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Clusters in Graphs

Finding clusters in real-world graphs have useful implications.



Social Groups in friendship networks



Functional modules in Protein-interaction networks



Graph Neural Networks (GNNs)

- GNNs achieve remarkable performance in various tasks.
- Several GNN-based approaches have been developed also for graph clustering.



GNNs are Vulnerable to Noise Edges

- GNN-based approaches in general are vulnerable to noise edges in graphs.
- Real-world graphs are often contaminated by noise edges (click error, spams, etc.)



Robust GNNs: Overview

- Several methods have been developed for robustness of GNNs.
- They are categorized into edge filtering and adjusted message-passing.



Robust GNNs: Edge Filtering

- Filtering edges based on graph topology or node attribute-based similarity.
- Learning a denoised adjacency matrix through end-to-end learning with constraints (e.g., ℓ_1 norm for sparsity, nuclear norm for low-rankness).



Robust GNNs: Adjust Message-Passing

- Adjust message-passing schemes to reduce messages passed through noise edges.
- It relies on supervision from node-label or graph-label, which are not contaminated by noise edges.



Robust Graph Clustering

How to improve the robustness of GNN-based graph clustering?



Challenges in Robust Graph Clustering

1. Lack of Supervision

 Existing robust GNNs rely on supervision from node-labels or graph-labels, which however, is not given in graph clustering.

2. Contaminated Objective Function

 The objective function of graph clustering is based on graph topology, and thus it is contaminated by noise edges.

MetaGC (Meta-weighting based Graph Clustering)



Our Contributions

Observations

GNN-based graph clustering is **vulnerable to noise edges**.



Define a theoretically suitable family of clustering loss functions for GNNbased clustering.





Methodology

Develop a **robust graph clustering** method based on **Meta-Weighting.**



Experiments

Extensive experiments on **5 real-world graphs under 3 levels of noise**.







GNN-based Graph Clustering Methods

- Graph clustering GNNs use a **GNN** followed by a **MLP** and **softmax**.
- Their output is a soft cluster assignment matrix *P*.
- The objective function is a **continuous relaxation** of a **clustering loss function**.



Meta-Weighting

- Meta-weighting is a meta-learning-based method that learns the weights of training samples while minimizing an objective function.
- Meta-weighting has been successful for classification and recommendation.







Proposed Method: MetaGC



Decomposable Clustering Loss Function f(P)

- Can be **decomposed** into a summation of **loss** on **each node pairs**.
- The loss on each pair is a weighted dot product of their assignment vectors.

[Definition] Decomposable clustering loss functions

Given G = (V, E) with |V| = N, $k \in \mathbb{N}$, and a soft cluster assignment matrix $P \in \mathcal{P}$, a clustering loss function $P \in \mathcal{P}$, a clustering loss function $f: \mathcal{P} \to \mathbb{R}$ *decomposable*, if there exist constant $c_{ij} = c_{ij}(G), \forall i, j \in [N]$ s.t.

$$f(P) = \sum_{\substack{(i,j) \in \\ all \text{ node pairs}}} c_{ij} P_i \cdot P_j$$

Decomposable Clustering Loss Function f(P)

- Decomposable clustering loss function is suitable for continuous relaxation.
- [Theoretical guarantee] optimal soft clustering assignments = optimal deterministic clustering assignments

(for details see Sec 3.3).

• We use a modularity-based objective function.

[Example] Modularity-based loss function

Modularity-based clustering loss function is a representative objective for clustering.

$$f(P) = \sum_{\substack{(i,j)\in\\all node pairs}} \frac{1}{2|E|} \left(A_{ij} - \frac{d_i d_j}{2|E|} \right) P_i \cdot P_j$$

GNN-based Clustering Model *C*

- GNN-based clustering model *C* yields a **soft cluster assignment matrix** *P*.
- Input of C: Adjacency matrix, Node Attributes
- **Output of** *C*: Soft cluster assignment matrix *P*



Meta-model M

- Meta-model M yields a node-pair weight matrix V, used to weight the loss function.
- Input of <u>M</u>: Adjacency matrix, Node Attributes,

Topology-based Node Similarities, Soft Cluster Assignments

 \rightarrow e.g., Common neighbors, Adamic-Adar index etc. \rightarrow The output of the clustering model C.

Output of <u>M</u>: Soft cluster assignment matrix P



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Output of <u>M</u>: Soft cluster assignment matrix P



Overall Training Procedure

We follow the standard training procedure for meta-weighting



Overall Training Procedure (Clean Validation)

- Conventional Meta-Weighting
 - Meta-weighting methods assume a clean validation set to train a meta-model.
 - In noisy graph, the clean parts are **typically unknown**.
- Our Hypothesis: Clean validation set is not "necessary"
 - Using distinct batches for training a meta-model and a clustering model.
 - Our empirical results show that it is still possible to train a meta-model meaningfully.





Experimental Questions

[Q1] Robustness & Accuracy

Is MetaGC more **robust** and **accurate** than the competitors on noisy graphs?

[Q2] Effectiveness of Meta-Weighting

Does the meta-model in MetaGC **properly adjust** the weights of loss terms?

[Q3] Ablation Study

Does each component of MetaGC contribute to performance improvement?

Experimental Setups (Cont.)

Dataset

- We use 5 real–world dataset.
- 4 citation graphs and 1 co-purchase graph.

Name	# Nodes	# Edges	# Attributes	# Classes
Cora	2,708	5,278	1,433	7
Cora-ML	2,995	8,158	2,879	7
Citeseer	3,327	4,552	3,703	6
Amazon-Photo	7,535	119,081	745	8
Pubmed	19,717	44,324	500	3
			-	·

Noisy-graph Generation

- We add noise edges randomly, selecting those with endpoints in different classes.
- Noise levels I, II, and III: 30%, 60%, and 90%

noise-to-existing edge ratios, respectively.



Experimental Setups (Cont.)

Competitors

- We compare MetaGC with **13 competitors**.
 - Four node embedding based methods
 - Three GNN-based graph clustering methods
 - Six graph denoising methods

Evaluation Metrics

- We use three evaluation metrics,
 - F1 Score
 - Normalize Mutual Information (NMI)
 - Modularity

(Q1) Robustness & Accuracy

• MetaGC gives the **best overall clustering performance** under each noise lebel.

Noise Level		Ι			II			ΔP		
Metric	F1 Score	NMI	Modularity	F1 Score	NMI	Modularity	F1 Score	NMI	Modularity	
DeepWalk	0.405 ± 0.048	0.465 ± 0.008	0.689 ± 0.006	0.297 ± 0.022	0.389 ± 0.010	0.659 ± 0.007	0.256 ± 0.014	0.352 ± 0.012	0.641 ± 0.007	6.0***
Node2Vec	0.410 ± 0.043	0.464 ± 0.006	0.690 ± 0.005	0.296 ± 0.023	0.389 ± 0.008	0.660 ± 0.004	0.261 ± 0.017	0.359 ± 0.011	0.642 ± 0.007	5.4***
DGI	0.230 ± 0.010	0.287 ± 0.003	0.151 ± 0.007	0.198 ± 0.009	0.239 ± 0.004	0.141 ± 0.010	0.183 ± 0.006	0.203 ± 0.013	0.122 ± 0.013	9.7***
GMI	0.099 ± 0.004	0.021 ± 0.001	-0.003 ± 0.001	0.103 ± 0.005	0.025 ± 0.001	-0.002 ± 0.001	0.109 ± 0.006	0.030 ± 0.001	-0.002±0.001	11.7***
MinCutPool	0.464 ± 0.000	0.000 ± 0.000	0.000 ± 0.000	0.464 ± 0.000	0.000 ± 0.000	0.000 ± 0.000	0.464 ± 0.000	0.000 ± 0.000	0.000 ± 0.000	9.4***
DMoN	0.556 ± 0.049	0.533 ± 0.041	0.609 ± 0.036	0.528 ± 0.028	0.494 ± 0.025	0.599 ± 0.023	0.470 ± 0.033	0.425 ± 0.036	0.531 ± 0.050	3.3***
GCC	0.538 ± 0.022	0.501 ± 0.039	0.619 ± 0.034	0.469 ± 0.007	0.377 ± 0.019	0.540 ± 0.027	0.459 ± 0.006	0.353 ± 0.018	0.526 ± 0.024	5.9***
GCN-Jaccard	0.557 ± 0.049	0.533 ± 0.040	0.610 ± 0.036	0.525 ± 0.034	0.493 ± 0.028	0.597 ± 0.032	0.473 ± 0.034	0.431 ± 0.038	0.538 ± 0.052	3.1***
GCN-SVD	0.390 ± 0.004	0.365 ± 0.009	0.497 ± 0.002	0.408 ± 0.005	0.379 ± 0.004	0.506 ± 0.006	0.403 ± 0.005	0.374 ± 0.017	0.507 ± 0.011	7.4^{***}
GDC	0.514 ± 0.073	0.502 ± 0.054	0.572 ± 0.043	0.474 ± 0.057	0.447 ± 0.052	0.547 ± 0.059	0.463 ± 0.033	0.418 ± 0.031	0.532 ± 0.050	4.9***
ProGNN	O.O.T.	O.O.T.	O.O.T.	O.O.T.	O.O.T.	O.O.T.	O.O.T.	O.O.T.	O.O.T.	N.A.
PTDNet	O.O.M.	O.O.M.	O.O.M.	O.O.M.	O.O.M.	O.O.M.	O.O.M.	O.O.M.	O.O.M.	N.A.
FGC	0.377 ± 0.000	0.071 ± 0.001	0.145 ± 0.003	0.366 ± 0.000	0.055 ± 0.000	0.103 ± 0.001	0.362 ± 0.000	0.048 ± 0.000	0.084 ± 0.001	9.6***
MetaGC	0.562 ± 0.015	0.566 ± 0.017	0.675 ± 0.008	0.528 ± 0.020	0.520 ± 0.013	0.664 ± 0.007	0.508 ± 0.014	0.498 ± 0.009	0.658 ± 0.006	1.2

