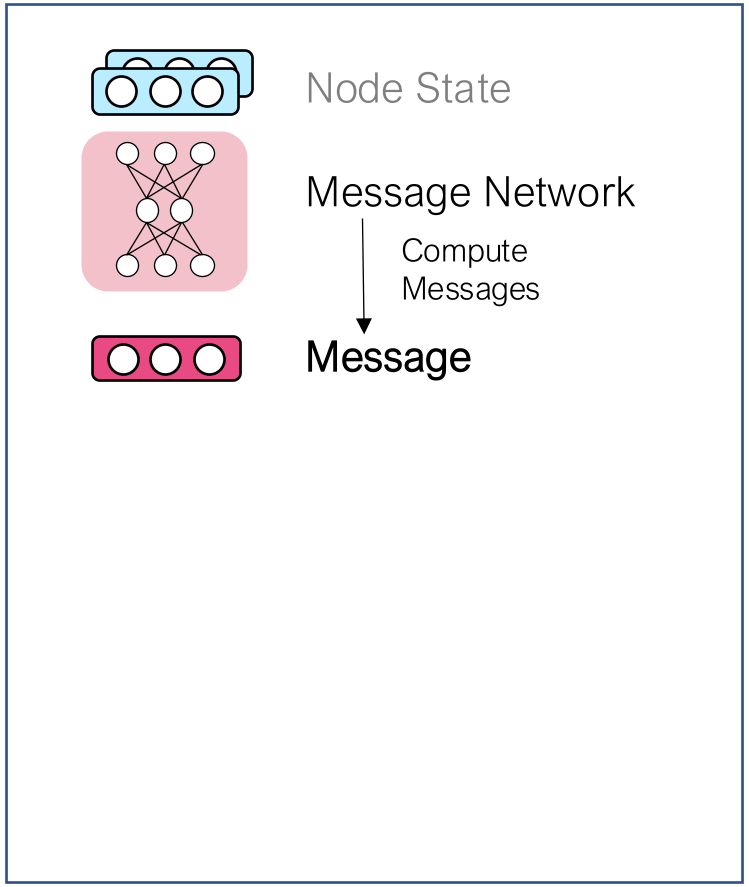
(t+1)-th message passing step/layer



Message Passing GNNs

$\mathbf{h}_i^t \quad \mathbf{h}_j^t$

$$\mathbf{m}_{ji}^t = f_{\text{msg}}(\mathbf{h}_j^t, \mathbf{h}_i^t)$$



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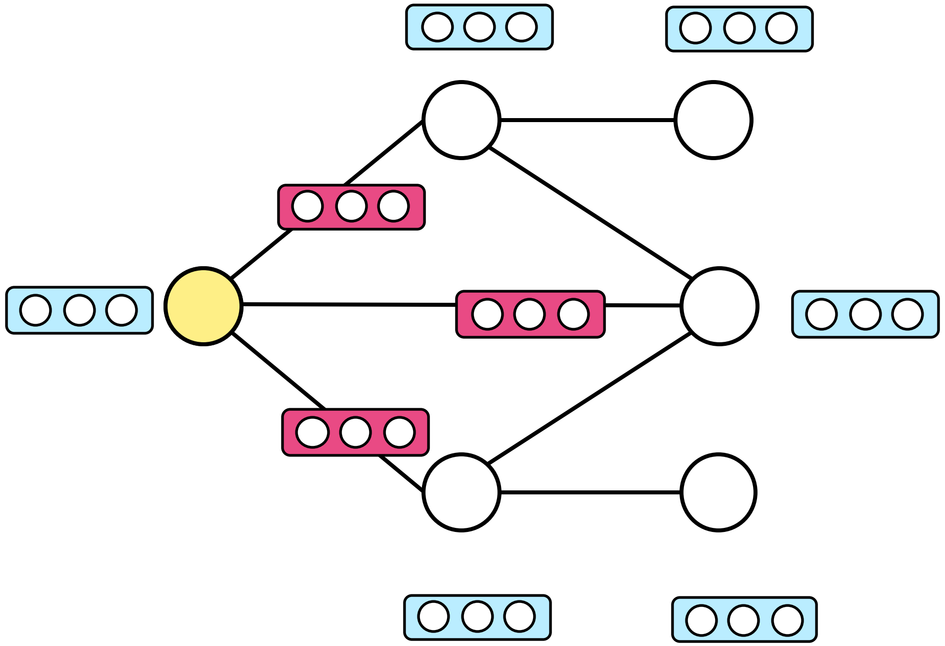

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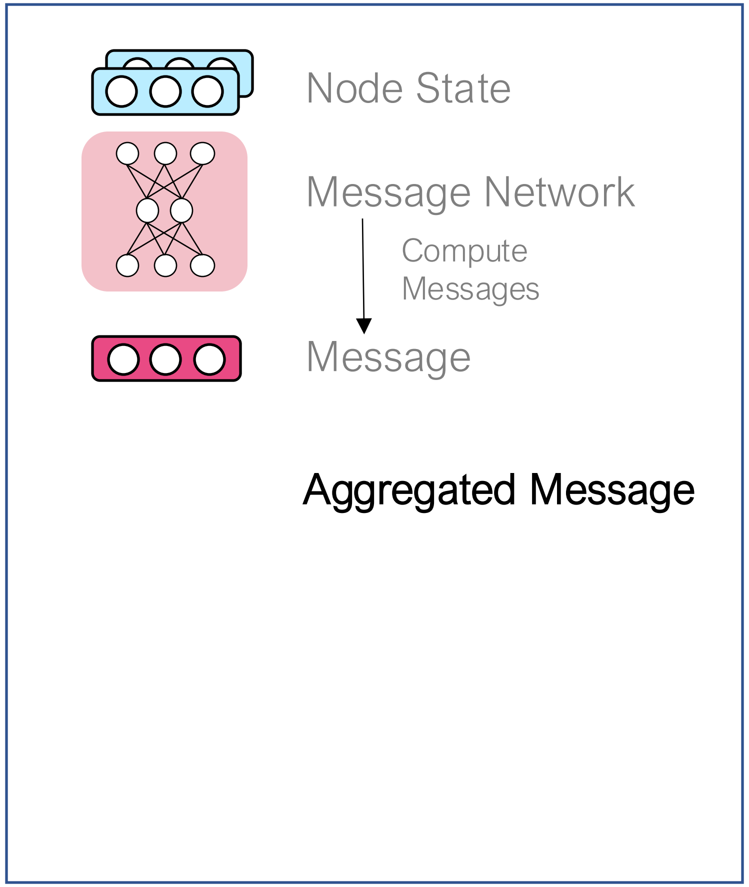

