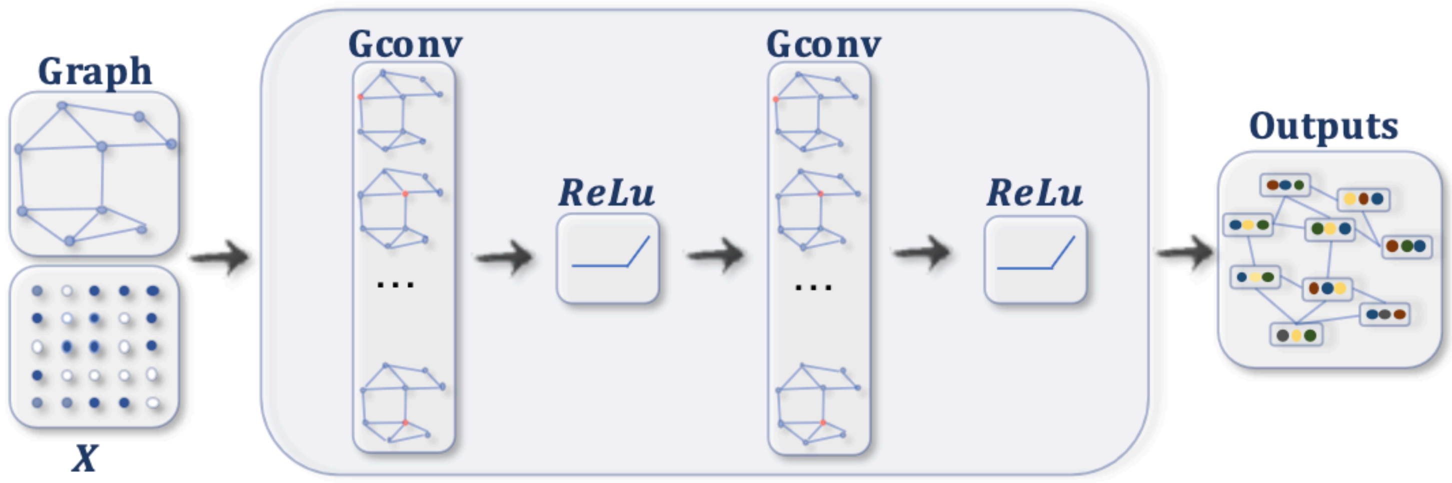
Graph Neural Networks with Diverse Spectral Filtering

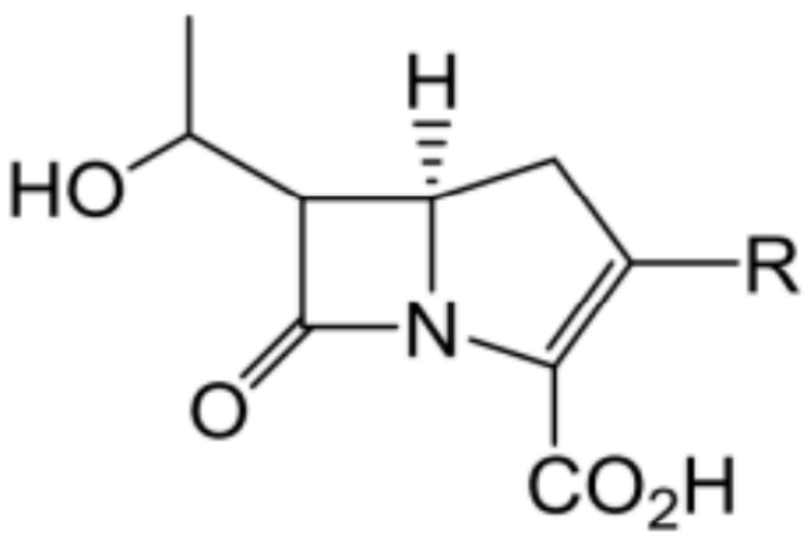



Jingwei Guo, Kaizhu Huang, Xinping Yi, Rui Zhang

Learning from Graph Structure Data



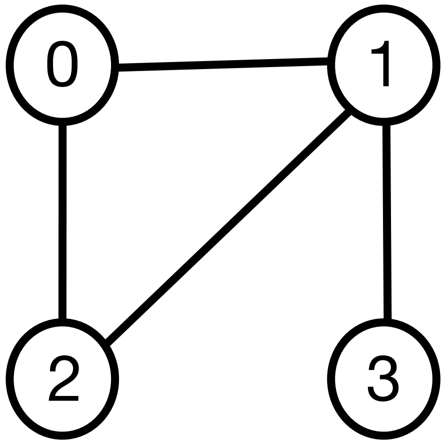
Graph Neural Networks collectively exploiting graph topology and node feature.



https://web.stanford.edu/class/cs224w/slides/01-intro.pdf

Wu et al. A Comprehensive Survey on Graph Neural Networks. In TNNLS, 2020.

Spectral GNNs: Graph Fourier Transform



$$\mathbf{A} = \begin{pmatrix} 0 & 1 & 1 & 0 \\ 1 & 0 & 1 & 1 \\ 1 & 1 & 0 & 0 \\ 0 & 1 & 0 & 0 \end{pmatrix} \quad \mathbf{D} = \begin{pmatrix} 2 & 0 & 0 & 0 \\ 0 & 3 & 0 & 0 \\ 0 & 0 & 2 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} \quad \mathbf{X} = \begin{pmatrix} 0 \\ 1 \\ 2 \\ 3 \end{pmatrix}$$

Normalized Graph Laplacian

Eigendecomposition

$$\hat{\mathbf{L}} = \mathbf{I} - \mathbf{D}^{-\frac{1}{2}}\mathbf{A}\mathbf{D}^{-\frac{1}{2}} = \mathbf{U}\mathbf{\Lambda}\mathbf{U}^T$$

λ_i : The i-th eigenvalue.

→ Frequency

$\mathbf{U}_i$: The i-th eigenvector.

→ Frequency Component

$$\tilde{\mathbf{X}} = \mathbf{U}^T\mathbf{X}$$

Graph Domain

Frequency Domain

$$\mathbf{X} = \mathbf{U}\tilde{\mathbf{X}}$$

Spectral GNNs: Graph Spectral Filter

Define a filter function $g : [0,2] \rightarrow \mathbb{R}$ in the frequency/spectral domain:

Fourier transform of node features → Filtering operation with frequency response → Inverse graph Fourier transform

$$\mathbf{S} = \mathbf{U}^T\mathbf{X} \qquad \tilde{\mathbf{S}}_{[i,:]} = g(\lambda_i)\mathbf{S}_{[i,:]} \qquad \mathbf{Z} = \mathbf{U}\tilde{\mathbf{S}}$$

$$\mathbf{Z} = g(\hat{\mathbf{L}}) = \mathbf{U}g(\mathbf{\Lambda})\mathbf{U}^T X$$

$$\mathbf{U}\boxed{\tilde{\mathbf{S}}} \qquad \mathbf{U}\boxed{\mathbf{S}}$$

New Coefficients

Old Coefficients

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Take one-dimension $\mathbf{X}$ as an example:

$$\mathbf{X} = \boxed{S_1} \cdot \mathbf{U}_1 + \boxed{S_2} \cdot \mathbf{U}_2 + \cdots + \boxed{S_N} \cdot \mathbf{U}_N$$

$$\downarrow$$

$$\mathbf{Z} = \boxed{\tilde{S}_1} \cdot \mathbf{U}_1 + \boxed{\tilde{S}_2} \cdot \mathbf{U}_2 + \cdots + \boxed{\tilde{S}_N} \cdot \mathbf{U}_N$$

Spectral GNNs: Polynomial Approximation

Polynomial approximation to the filter function g:

$$g(\lambda) = \sum_{k=0}^{K} \omega_k \lambda^k = \sum_{k=0}^{K} \alpha_k P_k(\lambda)$$

GCN: a first-order Chebyshev polynomial $g(\lambda) = 2 - \lambda$ as low-pass filter

GPR-GNN, BernNet, JacobiConv: trainable α_k to attain learnable filter

Theoretical expressive power in learning arbitrary filter function while $K \to \infty$.

Kipf & Welling. Semi-supervised Classification with Graph Convolutional Networks. In ICLR 2017.
Chien et al. Adaptive Universal Generalized Pagerank Graph Neural Network. In ICLR 2021.
He et al. BernNet: Learning Arbitrary Graph Spectral Filters via Bernstein Approximation. In NeurIPS 2021.
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Motivations: Homogenous Spectral Filtering

- Local modeling nature within K-hop neighborhood

$$\mathbf{Z} = \sum_{k=0}^{K} \alpha_k P_k(\hat{\mathbf{L}})\mathbf{X} \ \underline{\text{while practically}} \ \boxed{K \to \infty \Rightarrow \alpha_k \to 0}$$

- All nodes share the identical transforming coefficient

$$\mathbf{Z} = \boxed{\sum_{n=1}^{N} \tilde{S}_n \cdot \mathbf{U}_n}$$

$\tilde{S}_n$ is a scalar in case of one-channel $\mathbf{X}$ as an example

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Existing spectral filtering scheme implicitly assumes the homogenous distributions between different graph parts.