(a) Amazon-Photo

Introduction Preliminaries Method Ex

Experiments

Conclusion

(Q1) Robustness & Accuracy

	Ι			П			Ш		ΔP	Noise Level		Ι			П			III		AD
F1 Score	NMI	Moduarity	F1 Score	NMI	Moduarity	F1 Score	NMI	Moduarity		Metric	F1 Score	NMI	Moduarity	F1 Score	NMI	Moduarity	F1 Score	NMI	Moduarity	
0.300±0.024	0.243 ± 0.010	$0.680 {\pm} 0.009$	0.216±0.010	0.155±0.006	0.593 ± 0.011	0.169 ± 0.014	0.111±0.009	0.528 ± 0.008	8.3***	DeepWalk	0.128 ± 0.004	0.089 ± 0.003	0.650±0.004	0.103±0.004	0.053 ± 0.003	0.586 ± 0.005	0.086 ± 0.004	0.037±0.002	$0.545 {\pm} 0.003$	7.3***
0.292±0.028	0.247 ± 0.015	$0.684 {\pm} 0.009$	0.210±0.016	0.154 ± 0.010	0.594 ± 0.009	0.170 ± 0.009	0.111 ± 0.011	0.528 ± 0.009	8.3***	Node2Vec	0.127 ± 0.004	0.089 ± 0.003	0.650 ± 0.003	0.101 ± 0.005	0.053 ± 0.002	0.587 ± 0.005	0.085 ± 0.004	0.037±0.003	0.545 ± 0.005	7.6***
0.351 ± 0.040	0.415 ± 0.011	0.619 ± 0.015	0.294±0.027	0.330 ± 0.012	0.547 ± 0.017	0.248 ± 0.018	0.240 ± 0.017	$0.412 {\pm} 0.033$	6.1***	DGI	0.199 ± 0.019	0.108 ± 0.003	0.169±0.005	0.160 ± 0.007	0.064 ± 0.002	0.153 ± 0.007	0.130 ± 0.006	0.043 ± 0.003	0.160 ± 0.007	9.2***
0.277±0.023	0.319 ± 0.008	0.576 ± 0.010	0.226±0.016	0.229 ± 0.005	0.496 ± 0.007	0.152 ± 0.016	0.145 ± 0.012	0.391 ± 0.020	9.7***	GMI	0.159 ± 0.009	0.117 ± 0.002	0.154 ± 0.003	0.115 ± 0.010	0.072 ± 0.001	0.135 ± 0.002	0.116 ± 0.006	0.049 ± 0.001	0.115 ± 0.006	9.3***
0.265 ± 0.035	0.222 ± 0.023	0.614 ± 0.012	0.217±0.027	0.147±0.019	0.556 ± 0.012	0.219 ± 0.097	0.086 ± 0.039	0.436 ± 0.172	10.1***	MINCUTPOOL	0.380 ± 0.005	0.131 ± 0.005	0.512 ± 0.010	0.345 ± 0.017	0.097±0.009	0.487 ± 0.011	0.325 ± 0.020	0.079 ± 0.011	0.472 ± 0.016	5.9***
0.400 ± 0.023	0.343 ± 0.015	0.661 ± 0.012	0.355±0.023	0.280±0.013	0.620 ± 0.013	0.326 ± 0.016	0.231 ± 0.016	0.576 ± 0.012	4.6***	DMoN	0.406 ± 0.005	0.161 ± 0.004	0.542 ± 0.001	0.377 ± 0.008	0.125 ± 0.01 1	0.518 ± 0.003	0.346 ± 0.019	0.090 ± 0.023	0.497 ± 0.010	3.7***
0.375 ± 0.017	0.230 ± 0.013	$0.486 {\pm} 0.011$	0.364 ± 0.023	0.114 ± 0.014	0.312 ± 0.053	0.364 ± 0.041	0.076 ± 0.016	0.252 ± 0.073	9.6***	GCC	0.522±0.0°7	0 - 9.003	0.313 ± 0.005	0.459 ± 0.004	0.039 ± 0.001	0.421 ± 0.004	0.505 ± 0.053	0.019 ± 0.010	0.276 ± 0.149	7.4***
0.415 ± 0.022	0.364±0.017	0.661±0.014	0.369±0.030	0.310±0.014	0.627±0.013	0.348 ± 0.030	0.276±0.017	0.602±0.016	2.7**	GCN-JA		165±0.005	0.542±0.001	0.377±0.008	0.126±0.011	0.518 ± 0.003	0.346 ± 0.020	0.090 ± 0.023	0.498 ± 0.010	3.2***
0.313 ± 0.025	0.207 ± 0.019	0.487 ± 0.022	0.291±0.031	0.172 ± 0.023	0.468 ± 0.016	0.288 ± 0.024	0.156 ± 0.017	0.458 ± 0.018	8.0***	Gasp	0.043	0.094 ± 0.022	0.379±0.006	0.351±0.038	0.076 ± 0.014	0.372±0.006	0.332±0.035	0.060 ± 0.014	0.365 ± 0.005	7.1***
0.298 ± 0.030	0.218 ± 0.021	0.577 ± 0.020	0.266±0.027	0.183 ± 0.017	0.555 ± 0.011	0.269 ± 0.010	0.175 ± 0.016	0.540±0	8.1***	VD1	0.360 ± 0.022	0.113 ± 0.013	0.481 ± 0.010	0.351 ± 0.006	0.097 ± 0.005	0.477 ± 0.004	0.327±0.023	0.071±0.022	0.475 ± 0.011	6.2***
0.405 ± 0.023	0.348 ± 0.015	0.631 ± 0.015	0.370 ± 0.022	0.296±0.011	0.590 ± 0.016	0.341 ± 0.018	0.248±0.017	0 = 4± 01	.2***	ProGNN	O.O.T.	O.O.T.	0.0.T.	J. J.	O.O.T.	0.0.T.	0.0.T.	0.0.T.	O.O.T.	N.A.
0.198 ± 0.014	0.033 ± 0.010	0.300 ± 0.011	0.186 ± 0.010	0.031±0.005	0.279 ± 0.007	0.209 ± 0.018	25+95	0 th an	13.6***	PTDNet	O.O.M.	O.O.M.	0.0.M.	0.00	O.O.M.	O.O.M.	O.O.M.	O.O.M.	O.O.M.	N.A.
0.388 ± 0.005	$0.145 {\pm} 0.005$	$0.337 {\pm} 0.006$	0.374±0.005	0.123±0.006	0.314±0.006	0.364±0.0	1. 2	0	8.7***	FGC	0.598 ± 0.000	0.000+0.000	0.000	0_6000	0.059 ± 0.000	0.261±0.000	0.576 ± 0.000	0.044 ± 0.000	0.218 ± 0.000	7.1***
0.413±0.030	0.379±0.027	0.696±0.010	0.372±0.028	0.320±0.023	0.660±0.015	0.348±0.02	0.202±0.021	0.628±0.018	1.7	MetaGC	0.414±0.0	0.175: 0.010	0	0.396±0.004	0.160 ± 0.004	0.523±0.001	0.380 ± 0.003	0.141 ± 0.004	0.513 ± 0.001	2.6
(b) Cora														(a)	Pubmed					
	I			II			III			N st Level										
F1 Score	NMI									Matuia	Et Cara	ND (T	A for the sectors	Et Carrie	NIX (T	34 - 1	Et Comm		Ma landta	- AR
	141411	Moduarity	F1 Score	NMI	Moduarity	F1 Score	NMI		AIC	Metric	F1 Score	NMI	Moduarity	F1 Score	NMI	Moduarity	F1 Score	NMI	Moduarity	AR
0.375 ± 0.009	0.276±0.013	Moduarity 0.636±0.016	F1 Score 0.314±0.010	NMI 0.201±0.012	Moduarity 0.581±0.009	F1 Score 0.250±0.018	NMI	and to wild	6.4***	Metric DEEPWALK	F1 Score 0.177±0.013	NMI 0.083±0.005	Moduarity	F1 Score 0.136±0.012	NMI 0.054±0.007	Moduarity 0.656±0.010	F1 Score 0.112±0.014	NMI 0.044±0.004	Moduarity 0.596±0.007	AR 9.7***
0.375±0.009 0.377±0.007	0.276±0.013 0.282±0.006	Moduarity 0.636±0.016 0.644±0.005	F1 Score 0.314±0.010 0.308±0.010	NMI 0.201±0.012 0.199±0.011	Moduarity 0.581±0.009 0.584±0.006	F1 Score 0.250±0.018 0.2 0 15	NMI	t0.008	6.4*** 5.8***	Metric DeepWalk Node2Vec	F1 Score 0.177±0.013 0.180±0.011	NMI 0.083±0.005 0.084±0	Moduarity	F1 Score 0.136±0.012 0.146±0.013	NMI 0.054±0.007 0.057±0.004	Moduarity 0.656±0.010 0.661±0.007	F1 Score 0.112±0.014 0.116±0.011	NMI 0.044±0.004 0.041±0.005	Moduarity 0.596±0.007 0.596±0.011	- AR 9.7*** 9.2***
0.375±0.009 0.377±0.007 0.379±0.063	0.276±0.013 0.282±0.006 0.295±0.037	Moduarity 0.636±0.016 0.644±0.005 0.340±0.045	F1 Score 0.314±0.010 0.308±0.010 0.242±0.009	NMI 0.201±0.012 0.199±0.011 0.131±0.015	Moduarity 0.581±0.009 0.584±0.006 0.167±0.77	F1 Score 0.250±0.018 0.250±0.15 0.250±0.15	NMI	0.083±0.027	6.4*** 5.8*** 9.8***	Metric DeepWalk Node2Vec DGI	F1 Score 0.177±0.013 0.180±0.011 0.2.0±0.021	NMI 0.083±0.005 0.084±0	Moduarity 0.7 1 0 00 4 0.00 04±0.015	F1 Score 0.136±0.012 0.146±0.013 0.204±0.013	NMI 0.054±0.007 0.057±0.004 0.228±0.006	Moduarity 0.656±0.010 0.661±0.007 0.648±0.020	F1 Score 0.112±0.014 0.116±0.011 0.183±0.020	III NMI 0.044±0.004 0.041±0.005 0.176±0.004	Moduarity 0.596±0.007 0.596±0.011 0.562±0.032	AR 9.7*** 9.2*** 6.0***