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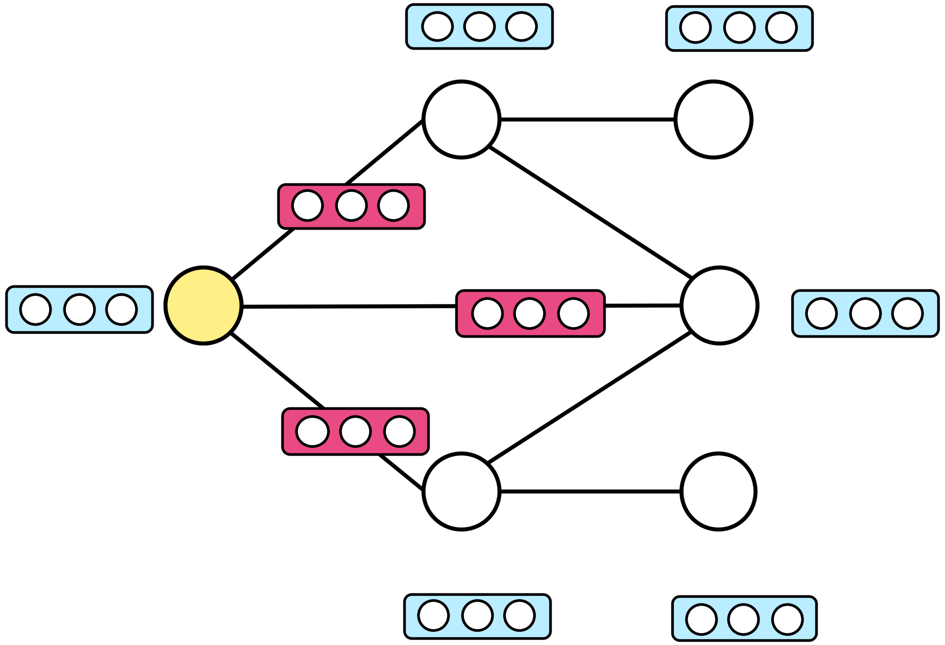
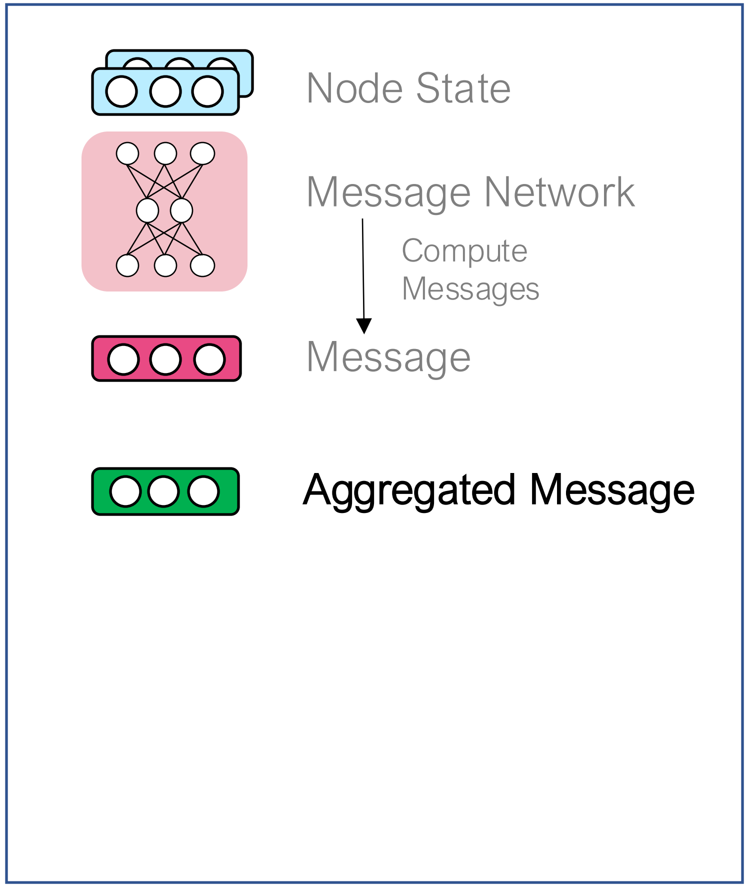


Message Passing GNNs

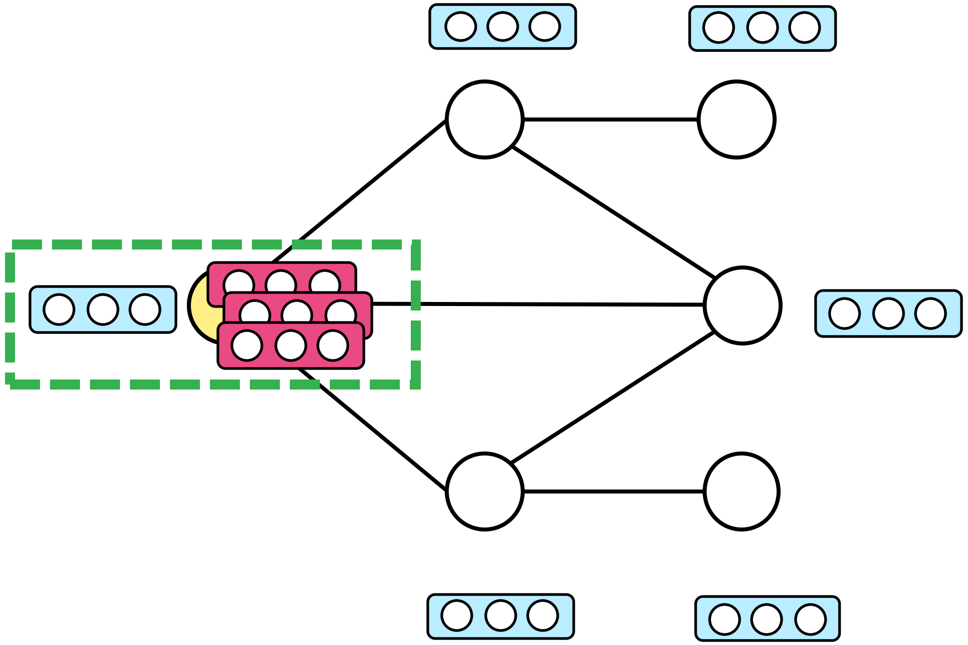
$\mathbf{h}_i^t \quad \mathbf{h}_j^t$

$$\mathbf{m}_{ji}^t = f_{\text{msg}}(\mathbf{h}_j^t, \mathbf{h}_i^t)$$

$$\bar{\mathbf{m}}_i^t = f_{\text{agg}}\left(\{\mathbf{m}_{ji}^t | j \in \mathcal{N}_i\}\right)$$



(t+1)-th message passing step/layer



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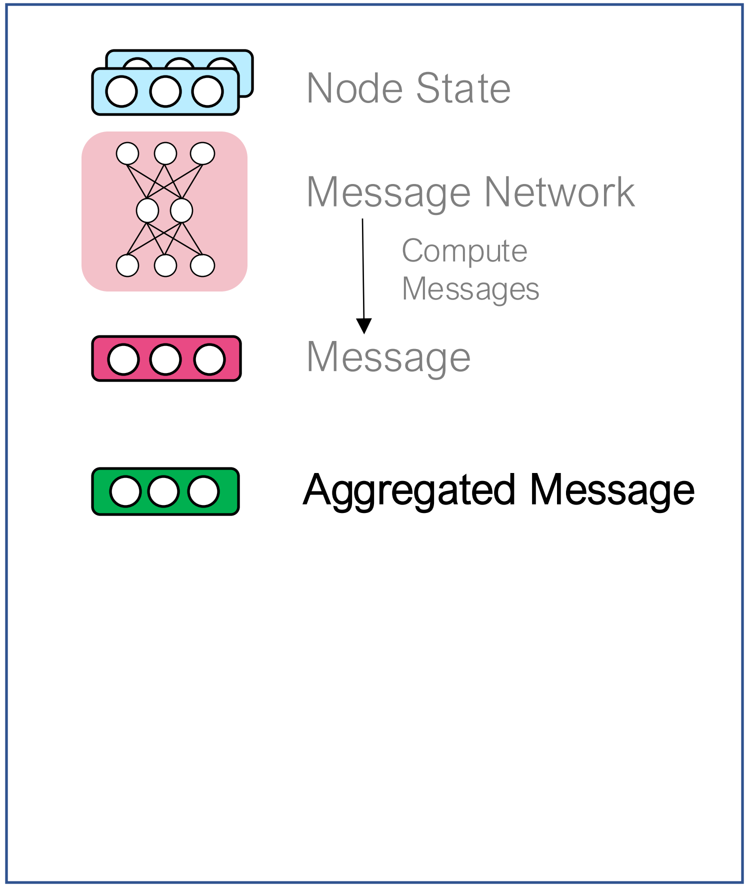

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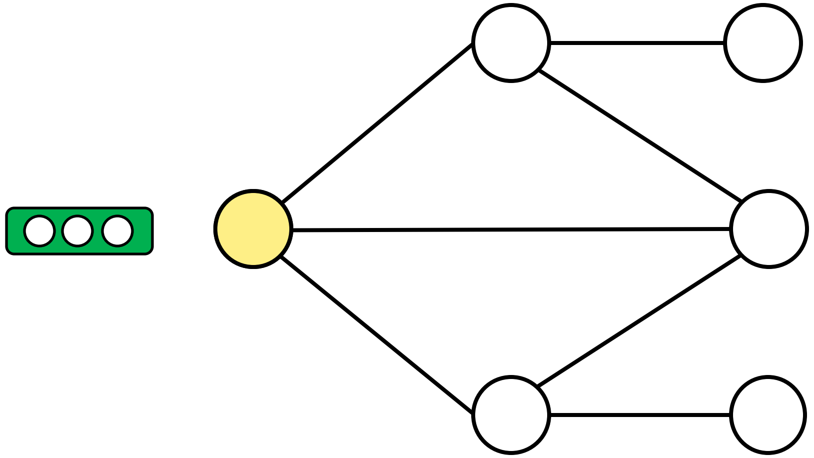

