

# Pre-Training Graph Neural Networks

CS224W: Machine Learning with Graphs

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<http://cs224w.stanford.edu>

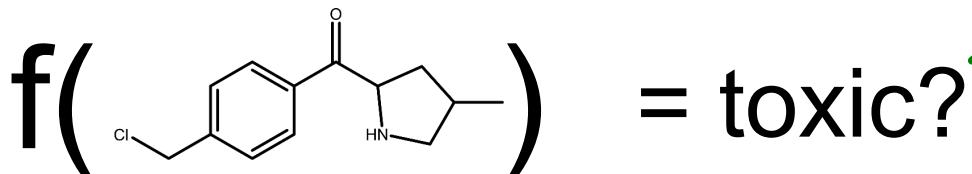


# Graph ML in Scientific Domains

- **Chemistry:** Molecular graphs

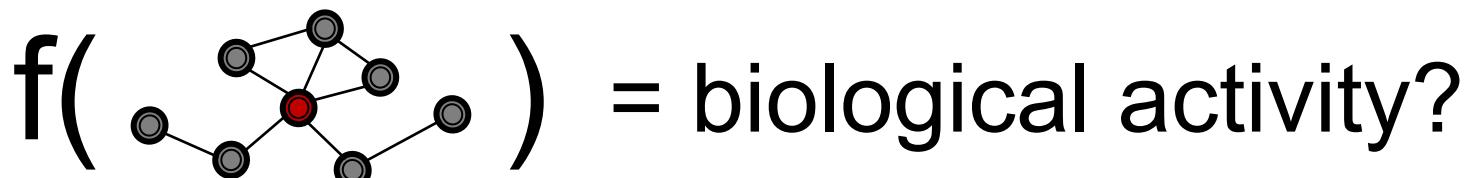
- Molecular property prediction

Our running example today



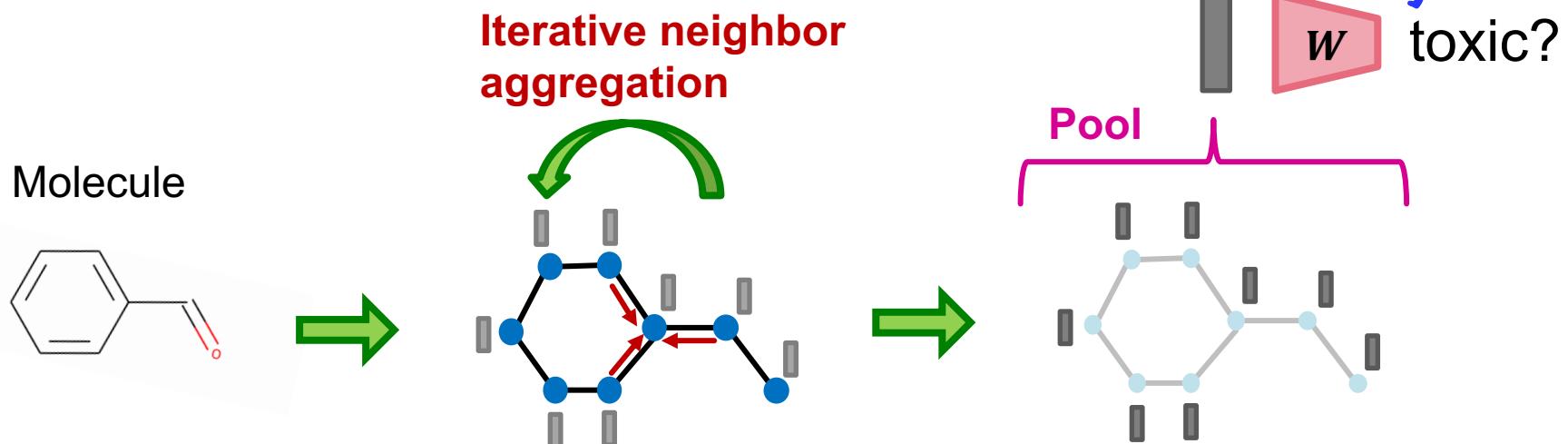
- **Biology:** Protein-protein association graphs

- Protein function prediction



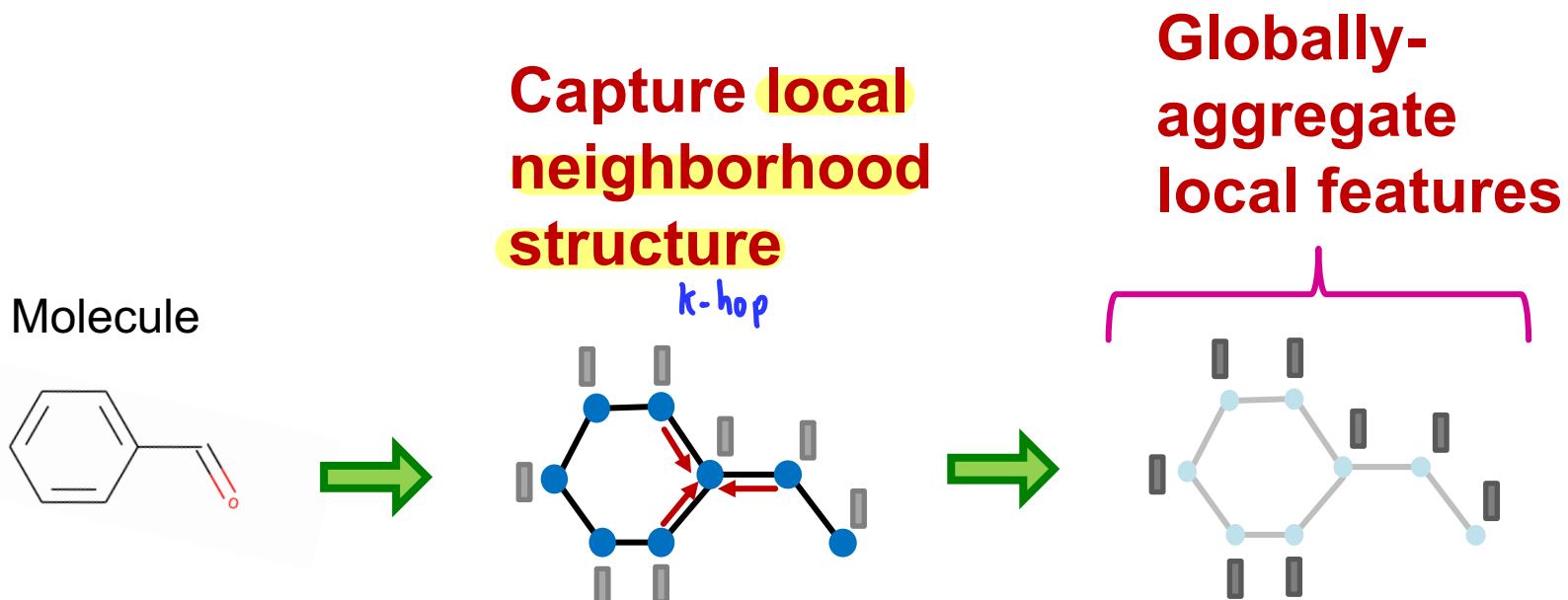
# GNNs for Graph Classification

- GNNs obtain an embedding of an entire graph by following two steps
  - Iteratively aggregate neighboring information to obtain node embeddings
  - Pool node embeddings to obtain a graph embedding



# GNNs for Graph Classification

- Node embeddings capture **local neighborhood structure**
- The embedding of an entire graph is a **global aggregation** of such node embeddings



# Challenges of Applying ML

- Two fundamental challenges in applying ML to scientific domains

## 1. Scarcity of labeled data

- Obtaining labels requires expensive lab experiments  
→ GNNs overfit to small training data

## 2. Out-of-distribution prediction

- Test examples tend to be very different from training examples  
→ GNNs extrapolate poorly

# Challenges for Deep Learning (1)

- Deep learning models have a lot parameters to train (e.g., in the order of millions).
- #(Labeled training data) << #(Parameters)
- Deep learning models are extremely prone to overfitting on small labeled data.

# Challenges for Deep Learning (2)

- **Deep learning models extrapolate poorly**  
■ Models often make predictions based on spurious correlations in a dataset [Sagawa et al. ICML 2020]  
■ Ex) Image classification between “polar bear” and “brown bear”  
■ During training:
  - Most “polar bears” have the snow background
  - Most “normal bears” have the grass background
  - **Model can learn to make prediction based on the image background, rather than the animal itself.**  
■ At test time, what if we see “polar bear” on the grass?



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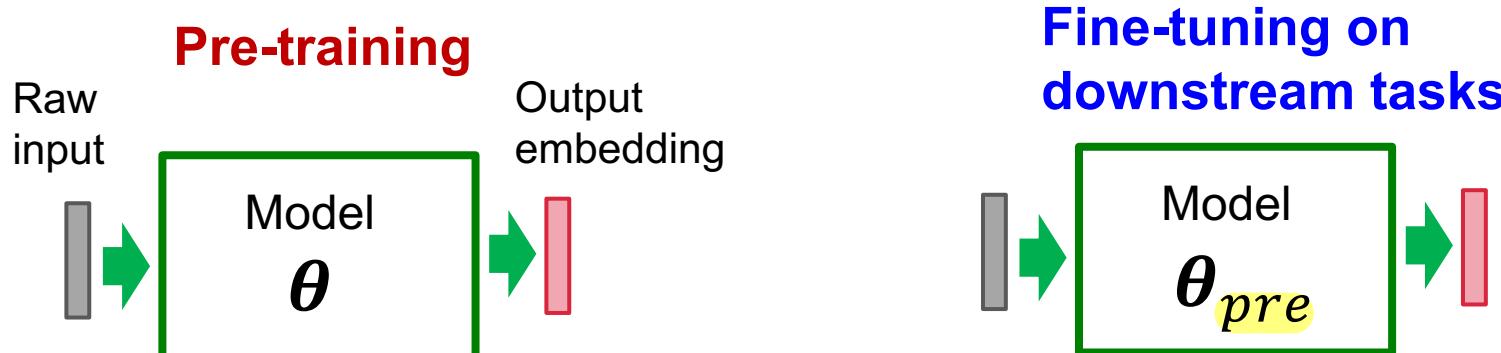
Adapted from  
Wikipedia

# Injecting Domain Knowledge

- **Goal:** Improve model's out-of-distribution prediction performance even with limited data.
- **Key idea:** Inject domain knowledge into a model before training on scarcely-labeled tasks!
  - The model already knows the domain knowledge before training on data
  - So that the model can
    - Generalize well without much task-specific labeled data
    - Extract essential (non-spurious) pattern that allows better extrapolation.

# Effective Solution: Pre-Training

- We **pre-train a model relevant tasks**, where data is abundant.
  - After pre-training, the model parameters already contain domain knowledge.
- **For downstream tasks (what we care about, typically with small #labeled data)**
  - We start from the pre-trained parameters and fine-tuning them.