0.375±0.009 0.377±0.007 0.379±0.063 0.366±0.018	$\begin{array}{c} 0.276 \pm 0.013 \\ 0.282 \pm 0.006 \\ 0.295 \pm 0.037 \\ 0.268 \pm 0.011 \end{array}$	$\begin{array}{c} Moduarity\\ 0.636 {\pm} 0.016\\ 0.644 {\pm} 0.005\\ 0.340 {\pm} 0.045\\ 0.395 {\pm} 0.013 \end{array}$	F1 Score 0.314±0.010 0.308±0.010 0.242±0.009 0.259±0.012	NMI 0.201±0.012 0.199±0.011 0.131±0.015 0.144±0.007	Moduarity 0.581±0.009 0.584±0.006 0.167±0.77 0.234).1 7	F1 Score 0.250±0.018 0.2 0 15 0.2 10 0.2 100000000000000000000000000000000000	NMI 0.152.1.01 0.063±0.017 0.062±0.005	0.083±0.027 0.115±0.008	6.4*** 5.8*** 9.8*** 10.1***	Metric DeepWalk Node2Vec DGI GMI	F1 Score 0.177±0.013 0.180±0.011 0.2; ±0.021	NMI 0.083±0.005 0.084±0 0.084±0 0.006	Moduarity 0.7 0 00 0.4 ±0.005 0.606±0.011	F1 Score 0.136±0.012 0.146±0.013 0.204±0.013 0.210±0.011	NMI 0.054±0.007 0.057±0.004 0.228±0.006 0.238±0.004	Moduarity 0.656±0.010 0.661±0.007 0.648±0.020 0.547±0.008	F1 Score 0.112±0.014 0.116±0.011 0.183±0.020 0.185±0.009	III NMI 0.044±0.004 0.041±0.005 0.176±0.004 0.199±0.006	Moduarity 0.596±0.007 0.596±0.011 0.562±0.032 0.486±0.015	AR 9.7*** 9.2*** 6.0*** 7.1***
$\begin{array}{c} 0.375 {\pm} 0.009 \\ 0.377 {\pm} 0.007 \\ 0.379 {\pm} 0.063 \\ 0.366 {\pm} 0.018 \\ \end{array}$	0.276±0.013 0.282±0.006 0.295±0.037 0.268±0.011 0.200±0.019	$\begin{array}{c} Moduarity\\ 0.636 {\pm} 0.016\\ 0.644 {\pm} 0.005\\ 0.340 {\pm} 0.045\\ 0.395 {\pm} 0.013\\ \hline 0.592 {\pm} 0.018 \end{array}$	F1 Score 0.314±0.010 0.308±0.010 0.242±0.009 0.259±0.012 0.278±0.103	NMI 0.201±0.012 0.199±0.011 0.131±0.015 0.144±0.007 0.105±0.054	Moduarity 0.581±0.009 0.584±0.006 0.167±0.5 0.230 1.1 7 0.3.5±0.236	F1 Score 0.250±0.018 0.250±0.018 0.250±0.05 0.250±0.023 0.250±0.023 0.437±0.067	NMI 41,000 0.063±0.017 0.062±0.005 0.012±0.026	0.035±0.124	6.4*** 5.8*** 9.8*** 10.1*** 9.3***	Metric DEEPWALK NODE2VEC DGI GMI	F1 Score 0.177±0.013 0.180±0.011 0.22±0.021 0.001	NMI 0.083±0.005 0.084±0 0.084±0 0.006	Moduarity 0.7 0 00 04±0.015 0.606±0.011 0.677±0.012	F1 Score 0.136±0.012 0.146±0.013 0.204±0.013 0.210±0.011 0.350±0,130	NMI 0.054±0.007 0.057±0.004 0.228±0.006 0.238±0.004 0.067±0.050	Moduarity 0.656±0.010 0.661±0.007 0.648±0.020 0.547±0.008 0.385±0.287	F1 Score 0.112±0.014 0.116±0.011 0.183±0.020 0.185±0.009 0.435±0.136	III NMI 0.044±0.004 0.041±0.005 0.176±0.004 0.199±0.006 0.021±0.037	Moduarity 0.596±0.007 0.596±0.011 0.562±0.032 0.486±0.015 0.154±0.256	AR 9.7*** 9.2*** 6.0*** 7.1*** 8.6***
$\begin{array}{c} 0.375 {\pm} 0.009 \\ 0.377 {\pm} 0.007 \\ 0.379 {\pm} 0.063 \\ 0.366 {\pm} 0.018 \\ \hline 0.271 {\pm} 0.026 \\ 0.340 {\pm} 0.026 \end{array}$	0.276±0.013 0.282±0.006 0.295±0.037 0.268±0.011 0.200±0.019 0.289±0.025	Moduarity 0.636±0.016 0.644±0.005 0.340±0.045 0.395±0.013 0.592±0.018 0.661±0.016	F1 Score 0.314±0.010 0.308±0.010 0.242±0.009 0.259±0.012 0.278±0.103 0.314±0.020	NMI 0.201±0.012 0.199±0.011 0.131±0.015 0.144±0.007 0.105±0.054 0.237±0.023	Moduarity 0.581±0.009 0.584±0.006 0.167±0.7 0.230 1.1 7 0.3.5±0.236 0.630±0.016	F1 Score 0.250±0.018 0.250±0.018 0.250±0.018 0.250±0.023 0.250±0.018	NMI 	0.083±0.027 0.115±0.008 0.035±0.124 0.600±0.016	6.4*** 5.8*** 9.8*** 10.1*** 9.3***	Metric DEEPWALK NODE2VEC DGI GMI	F1 Score 0.177±0.013 0.180±0.011 0.21±0.021 0.021±0.021 0.0054 0.346±0.024	NMI 0.083±0.005 0.084±0 5 5 5 5 5 5 5 5 5 5 5 5 5 5 5 5 5 5 5	Moduarity 0.7 0 00 04±0.015 0.606±0.011 0.677±0.012 0.665±0.011	F1 Score 0.136±0.012 0.146±0.013 0.204±0.013 0.210±0.011 0.350±0.130 0.308±0.012	NMI 0.054±0.007 0.057±0.004 0.228±0.006 0.238±0.004 0.067±0.050 0.139±0.009	Moduarity 0.656±0.010 0.661±0.007 0.648±0.020 0.547±0.008 0.385±0.287 0.624±0.008	F1 Score 0.112±0.014 0.116±0.011 0.183±0.020 0.185±0.009 0.435±0.136 0.283±0.009	III NMI 0.044±0.004 0.041±0.005 0.176±0.004 0.199±0.006 0.021±0.037 0.112±0.006	Moduarity 0.596±0.007 0.596±0.011 0.562±0.032 0.486±0.015 0.154±0.256 0.591±0.009	AR 9.7*** 9.2*** 6.0*** 7.1*** 8.6*** 6.6***
$\begin{array}{c} 0.375 \pm 0.009 \\ 0.377 \pm 0.007 \\ 0.379 \pm 0.063 \\ 0.366 \pm 0.018 \\ \end{array}$ $\begin{array}{c} 0.271 \pm 0.026 \\ 0.340 \pm 0.026 \\ \hline 0.461 \pm 0.022 \end{array}$	0.276±0.013 0.282±0.006 0.295±0.037 0.268±0.011 0.200±0.019 0.289±0.025 0.299±0.024	Moduarity 0.636±0.016 0.644±0.005 0.340±0.045 0.395±0.013 0.592±0.018 0.661±0.016 0.441±0.041	F1 Score 0.314±0.010 0.308±0.010 0.242±0.009 0.259±0.012 0.278±0.103 0.314±0.020 0.415±0.014	NMI 0.201±0.012 0.199±0.011 0.131±0.015 0.144±0.007 0.105±0.054 0.237±0.023 0.165±0.049	Moduarity 0.581±0.009 0.584±0.006 0.167±0.7 0.33 1.7 0.35 ±0.236 0.630±0.016 0.306±0.086	F1 Score 0.250±0.018 0.20100 0.20100 0.2010000000000	NMI 122, 1,01 0.063±0.017 0.062±0.005 0.012±0.026 0.204±0.019 0.105±0.036	0.083±0.027 0.115±0.008 0.035±0.124 0.600±0.016 0.232	6.4*** 5.8*** 9.8*** 10.1*** 9.3*** 5.) **	Metric DEEPWALK NODE2VEC DGI GMI	F1 Score 0.177±0.013 0.180±0.011 0.21±0.021 0.004 0.346±0.024 0.410±0.011	NMI 0.083±0.005 0.084±0 0.057±0.024 0.157±0.024 0.182±0.017 0.191±0.031	Moduarity 0.7 0 00 04±0.015 0.606±0.011 0.677±0.012 0.665±0.011 0.545±0.066	F1 Score 0.136±0.012 0.146±0.013 0.204±0.013 0.210±0.011 0.350±0.130 0.308±0.012 0.415±0.024	NMI 0.054±0.007 0.057±0.004 0.228±0.006 0.238±0.004 0.067±0.050 0.139±0.009 0.147±0.039	Moduarity 0.656±0.010 0.661±0.007 0.643±0.020 0.547±0.008 0.385±0.287 0.624±0.008 0.448±0.114	F1 Score 0.112±0.014 0.116±0.011 0.185±0.009 0.435±0.136 0.283±0.009 0.419±0.054	III NMI 0.044±0.004 0.041±0.005 0.176±0.004 0.199±0.006 0.021±0.037 0.112±0.006 0.078±0.039	Moduarity 0.596±0.007 0.596±0.011 0.562±0.032 0.486±0.015 0.154±0.256 0.591±0.009 0.312±0.161	AR 9.7*** 9.2*** 6.0*** 7.1*** 8.6*** 6.3***