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Motivations: Heterogeneous Linking Pattern

Definition 1 (Local Label Homophily). We define the Local Label Homophily as a measure of the local homophily level surrounding each node v_i:

$$h_i = \frac{|\{(v_p, v_q)|\mathbf{y}_p = \mathbf{y}_q \wedge (v_p, v_q) \in \mathcal{E}_{i,k}\}|}{|\mathcal{E}_{i,k}|}$$

Here, h_i directly computes the edge homophily ratio [50] on the subgraph made up of the k-hop neighbors, and $\mathcal{E}_{i,k} = \{(v_p, v_q)|v_p, v_q \in \mathcal{N}_{i,k} \wedge (v_p, v_q) \in \mathcal{E}\}$ denotes its edge set.

<u>Label Homophily:</u>

$$h = \frac{|\{(v_i,v_j)|\mathbf{y}_i = \mathbf{y}_j \wedge (v_i,v_j) \in \mathcal{E}\}|}{|\mathcal{E}|}$$

Definition 2 (Local Graph Frequency). The Local Graph Frequency is defined by measuring the local smoothness level of the decomposed Laplacian eigenbases, and for each node v_i we have:

$$\lambda_{n,i} = \sum_{(v_p,v_q)\in\mathcal{E}_{i,k}} \left(\frac{1}{\sqrt{\deg_p}}\mathbf{u}_{n,p} - \frac{1}{\sqrt{\deg_q}}\mathbf{u}_{n,q}\right)^2$$

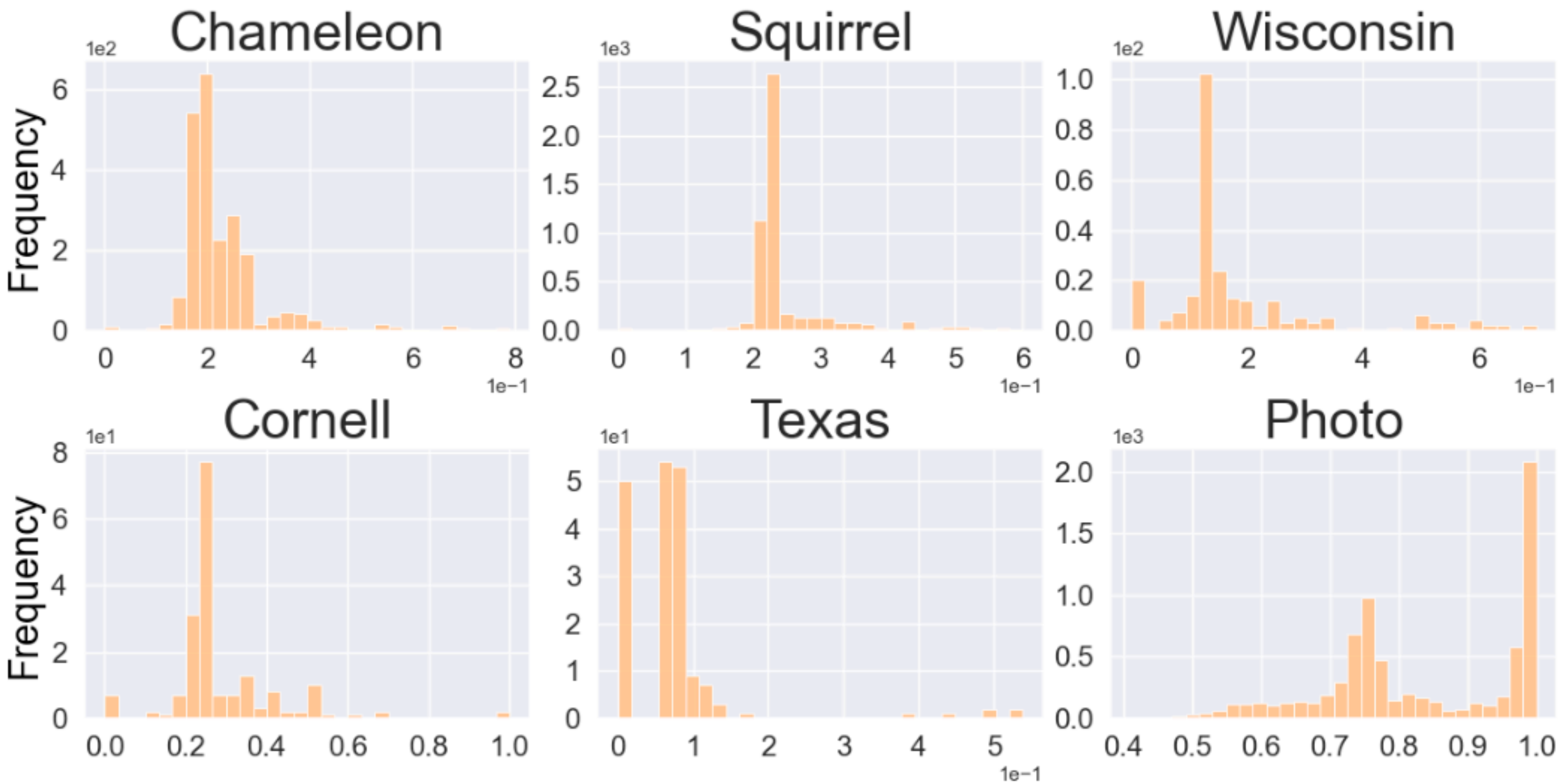
where $\lambda_{n,i}$ denotes the frequency or smoothness level of each Laplacian eigenbasis $\mathbf{u}_n$ upon the subgraph induced by the k-hop neighbors. Since all summed elements in Eq. 1 are positive and $\mathcal{E}_{i,k} \subseteq \mathcal{E}$, we can always have a $\xi_i \in (0, 1)$ such that $\lambda_{n,i} = \xi_i \lambda_n$.

<u>Frequency (Eigenvalue):</u>

$$\lambda_n = \mathbf{u}_n^T \hat{\mathbf{L}} \mathbf{u}_n$$

$$= \sum_{(v_p,v_q)\in\mathcal{E}} \left(\frac{1}{\sqrt{\deg_p}}\mathbf{u}_{n,p} - \frac{1}{\sqrt{\deg_q}}\mathbf{u}_{n,q}\right)^2$$

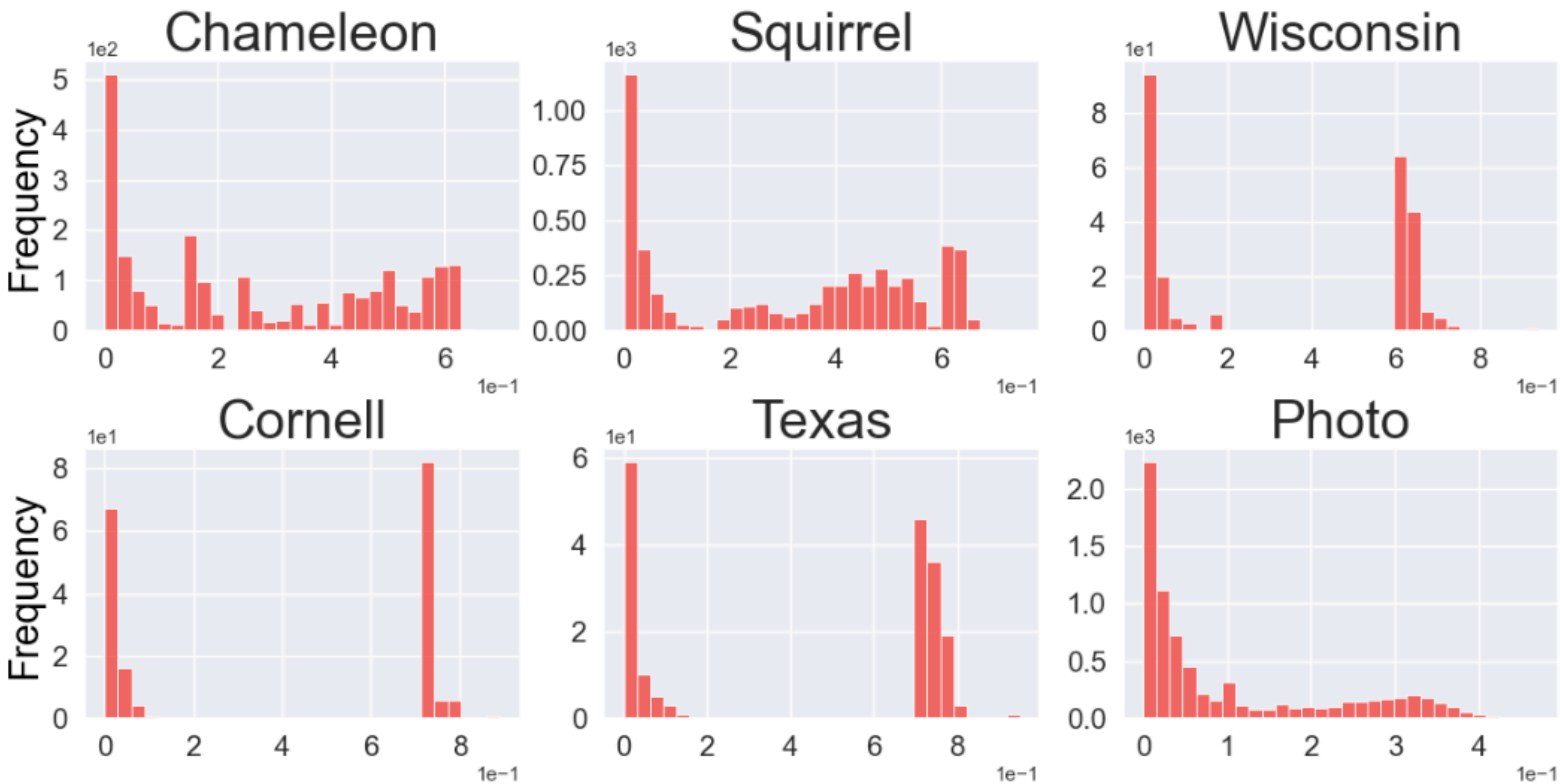
Motivations: Heterogeneous Linking Pattern