# Pre-Training is Successful

- Pre-training has been hugely successful in computer vision and natural language processing.
  - Pre-training improves label-efficiency.
  - Pre-training improves out-of-distribution performance [Hendrycks et al. ICML 2019]
- Pre-training is a powerful solution to the two ML challenges in scientific applications
  - Scarce labels
  - Out-of-distribution prediction

# Pre-training GNNs

- Let's consider pre-training GNNs!
- We design GNN pre-training strategies and systematically investigate

**Q1.** How effective is pre-training GNNs?

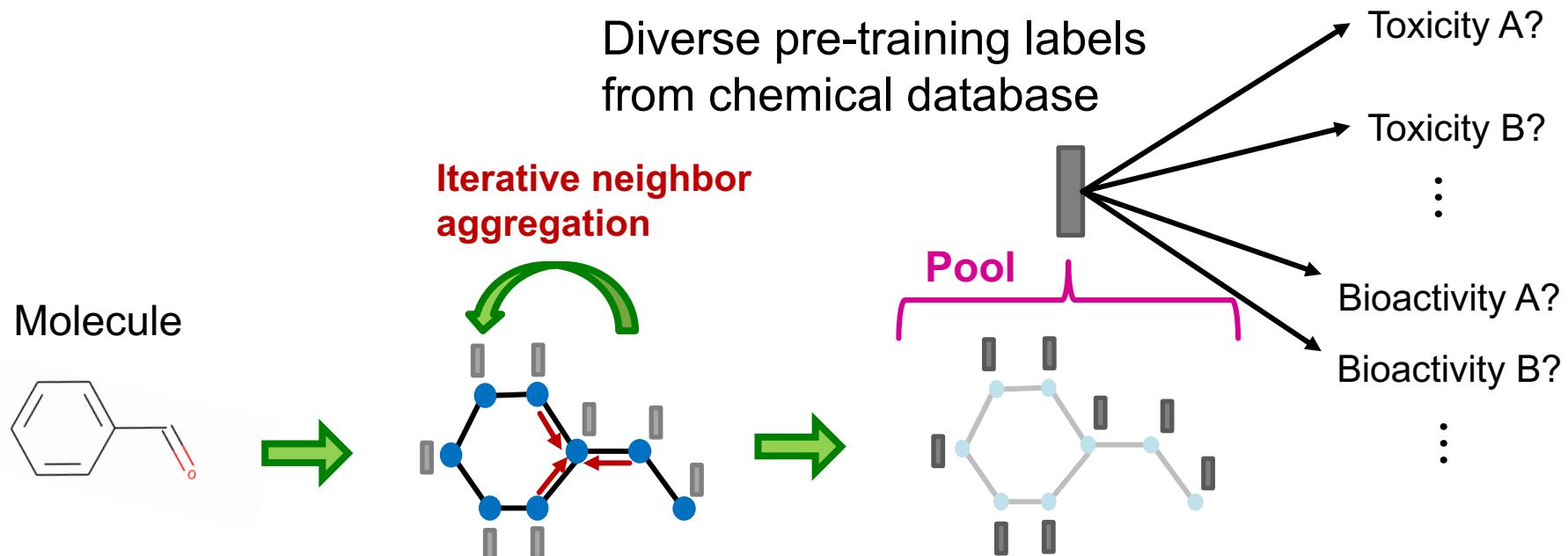
**Q2.** What is the effective pre-training strategy?

# How Effective is Pre-training GNNs?

Let's think about molecular property prediction for drug discovery.

## ■ Naïve strategy

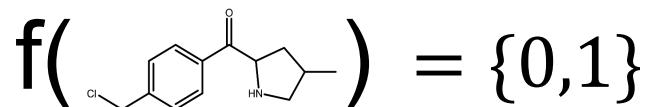
Multi-task supervised pre-training on relevant labels.



# Experimental Setting

## ■ Molecule classification

- **Task:** Binary classification. ROC-AUC as metric



- **Supervised pre-training data**

- 1310 diverse binary bioassays annotated over ~450K molecules

- **Downstream task** (what we care about!)

- 8 molecular classification datasets (relatively-small, 1K—100K molecules)

- **Data split:** Scaffold (test molecules are out-of-distribution)

# How Effective is Pre-training GNNs?

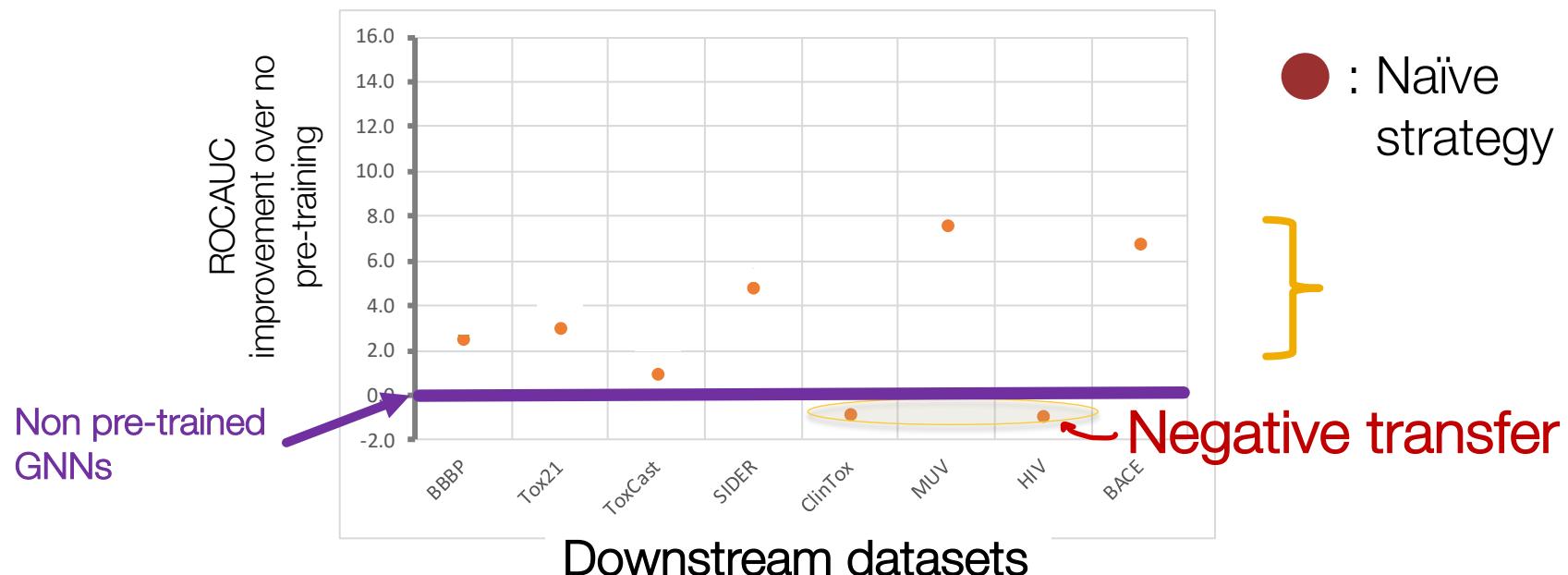
- **Naïve strategy:** *doesn't work very well*

Multi-task supervised pre-training on relevant labels.

→ **Limited performance improvement on downstream tasks. Often leads to negative transfer**

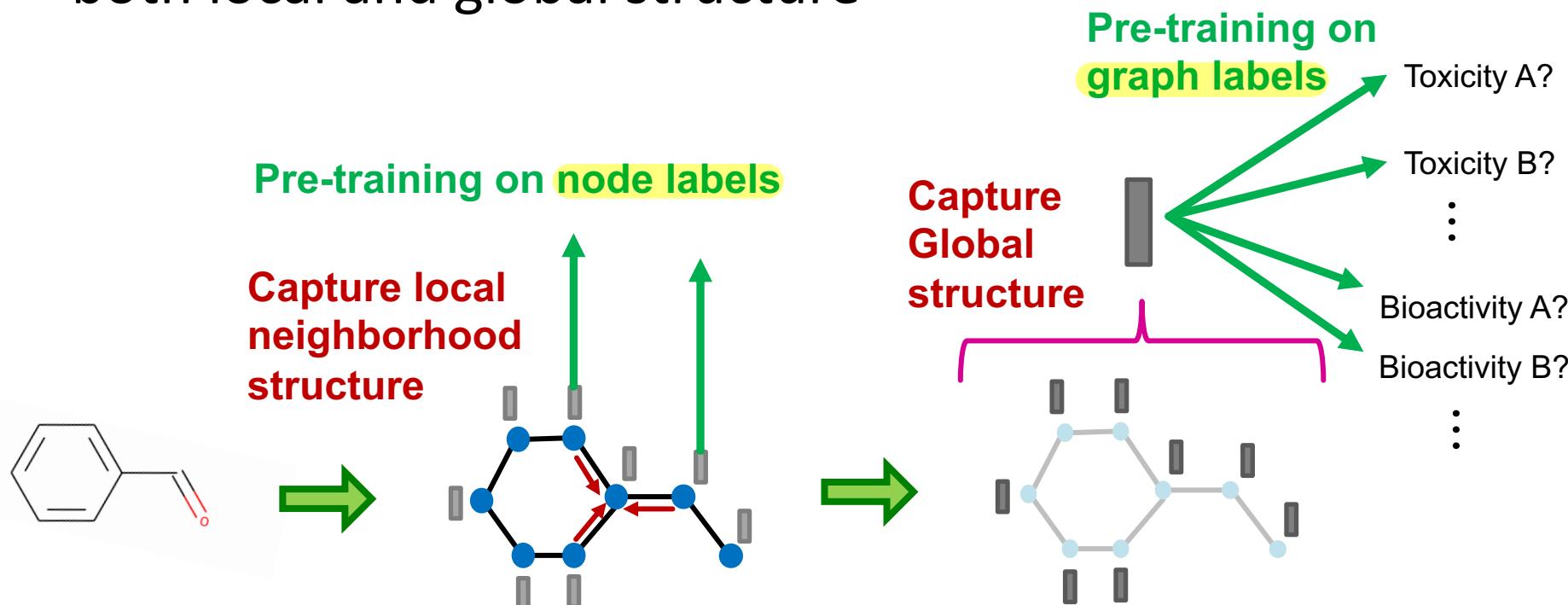
*pre-trained model performs worse than randomly initialized model*

Molecule classification performance



# What is the Effective Strategy?

- **Key idea:** Pre-train both node and graph embeddings.  
→ GNN can capture domain-specific knowledge of both local and global structure

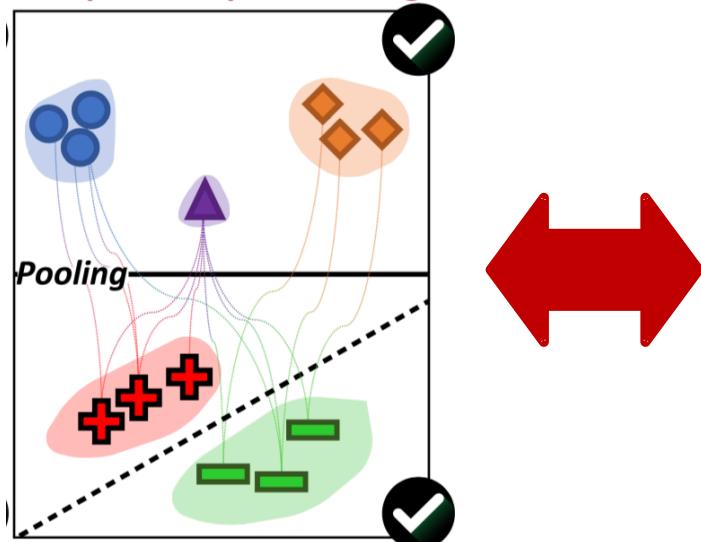


# What is the Effective Strategy?

- **Key idea:** Pre-train both node and graph embeddings.