0.375±0.009 0.377±0.007 0.379±0.063 0.366±0.018 0.271±0.026 0.340±0.026 0.461±0.022 0.358±0.033	0.276±0.013 0.282±0.006 0.295±0.037 0.268±0.011 0.200±0.019 0.289±0.025 0.299±0.024 0.283±0.033	Moduarity 0.636±0.016 0.644±0.005 0.340±0.045 0.395±0.013 0.592±0.018 0.661±0.016 0.441±0.041 0.600±0.015	F1 Score 0.314±0.010 0.308±0.010 0.242±0.009 0.259±0.012 0.278±0.103 0.314±0.020 0.415±0.014 0.323±0.025	NMI 0.201±0.012 0.199±0.011 0.131±0.015 0.144±0.007 0.105±0.054 0.237±0.023 0.165±0.049 0.232±0.025	Moduarity 0.581±0.009 0.584±0.006 0.167±0.7 0.33 1.7 0.35±0.236 0.630±0.016 0.306±0.086 0.569±0.011	F1 Score 0.250±0.018 0.250±0.023 0.22±0.023 0.437±0.067 0.291±0.018 0.379±0.030 0.295±0.025	NMI 40 4.01 0.053±0.017 0.062±0.005 0.012±0.026 0.204±0.019 0.105±0.036 0.200±0.5	0.083±0.027 0.115±0.008 0.035±0.124 0.600±0.016 0.232 0.35 0.35 0.7	6.4*** 5.8*** 9.8*** 10.1*** 9.3*** 5.)** 5.1**	Metric DEEPWALK NODE2VEC DGI GMI GCC GCN-JACCARD	F1 Score 0.177±0.013 0.180±0.011 0.27±0.021 0.004 0.346±0.024 0.410±0.011 0.369±0.031	NMI 0.083±0.005 0.084±0 0.157±0.024 0.182±0.017 0.191±0.031 0.209±0.018	Moduarity 0.7 000 0.4±0.015 0.606±0.011 0.677±0.012 0.665±0.011 0.545±0.066 0.676±0.009	F1 Score 0.136±0.012 0.146±0.013 0.204±0.013 0.210±0.011 0.350±0.130 0.308±0.012 0.415±0.024 0.337±0.011	NMI 0.054±0.007 0.057±0.004 0.228±0.006 0.238±0.004 0.067±0.050 0.139±0.009 0.147±0.039 0.171±0.008	Moduarity 0.656±0.010 0.61±0.007 0.643±0.020 0.547±0.008 0.385±0.287 0.624±0.008 0.448±0.114 0.643±0.004	F1 Score 0.112±0.014 0.116±0.011 0.183±0.020 0.185±0.009 0.435±0.136 0.283±0.009 0.419±0.054 0.306±0.012	III NMI 0.044±0.004 0.041±0.005 0.176±0.004 0.199±0.006 0.021±0.037 0.112±0.006 0.078±0.039 0.139±0.007	Moduarity 0.596±0.007 0.596±0.011 0.562±0.032 0.486±0.015 0.154±0.256 0.591±0.009 0.312±0.161 0.612±0.007	AR 9.7*** 9.2*** 6.0*** 7.1*** 8.6*** 6.6*** 6.3*** 4.0***
0.375±0.009 0.377±0.007 0.379±0.063 0.366±0.018 0.271±0.026 0.340±0.026 0.461±0.022 0.358±0.033 0.275±0.022	0.276±0.013 0.282±0.006 0.295±0.037 0.268±0.011 0.200±0.019 0.289±0.025 0.299±0.024 0.283±0.033 0.165±0.024	Moduarity 0.636±0.016 0.644±0.005 0.395±0.013 0.592±0.018 0.661±0.016 0.441±0.041 0.600±0.015 0.403±0.029	F1 Score 0.314±0.010 0.308±0.010 0.242±0.009 0.259±0.012 0.278±0.103 0.314±0.020 0.415±0.014 0.323±0.025 0.247±0.017	NMI 0.201±0.012 0.199±0.011 0.31±0.015 0.144±0.007 0.105±0.054 0.237±0.023 0.165±0.049 0.232±0.025 0.142±0.011	Moduarity 0.581±0.009 0.584±0.006 0.167±0.77 0.33±10.77 0.35±20.236 0.630±0.016 0.306±0.086 0.569±0.011 0.365±0.015	F1 Score 0.250±0.018 0.250±0.018 0.250±0.023 0.437±0.067 0.291±0.018 0.379±0.030 0.295±0.020 0.261±0.016	NMI 0.0524.00 0.063±0.017 0.062±0.005 0.012±0.026 0.204±0.019 0.105±0.036 0.200±0.1 0.200±0.1 0.1 0.200±0.1 0.	0.083±0.027 0.115±0.008 0.035±0.124 0.600±0.016 0.232 0.35±0.016	6.4*** 5.8*** 9.8*** 10.1*** 5.3*** 5.3*** 5.4*** 9.4***	Metric DEEPWALK NODE2VEC DGI GMI GCC GCC GCC-JACCARD GCN-SVD	F1 Score 0.177±0.013 0.180±0.011 0.21±0.021 0.024 0.346±0.024 0.410±0.011 0.369±0.033	NMI 0.083±0.005 0.084±0 5522.006 0.157±0.024 0.157±0.024 0.191±0.031 0.209±0.018 0.120±0.013	Moduarity 0.04±0.015 0.606±0.011 0.675±0.066 0.676±0.009 0.448±0.021	F1 Score 0.136±0.012 0.146±0.013 0.204±0.013 0.210±0.011 0.350±0.130 0.308±0.012 0.415±0.024 0.337±0.011 0.248±0.027	NMI 0.054±0.007 0.057±0.004 0.228±0.006 0.238±0.004 0.067±0.050 0.139±0.009 0.147±0.039 0.171±0.008 0.084±0.008	Moduarity 0.656±0.010 0.661±0.007 0.643±0.020 0.547±0.008 0.385±0.287 0.624±0.008 0.448±0.114 0.643±0.004 0.422±0.022	F1 Score 0.112±0.014 0.116±0.011 0.183±0.020 0.185±0.009 0.435±0.136 0.283±0.009 0.419±0.054 0.306±0.012 0.237±0.027	III NMI 0.044±0.004 0.041±0.005 0.176±0.004 0.199±0.006 0.021±0.037 0.112±0.006 0.078±0.039 0.139±0.007 0.062±0.010	Moduarity 0.596±0.007 0.596±0.011 0.562±0.032 0.486±0.015 0.154±0.256 0.591±0.009 0.312±0.161 0.612±0.007 0.398±0.022	AR 9.7*** 9.2*** 6.0*** 7.1*** 8.6*** 6.6*** 6.3*** 4.0*** 9.8***
$\begin{array}{c} 0.375 {\pm} 0.009 \\ 0.377 {\pm} 0.007 \\ 0.379 {\pm} 0.063 \\ 0.366 {\pm} 0.018 \\ \end{array}$	$\begin{array}{c} 0.276\pm0.013\\ 0.282\pm0.006\\ 0.295\pm0.037\\ 0.268\pm0.011\\ 0.200\pm0.019\\ 0.289\pm0.025\\ 0.299\pm0.024\\ 0.283\pm0.033\\ 0.165\pm0.024\\ 0.159\pm0.016\\ \end{array}$	Moduarity 0.636±0.016 0.644±0.005 0.340±0.045 0.395±0.013 0.592±0.018 0.661±0.016 0.441±0.041 0.600±0.015 0.403±0.029 0.475±0.019	$\begin{tabular}{ c c c c c c c c c c c c c c c c c c c$	NMI 0.201±0.012 0.199±0.011 0.131±0.015 0.144±0.007 0.105±0.054 0.237±0.023 0.165±0.049 0.232±0.025 0.142±0.011 0.102±0.012	Moduarity 0.581±0.009 0.584±0.006 0.167±0.7 0.230±14.7 0.30±0.016 0.306±0.086 0.569±0.011 0.366±0.015 0.366±0.013	F1 Score 0.250±0.018. 0.250±0.018. 0.250±0.018. 0.250±0.018. 0.250±0.023. 0.437±0.067. 0.291±0.018. 0.379±0.030. 0.261±0.016. 0.190±0.024.	NMI 0.062±0.005 0.012±0.026 0.012±0.026 0.204±0.019 0.105±0.036 0.200±0.2 0.4 ±0.014	State State State State State State State State State State State State State State State State State State State State State State State State State State State State State State State State State State State State State State State State State State State State State State State State State State State State State State State State State State State State State State State State State State State State State State State State State State State State State State State State State State State State State State State State State State State State State State State State State State State State State State State State State State State State State State State State State State State State State State State State State State State State State State State State State State State State State State State State State State State State State State State State State State State State State State State State State State State State State State State State State State State State State State State State State State State State State State State State State State State State State State State State State State State State State State State State State State State State State State State State State State State