(a) Local Label Homophily

<u>Skewed and even multi-modal distributions</u>: evident heterogeneity

Motivations: Heterogeneous Linking Pattern



(b) Local Graph Frequency

<u>Skewed and even multi-modal distributions</u>: evident heterogeneity

Our Solution: Diverse Spectral Filtering (DSF)

Homogenous spectral filtering:

Dot product

$$\mathbf{Z} = \sum_{n=1}^{N} \tilde{S}_n \cdot \mathbf{U}_n$$

Scalar coefficient — Graph frequency

$$\tilde{S}_n = \sum_{k=0}^{K} \alpha_k P_k(\lambda_n) \mathbf{U}_n^T \mathbf{X}$$

Diverse spectral filtering:

Hadamard product

$$\mathbf{Z} = \sum_{n=1}^{N} \tilde{\mathbf{S}}_n \odot \mathbf{U}_n$$

Vector

The i-th element of vector coefficients

$$\tilde{\mathbf{S}}_n(i) = \sum_{k=0}^{K} \alpha_k P_k(\lambda_{n,i}) \mathbf{U}_n^T \mathbf{X}$$

Local graph frequency

$\mathbf{X}$ is taken as one-dimension as an example

Our Solution: Diverse Spectral Filtering (DSF)

The calculation of $\lambda_{n,i}$ would be computationally expensive, which <u>requires not only Laplacian decomposition but also subgraph extraction</u>.

$\mathbf{X}$ is taken as one-dimension as an example

Our Solution: Diverse Spectral Filtering (DSF)

Substitution using $\lambda_{n,i} = \xi_i \lambda_n$ s.t. $0 < \xi_i < 1$

Proposition 1. Suppose a K-order polynomial function $f : [0, 2] \to \mathbb{R}$ with polynomial basis $P_k(\cdot)$ and coefficients $\{\alpha_k\}_{k=0}^{K}$ in real number. For any pair of variables $x, \hat{x} \in [0, 2]$ satisfying $x = \xi \hat{x}$ where ξ is a constant real number, we always have a function $g : [0, 2] \to \mathbb{R}$ with the same polynomial basis but a different set of coefficients $\{\beta_k\}_{k=0}^{K}$ such that $f(x) = g(\hat{x})$.

It allows $\mathbf{S}'_n(i) = \sum_{k=0}^{K} \boxed{\alpha_k P_k(\lambda_{n,i})} \mathbf{U}_n^T \mathbf{X} = \sum_{k=0}^{K} \boxed{\beta_{k,i} P_k(\lambda_i)} \mathbf{U}_n^T \mathbf{X}$

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It allows $\mathbf{S}'_n(i) = \sum_{k=0}^{K} \boxed{\alpha_k P_k(\lambda_{n,i})} \mathbf{U}_n^T \mathbf{X} = \sum_{k=0}^{K} \boxed{\beta_{k,i} P_k(\lambda_i)} \mathbf{U}_n^T \mathbf{X}$

<u>DSF:</u>

$$\mathbf{Z} = \sum_{k=0}^{K} \begin{pmatrix} \beta_{k,1} & 0 & \cdots & 0 \\ 0 & \beta_{k,2} & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & \beta_{k,N} \end{pmatrix} P_k(\hat{\mathbf{L}})\mathbf{X}$$

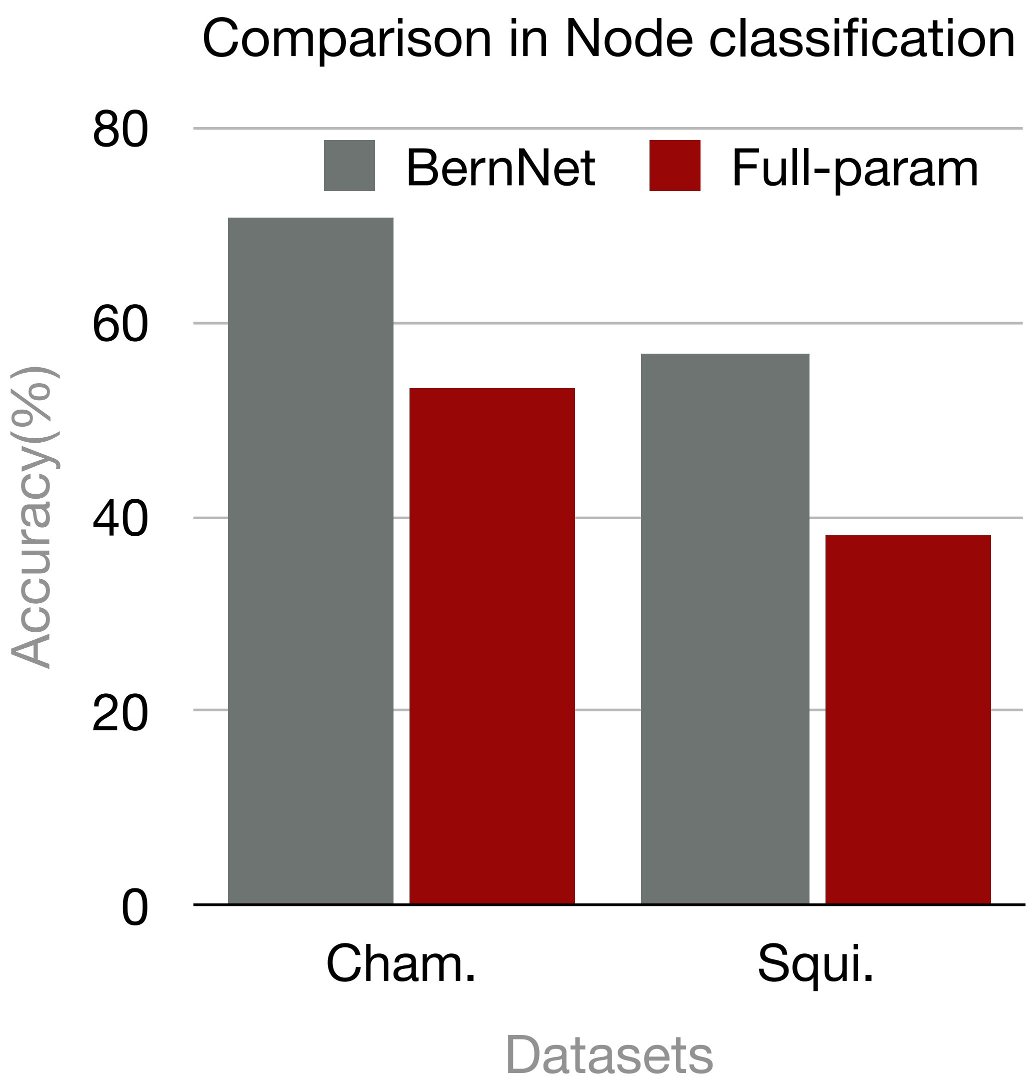
Graph Filter Weights

$\alpha_k \to \mathrm{diag}(\beta_{k,1}, \beta_{k,2}, \cdots, \beta_{k,N})$

Node-specific Filter Weights

Challenges: Complexity & Noise Overfitting

Issue: Parameterizing a large number of filter weights ($\propto$ # nodes) would increase model complexity and cause severe overfitting to local noises.



Learning with full-parametrization leads a clear accuracy drop.