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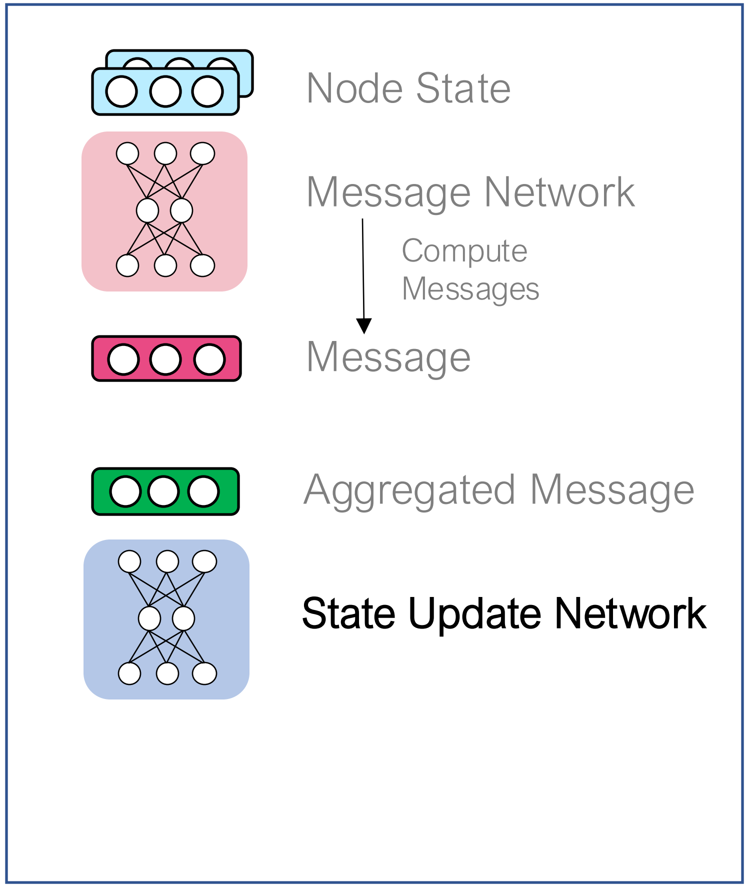

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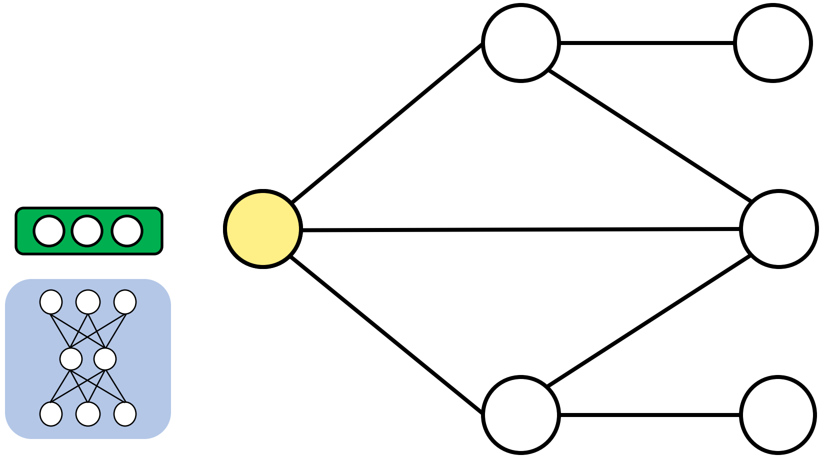

Message Passing GNNs

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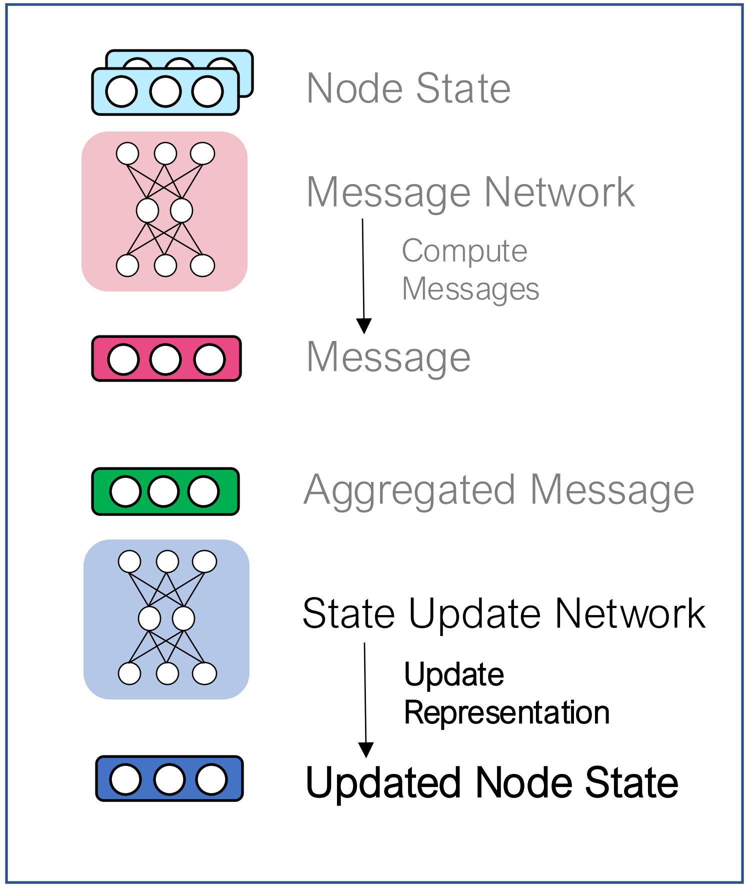
$$\mathbf{h}_i^{t+1} = f_{\text{update}}(\mathbf{h}_i^t, \bar{\mathbf{m}}_i^t)$$



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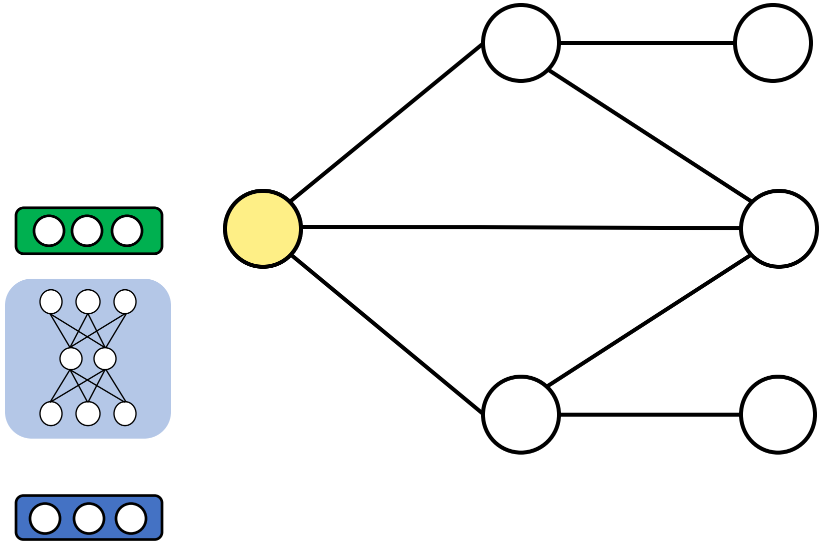

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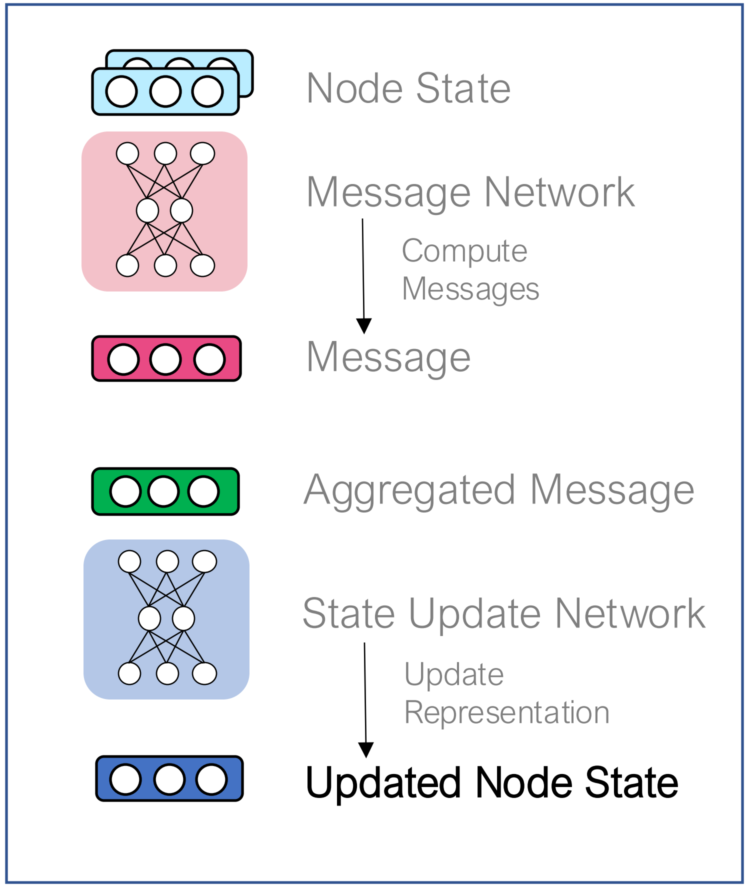