State State State State State State State State State State State State State State State State State State State State State State State State St	6.4*** 5.8*** 9.8*** 10.1*** 9.3*** 5.3** 5.4*** 9.4*** 11.0***	Metric DEEPWALK NODE2VEC DGI GMI GCC GCC-JACCARD GCC-SVD GDC	F1 Score 0.177±0.013 0.180±0.011 0.21±0.021 0.346±0.024 0.410±0.011 0.369±0.031 0.280±0.033 0.257±0.026	NMI 0.083±0.005 0.084±0 0.157±0.024 0.157±0.024 0.182±0.017 0.191±0.031 0.209±0.018 0.120±0.013 0.117±0.015	Moduarity 0.04±0.015 0.606±0.011 0.677±0.012 0.665±0.011 0.545±0.066 0.676±0.009 0.448±0.021 0.548±0.021	F1 Score 0.136±0.012 0.146±0.013 0.204±0.013 0.210±0.011 0.355±0.130 0.305±0.130 0.305±0.012 0.415±0.024 0.337±0.011 0.248±0.027 0.231±0.015	NMI 0.054±0.007 0.057±0.004 0.228±0.006 0.238±0.004 0.067±0.050 0.139±0.009 0.147±0.039 0.147±0.039 0.084±0.008	Moduarity 0.656±0.010 0.661±0.007 0.643±0.020 0.547±0.008 0.385±0.287 0.624±0.008 0.448±0.114 0.643±0.004 0.422±0.022 0.530±0.013	F1 Score 0.112±0.014 0.116±0.011 0.185±0.020 0.435±0.136 0.283±0.009 0.419±0.054 0.306±0.012 0.237±0.027 0.232±0.018	III NMI 0.044±0.004 0.041±0.005 0.176±0.004 0.199±0.006 0.021±0.037 0.112±0.006 0.078±0.039 0.139±0.007 0.062±0.010 0.089±0.012	Moduarity 0.596±0.007 0.596±0.011 0.562±0.032 0.486±0.015 0.154±0.256 0.591±0.009 0.312±0.161 0.612±0.007 0.398±0.022 0.529±0.014	AR 9.7*** 9.2*** 6.0*** 7.1*** 8.6*** 6.3*** 4.0*** 9.4***
$\begin{array}{c} 0.375 {\pm} 0.009 \\ 0.377 {\pm} 0.007 \\ 0.379 {\pm} 0.063 \\ 0.366 {\pm} 0.018 \\ \hline 0.271 {\pm} 0.026 \\ \hline 0.340 {\pm} 0.026 \\ \hline 0.461 {\pm} 0.022 \\ \hline 0.358 {\pm} 0.033 \\ 0.275 {\pm} 0.022 \\ 0.267 {\pm} 0.019 \\ \hline 0.345 {\pm} 0.026 \\ \hline \end{array}$	0.276±0.013 0.282±0.006 0.295±0.037 0.268±0.011 0.200±0.019 0.289±0.025 0.299±0.024 0.283±0.033 0.165±0.024 0.159±0.016 0.297±0.025	Moduarity 0.636±0.016 0.644±0.005 0.349±0.045 0.395±0.013 0.592±0.018 0.661±0.016 0.441±0.041 0.600±0.015 0.403±0.029 0.475±0.019 0.662±0.016	$\begin{tabular}{ c c c c c c c c c c c c c c c c c c c$	NMI 0.201±0.012 0.199±0.011 0.131±0.015 0.144±0.007 0.105±0.054 0.237±0.023 0.165±0.049 0.232±0.025 0.142±0.011 0.102±0.012 0.244±0.023	Moduarity 0.581±0.009 0.584±0.006 0.167±0.12 0.30±0.016 0.306±0.086 0.569±0.011 0.366±0.013 0.631±0.015	F1 Score 0.250±0.018 0.250±0.018 0.250±0.023 0.250±0.023 0.437±0.067 0.291±0.018 0.379±0.030 0.261±0.016 0.190±0.024 0.297±0.018	NMI 0.062±0.017 0.062±0.005 0.012±0.026 0.204±0.019 0.105±0.036 0.200±0.036	0.083±0.027 0.115±0.008 0.035±0.124 0.600±0.016 0.232 0.3-8±0.016 0.285±0.009 0.603±0.015	6.4*** 5.8*** 9.8*** 10.1*** 9.3*** 5.3 5.4*** 9.4*** 11.0*** 3.6***	Metric DEEPWALK NODE2VEC DGI GMI MCC GCC GCN-JACCARD GCC GCN-JACCARD GDC PROGNN	$\begin{array}{c} F1 \ Score \\ 0.177 \pm 0.013 \\ 0.180 \pm 0.011 \\ 0.21 \pm 0.021 \\ 0.26 \pm 0.024 \\ 0.346 \pm 0.024 \\ 0.410 \pm 0.011 \\ 0.369 \pm 0.031 \\ 0.287 \pm 0.025 \\ 0.359 \pm 0.025 \end{array}$	NMI 0.083±0.005 0.084±0 0.157±0.024 0.157±0.024 0.191±0.013 0.107±0.013 0.117±0.015 0.191±0.017	Moduarity 0.04±0.015 0.606±0.011 0.677±0.012 0.665±0.011 0.545±0.066 0.676±0.009 0.448±0.021 0.548±0.021 0.636±0.012	F1 Score 0.136±0.012 0.146±0.013 0.204±0.013 0.210±0.011 0.350±0.130 0.305±0.130 0.305±0.012 0.415±0.024 0.337±0.011 0.234±0.027 0.231±0.015 0.326±0.016	NMI 0.054±0.007 0.057±0.004 0.228±0.006 0.238±0.004 0.067±0.050 0.139±0.009 0.147±0.039 0.171±0.008 0.084±0.008 0.096±0.012 0.153±0.009	Moduarity 0.655±0.010 0.661±0.007 0.648±0.020 0.547±0.008 0.385±0.287 0.624±0.008 0.448±0.114 0.643±0.004 0.422±0.022 0.530±0.013 0.587±0.013	$\begin{array}{c} F1 \ Score \\ 0.112\pm0.014 \\ 0.116\pm0.011 \\ 0.183\pm0.020 \\ 0.185\pm0.009 \\ \hline 0.435\pm0.136 \\ 0.283\pm0.009 \\ \hline 0.419\pm0.054 \\ 0.306\pm0.012 \\ 0.237\pm0.027 \\ 0.232\pm0.018 \\ 0.302\pm0.012 \\ \hline \end{array}$	III NMI 0.044±0.004 0.041±0.005 0.176±0.004 0.199±0.006 0.021±0.037 0.112±0.006 0.078±0.039 0.139±0.007 0.062±0.010 0.089±0.012 0.125±0.006	Moduarity 0.596±0.007 0.596±0.011 0.562±0.032 0.486±0.015 0.154±0.256 0.591±0.009 0.312±0.161 0.612±0.007 0.398±0.022 0.529±0.014 0.544±0.012	AR 9.7*** 9.2*** 6.0*** 7.1*** 8.6*** 6.3*** 4.0*** 9.8*** 9.4*** 5.9***
$\begin{array}{c} 0.375 {\pm} 0.009 \\ 0.377 {\pm} 0.007 \\ 0.379 {\pm} 0.063 \\ 0.366 {\pm} 0.018 \\ \hline 0.271 {\pm} 0.026 \\ \hline 0.461 {\pm} 0.022 \\ \hline 0.358 {\pm} 0.033 \\ 0.275 {\pm} 0.022 \\ 0.267 {\pm} 0.019 \\ 0.345 {\pm} 0.026 \\ 0.235 {\pm} 0.026 \\ \hline 0.235 {\pm} 0.045 \\ \hline \end{array}$	$\begin{array}{c} 1.411\\ 0.276\pm 0.013\\ 0.282\pm 0.006\\ 0.295\pm 0.037\\ 0.268\pm 0.011\\ \hline 0.200\pm 0.019\\ 0.289\pm 0.025\\ \hline 0.299\pm 0.024\\ \hline 0.283\pm 0.033\\ 0.165\pm 0.024\\ \hline 0.159\pm 0.016\\ 0.297\pm 0.025\\ 0.058\pm 0.007\\ \hline \end{array}$	Moduarity 0.636±0.016 0.644±0.005 0.340±0.045 0.395±0.013 0.592±0.018 0.661±0.016 0.441±0.041 0.600±0.015 0.403±0.029 0.475±0.019 0.662±0.016 0.628±0.007	$\begin{tabular}{ c c c c c c c }\hline F1 & Score \\ \hline 0.314 \pm 0.010 \\ 0.308 \pm 0.010 \\ 0.242 \pm 0.009 \\ 0.259 \pm 0.012 \\ \hline 0.278 \pm 0.013 \\ 0.314 \pm 0.020 \\ \hline 0.415 \pm 0.014 \\ \hline 0.323 \pm 0.025 \\ 0.247 \pm 0.017 \\ 0.320 \pm 0.020 \\ 0.319 \pm 0.020 \\ 0.216 \pm 0.055 \\ \hline \end{tabular}$	NMI 0.201±0.012 0.199±0.011 0.131±0.015 0.105±0.054 0.237±0.023 0.165±0.049 0.232±0.025 0.142±0.011 0.102±0.012 0.244±0.023 0.244±0.023 0.46±0.006	Moduarity 0.581±0.009 0.584±0.006 0.167±0 0.30±0.236 0.630±0.016 0.306±0.086 0.569±0.011 0.365±0.015 0.361±0.015 0.249±0.012	F1 Score 0.250±0.018 0.250±0.018 0.250±0.023 0.291±0.018 0.379±0.030 0.295±0.020 0.261±0.016 0.190±0.024 0.297±0.018 0.271±0.041	NMI 0.1024.00 0.0024.0017 0.062±0.005 0.012±0.026 0.204±0.019 0.105±0.036 0.200±0.036 0.200±0.036 0.200±0.036 0.200±0.014 0.212±0.020 0.044±0.006	0.083±0.027 