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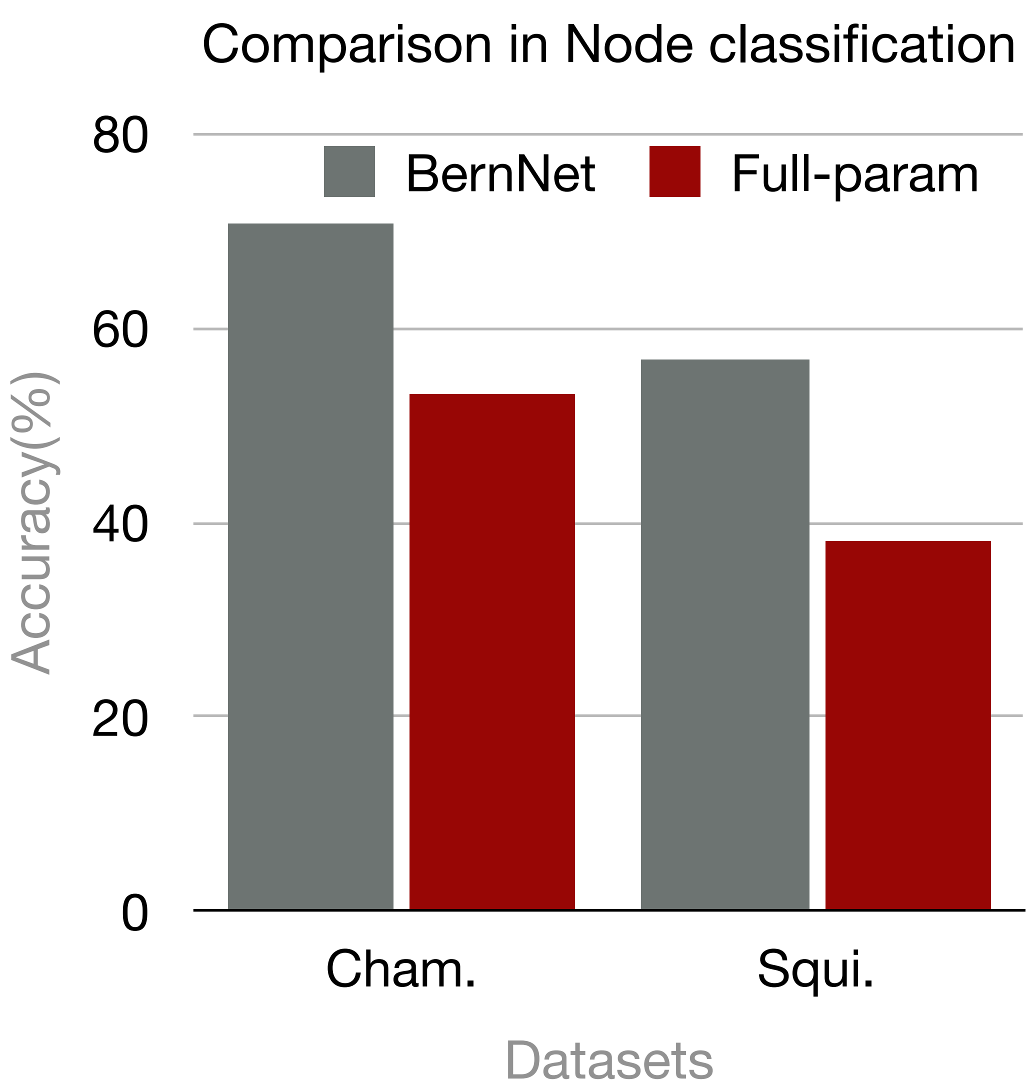
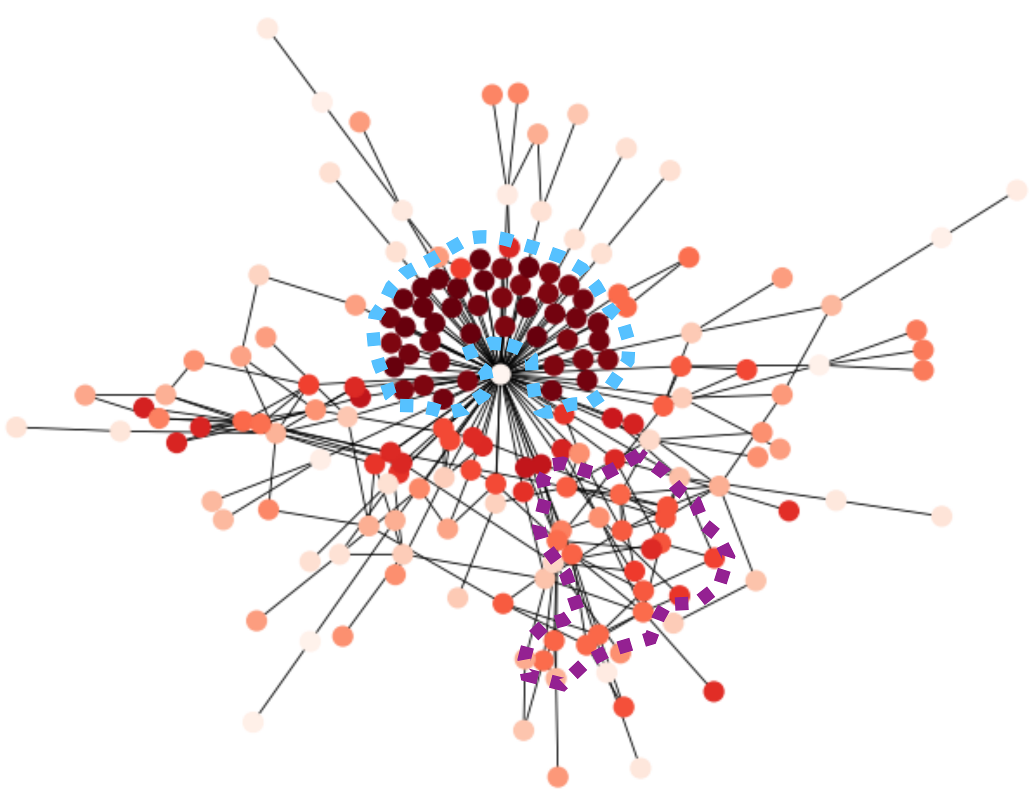


Learning with full-parametrization leads a clear accuracy drop.

"A reason design should be built upon a shared global model whilst locally adapted to each node with awareness of its graph position."

Challenges: Complexity & Noise Overfitting

Observ. 1: Nearby nodes display similar local structures due to their overlapped neighborhoods.



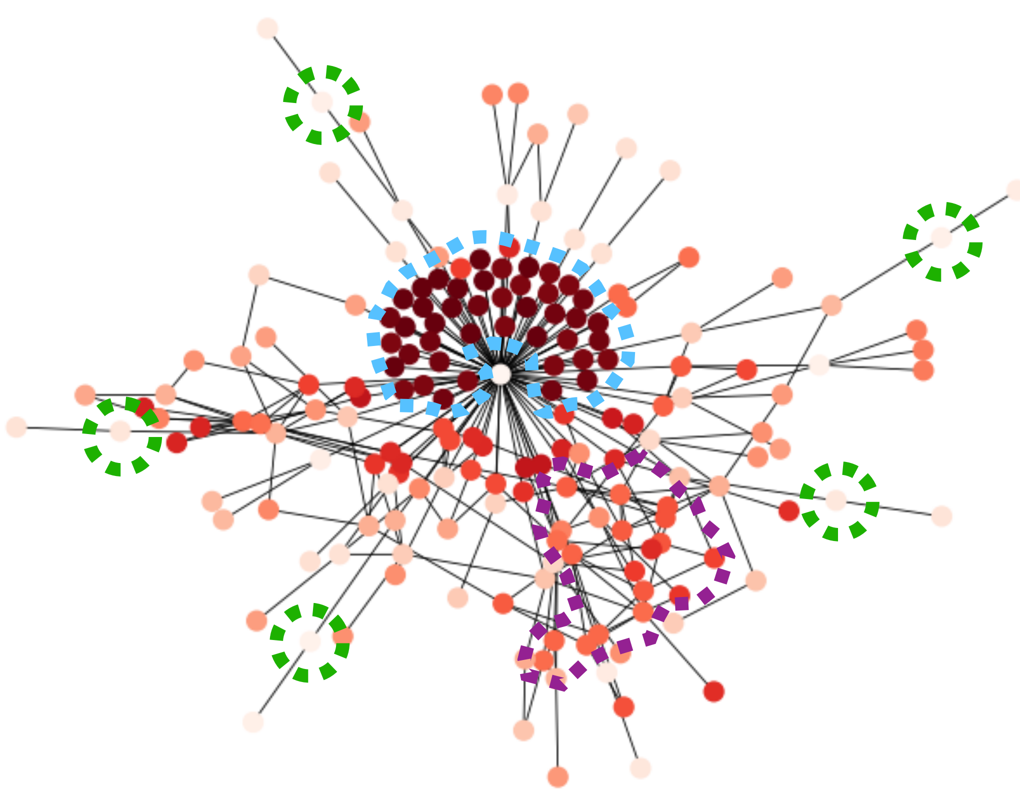
Cornell (webpage network): similar color means akin local structure

- Observ. 1 →

Challenges: Complexity & Noise Overfitting

Observ. 1: Nearby nodes display similar local structures due to their overlapped neighborhoods.

Observ. 2: Distant nodes may still posses alike local context because of the invariant global properties.