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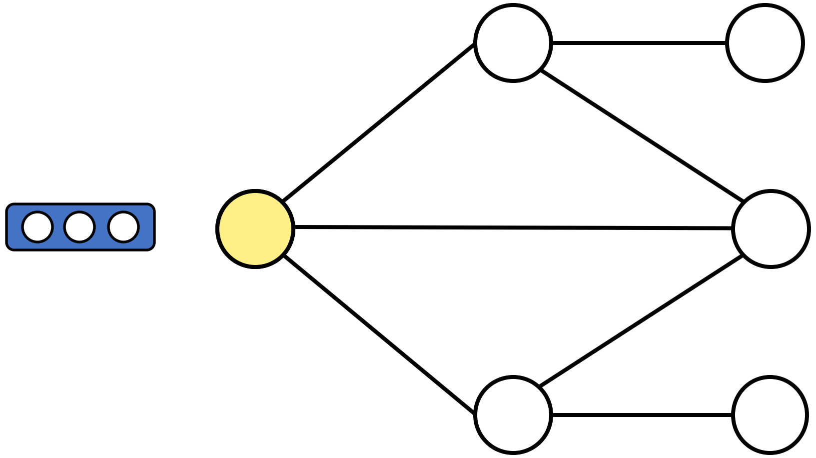
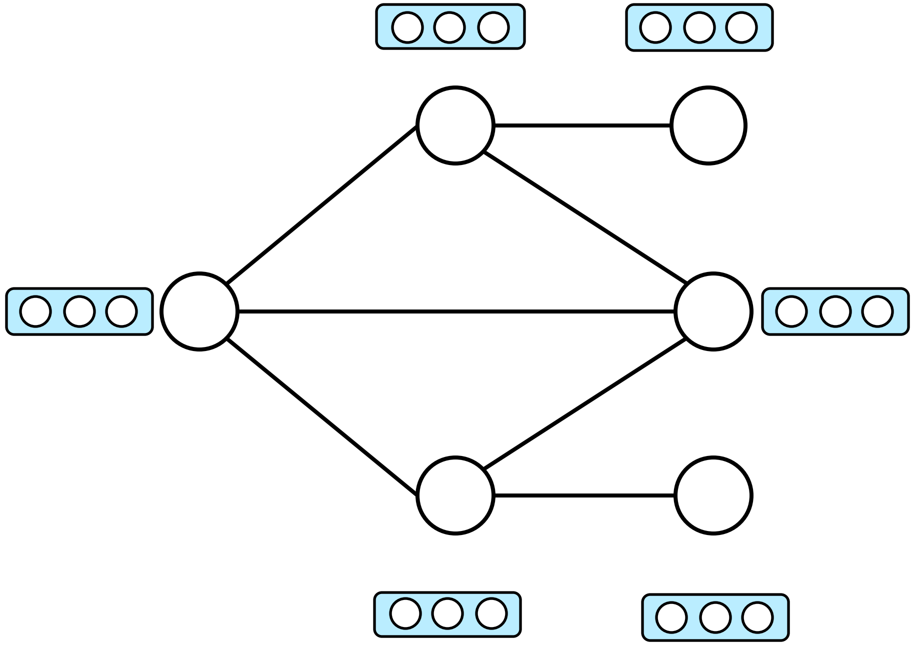
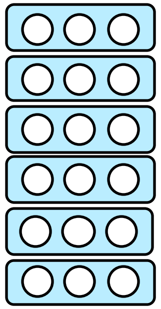


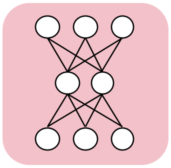
GCNs are Message Passing Networks



- Node State X

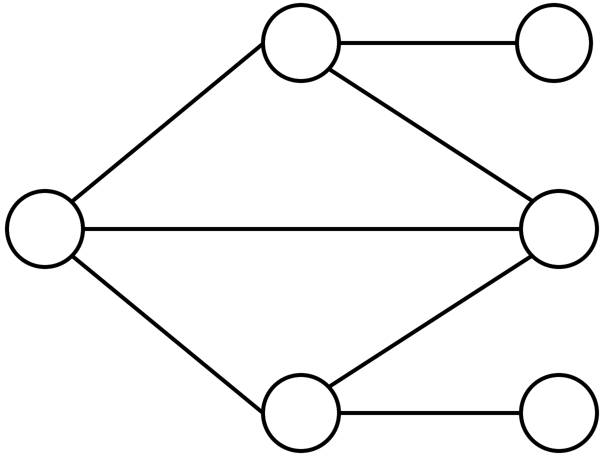


- Graph Laplacian



$$\tilde{L} = \tilde{D}^{-\frac{1}{2}}(A + I)\tilde{D}^{-\frac{1}{2}}$$

GCNs are Message Passing Networks



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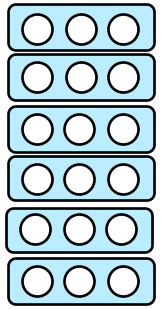
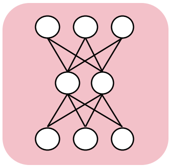
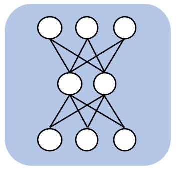


- Graph Laplacian

$$\tilde{L} = \tilde{D}^{-\frac{1}{2}}(A+I)\tilde{D}^{-\frac{1}{2}}$$



- Aggregated Message LX
- State Update Network W



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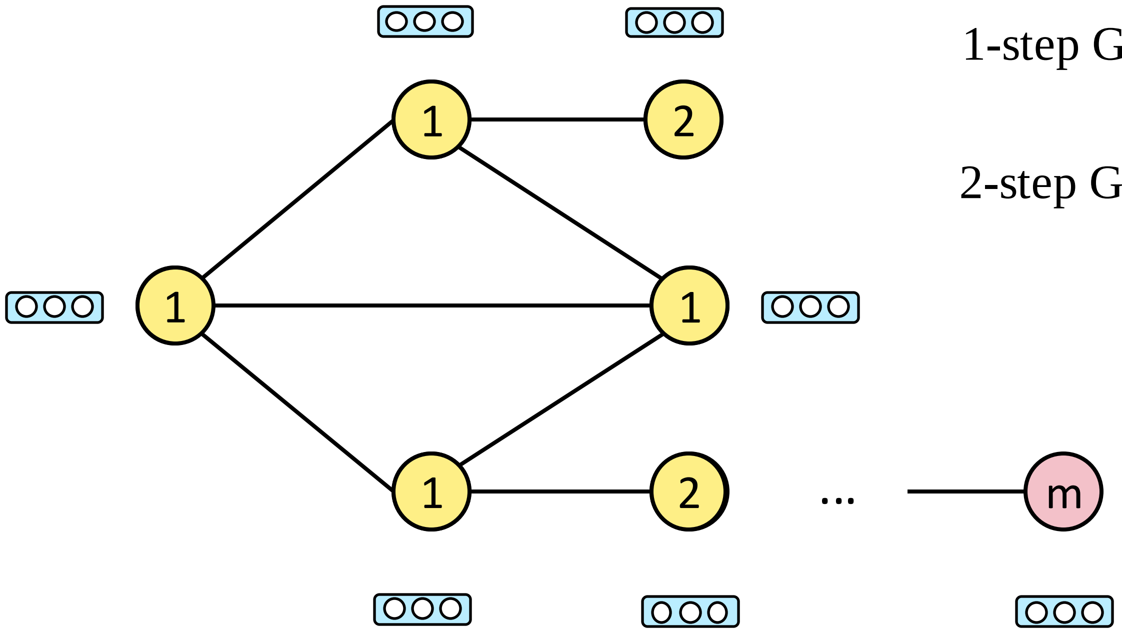
Revisit Spectral Filtering