0.115±0.008 0.035±0.124 0.600±0.016 0.232 0.55±0.009 0.603±0.015 0.244±0.013	6.4*** 5.8*** 9.8*** 10.1*** 9.3*** 5.0*** 5.0*** 9.4*** 11.0*** 3.6*** 11.9***	Metric DEEPWALK NODE2VEC DGI GMI CONSUL GCC GCN-JACCARD GCC-SVD GDC PROGNN PTDNET	$\begin{array}{c} F1 \ Score \\ \hline 0.177 \pm 0.013 \\ 0.180 \pm 0.011 \\ 0.21 \pm 0.021 \\ \hline 0.21 \pm 0.021 \\ 0.25 \pm 0.024 \\ 0.346 \pm 0.024 \\ 0.410 \pm 0.011 \\ 0.369 \pm 0.033 \\ 0.257 \pm 0.026 \\ 0.359 \pm 0.025 \\ 0.278 \pm 0$	NMI 0.083±0.005 0.084±0 0.157±0.024 0.157±0.024 0.191±0.031 0.209±0.018 0.117±0.013 0.117±0.015 0.191±0.017 0.048±0.004	Moduarity 0.04±0.015 0.606±0.011 0.677±0.012 0.665±0.011 0.545±0.066 0.676±0.009 0.448±0.021 0.548±0.021 0.636±0.012 0.344±0.007	F1 Score 0.136±0.012 0.146±0.013 0.204±0.013 0.210±0.011 0.350±0.130 0.308±0.012 0.415±0.024 0.337±0.011 0.248±0.027 0.231±0.015 0.326±0.016 0.277±0.044	NMI 0.054±0.007 0.057±0.004 0.228±0.006 0.238±0.004 0.067±0.050 0.139±0.009 0.147±0.039 0.171±0.008 0.096±0.012 0.153±0.009 0.036±0.014	$\begin{array}{r} \mbox{Moduarity} \\ \mbox{0.656\pm0.010} \\ \mbox{0.661\pm0.007} \\ \mbox{0.648\pm0.020} \\ \mbox{0.547\pm0.008} \\ \mbox{0.385\pm0.287} \\ \mbox{0.624\pm0.008} \\ \mbox{0.448\pm0.114} \\ \mbox{0.643\pm0.004} \\ \mbox{0.422\pm0.022} \\ \mbox{0.530\pm0.013} \\ \mbox{0.587\pm0.013} \\ \mbox{0.317\pm0.019} \\ \end{array}$	$\begin{array}{c} F1 \ Score \\ 0.112\pm0.014 \\ 0.116\pm0.011 \\ 0.183\pm0.020 \\ 0.185\pm0.009 \\ \hline 0.435\pm0.019 \\ 0.435\pm0.009 \\ 0.419\pm0.054 \\ \hline 0.306\pm0.012 \\ 0.237\pm0.027 \\ 0.232\pm0.018 \\ 0.302\pm0.012 \\ 0.293\pm0.037 \\ \hline \end{array}$	$\begin{array}{c c} & \text{III} \\ \hline & \text{NMI} \\ \hline & 0.044\pm 0.004 \\ \hline & 0.041\pm 0.005 \\ \hline & 0.176\pm 0.004 \\ \hline & 0.199\pm 0.006 \\ \hline & 0.021\pm 0.037 \\ \hline & 0.112\pm 0.006 \\ \hline & 0.078\pm 0.039 \\ \hline & 0.139\pm 0.007 \\ \hline & 0.062\pm 0.010 \\ \hline & 0.089\pm 0.012 \\ \hline & 0.125\pm 0.006 \\ \hline & 0.056\pm 0.025 \\ \hline \end{array}$	$\begin{tabular}{ c c c c c } \hline Moduarity \\ \hline 0.596\pm0.007 \\ \hline 0.596\pm0.011 \\ \hline 0.562\pm0.032 \\ \hline 0.486\pm0.015 \\ \hline 0.154\pm0.256 \\ \hline 0.591\pm0.009 \\ \hline 0.312\pm0.161 \\ \hline 0.612\pm0.007 \\ \hline 0.398\pm0.022 \\ \hline 0.529\pm0.014 \\ \hline 0.544\pm0.012 \\ \hline 0.301\pm0.018 \\ \hline \end{tabular}$	AR 9.7*** 9.2*** 6.0*** 7.1*** 8.6*** 6.3*** 9.8*** 9.8*** 9.4*** 5.9*** 11.3***
$\begin{array}{c} 0.375 {\pm} 0.009 \\ 0.377 {\pm} 0.007 \\ 0.379 {\pm} 0.063 \\ 0.366 {\pm} 0.018 \\ \hline 0.271 {\pm} 0.026 \\ \hline 0.340 {\pm} 0.026 \\ \hline 0.461 {\pm} 0.022 \\ \hline 0.358 {\pm} 0.033 \\ 0.275 {\pm} 0.022 \\ 0.267 {\pm} 0.019 \\ 0.345 {\pm} 0.026 \\ 0.235 {\pm} 0.045 \\ \hline 0.395 {\pm} 0.013 \\ \hline \end{array}$	$\begin{array}{c} 1.411\\ 0.276\pm 0.013\\ 0.282\pm 0.006\\ 0.295\pm 0.037\\ 0.268\pm 0.011\\ \hline 0.200\pm 0.019\\ 0.289\pm 0.025\\ \hline 0.299\pm 0.024\\ 0.283\pm 0.033\\ 0.165\pm 0.024\\ 0.159\pm 0.016\\ \hline 0.297\pm 0.025\\ 0.058\pm 0.007\\ 0.035\pm 0.011\\ \hline \end{array}$	Moduarity 0.636±0.016 0.64±0.005 0.340±0.045 0.395±0.013 0.592±0.018 0.661±0.016 0.441±0.041 0.600±0.015 0.403±0.029 0.475±0.019 0.662±0.016 0.628±0.007 0.111±0.029	$\begin{tabular}{ c c c c c c c } \hline F1 & Score \\ \hline 0.314 \pm 0.010 \\ \hline 0.308 \pm 0.010 \\ \hline 0.208 \pm 0.012 \\ \hline 0.259 \pm 0.012 \\ \hline 0.278 \pm 0.103 \\ \hline 0.314 \pm 0.020 \\ \hline 0.415 \pm 0.014 \\ \hline 0.323 \pm 0.025 \\ \hline 0.247 \pm 0.017 \\ \hline 0.230 \pm 0.020 \\ \hline 0.319 \pm 0.020 \\ \hline 0.319 \pm 0.020 \\ \hline 0.216 \pm 0.055 \\ \hline 0.415 \pm 0.002 \\ \hline \end{tabular}$	NMI 0.201±0.012 0.199±0.011 0.131±0.015 0.105±0.054 0.237±0.023 0.165±0.049 0.232±0.025 0.142±0.011 0.102±0.012 0.244±0.023 0.046±0.006 0.047±0.003	Moduarity 0.581±0.009 0.584±0.006 0.167±0 0.33 0.77 0.3 00236 0.630±0.016 0.306±0.016 0.365±0.015 0.366±0.013 0.631±0.015 0.249±0.012 0.059±0.005	F1 Score 0.250±0.018 0.250±0.018 0.250±0.023 0.437±0.067 0.291±0.018 0.379±0.030 0.295±0.020 0.261±0.016 0.190±0.024 0.297±0.018 0.271±0.041 0.424±0.003	NMI 	0.083±0.027 0.115±0.008 0.035±0.124 0.600±0.016 0.232 13 0.33&07 0.33&07 0.33&07 0.603±0.015 0.244±0.013 0.038±0.006	6.4*** 5.8*** 9.8*** 10.1*** 9.3*** 9.4*** 11.0*** 3.6*** 11.9*** 9.8***	Metric DEEPWALK NODE2VEC DGI GMI GCN-JACCARD GCN-JACCARD GCN-SVD GDC PROGNN PTIDNET FGC	F1 Score 0.177±0.013 0.180±0.011 0.21±0.021 0.0054 0.346±0.024 0.410±0.011 0.369±0.031 0.280±0.033 0.257±0.026 0.359±0.025 0.278±0.029 0.410±0.004	NMI 0.083±0.005 0.084±0 0.157±0.024 0.157±0.024 0.191±0.031 0.209±0.018 0.120±0.013 0.117±0.015 0.191±0.017 0.048±0.004 0.131±0.005	Moduarity 0.4±0.015 0.606±0.011 0.677±0.012 0.665±0.011 0.545±0.066 0.676±0.009 0.448±0.021 0.636±0.012 0.344±0.007 0.344±0.007	F1 Score 0.136±0.012 0.146±0.013 0.204±0.013 0.210±0.011 0.350±0.130 0.308±0.012 0.415±0.024 0.337±0.011 0.248±0.027 0.321±0.015 0.326±0.016 0.277±0.044 0.398±0.005	NMI 0.054±0.007 0.057±0.004 0.228±0.006 0.238±0.004 0.067±0.050 0.139±0.009 0.147±0.039 0.171±0.008 0.084±0.008 0.096±0.012 0.153±0.009 0.036±0.014 0.112±0.007	$\begin{array}{r} \mbox{Moduarity}\\ \hline 0.656\pm 0.010\\ \hline 0.661\pm 0.007\\ \hline 0.64\pm 0.020\\ \hline 0.547\pm 0.008\\ \hline 0.385\pm 0.287\\ \hline 0.624\pm 0.008\\ \hline 0.448\pm 0.114\\ \hline 0.643\pm 0.004\\ \hline 0.422\pm 0.022\\ \hline 0.530\pm 0.013\\ \hline 0.587\pm 0.013\\ \hline 0.317\pm 0.019\\ \hline 0.381\pm 0.008\\ \hline \end{array}$	$\begin{array}{c} F1 \ Score \\ 0.112\pm0.014 \\ 0.116\pm0.011 \\ 0.183\pm0.020 \\ 0.185\pm0.009 \\ \hline \\ 0.435\pm0.136 \\ 0.283\pm0.009 \\ \hline \\ 0.419\pm0.054 \\ \hline \\ 0.306\pm0.012 \\ 0.237\pm0.027 \\ 0.232\pm0.018 \\ 0.302\pm0.012 \\ 0.293\pm0.037 \\ \hline \\ 0.400\pm0.005 \\ \hline \end{array}$	$\begin{array}{c c} & \text{III} \\ \hline & \text{NMI} \\ \hline & 0.044 \pm 0.004 \\ \hline & 0.041 \pm 0.005 \\ \hline & 0.176 \pm 0.004 \\ \hline & 0.199 \pm 0.006 \\ \hline & 0.021 \pm 0.037 \\ \hline & 0.112 \pm 0.006 \\ \hline & 0.078 \pm 0.039 \\ \hline & 0.139 \pm 0.007 \\ \hline & 0.062 \pm 0.010 \\ \hline & 0.089 \pm 0.012 \\ \hline & 0.125 \pm 0.006 \\ \hline & 0.056 \pm 0.025 \\ \hline & 0.105 \pm 0.005 \\ \hline \end{array}$	Moduarity 0.596 ± 0.007 0.596 ± 0.011 0.562 ± 0.032 0.486 ± 0.015 0.154 ± 0.256 0.591 ± 0.009 0.312 ± 0.161 0.612 ± 0.007 0.398 ± 0.022 0.529 ± 0.014 0.59 ± 0.012 0.31 ± 0.018 0.370 ± 0.008	AR 9.7*** 9.2*** 6.0*** 7.1*** 8.6*** 6.3*** 4.0*** 9.8*** 5.9*** 11.3*** 7.4***