Cornell (webpage network): similar color means akin local structure

- Observ. 1 → ■ ■
- Observ. 2 → ■ in •–•–•

DSF: LGWD & Positional-aware Filter Weights

<u>Local and Global Weight Decomposition (LGWD)</u>

global invariant graph properties

$$\beta_{k,i} \leftarrow \gamma_i \cdot \theta_{k,i}$$

local diverse node contexts

DSF: LGWD & Positional-aware Filter Weights

Local and Global Weight Decomposition (LGWD)

global invariant graph properties

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local diverse node contexts

Position-aware Filter Weights

$$\arg\min_{\mathbf{P}} \mathscr{L}_P = \|\mathbf{P}^{(0)} - \mathbf{P}\|_2^2 + \kappa_1 tr(\mathbf{P}^T \hat{\mathbf{L}} \mathbf{P}) + \kappa_2 \|\mathbf{P}^T\mathbf{P} - \mathbf{I}\|_2^2$$

$\mathbf{P}$ denotes node positional embeddings

κ_1 and κ_2 are trade-off coefficients

DSF: LGWD & Positional-aware Filter Weights

Position-aware Filter Weights

Iterative gradient method with stepwise $b = \eta_1/2$:

$$\mathbf{P}^{(k)} = \mathbf{P}^{(k-1)} - b \cdot \frac{\partial \mathscr{L}_p}{\partial \mathbf{P}} \bigg|_{\mathbf{P}=\mathbf{P}^{(k-1)}}$$

η_1 and η_2 are constants made up of κ_1 and κ_2

$$= \eta_1 \mathbf{P}^{(0)} + \left(1 - \eta_1\right) \left(\left(1 + \eta_2\right) \hat{\mathbf{A}} - \eta_2 \left(\mathbf{P}^{(k-1)} \mathbf{P}^{(k-1)^T} \right) \right) \mathbf{P}^{(k-1)}$$

DSF: LGWD & Positional-aware Filter Weights

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$$= \eta_1 \mathbf{P}^{(0)} + (1-\eta_1)\left((1+\eta_2)\hat{\mathbf{A}} - \eta_2\left(\mathbf{P}^{(k-1)}\mathbf{P}^{(k-1)^T}\right)\right)\mathbf{P}^{(k-1)}$$

$$\mathbf{P}^{(k)} = \eta_1 \mathbf{P}^{(0)} + (1-\eta_1)\left((1+\eta_2)\hat{\mathbf{A}} - \eta_2\sigma\left(\mathbf{P}^{(k-1)}\mathbf{W}\mathbf{P}^{(k-1)^T}\right)\right)\mathbf{P}^{(k-1)}$$

$$\mathbf{P}^{(k)} \leftarrow \tanh(\mathbf{P}^{(k)})$$

$\theta_{k,i} = \sigma_p(\mathbf{W}^{(k)}\mathbf{P}_i^{(k)} + \mathbf{b}^{(k)})$ for each node v_i $\qquad k = 1,2,\cdots,K$

DSF: Overall Algorithm

Original Design → DSF-x-I:

$$\arg\min_{\mathbf{P}} \mathscr{L}_P = \|\mathbf{P}^{(0)} - \mathbf{P}\|_2^2 + \kappa_1 tr(\mathbf{P}^T\hat{\mathbf{L}}\mathbf{P}) + \kappa_2 \boxed{\|\mathbf{P}^T\mathbf{P} - \mathbf{I}\|_2^2}$$

Complexity Overhead with $\mathcal{O}(N^2)$

$$\mathbf{P}^{(k)} = \eta_1\mathbf{P}^{(0)} + \left(1 - \eta_1\right)\left(\left(1 + \eta_2\right)\hat{\mathbf{A}} - \eta_2 \boxed{\sigma\left(\mathbf{P}^{(k-1)}\mathbf{W}\mathbf{P}^{(k-1)^T}\right)}\right)\mathbf{P}^{(k-1)}$$

[1] Chien et al. Adaptive Universal Generalized Pagerank Graph Neural Network. In ICLR 2021.
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Complexity Overhead with $\mathcal{O}(N^2)$

$$\mathbf{P}^{(k)} = \eta_1 \mathbf{P}^{(0)} + (1-\eta_1)\left(\left(1+\eta_2\right)\hat{\mathbf{A}} - \eta_2 \boxed{\sigma\left(\mathbf{P}^{(k-1)}\mathbf{W}\mathbf{P}^{(k-1)^T}\right)}\right)\mathbf{P}^{(k-1)}$$

Orthogonal Regularization → DSF-x-R:

$$\mathscr{L}_{Orth} = \|\hat{\mathbf{P}}^{(K)}\hat{\mathbf{P}}^{(K)} - \mathbf{I}\|_2^2 \quad \& \quad \eta_2 = 0 \qquad \hat{\mathbf{P}}^{(K)} \xleftarrow{\text{normalization}} \mathbf{P}^{(K)}$$

$$\mathscr{L} = \mathscr{L}_{task} + \lambda_{orth}\mathscr{L}_{orth}$$

$$\boxed{x \in \{\text{GPR}^{[1]}, \text{Bern}^{[2]}, \text{Jacobi}^{[3]}\}}$$

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DSF: Overall Algorithm

Original Design → DSF-x-I:

Table 1: Average running time per epoch (ms)/average total running time (s). Although DSF-GPR-I is less efficient on large networks, DSF-GPR-R, (our major model) can reduce it by more than 75% on average (though reasonably slower than GPR-GNN).

Datasets	Small-scale	Large-scale	Average
GPR-GNN	1.10/2.24	0.98/5.01	1.08/2.74
DSF-GPR-I	5.96/12.19	40.34/131.77	12.21/33.93
DSF-GPR-R	2.49/6.29	3.02/14.48	2.59/7.78

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DSF effectively improves SOTAs spectral GNNs

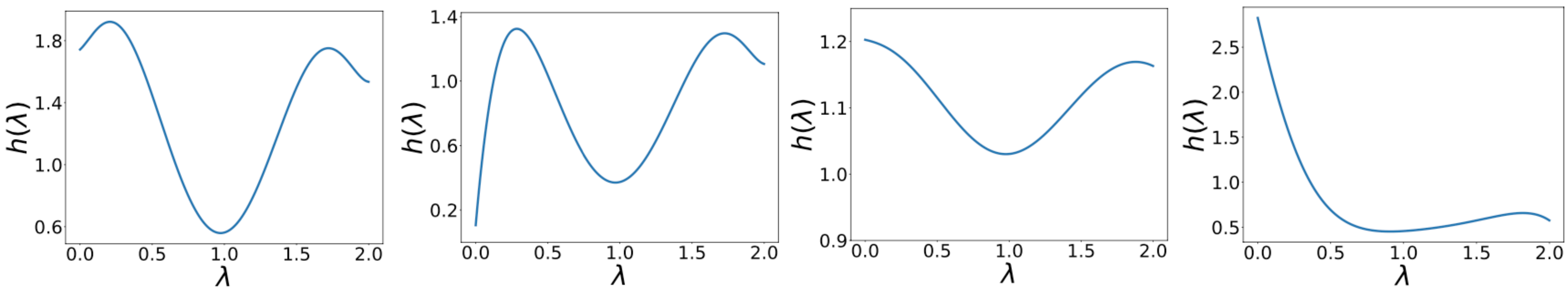
Table 2: Node classification accuracies (%) ± 95% confidence interval over 100 runs. The row of PA-GNN [49]* lists the relative improvements of PA-GNN upon GPR-GNN based on the results obtained from its paper, where – denotes values not provided. Our Improv. gives the best relative improvements between our DSF variants over their common underlying model.