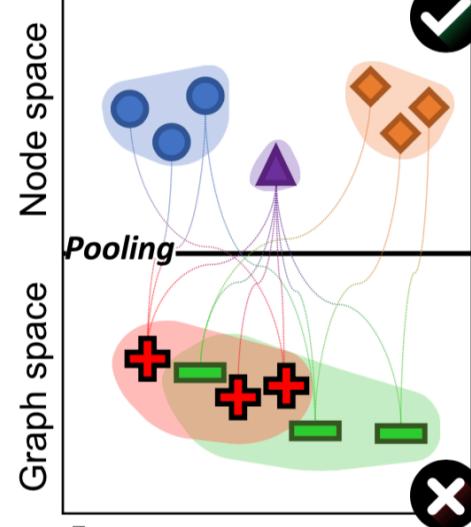
## Embedding illustration

(a.iii) Node-level +  
Graph-level pre-training

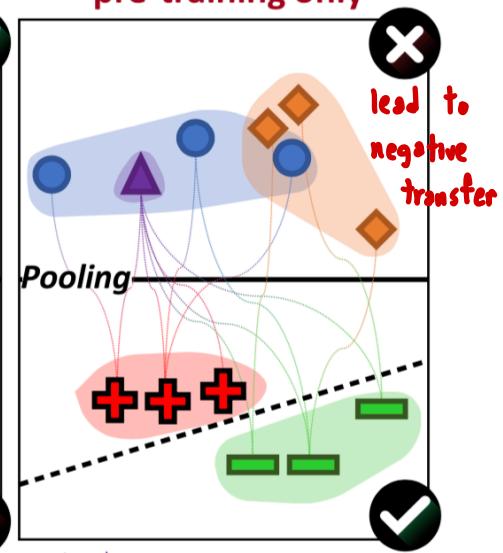


## Naïve strategies

(a.i) Node-level  
pre-training only



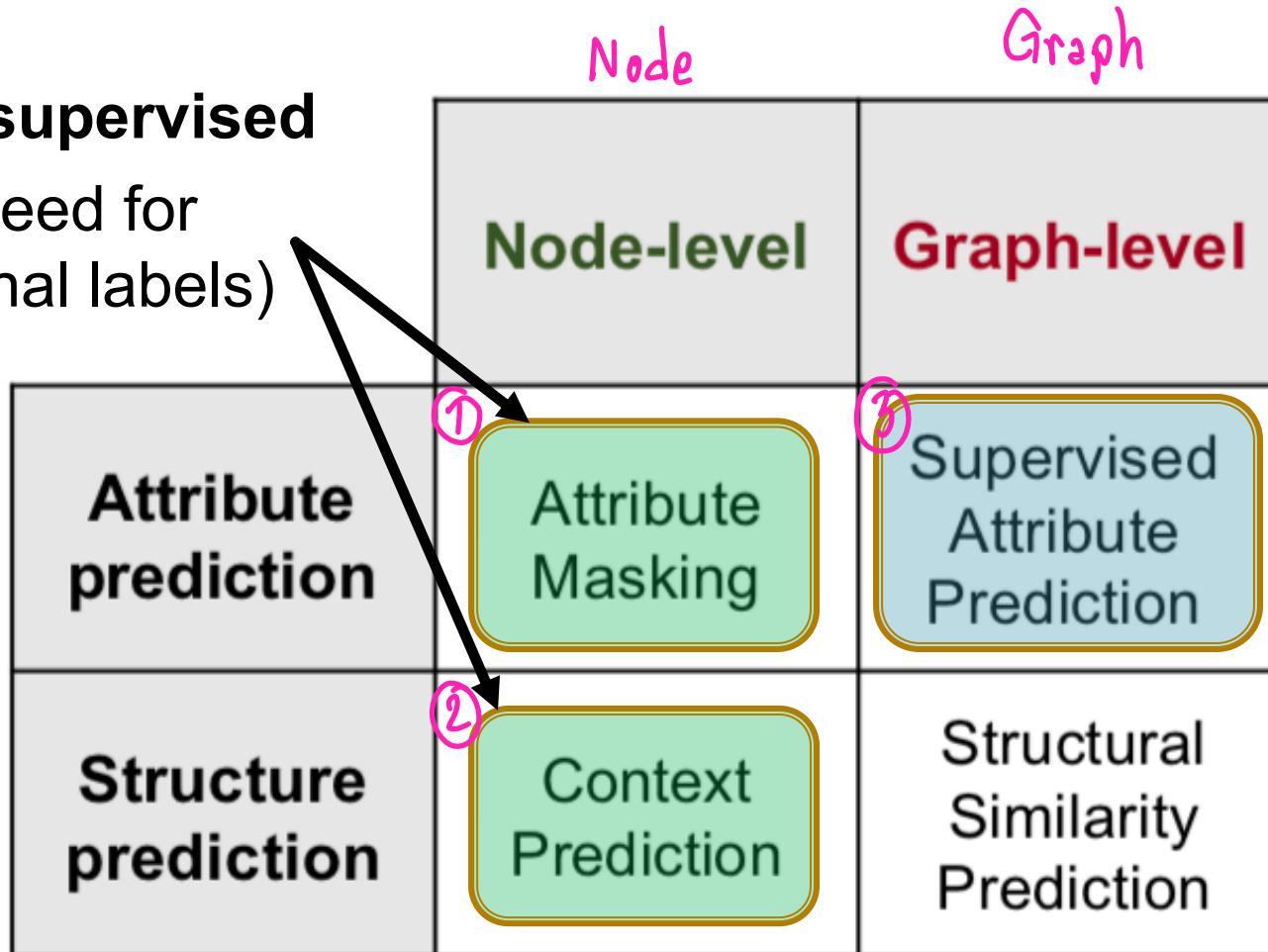
(a.ii) Graph-level  
pre-training only



# Proposed Pre-Training Methods

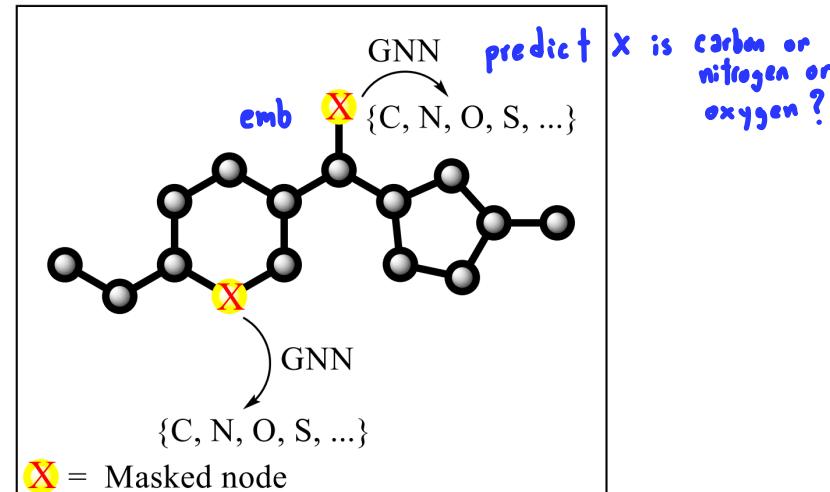
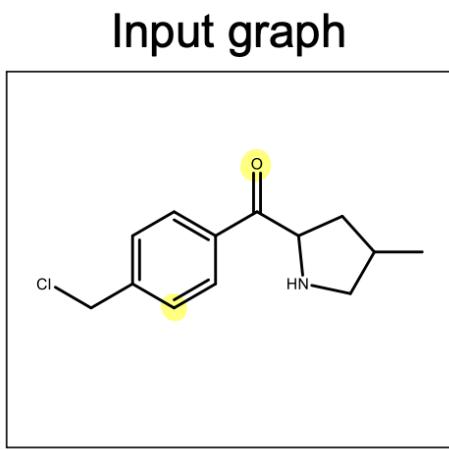
## Self-supervised

(No need for external labels)



# ① Attribute Masking: Algorithm

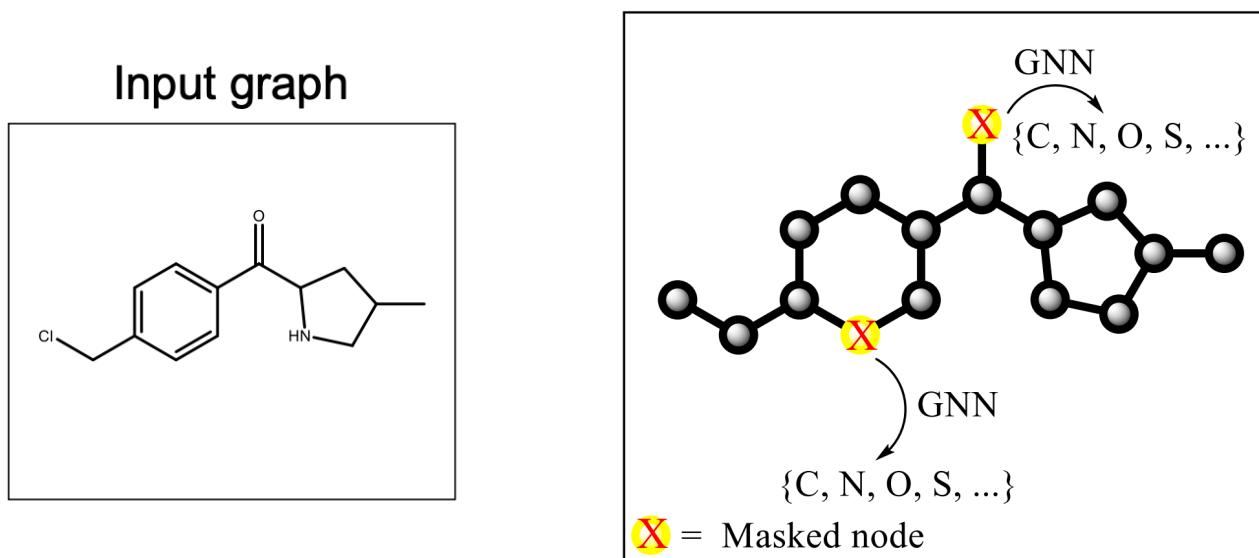
- Mask node attributes
- Use GNNs to generate node embeddings.
- Use the embeddings to predict masked attributes.



# Attribute Masking: Intuition

## Intuition

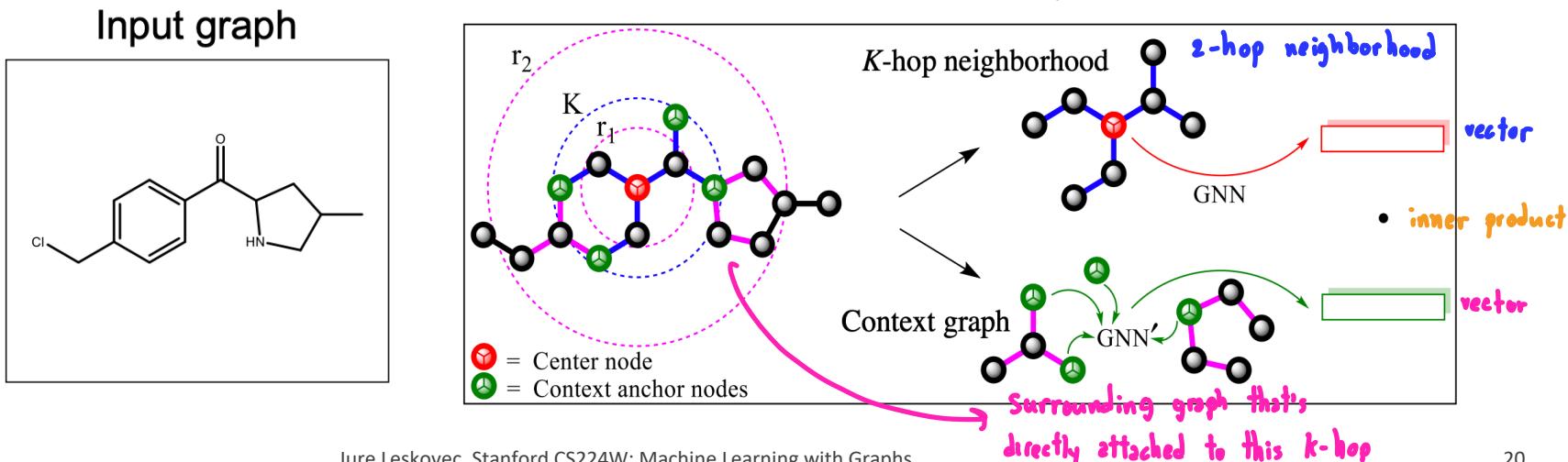
- Through solving the masked attribute prediction task, a GNN is forced to learn domain knowledge, .e.g., chemical rules.



## ② Context Prediction: Algorithm

- For each graph, sample one center node.
  - Extract neighborhood and context graphs.
  - Use GNNs to encode neighborhood and context graphs into vectors.
  - Maximize/minimize the inner product between true/false (neighborhood, context) pairs.