Our Spectral Filters are Localized:

$$\tilde{L} = \tilde{D}^{-\frac{1}{2}}(A+I)\tilde{D}^{-\frac{1}{2}}$$



1-step Graph Convolution: $h_W * X \approx \tilde{L}XW$

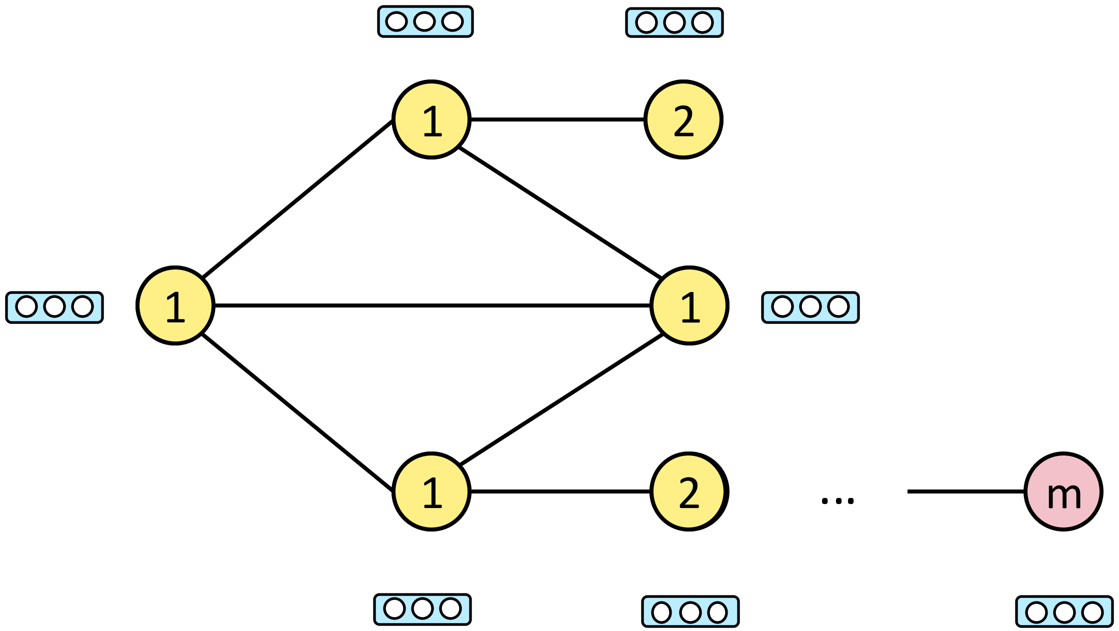
2-step Graph Convolution: $h_{W_2} * h_{W_1} * X \approx \tilde{L}^2 X W_1 W_2$

What if the graph diameter m is large?

Revisit Spectral Filtering

Our Spectral Filters are Localized:

m-step Graph Convolution: $h_W * X \approx \tilde{L}^m X W$



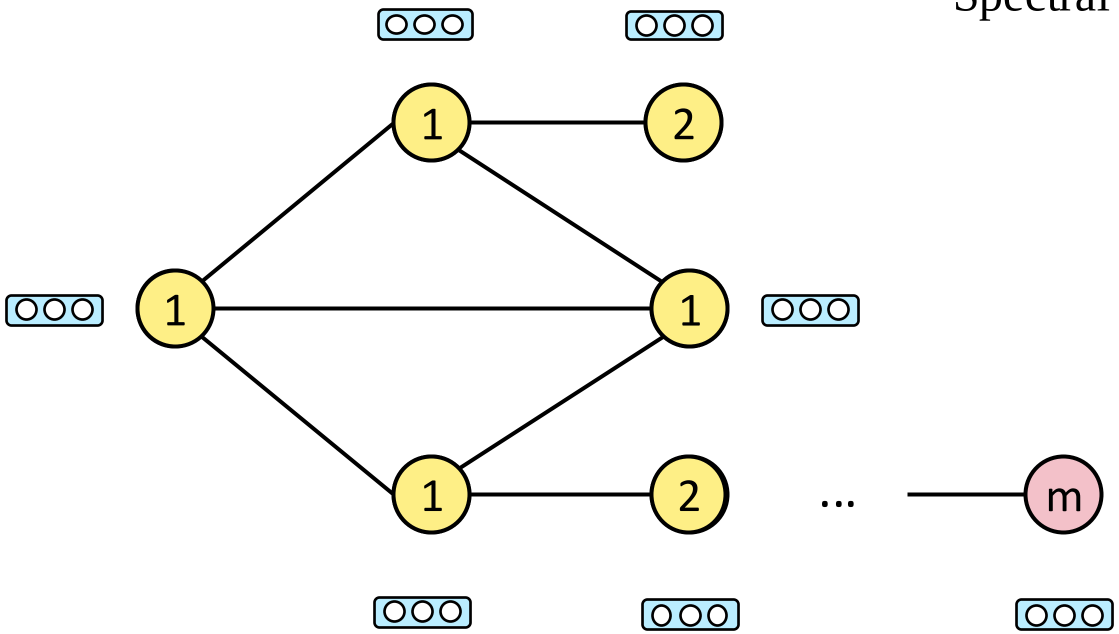
Revisit Spectral Filtering

Our Spectral Filters are Localized:

m-step Graph Convolution: $h_W * X \approx \tilde{L}^m X W$

Spectral Decomposition: $\tilde{L} = U \Lambda U^\top$

$\tilde{L}^m = U \Lambda^m U^\top$



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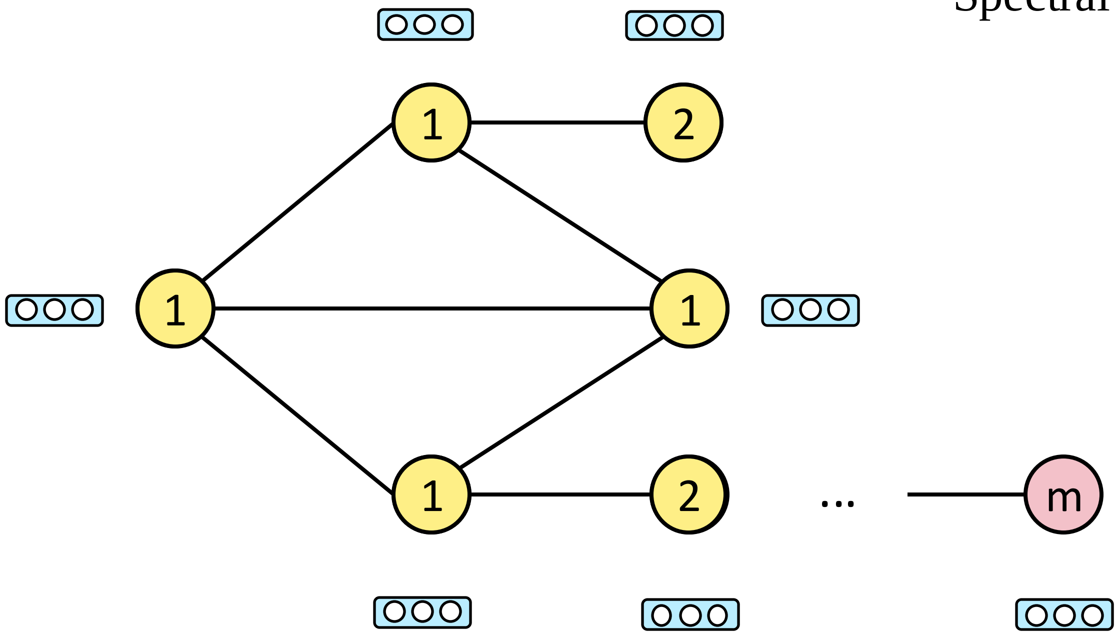


m-step Graph Convolution: $h_W * X \approx \tilde{L}^m XW$

Spectral Decomposition: $\tilde{L} = U \Lambda U^\top$

$$\tilde{L}^m = U \Lambda^m U^\top$$

Cubic complexity O(N^3) !

Lanczos Algorithm

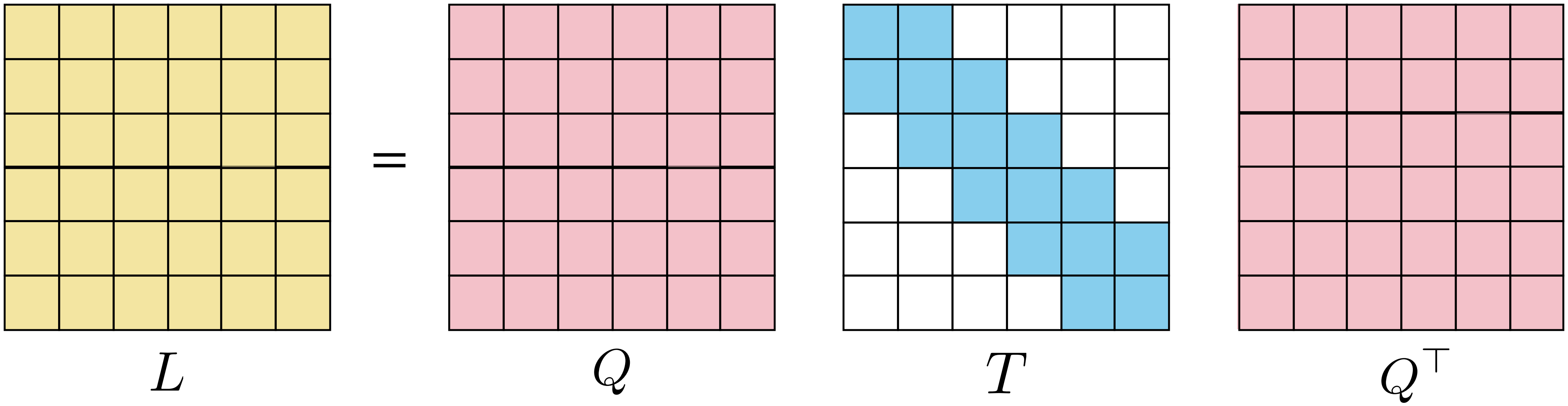
Algorithm 1 : Lanczos Algorithm

```
Input: S, x, K, ε
Initialization: β_0 = 0, q_0 = 0, and q_1 = x/‖x‖
For j = 1, 2, ..., K:
        z = S q_j
        γ_j = q_j^⊤ z
        z = z − γ_j q_j − β_{j−1} q_{j−1}
        β_j = ‖z‖_2
        If β_j < ε, quit
        q_{j+1} = z/β_j

Q = [q_1, q_2, ···, q_K]
Construct T following Eq. (2)
Eigen decomposition T = B R B^⊤
Return V = QB and R.
```