	F1 Score 0.300±0.024 0.292±0.028 0.351±0.040 0.277±0.023 0.265±0.035 0.400±0.023 0.375±0.017 0.415±0.022 0.313±0.025 0.298±0.030 0.405±0.023 0.198±0.014 0.388±0.005 0.413±0.030	$\begin{tabular}{ c c c c c }\hline I \\\hline F1 Score & NMI \\\hline 0.300 \pm 0.024 & 0.243 \pm 0.010 \\0.292 \pm 0.028 & 0.247 \pm 0.015 \\0.351 \pm 0.040 & 0.415 \pm 0.011 \\0.277 \pm 0.023 & 0.319 \pm 0.008 \\\hline 0.265 \pm 0.035 & 0.222 \pm 0.023 \\0.400 \pm 0.023 & 0.343 \pm 0.015 \\0.375 \pm 0.017 & 0.230 \pm 0.013 \\\hline 0.415 \pm 0.022 & 0.364 \pm 0.017 \\0.313 \pm 0.025 & 0.207 \pm 0.019 \\0.298 \pm 0.030 & 0.218 \pm 0.021 \\0.405 \pm 0.023 & 0.348 \pm 0.015 \\0.198 \pm 0.014 & 0.033 \pm 0.010 \\0.388 \pm 0.005 & 0.145 \pm 0.005 \\\hline\hline 0.413 \pm 0.030 & 0.379 \pm 0.027 \\\hline \end{tabular}$	$\begin{tabular}{ c c c c c c }\hline I \\\hline F1 Score & NMI & Moduarity \\\hline 0.300 \pm 0.024 & 0.243 \pm 0.010 & 0.680 \pm 0.009 \\\hline 0.292 \pm 0.028 & 0.247 \pm 0.015 & 0.684 \pm 0.009 \\\hline 0.292 \pm 0.028 & 0.247 \pm 0.015 & 0.619 \pm 0.015 \\\hline 0.277 \pm 0.023 & 0.319 \pm 0.008 & 0.576 \pm 0.010 \\\hline 0.265 \pm 0.035 & 0.222 \pm 0.023 & 0.614 \pm 0.012 \\\hline 0.400 \pm 0.023 & 0.343 \pm 0.015 & 0.661 \pm 0.012 \\\hline 0.375 \pm 0.017 & 0.230 \pm 0.013 & 0.486 \pm 0.011 \\\hline 0.415 \pm 0.022 & 0.364 \pm 0.017 & 0.661 \pm 0.012 \\\hline 0.313 \pm 0.025 & 0.207 \pm 0.019 & 0.487 \pm 0.022 \\\hline 0.298 \pm 0.030 & 0.218 \pm 0.021 & 0.577 \pm 0.020 \\\hline 0.405 \pm 0.023 & 0.348 \pm 0.015 & 0.631 \pm 0.015 \\\hline 0.198 \pm 0.014 & 0.033 \pm 0.010 & 0.300 \pm 0.011 \\\hline 0.388 \pm 0.005 & 0.145 \pm 0.027 & 0.696 \pm 0.010 \\\hline\hline I & I \\\hline \end{tabular}$	$\begin{tabular}{ c c c c c c c c c c c c c c c c c c c$	$\begin{array}{c c c c c c c c c c c c c c c c c c c $	$\begin{tabular}{ c c c c c c c c c c c c c c c c c c c$	$\begin{array}{c c c c c c c c c c c c c c c c c c c $	I II III F1 Score NMI Moduarity F1 Score NMI Moduarity F1 Score NMI Moduarity F1 Score NMI 0.300±0.024 0.243±0.010 0.680±0.009 0.216±0.010 0.155±0.006 0.593±0.011 0.169±0.014 0.111±0.019 0.322±0.028 0.247±0.015 0.684±0.009 0.210±0.016 0.154±0.010 0.594±0.009 0.170±0.009 0.111±0.011 0.351±0.040 0.415±0.011 0.619±0.015 0.294±0.027 0.330±0.012 0.547±0.017 0.248±0.018 0.240±0.017 0.277±0.023 0.319±0.008 0.576±0.010 0.226±0.016 0.229±0.005 0.496±0.007 0.152±0.016 0.145±0.012 0.265±0.035 0.222±0.023 0.61±0.012 0.335±0.023 0.280±0.013 0.620±0.013 0.326±0.016 0.231±0.039 0.400±0.022 0.343±0.015 0.661±0.014 0.369±0.030 0.310±0.014 0.627±0.013 0.364±0.041 0.076±0.017 0.313±0.025 0.207±0.019 0.487±0.022 0.291±0.031 0.310±0.014 0.627	I II III F1 Score NMI Moduarity F1 Score NMI Moduarity F1 Score NMI Moduarity F1 Score NMI Moduarity 0.300±0.024 0.243±0.010 0.680±0.009 0.216±0.010 0.155±0.006 0.593±0.011 0.169±0.014 0.111±0.009 0.528±0.008 0.292±0.028 0.247±0.015 0.684±0.009 0.210±0.016 0.15±0.006 0.593±0.017 0.248±0.018 0.240±0.017 0.412±0.033 0.277±0.023 0.319±0.008 0.576±0.010 0.229±0.005 0.496±0.007 0.152±0.016 0.145±0.012 0.391±0.020 0.265±0.035 0.222±0.023 0.614±0.012 0.217±0.027 0.147±0.019 0.556±0.012 0.219±0.097 0.086±0.039 0.436±0.172 0.400±0.023 0.343±0.015 0.661±0.012 0.355±0.023 0.280±0.013 0.622±0.013 0.364±0.011 0.364±0.027 0.147±0.019 0.556±0.012 0.236±0.016 0.231±0.016 0.232±0.016 0.231±0.016 0.231±0.016 0.231±0.016 0.376±0.017 0.662±0.011 0.364±0.011	I II III III AR F1 Score NMI Moduarity F1 Score NMI Moduarity F1 Score NMI Moduarity AR 0.300±0.024 0.243±0.010 0.680±0.009 0.216±0.010 0.155±0.006 0.593±0.011 0.169±0.014 0.111±0.009 0.528±0.008 8.3*** 0.322±0.028 0.247±0.015 0.684±0.009 0.210±0.016 0.154±0.010 0.594±0.009 0.110±0.019 0.528±0.008 8.3*** 0.351±0.040 0.415±0.011 0.619±0.015 0.294±0.027 0.330±0.012 0.547±0.017 0.248±0.018 0.240±0.017 0.412±0.033 6.1**** 0.272±0.023 0.614±0.012 0.217±0.027 0.147±0.019 0.556±0.012 0.219±0.097 0.086±0.039 0.436±0.172 10.1*** 0.400±0.023 0.343±0.015 0.661±0.012 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0.326±0.014 0.326±0.014 0.276±0.012 45*** DMoN 0.406±0.005 0.372±0.010 0.487±0.023 0.310±0.014 0.362±0.012	I II III AR F1 Score NMI Moduarity F1 Score NMI Moduarity AR 0.300±0.024 0.243±0.010 0.680±0.009 0.210±0.016 0.155±0.006 0.593±0.011 0.169±0.014 0.111±0.009 0.528±0.008 8.3*** 0.292±0.023 0.247±0.015 0.684±0.009 0.210±0.016 0.554±0.000 0.593±0.011 0.169±0.017 0.528±0.008 8.3*** 0.303±0.012 0.415±0.011 0.619±0.015 0.294±0.027 0.330±0.012 0.547±0.017 0.248±0.018 0.240±0.017 0.412±0.033 6.1*** DGI 0.199±0.019 0.185±0.003 0.391±0.020 9.7*** DGI 0.199±0.019 0.185±0.003 0.391±0.020 9.7*** DGI 0.199±0.019 0.185±0.003 0.310±0.005 0.331±0.005 0.331±0.015 0.532±0.023 0.634±0.012 0.354±0.023 0.264±0.017 0.622±0.013 0.364±0.011 0.362±0.013 0.362±0.013 0.362±0.013 0.362±0.013 0.362±0.013 0.362±0.013 0.362±0.013 0.362±0.013 0.362±0.013 0.362±0	I II III Noise Level I F1 Score NMI Moduarity Moduarity F1 Score NMI Moduarity F1 Score	I II III Noise Level I F1 Score NMI Moduarity F1 Score NMI 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(c) Cora-ML