↳ obtained by randomly sample context graph form other neighborhoods

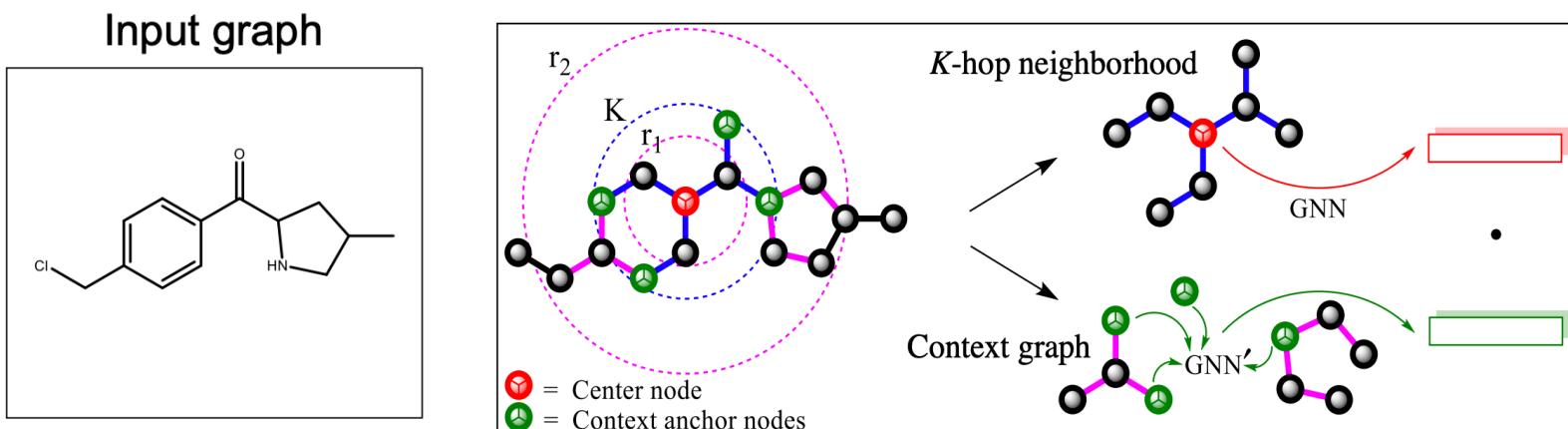


# Context Prediction: Intuition

## ■ Intuition

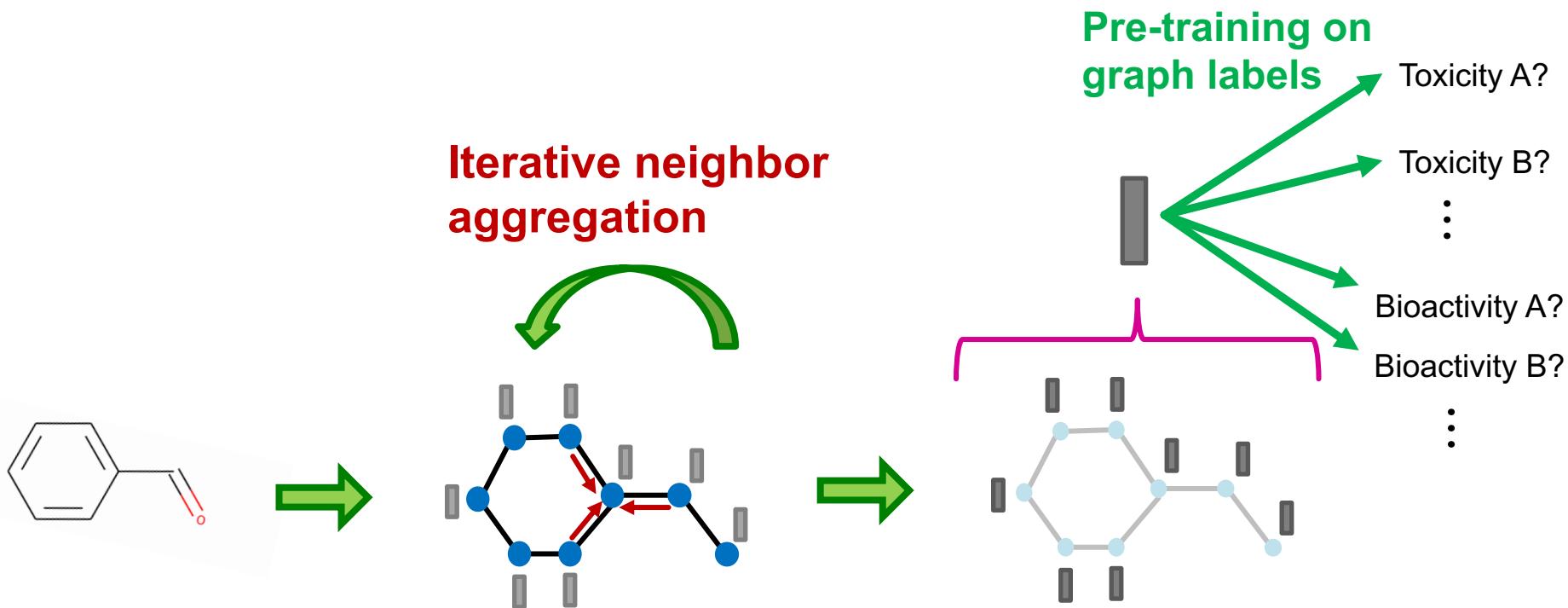
Subgraphs that are surrounded by similar contexts are semantically similar.

- In natural language processing, this is called distributional hypothesis, and is exploited in the word2vec model [Mikolov et al. NIPS 2013].  
words appearing with similar context have similar meaning



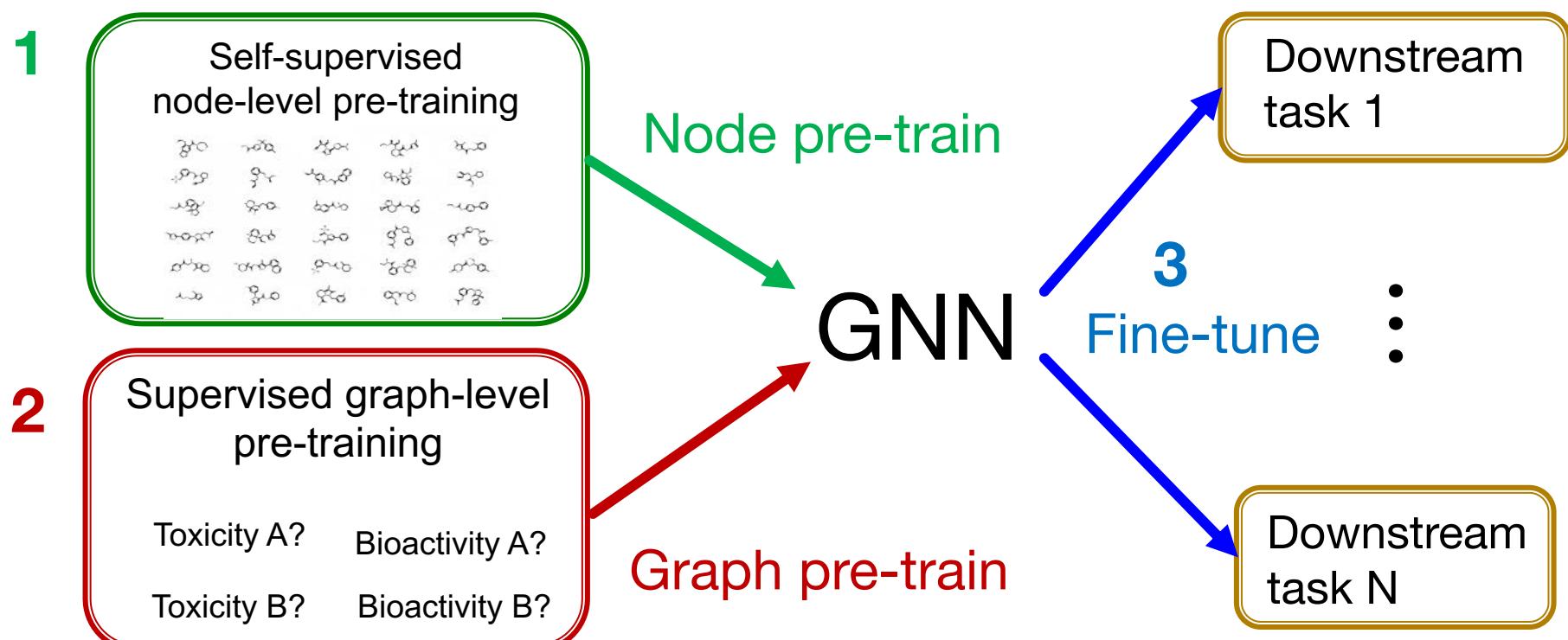
# ③ Supervised Attribute Prediction

- Multi-task supervised training on many relevant labels.



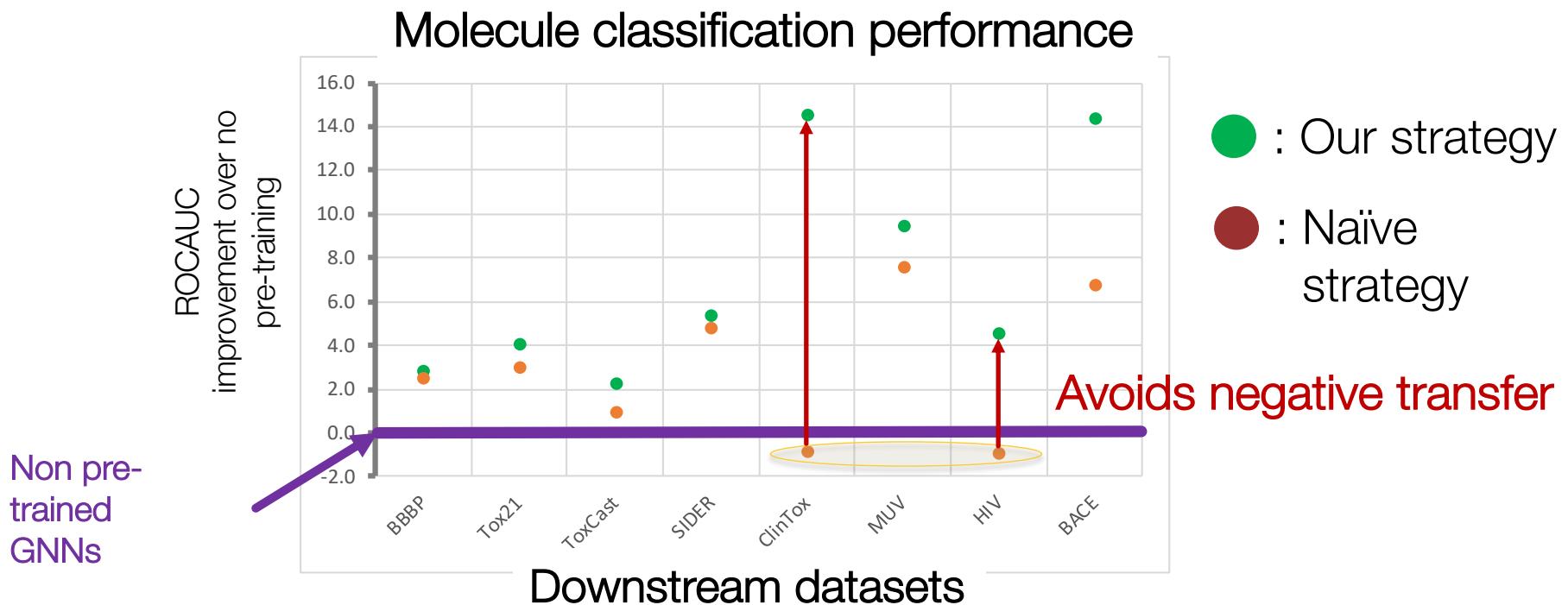
# Overall Strategy

1. Node-level pre-training
2. Graph-level pre-training
3. Fine-tuning on downstream tasks



# Results of Our Strategy

- Avoids negative transfer.
- Significantly improve the performance.



# Comparison of GNN models

- When different GNN models are pre-trained, the most expressive model (GIN) benefits the most from pre-training.
- Intuition: Expressive model can learn to capture more domain knowledge than less expressive models.

most expressive model

Graph Isomorphism Networks  
Lect. 9 Page 42

	Chemistry			Biology		
	Non-pre-trained	Pre-trained	Gain	Non-pre-trained	Pre-trained	Gain
GIN	67.0	<b>74.2</b>	<b>+7.2</b>	$64.8 \pm 1.0$	$74.2 \pm 1.5$	<b>+9.4</b>
GCN	<b>68.9</b>	72.2	+3.4	$63.2 \pm 1.0$	$70.9 \pm 1.7$	+7.7
GraphSAGE	68.3	70.3	+2.0	$65.7 \pm 1.2$	$68.5 \pm 1.5$	+2.8
GAT	66.8	60.3	-6.5	$68.2 \pm 1.1$	$67.8 \pm 3.6$	-0.4

lect. 7

# Pre-Training GNNs: Summary

- GNNs have important applications in scientific applications, but they present challenges of
  - **Label scarcity**
  - **Out-of-distribution prediction**
- **Pre-training** is promising to tackle the challenges.
- However, naïve pre-training strategy gives sub-optimal performance and **even leads to negative transfer.**
- **Our strategy: Pre-train both node and graph embeddings** → Leads to significant performance gain on downstream tasks.