Datasets	Heterophilic Graphs						Homophilic Graphs				
	Chameleon	Squirrel	Wisconsin	Cornell	Texas	Twitch-DE	Cora	Citeseer	Pubmed	Computers	Photo
GCN [24]	67.22±0.43	54.21±0.41	59.45±0.72	52.76±1.17	61.66±0.71	73.94±0.15	88.13±0.25	77.00±0.27	89.07±0.11	91.06±0.12	93.99±0.12
GAT [40]	67.72±0.41	52.26±0.58	57.94±0.89	50.20±0.93	55.37±1.10	73.00±0.15	88.47±0.22	77.23±0.27	88.30±0.11	91.69±0.11	94.55±0.11
ChebNet [11]	64.85±0.44	48.14±0.33	80.93±0.72	77.98±1.00	75.83±1.20	73.73±0.14	87.64±0.21	76.93±0.24	89.91±0.11	91.65±0.12	95.27±0.07
APPNP [15]	53.66±0.33	36.08±0.36	81.23±0.64	81.29±0.78	79.42±1.05	72.65±0.11	88.70±0.21	77.77±0.24	89.93±0.09	91.62±0.10	94.92±0.09
GNN-LF [51]	54.29±0.36	36.87±0.33	59.85±0.60	62.90±0.98	61.88±0.95	73.03±0.13	88.90±0.25	77.35±0.29	88.89±0.10	91.12±0.11	95.13±0.08
GNN-HF [51]	55.22±0.42	35.45±0.30	68.17±0.72	72.98±1.02	66.66±1.34	71.92±0.13	89.01±0.19	77.74±0.23	89.53±0.10	90.73±0.10	95.26±0.09
FAGCN [6]	68.38±0.51	50.08±0.60	82.11±0.85	79.00±0.93	81.00±0.95	74.15±0.13	88.82±0.20	77.65±0.29	90.13±0.11	91.90±0.11	95.25±0.10
GPR-GNN [9]	69.01±0.50	55.39±0.33	82.72±0.85	80.81±0.78	81.66±1.02	74.07±0.18	89.03±0.20	77.63±0.28	90.10±0.44	92.34±0.13	95.34±0.09
DSF-GPR-I	71.18±0.52	57.08±0.29	**87.64**±0.79	84.76±0.90	85.44±1.05	74.58±0.16	**89.64**±0.20	78.03±0.26	90.26±0.08	92.49±0.12	95.64±0.07
DSF-GPR-R	**71.64**±0.55	**58.44**±0.30	87.43±0.74	**84.93**±0.90	**85.56**±0.93	**74.81**±0.14	89.63±0.17	**78.22**±0.29	**90.51**±0.07	**92.80**±0.12	**95.73**±0.08
Our Improv.	2.63%	3.05%	4.92%	4.12%	3.9%	0.74%	0.61%	0.59%	0.41%	0.46%	0.39%
PA-GNN [49]*	0.66%	1.28%	–	–	–	–	-0.09%	-0.74%	-0.03%	1.03%	0.02%
BernNet [20]	70.59±0.42	56.63±0.32	85.00±0.94	82.10±0.95	82.20±0.98	74.45±0.15	88.72±0.23	77.52±0.29	90.21±0.46	92.57±0.10	95.42±0.08
DSF-Bern-I	72.95±0.53	59.45±0.32	**88.23**±0.81	**85.07**±0.93	**84.59**±1.07	74.96±0.15	89.05±0.22	**78.32**±0.27	90.40±0.10	92.76±0.10	95.73±0.07
DSF-Bern-R	**73.60**±0.53	**59.99**±0.30	88.02±0.91	84.29±0.93	84.42±1.00	**75.00**±0.15	**89.10**±0.22	78.27±0.26	**90.52**±0.10	**92.84**±0.10	**95.79**±0.06
Our Improv.	3.01%	3.36%	3.23%	2.97%	2.39%	0.55%	0.38%	0.80%	0.31%	0.27%	0.37%
JacobiConv [42]	73.71±0.42	57.22±0.24	83.21±0.68	82.34±0.88	82.42±0.90	74.34±0.12	89.24±0.19	77.81±0.29	89.50±0.47	92.26±0.10	95.62±0.06
DSF-Jacobi-I	74.88±0.39	58.26±0.26	85.34±0.74	**84.54**±0.81	83.68±1.12	74.65±0.13	89.54±0.19	78.18±0.26	89.78±0.09	92.38±0.11	**95.76**±0.07
DSF-Jacobi-R	**75.00**±0.38	**59.23**±0.27	**86.13**±0.70	84.39±0.88	**84.46**±0.81	**74.75**±0.15	**89.66**±0.19	**78.23**±0.25	**90.07**±0.10	**92.44**±0.11	95.75±0.08
Our Improv.	1.29%	2.01%	2.92%	2.20%	2.04%	0.41%	0.42%	0.42%	0.41%	0.18%	0.14%

Het. graphs: tend to showcase heterogeneous graph pattern

Hom. graphs: mostly exhibit homogeneous graph pattern

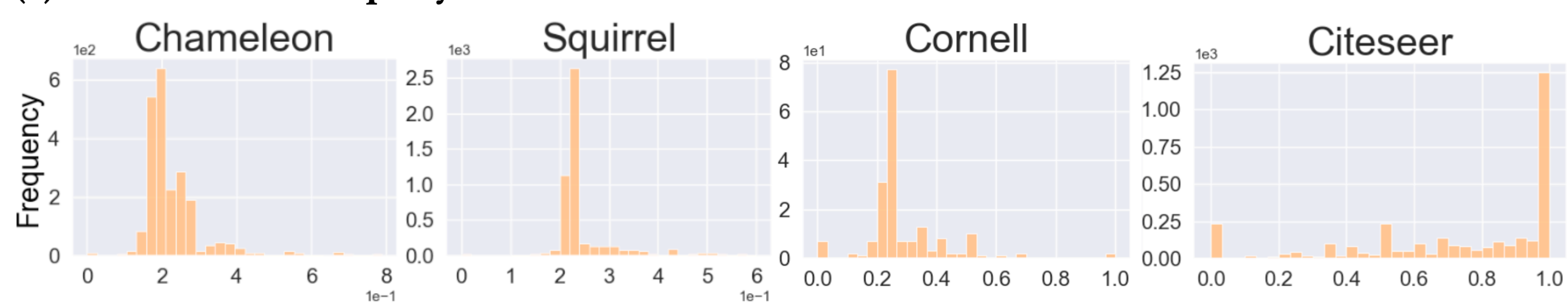
Limited interpretability: BernNet learns a single filter



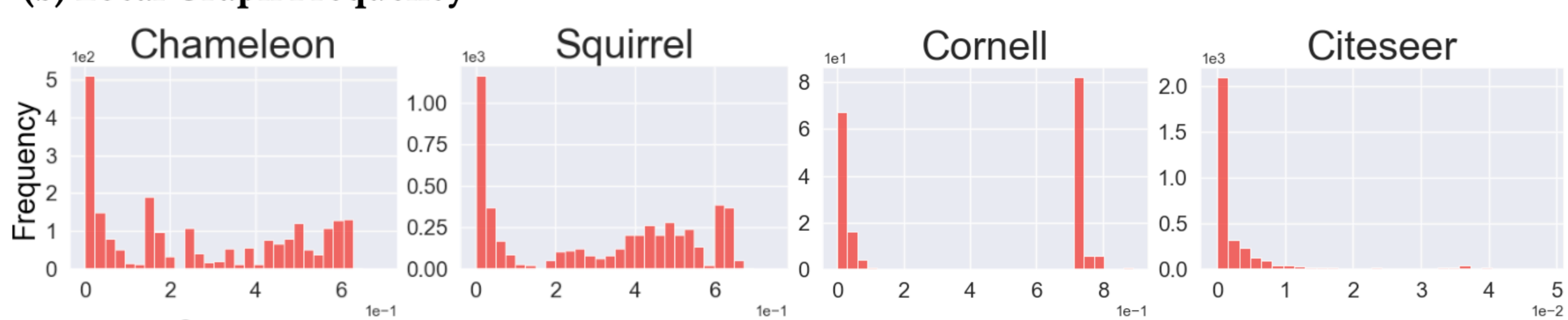
(f) Chameleon (h) Squirrel (j) Cornell (b) CiteSeer

Recall:

(a) Local Label Homophily

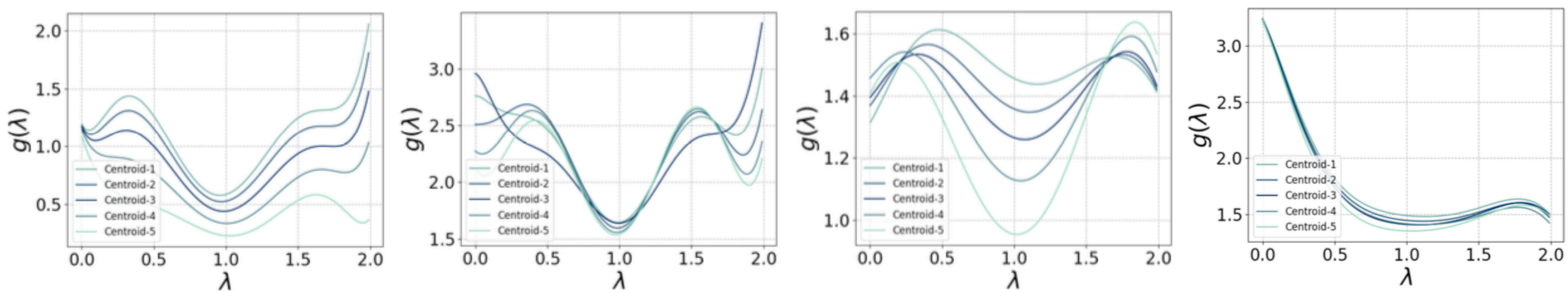


(b) Local Graph Frequency



He et al. BernNet: Learning Arbitrary Graph Spectral Filters via Bernstein Approximation. In NeurIPS 2021.