(e) Citeseer

(Q2) Effectiveness of Meta-Weighting

The meta-model accurately distinguish noise edges from the real ones.

Dataset	Cora			Cora-ML			Citeseer			Amazon-Photo			Pubmed		
Noise Level	Ι	II	III	Ι	II	III	Ι	Π	III	Ι	П	III	Ι	II	III
Meta-Weighting	0.927	0.875	0.831	0.934	0.878	0.825	0.908	0.843	0.793	0.993	0.985	0.976	0.890	0.813	0.757
Baseline	0.769	0.625	0.526	0.769	0.625	0.526	0.769	0.625	0.526	0.769	0.625	0.526	0.769	0.625	0.526



(Q3) Ablation Study

• **Every component** of MetaGC **contributes** to the performance gain.

Noise Level		Ι			II		III			
Metric	F1 Score	NMI	Modularity	F1 Score	NMI	Modularity	F1 Score	NMI	Moduarity	
MetaGC-X	0.340 ± 0.022	0.203±0.016	0.695±0.006	0.308±0.017	0.173 ± 0.014	0.662 ± 0.007	0.280±0.018	0.142±0.013	0.634 ± 0.009	
MetaGC-A	0.346 ± 0.020	0.214 ± 0.014	0.701 ± 0.007	0.324 ± 0.019	0.187 ± 0.016	0.674 ± 0.011	0.288 ± 0.017	0.150 ± 0.012	0.638 ± 0.009	
MetaGC	0.363±0.017	$0.230{\pm}0.013$	0.707±0.007	$0.330 {\pm} 0.025$	0.194±0.021	0.677±0.012	0.289±0.017	0.151±0.013	$0.640 {\pm} 0.009$	

- MetaGC-X: MetaGC without the meta-model, i.e., the weights for all node pair are the same.
- MetaGC-A: MetaGC with the meta-model <u>using only node attributes</u>.





Conclusion

• We propose **MetaGC** for **robust GNN-based graph clustering** against noise edges.

 MetaGC is robust against noise edges, achieving the best clustering performance overall among all the 14 considered methods.

 The meta-model in MetaGC assigns high weights to real edges and low weights to noise edges, leading to MetaGC's performance gain.