# Hyperbolic Graph Embeddings

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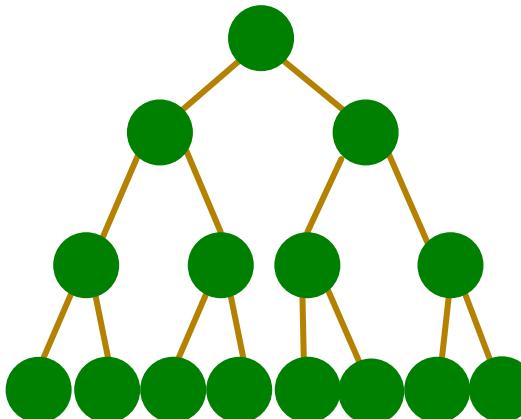
Jure Leskovec, Stanford University

<http://cs224w.stanford.edu>



# Hyperbolic Graph Embeddings

- In previous lectures, we focus on graph representation learning in **Euclidean embedding spaces**  $\mathbb{R}^n$
- However, Euclidean embeddings cannot always capture complex graph structures
- Example: Tree structure

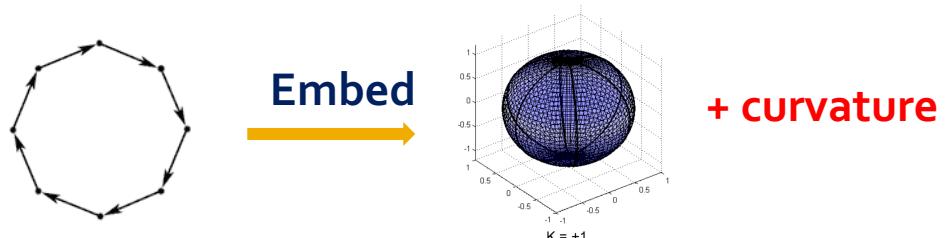


Often Exponential increase in number of nodes as depth increases

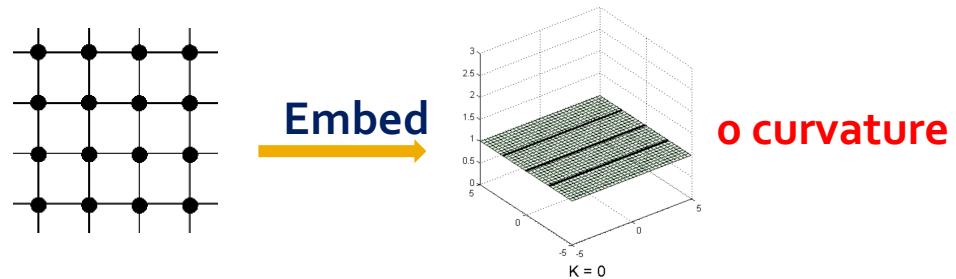
- **Tree-like graphs:** graphs that are similar to a tree, but can contain very few cycles

# Graph Embedding Geometry

- Graphs with many large cycles
  - Best with **spherical** space embeddings



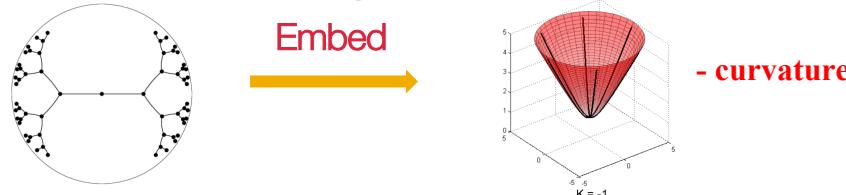
- Grid-like graphs
  - Best with **Euclidean** space embeddings



- **Hierarchical, tree-like** graphs?

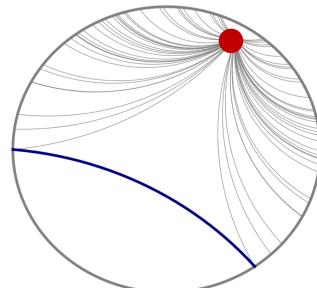
# Hyperbolic Embedding Space

- Modeling **Hierarchical, tree-like** graphs
- Hyperbolic space: an alternative embedding space to model embeddings for trees with tree-like structure
- **Advantage**: hyperbolic embedding properties (explained later) allow it to naturally model trees
- **Challenges**: existing deep learning and optimization toolkits can only be applied to hyperbolic embeddings



# Hyperbolic Space Model

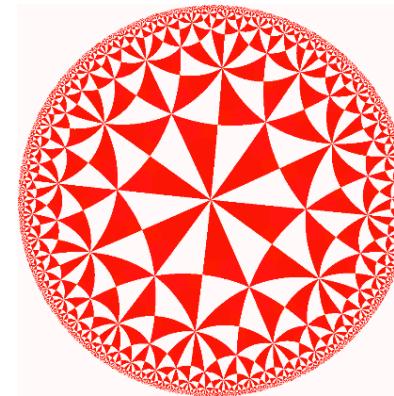
- **Hierarchical, tree-like** graphs
- Hyperbolic geometry differs from Euclidean geometry by the **parallel postulate (5<sup>th</sup> axiom)**
- In Euclidean geometry:  
In a plane, given a line and a point not on it, at most one line parallel to the given line can be drawn through the point.
- However, in hyperbolic geometry, there are infinite number of lines parallel to the given line through the point



Set of geodesic lines from the **red** point to boundary of the Poincare ball that are parallel to the **blue line**

# Hyperbolic Space Model

- Hyperbolic space cannot be naturally represented in Euclidean space due to its special properties
- We commonly use 2 geometry models to **represent or visualize hyperbolic spaces**
- They are equivalent: there exists mappings between these spaces
- Poincaré Model
  - Radius proportional to  $\sqrt{K}$  ( $K$ : inverse of curvature)
  - Open ball (exclude boundary)
  - Each triangle in the figure has the **same** area



Poincaré model:  
intuitive visualization

# Hyperbolic Space Model

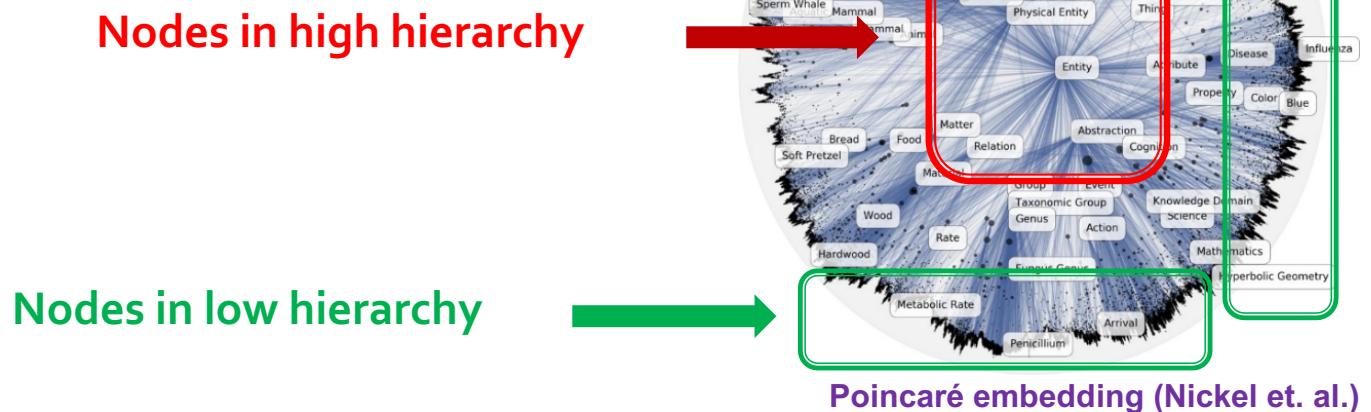
- Hyperboloid Model (Lorentz Model)
  - Upper sheet of 2-sheet hyperboloid
  - Subset of Euclidean space
- Hyperboloid Model is numerically stable
- In comparison, Poincaré Model needs to represent exponentially many embedding points close to the boundary of the Poincare ball



Hyperboloid:  
numerically more  
stable, simpler formula

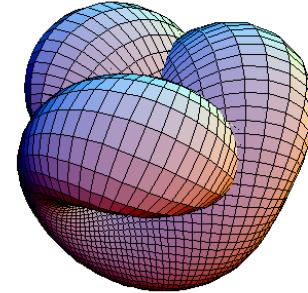
# Task

- Graph representation learning on **hierarchical graphs**
  - Link Prediction
  - Node Classification



# Hyperbolic Geometry (1)

- **Manifold:** high-dimensional surface
- **Riemannian Manifold**
  - Equipped with
    - *Inner product*  $\langle \cdot, \cdot \rangle$  : metric space
    - *Tangent space*  $\mathcal{T}_x$  : an  $\mathbb{R}^n$  that approximates the manifold at any point  $x$
  - Both functions vary smoothly (differentiable) on the manifold



# Hyperbolic Geometry (2)

- **Geodesic:** shortest path in manifold
  - Analogous to straight lines in  $\mathbb{R}^n$
- **Hyperbolic space** is a Riemannian manifold with **constant negative curvature**  $-\frac{1}{K}$ , where ( $K > 0$ )
  - Becomes Euclidean when  $K \rightarrow \infty$
  - The more negative is the curvature, the more curved the space is

**How does curvature affect the embedding space?**

# Hyperbolic Geometry Models

- We use  $-\frac{1}{K}$  to denote the **curvature**
- $\sqrt{K}$  is also the **radius** of the Poincaré ball
- Hyperboloid model as a Riemannian manifold:

- Constant **Minkowski inner product**

$$\langle \cdot, \cdot \rangle_{\mathcal{L}} : \mathbb{R}^{d+1} \times \mathbb{R}^{d+1} \rightarrow \mathbb{R}$$
$$\langle x, y \rangle_{\mathcal{L}} = \boxed{-x_0y_0} + \boxed{x_1y_1 + \dots + x_dy_d} = -\frac{1}{K} \quad (K > 0)$$

negative part      positive part

Time-like                          Space-like

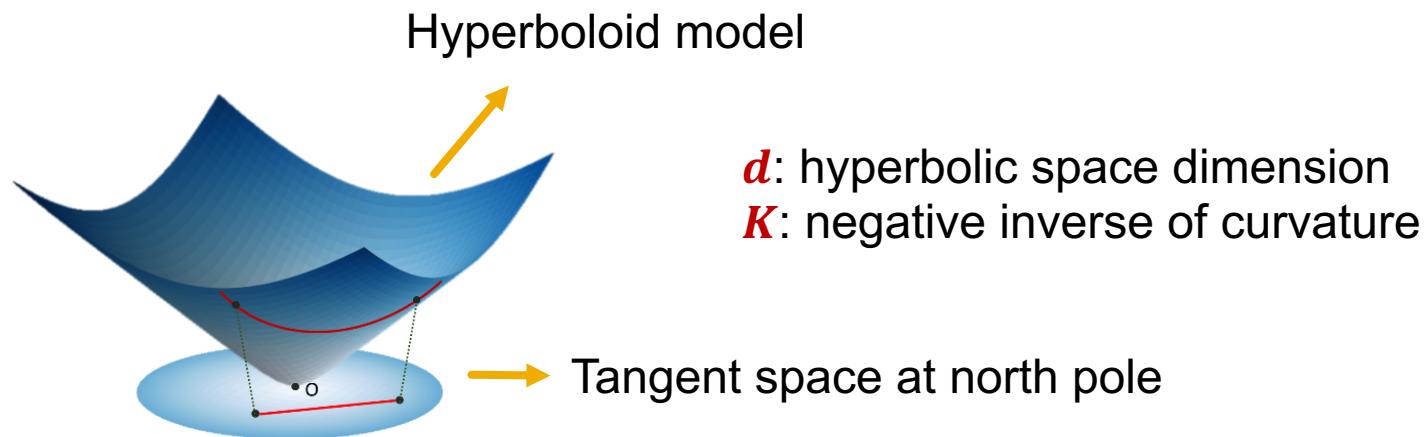


- **Distance** between two hyperbolic points  $x, y$ :

$$d_{\mathcal{L}}^K(\mathbf{x}, \mathbf{y}) = \sqrt{K} \operatorname{arcosh}(-\langle \mathbf{x}, \mathbf{y} \rangle_{\mathcal{L}} / K)$$