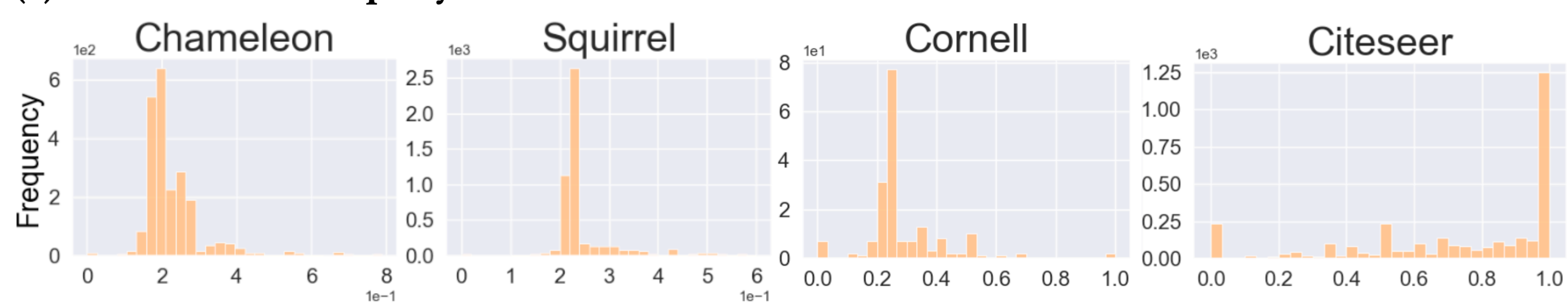
Enhanced Interpretability: DSF learns diverse filters



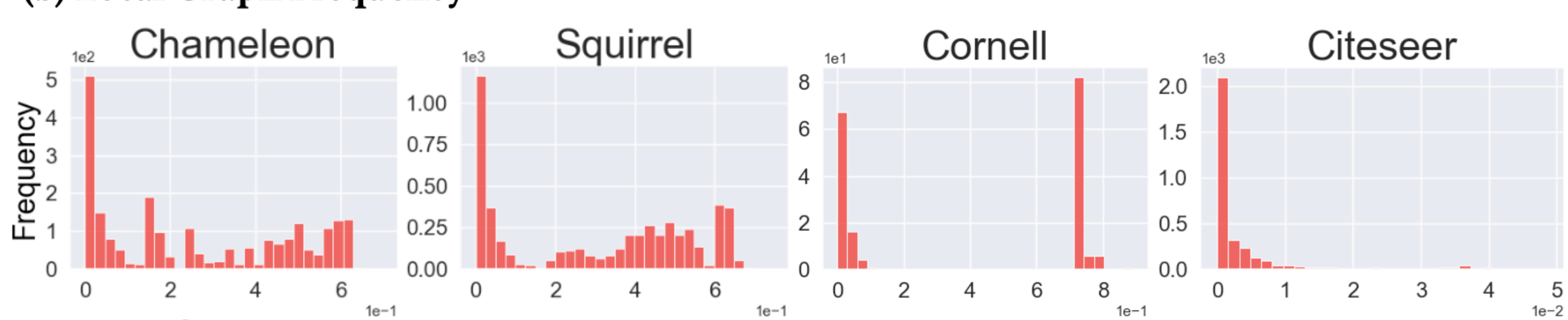
(a) Chameleon **(b) Squirrel** **(c) Cornell** **(d) Citeseer**

Recall:

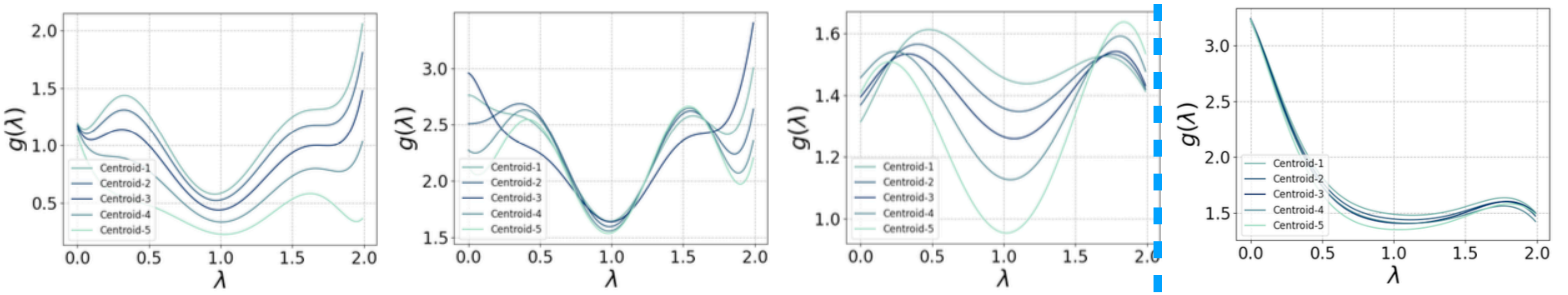
(a) Local Label Homophily



(b) Local Graph Frequency

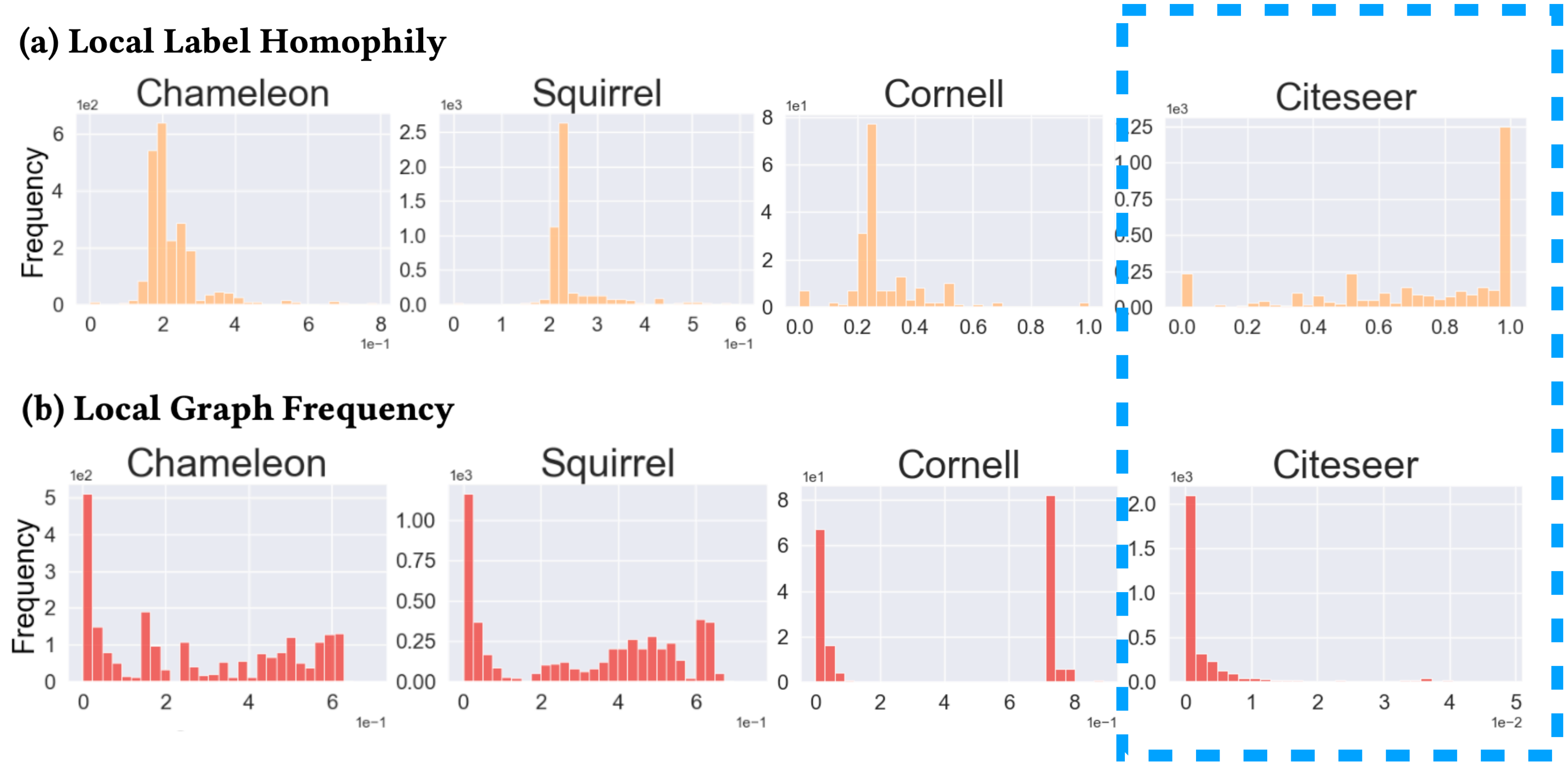


Enhanced Interpretability: DSF learns diverse filters

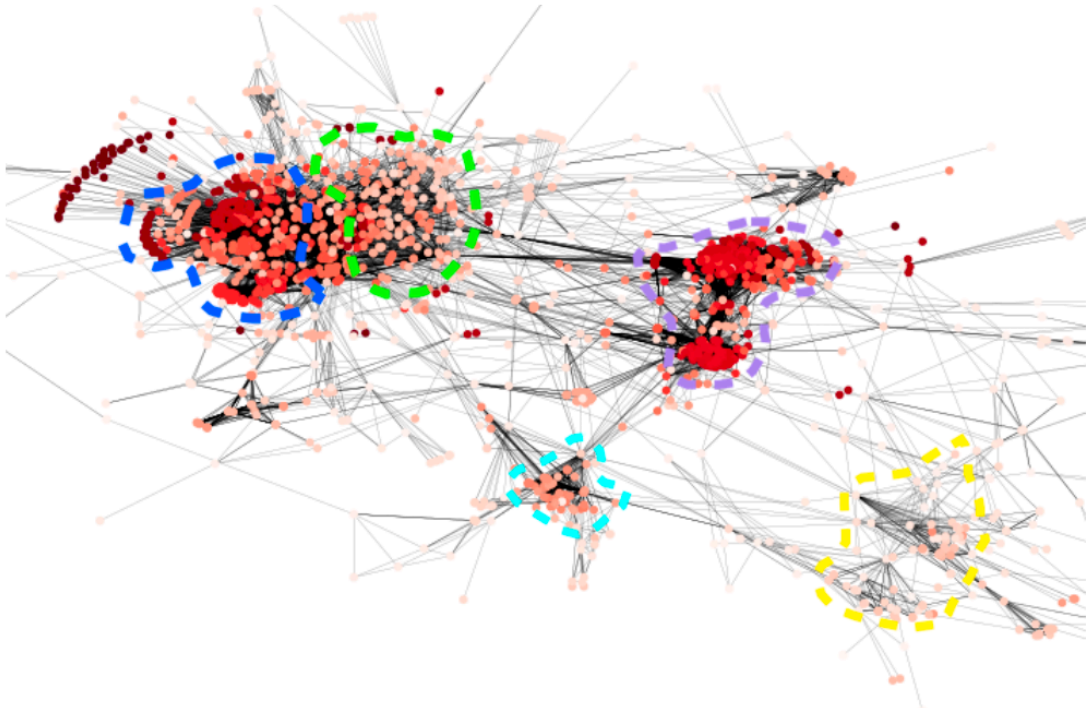


(a) Chameleon (b) Squirrel (c) Cornell (d) Citeseer

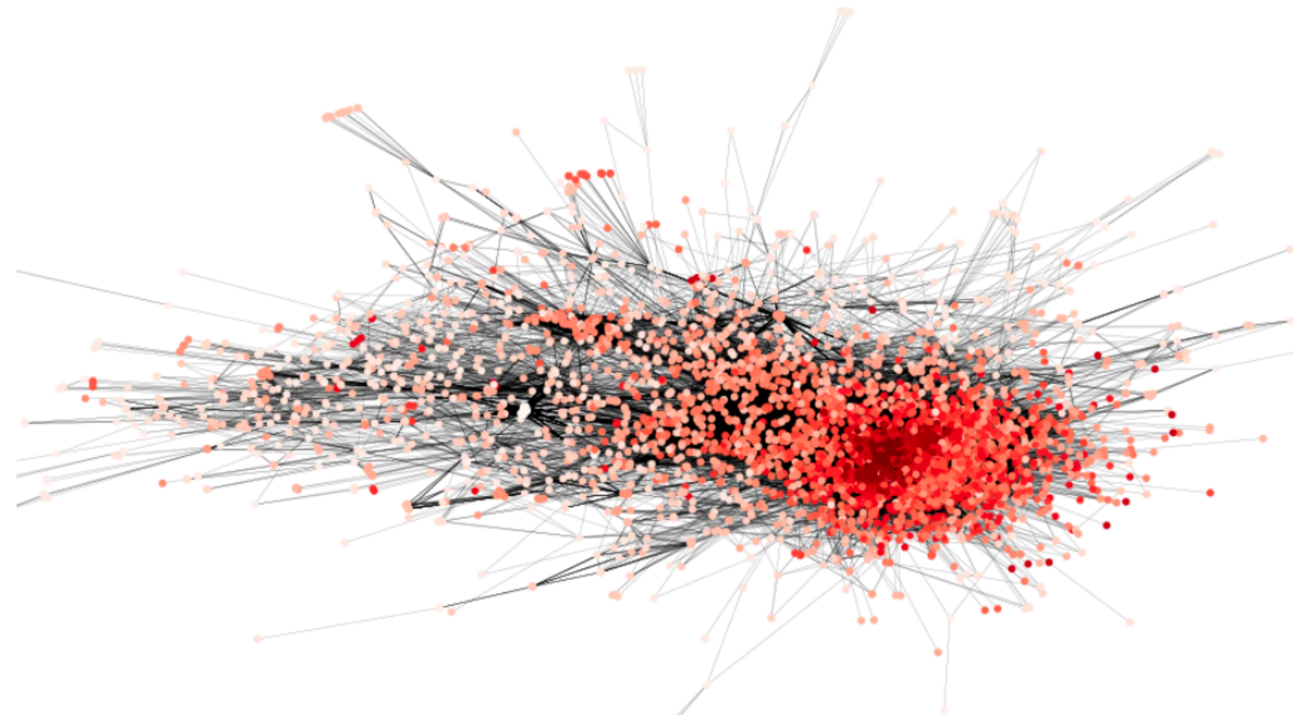
Recall:



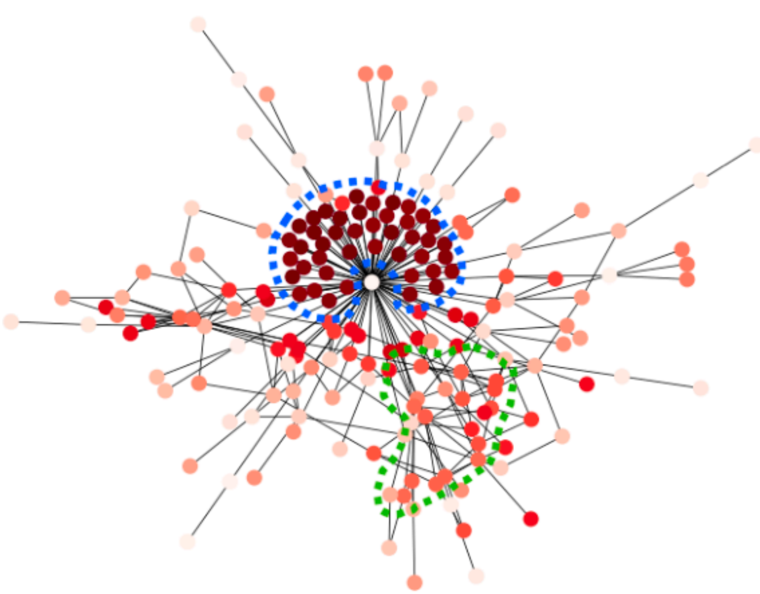
Enhanced Interpretability: DSF learns diverse filters



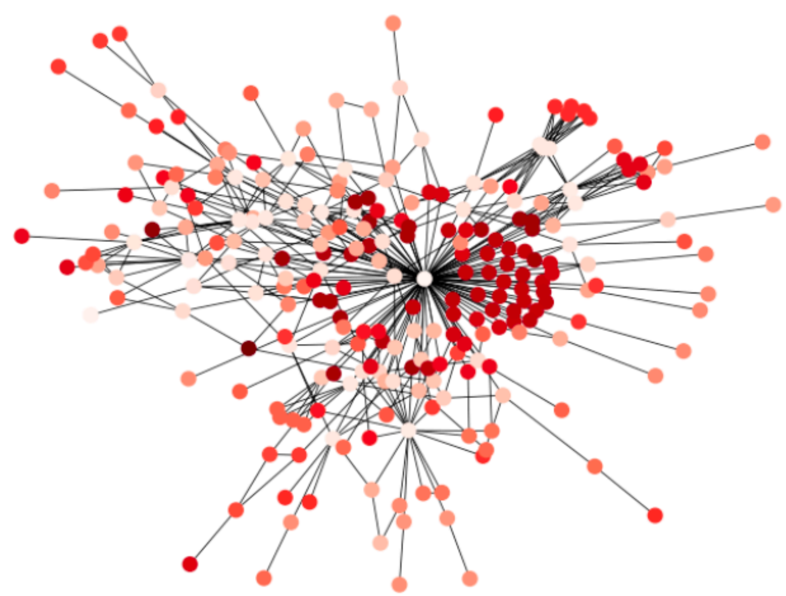
Chameleon



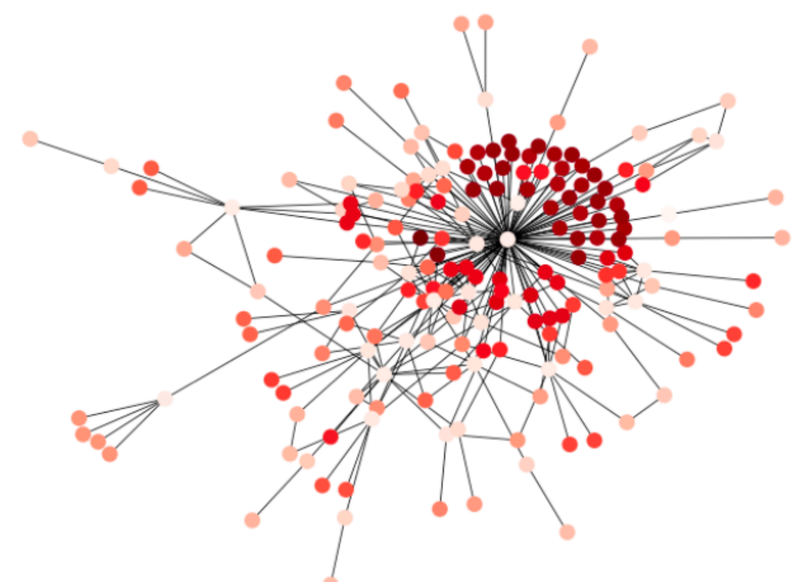
Squirrel



Cornell



Wisconsin



Texas

Our Contributions

- Most spectral GNNs are restricted in a homogenous spectral filtering.
- Regional heterogeneity is evident in real-world graphs.
- Our DSF learn diverse filters with clear performance gains and enhanced interpretability.

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Thank you!

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