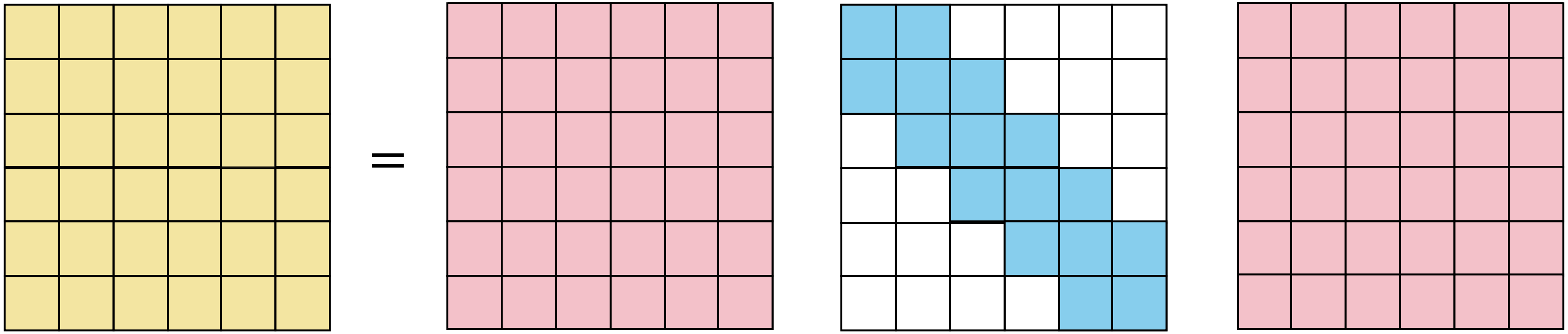
Lanczos Algorithm

Tridiagonal Decomposition $L = QTQ^\top$



Lanczos Algorithm

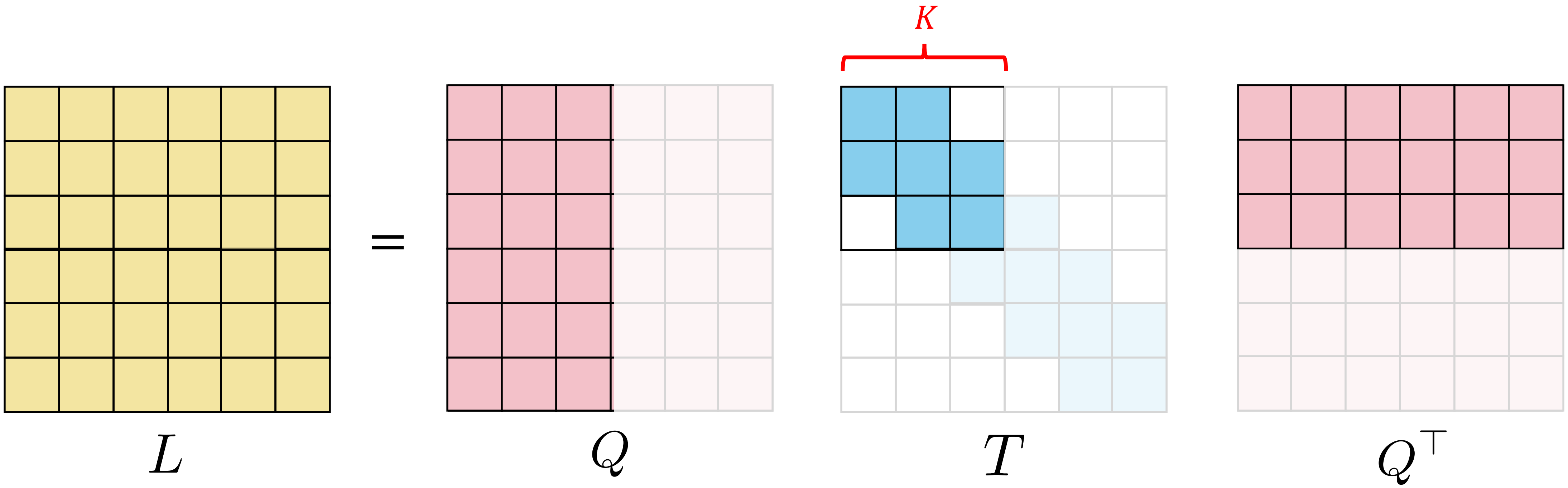
Tridiagonal Decomposition $L = QTQ^\top$



L Q T $Q^\top$

Lanczos Algorithm

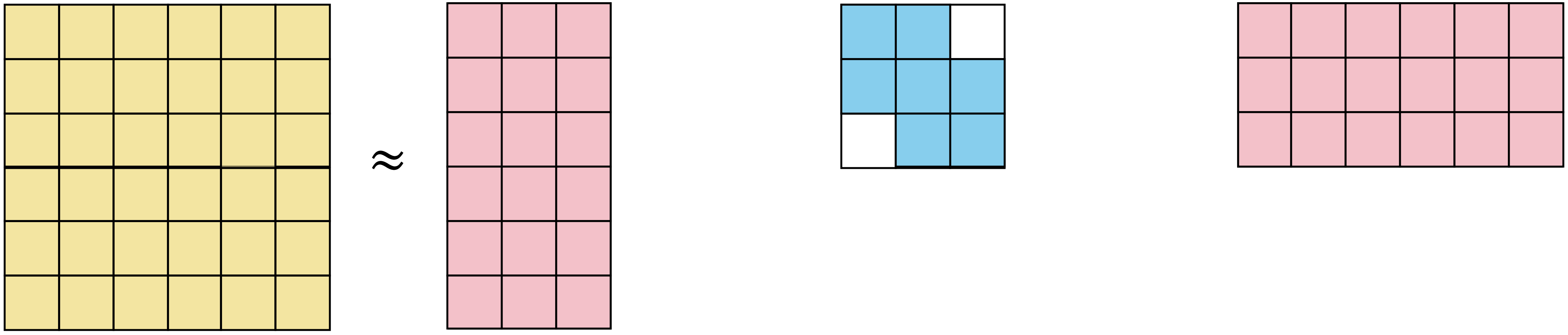
Tridiagonal Decomposition $L = QTQ^{\top}$