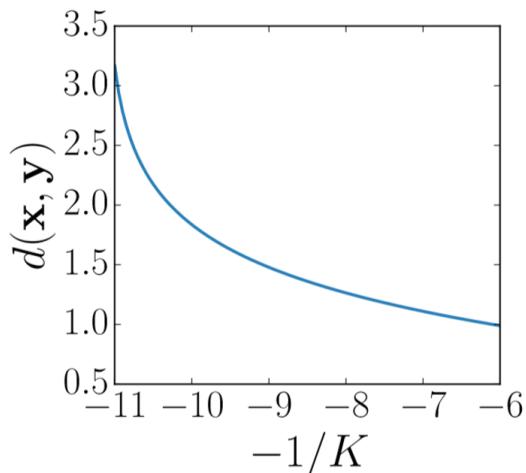
# Tangent Space

- **Tangent space** expression under hyperboloid model
  - $\mathcal{T}_x \mathbb{H}^{d,K} = \{\boldsymbol{v} \in \mathbb{R}^{d+1}: \langle \boldsymbol{v}, \boldsymbol{x} \rangle_{\mathcal{L}} = 0\}$



# Geodesic Distance (1)

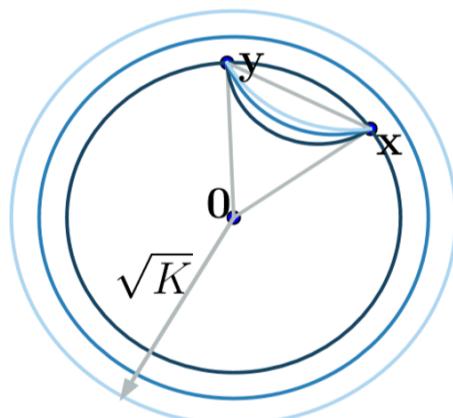
- Geodesic distance in hyperbolic space is analogous to the shortest path distance in Euclidean space
- “Straight line” in hyperbolic space
- The more negative the curvature:
  - the more geodesics bends inward
  - distance between  $x$  and  $y$  also increases:



Distance between  $x$  and  $y$  increases as curvature becomes more negative

# Geodesic Distance (2)

- Geodesic distance between two hyperbolic points will bend inward more as curvature becomes more negative
- **Larger curvature** results in **smaller radius** of the Poincare ball
- Distance between the same coordinates  $(x, y)$  increases as the radius gets smaller



**Dark blue:** high curvature boundary and geodesics  
**Light blue:** low curvature boundary and geodesics

# Mapping to and from Tangent Space

- Exponential map: from tangent space (Euclidean) to manifold
- Logarithmic map: inverse operation of exponential map
- Norm  $\|\boldsymbol{v}\|_{\mathcal{L}} = \langle \boldsymbol{v}, \boldsymbol{v} \rangle_{\mathcal{L}}$

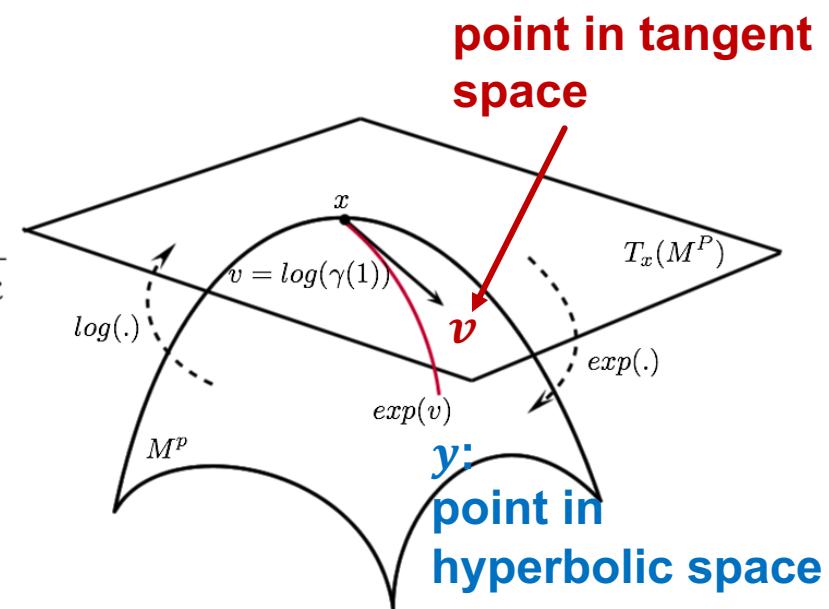
**Hyperbolic trigonometry**

**Exp map**

$$\exp_x^K(\boldsymbol{v}) = \cosh\left(\frac{\|\boldsymbol{v}\|_{\mathcal{L}}}{\sqrt{K}}\right)\mathbf{x} + \sqrt{K}\sinh\left(\frac{\|\boldsymbol{v}\|_{\mathcal{L}}}{\sqrt{K}}\right)\frac{\boldsymbol{v}}{\|\boldsymbol{v}\|_{\mathcal{L}}}$$

**Log map**

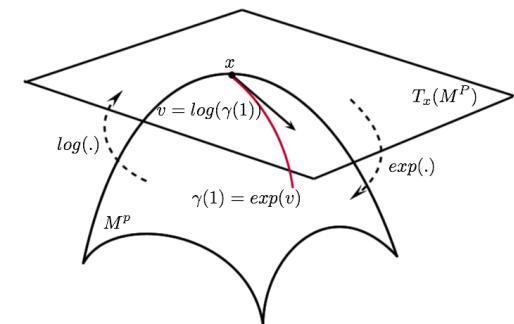
$$\log_x^K(\mathbf{y}) = d_{\mathcal{L}}^K(\mathbf{x}, \mathbf{y}) \frac{\mathbf{y} + \frac{1}{K} \langle \mathbf{x}, \mathbf{y} \rangle_{\mathcal{L}} \mathbf{x}}{\|\mathbf{y} + \frac{1}{K} \langle \mathbf{x}, \mathbf{y} \rangle_{\mathcal{L}} \mathbf{x}\|_{\mathcal{L}}}$$



# Hyperbolic GNN (1)

## ■ Challenges

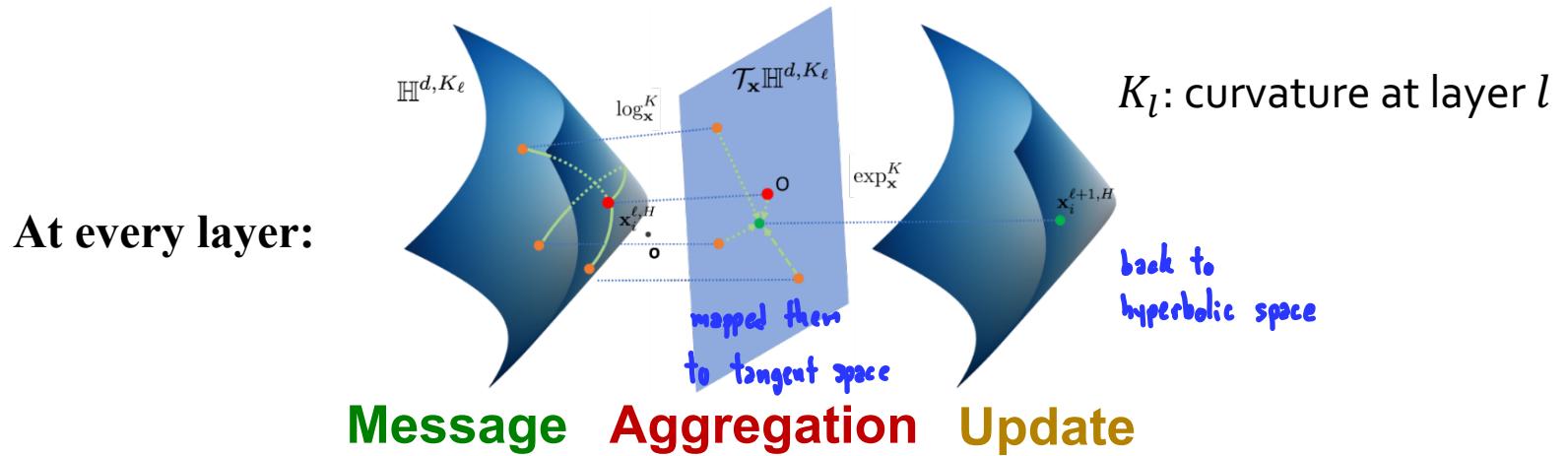
- Input node features are usually **Euclidean**
- Perform hyperbolic aggregation for message passing
- Choose hyperbolic spaces with the **right amount of curvature** at every layer of the GNN



Hyperbolic Graph Convolutional Neural Networks, NeurIPS 2019

# Hyperbolic GNN (2)

- $\mathbf{h}_i^{l,H} = \text{Msg}(\mathbf{x}_i^{l-1,H})$  **Message**
- $\mathbf{y}_i^{l,H} = \text{AGG}^{K_{l-1}}(\mathbf{h}^{l,H})_i$  **Aggregation**
- $\mathbf{x}_i^{l,H} = \text{Update}^{K_{\underline{l-1}}, K_l}(\mathbf{y}_i^{l,H})$  **Update**



Hyperbolic Graph Convolutional Neural Networks, NeurIPS 2019

# Hyperbolic GNN (3)

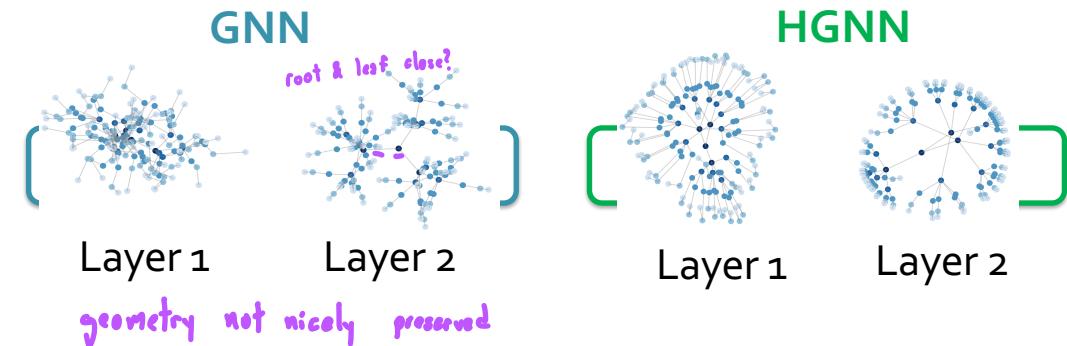
- Input Transformation:  $x^{0,H} := \exp_o^K((0, x^{0,E}))$
- **Message:**  $h_i^{l,H} = (W^l \otimes^{K_{l-1}} x_i^{l-1,H}) \oplus^{K_{l-1}} b^l$ 
  - Hyperbolic linear:  $W \otimes^K x^{l,H} := \exp_o^K(W \cdot \log_o^K(x^{l,H}))$  map back to hyperbolic
  - Möbius addition:  $x^H \oplus^K b := \exp_{x^H}^K(P_{o \rightarrow x^H}^K(b))$  map to euclidean tangent space
- **Aggregation:**  $AGG(x^H)_i := \exp_{x_i^H}^K(\sum_{j \in \mathcal{N}(i)} w_{ij} \log_{x_i^H}^K(x_j^H))$ 
  - $P_{\mathbf{x} \rightarrow \mathbf{y}}(\mathbf{v}) = \mathbf{v} - \frac{\langle \log_{\mathbf{x}}(\mathbf{y}), \mathbf{v} \rangle_{\mathcal{L}}}{d_{\mathcal{L}}^1(\mathbf{x}, \mathbf{y})^2} (\log_{\mathbf{x}}(\mathbf{y}) + \log_{\mathbf{y}}(\mathbf{x}))$
  - Attention weights
- **Update:**  $\text{Update}^{K_{l-1}, K_l}(x^H) := \exp_o^{K_l}(\sigma(\log_o^{K_{l-1}}(x^H)))$ 
  - Trainable curvature

# Hyperbolic GNN (4)

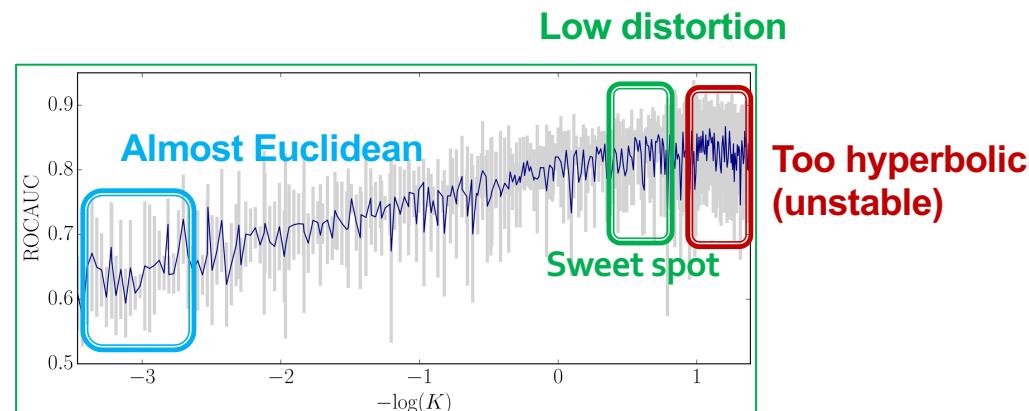
Node Classification (tree)

Disease spreading graph:

1044 nodes, 2 classes



- **Predict:** whether a person is infected
- **Groundtruth:** FIR disease spreading model
- **Curvature** is important!



# Hyperbolic GNN Results

- Performance on a variety of datasets
- We use **hyperbolicity  $\delta$**  to measure whether a graph dataset is tree-like and hierarchical
- See *Gromov et al. 1987* for its formula, and an implementation can be found [here](#)
- Lower value of hyperbolicity: graph is more tree-like

Inductive task

Non-hierarchical  
dataset

Dataset Hyperbolicity $\delta$	DISEASE $\delta = 0$		DISEASE-M $\delta = 0$		AIRPORT $\delta = 1$		PUBMED $\delta = 3.5$		CORA $\delta = 11$		
	Method	LP	NC	LP	NC	LP	NC	LP	NC	LP	NC
Shallow NN	EUC	59.8 ± 2.0	32.5 ± 1.1	-	-	92.0 ± 0.0	60.9 ± 3.4	83.3 ± 0.1	48.2 ± 0.7	82.5 ± 0.3	23.8 ± 0.7
	HYP [28]	63.5 ± 0.6	45.5 ± 3.3	-	-	94.5 ± 0.0	70.2 ± 0.1	87.5 ± 0.1	68.5 ± 0.3	87.6 ± 0.2	22.0 ± 1.5
	EUC-MIXED	49.6 ± 1.1	35.2 ± 3.4	-	-	91.5 ± 0.1	68.3 ± 2.3	86.0 ± 1.3	63.0 ± 0.3	84.4 ± 0.2	46.1 ± 0.4
	HYP-MIXED	55.1 ± 1.3	56.9 ± 1.5	-	-	93.3 ± 0.0	69.6 ± 0.1	83.8 ± 0.3	73.9 ± 0.2	85.6 ± 0.5	45.9 ± 0.3
GNN	MLP	72.6 ± 0.6	28.8 ± 2.5	55.3 ± 0.5	55.9 ± 0.3	89.8 ± 0.5	68.6 ± 0.6	84.1 ± 0.9	72.4 ± 0.2	83.1 ± 0.5	51.5 ± 1.0
	HNN[10]	75.1 ± 0.3	41.0 ± 1.8	60.9 ± 0.4	56.2 ± 0.3	90.8 ± 0.2	80.5 ± 0.5	94.9 ± 0.1	69.8 ± 0.4	89.0 ± 0.1	54.6 ± 0.4
	GCN[20]	64.7 ± 0.5	69.7 ± 0.4	66.0 ± 0.8	59.4 ± 3.4	89.3 ± 0.4	81.4 ± 0.6	91.1 ± 0.5	78.1 ± 0.2	90.4 ± 0.2	81.3 ± 0.3
	GAT [39]	69.8 ± 0.3	70.4 ± 0.4	69.5 ± 0.4	62.5 ± 0.7	90.5 ± 0.3	81.5 ± 0.3	91.2 ± 0.1	79.0 ± 0.3	93.7 ± 0.1	83.0 ± 0.7
Ours	SAGE [14]	65.9 ± 0.3	69.1 ± 0.6	67.4 ± 0.5	61.3 ± 0.4	90.4 ± 0.5	82.1 ± 0.5	86.2 ± 1.0	77.4 ± 2.2	85.5 ± 0.6	77.9 ± 2.4
	SGC [42]	65.1 ± 0.2	69.5 ± 0.2	66.2 ± 0.2	60.5 ± 0.3	89.8 ± 0.3	80.6 ± 0.1	94.1 ± 0.0	78.9 ± 0.0	91.5 ± 0.1	81.0 ± 0.1
HGCN		<b>90.8</b> ± 0.3	<b>74.5</b> ± 0.9	<b>78.1</b> ± 0.4	<b>72.2</b> ± 0.5	<b>96.4</b> ± 0.1	<b>90.6</b> ± 0.2	<b>96.3</b> ± 0.0	<b>80.3</b> ± 0.3	92.9 ± 0.1	79.9 ± 0.2
(% ) ERR RED		-63.1%	-13.8%	-28.2%	-25.9%	-60.9%	-47.5%	-27.5%	-6.2%	+12.7%	+18.2%

# Hyperbolic GNN: Summary

- We introduce **hyperbolic geometry** as the embedding space to embed hierarchical, tree-like graphs
- 2 models for representing hyperbolic space:  
**Poincaré ball** model and **hyperboloid** model
- Use **exponential and logarithmic map** to map points to and from **tangent spaces** where neural network operations can be performed
- **Learnable curvature** allows the model to learn a tradeoff between performance and stability

# Design Space of Graph Neural Networks

CS224W: Machine Learning with Graphs

Jure Leskovec, Stanford University

<http://cs224w.stanford.edu>



# Key Questions for GNN Design

- **GNN architectural design:**
  - How to find a good GNN design for a specific GNN task?
- **Important but challenging:**
  - GNNs have been very successful in various applications
  - Domain experts want to use SOTA GNN on their specific tasks, however...
    - There are tons of possible GNN models
    - Best design in one task can perform badly for another task
    - Redo grid search for each new task is NOT feasible
- **Our key contribution:**
  - The first systematic study for the ***GNN design space and task space***
  - **GraphGym**, a powerful platform for exploring different GNN designs and tasks

# Background: Terminology

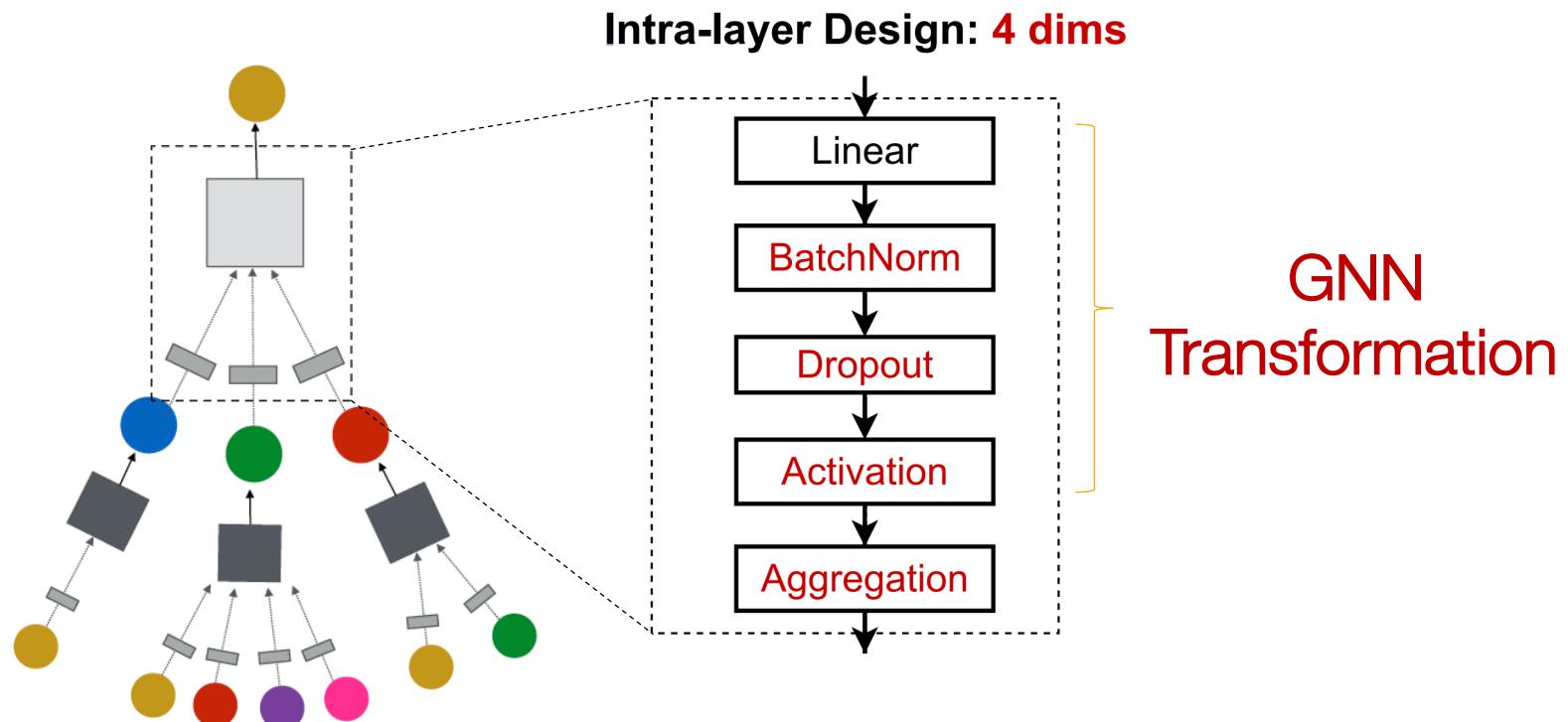
- **Design:** a concrete model instantiation
  - E.g., a 4-layer GraphSAGE
- **Design dimensions** characterize a design
  - E.g., the number of layers  $L \in \{2, 4, 6, 8\}$
- **Design choice** is the actual selected value in the design dimension
  - E.g.,  $L = 2$
- **Design space** consists of a Cartesian product of design dimensions
- **Task:** A specific task of interest
  - E.g., node classification on Cora, graph classification on ENZYMEs
- **Task space** consists of multiple tasks