Lanczos Algorithm

Tridiagonal Decomposition $\qquad L = QTQ^\top$

Low-rank approximation

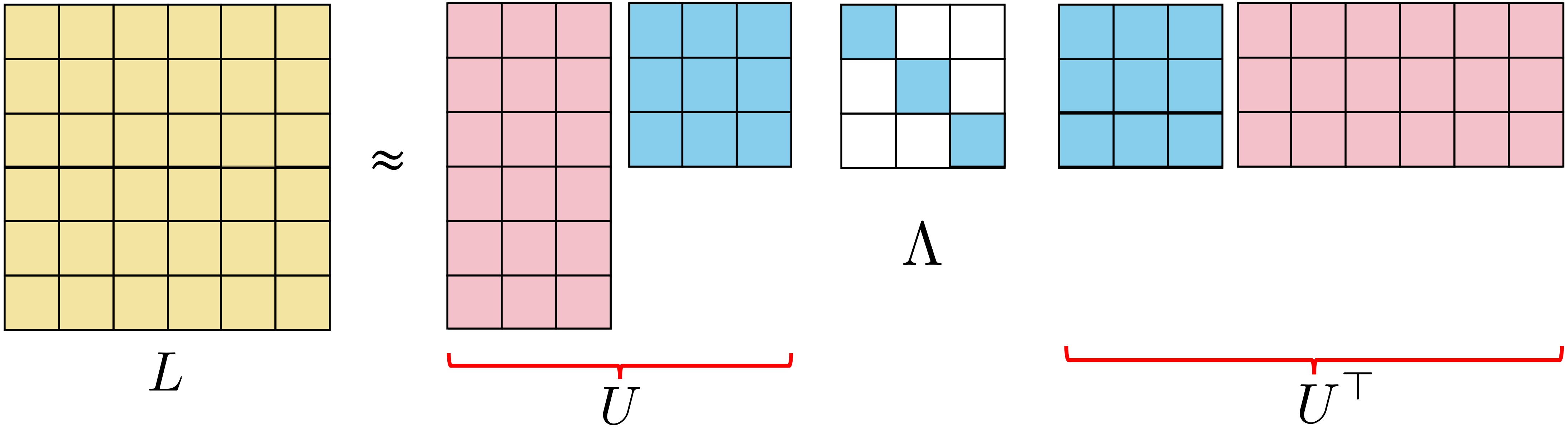


$L \approx Q \quad T \quad Q^\top$

Lanczos Algorithm

Tridiagonal Decomposition $L = QTQ^\top$

Low-rank approximation with **top K eigenpairs**



$O(N^3)$ → $O(KN^2)$

Multi-scale Graph Convolutional Networks

- m-step GraphConv (Prior Work) $H = L^m XW$

LanczosNet [9]:

- m-step GraphConv $H = U \Lambda^m U^\top XW$
- Learn Nonlinear Spectral Filter $H = U f_\theta (\Lambda^m) U^\top XW$
- Learning Graph Kernel / Metric $L_{ij} \propto \exp\left(-\|(X_i - X_j) M\|^2\right)$

SignNet

Eigenvectors of graph Laplacian are shown to be powerful node features, e.g., [10].

However, the sign-change of eigenvectors leaves the eigenspace unchanged. In other words, we need a network that is invariant to the sign-change. SingNet [11] does the job!

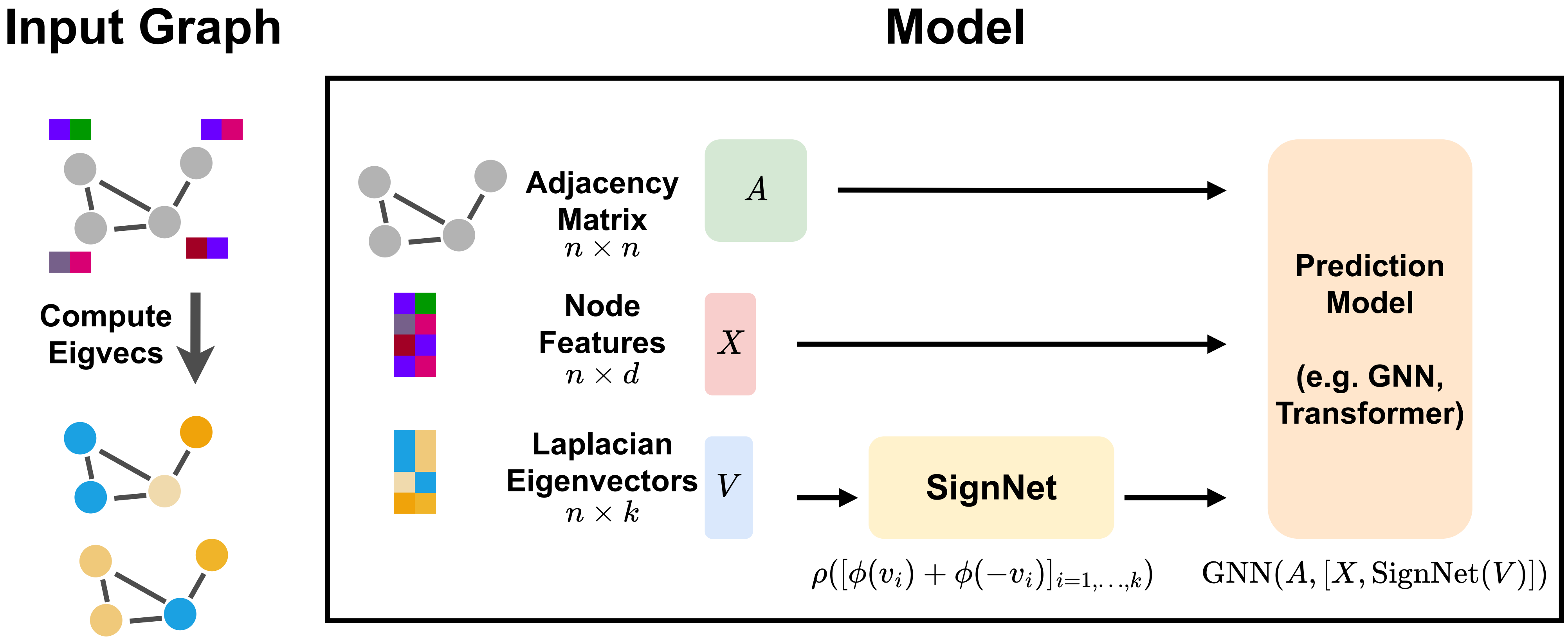


Image Credit: [11]

SignNet

The variant of SingNet [11], called BasisNet [11], is also invariant to the change of basis of the eigenspaces:

$$f(V_1, \ldots, V_l) = f(V_1 Q_1, \ldots, V_l Q_l),$$
$$Q_i \in O(d_i)$$

In particular, the model has the form:

$$f(V_1, \ldots, V_l) = \rho\left([\phi_{d_i}(V_i V_i^\top)]_{i=1}^l\right)$$

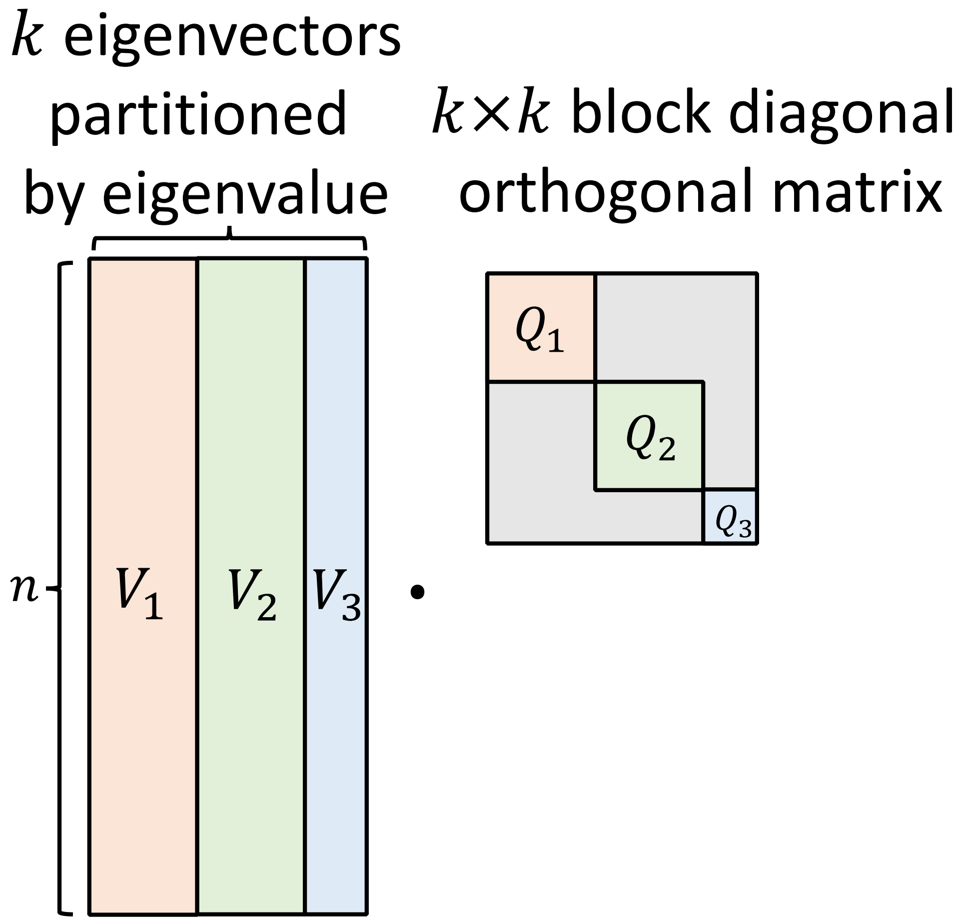
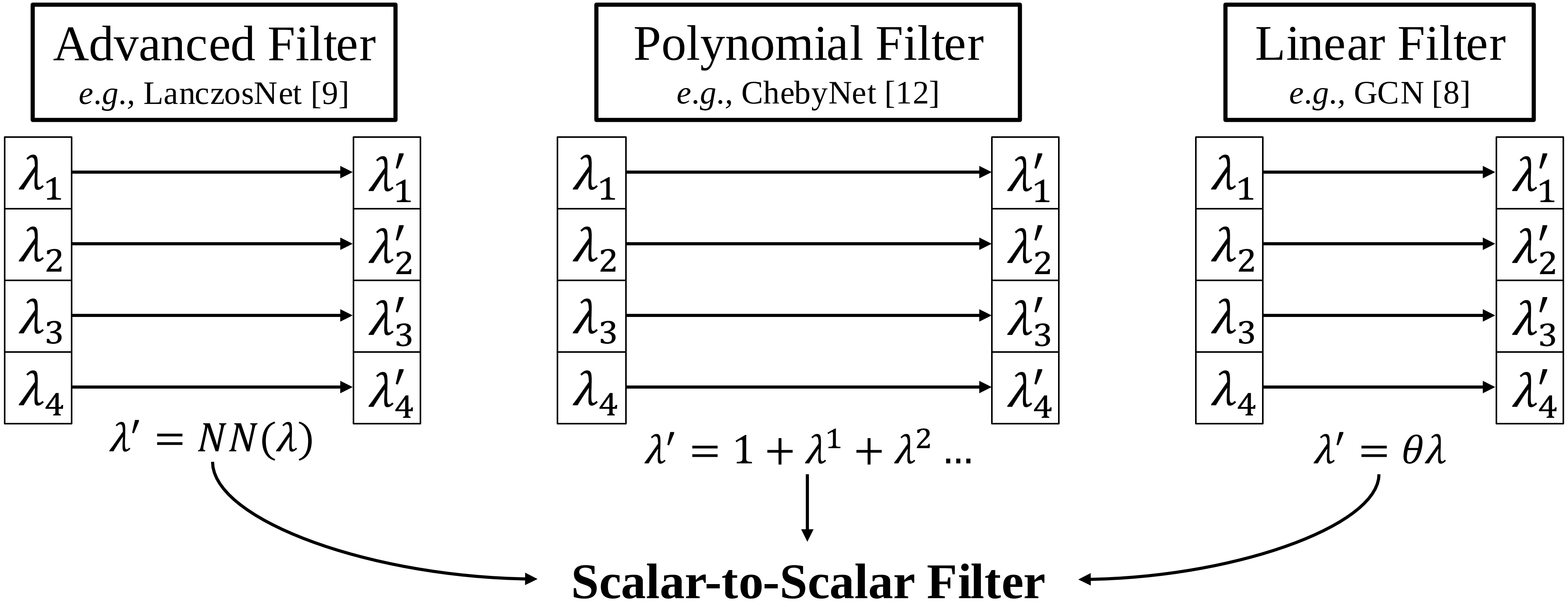


Image Credit: [11]

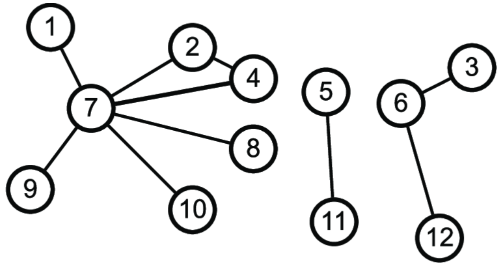
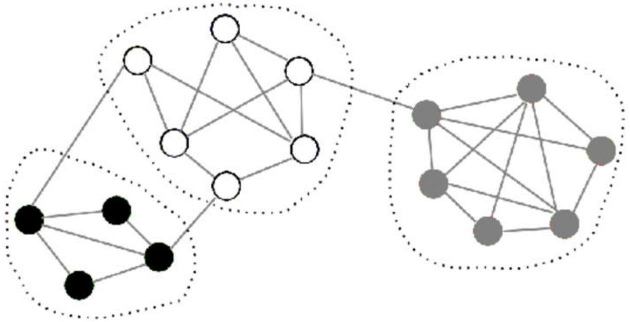
Specformer

Previous work employ scalar-to-scalar spectral filters



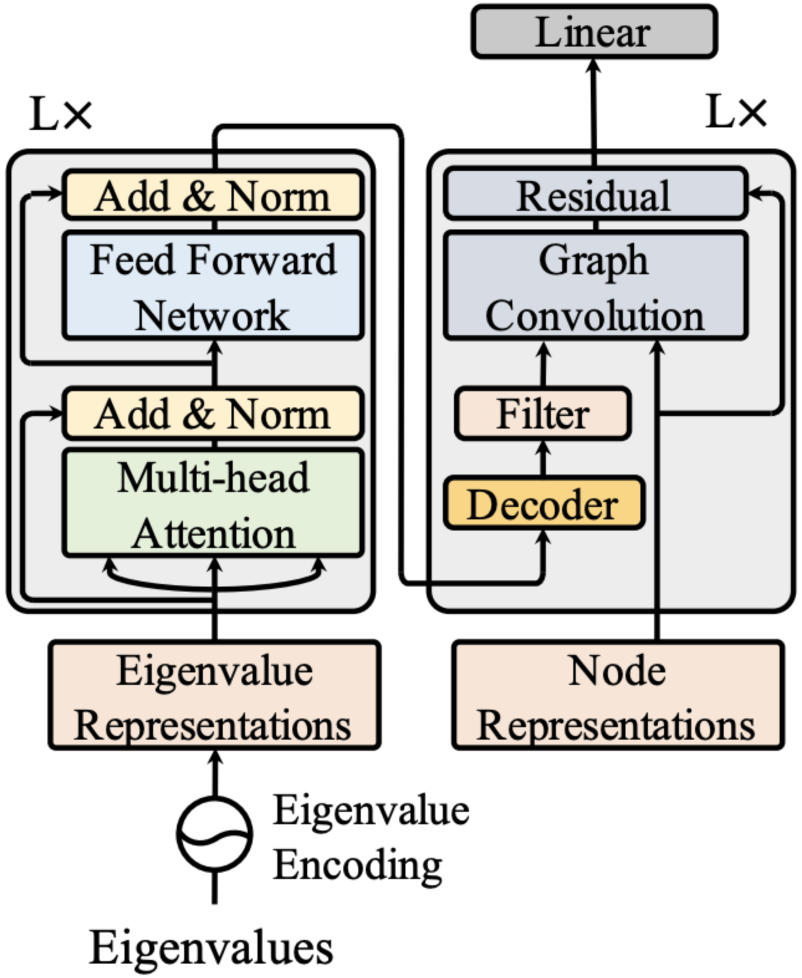
Specformer

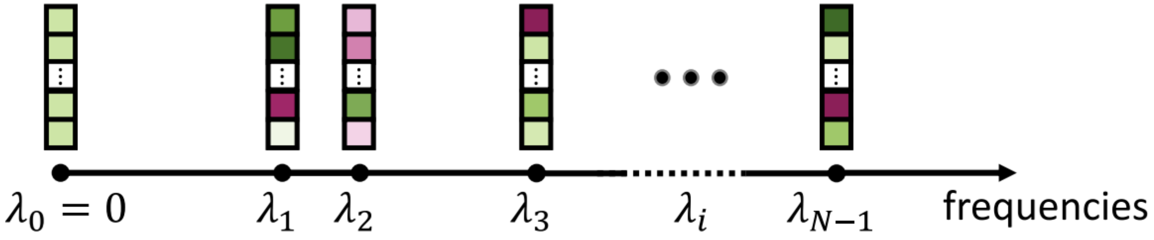
Previous work employ scalar-to-scalar spectral filters, which may fail to capture global graph properties.

Spectrum Information	Example	Definition	Scalar Input	Set Input
Algebraic Connectivity		$\text{Count}(\lambda = 0)$	✗	✓
Diameter		$[\frac{4}{n\lambda_2}, \frac{1}{2m\lambda_1}]$	✗	✓
Clusterability		$\lambda_2 - \lambda_1$ $(\lambda_1 \neq \lambda_2 \neq 0)$	✗	✓

Specformer

Instead of employing scalar-to-scalar spectral filters, Specformer [13] uses set-to-set spectral filters:





$$\rho(\lambda, 2i) = \sin\left(\epsilon\lambda / 10000^{2i/d}\right)$$
$$\rho(\lambda, 2i+1) = \cos\left(\epsilon\lambda / 10000^{2i/d}\right)$$

Due to the eigenvalue encoding, the spectral filter is permutation invariant!

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Questions?