# Recap: GNN Design Space

## Intra-layer Design:

GNN Layer = Transformation + Aggregation

- We propose a general instantiation under this perspective

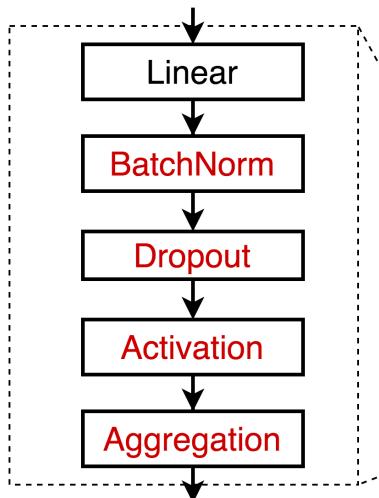


# Recap: GNN Design Space

## Inter-layer Design

- We explore different ways of organizing GNN layers

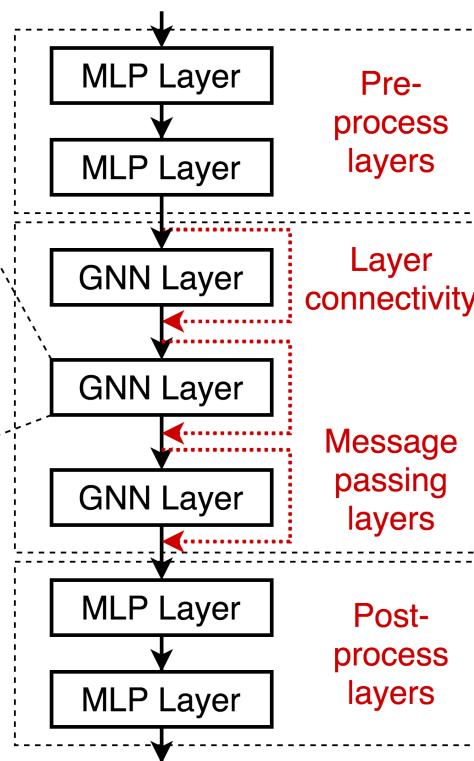
Intra-layer Design: 4 dims



Learning Configuration: 4 dims

Batch size  
Learning rate  
Optimizer  
Training epochs

Inter-layer Design: 4 dims



### Pre-process layers:

Important when expressive node feature encoder is needed

E.g., when nodes are images/text

### Skip connections:

Improve deep GNN's performance

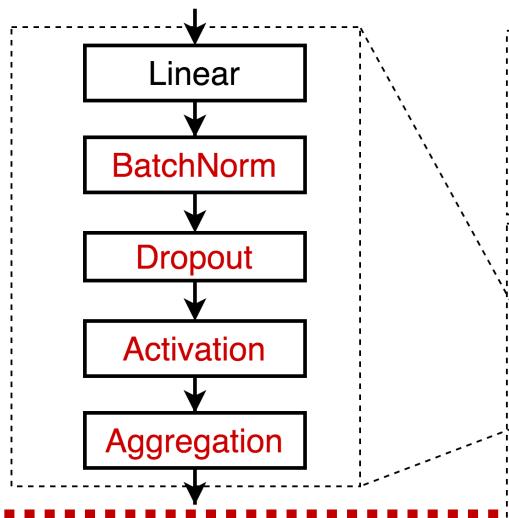
### Post-process layers:

Important when reasoning or transformation over node embeddings are needed

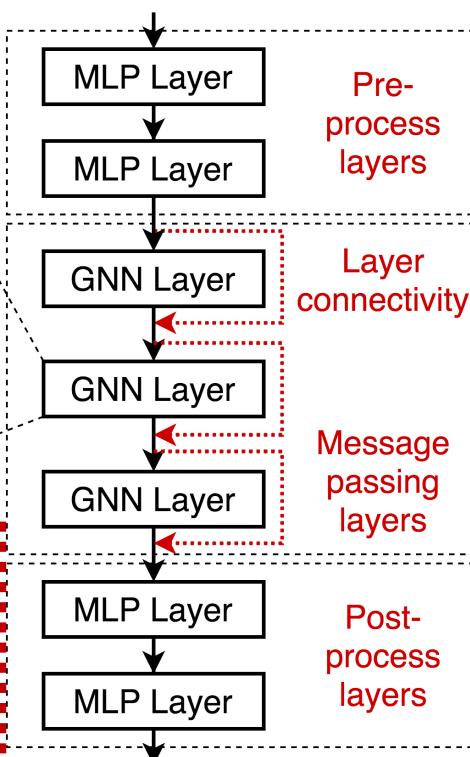
E.g., graph classification, knowledge graphs

# Recap: GNN Design Space

Intra-layer Design: 4 dims



Inter-layer Design: 4 dims



Learning Configuration: 4 dims

Batch size  
Learning rate  
Optimizer  
Training epochs

## Learning configurations

- Often neglected in current literature
- But we found they have high impact on performance

# Summary: GNN Design Space

## ■ Overall: A GNN design space

### ■ Intra-layer design

Batch Normalization	Dropout	Activation	Aggregation
True, False	False, 0.3, 0.6	RELU, PRELU, SWISH	MEAN, MAX, SUM

### ■ Inter-layer design

Layer connectivity	Pre-process layers	Message passing layers	Post-precess layers
STACK, SKIP-SUM, SKIP-CAT	1, 2, 3	2, 4, 6, 8	1, 2, 3

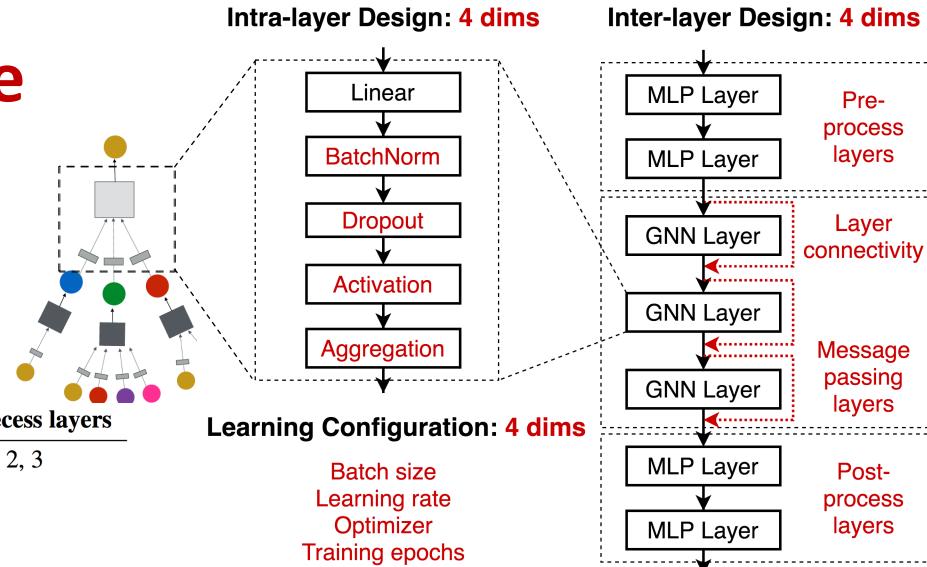
### ■ Learning configuration

Batch size	Learning rate	Optimizer	Training epochs
16, 32, 64	0.1, 0.01, 0.001	SGD, ADAM	100, 200, 400

### ■ In total: 315K possible designs

## ■ Our Purpose:

- We don't want to (and we cannot) cover all the possible designs
- We want to demonstrate that **studying a design space is more effective than studying individual GNN designs**



# A General GNN Task Space

- **Categorizing GNN tasks**
  - **Common practice:** node / edge / graph level task
  - Reasonable but not precise
    - **Node prediction:** predict clustering coefficient vs. predict a node's subject area – completely different task
  - But creating a precise taxonomy of GNN tasks is very hard!
    - Novel GNN applications can always emerge
- **Our innovation: a quantitative task similarity metric**
  - **Purpose: understand GNN tasks, transfer the best GNN models across tasks**

# A General GNN Task Space

- **Innovation:** quantitative **task similarity metric**
  - 1) Select “anchor” models ( $M_1, \dots, M_5$ )
  - 2) Characterize a task by **ranking the performance of anchor models**
  - 3) Tasks with **similar rankings** are considered as similar

Task Similarity Metric

	Anchor Model Performance ranking					Similarity to Task A
Task A	$M_1$	$M_2$	$M_3$	$M_4$	$M_5$	1.0
Task B	$M_1$	$M_3$	$M_2$	$M_4$	$M_5$	0.8
Task C	$M_5$	$M_1$	$M_4$	$M_3$	$M_2$	-0.4

Task A is similar to Task B

Task A is not similar to Task C

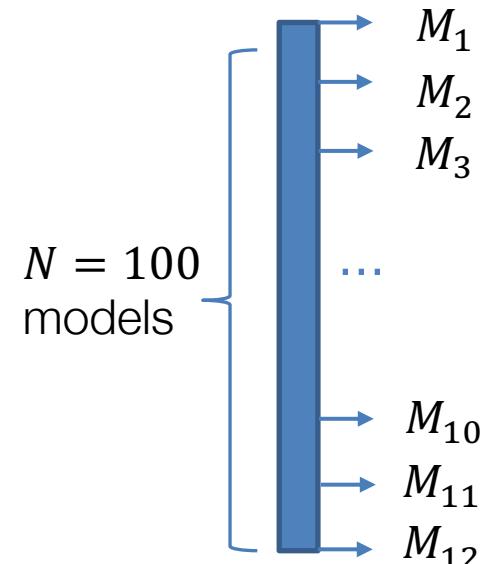
- **How do we select the anchor models?**

# A General GNN Task Space

## ■ Selecting the anchor models

- 1) Select a small dataset *easy to work on*
  - E.g., node classification on Cora
- 2) Randomly **sample  $N$  models from our design space**, run on the dataset
  - E.g., we sample 100 models
- 3) Sort these models based on their performance, evenly select  $M$  models as the anchor models, whose **performance range from the worst to the best**
  - E.g., we sample 12 models in our experiments
- **Intuition:** a bad model in one task could be great for another task

Sorted by performance



# A General GNN Task Space

## ■ We collect 32 tasks: node / graph classification

### Task name

node AMAZON COMPUTERS N/A N/A
node AMAZON PHOTO N/A N/A
node CITESEER N/A N/A
node COAUTHOR CS N/A N/A
node COAUTHOR PHYSICS N/A N/A
node CORA N/A N/A
node SCALEFREE CLUSTERING PAGERANK
node SCALEFREE CONST CLUSTERING
node SCALEFREE CONST PAGERANK
node SCALEFREE ONEHOT CLUSTERING
node SCALEFREE ONEHOT PAGERANK
node SCALEFREE PAGERANK CLUSTERING
node SMALLWORLD CLUSTERING PAGERANK
node SMALLWORLD CONST CLUSTERING
node SMALLWORLD CONST PAGERANK
node SMALLWORLD ONEHOT CLUSTERING
node SMALLWORLD ONEHOT PAGERANK
node SMALLWORLD PAGERANK CLUSTERING
graph PROTEINS N/A N/A
graph BZR N/A N/A
graph COX2 N/A N/A
graph DD N/A N/A
graph ENZYMES N/A N/A
graph IMDB N/A N/A
graph SCALEFREE CLUSTERING PATH
graph SCALEFREE CONST PATH
graph SCALEFREE ONEHOT PATH
graph SCALEFREE PAGERANK PATH
graph SMALLWORLD CLUSTERING PATH
graph SMALLWORLD CONST PATH
graph SMALLWORLD ONEHOT PATH
graph SMALLWORLD PAGERANK PATH
graph OGBG MOLHIV N/A N/A

(We include link prediction results in the Appendix)

6 Real-world node classification tasks

12 Synthetic node classification tasks

Predict node properties:

- Clustering coefficient
- PageRank

6 Real-world graph classification tasks

8 Synthetic node classification tasks

Predict graph properties:

- Average path length

# Evaluating GNN Designs

- **Evaluating a design dimension:**
  - “Is BatchNorm generally useful for GNNs?”
- **The common practice:**
  - (1) Pick one model (e.g., a 5-layer 64-dim GCN)
  - (2) Compare two models, with BN = True / False
    - with or without BatchNorm
- **Our approach:**
  - Note that **we have defined 315K (models) \* 32 (tasks)  $\approx$  10M model-task combinations**
  - **(1) Sample from 10M possible model-task combinations**
  - **(2) Rank the models** with BN = True / False
  - How do we make it **scalable & convincing?**

# Evaluating GNN Designs

- Evaluating a design dimension: controlled random search
  - a) Sample random model-task configurations, perturb BatchNorm = [True, False]
  - Here we control the computational budget for all the models

(a) Controlled Random Search

GNN Design Space					GNN Task Space	
BatchNorm	Activation	...	Message layers	Layer Connectivity	Task level	dataset
True	relu	...	8	skip_sum	node	CiteSeer
False	relu	...	8	skip_sum	node	CiteSeer
True	relu	...	2	skip_cat	graph	BZR
False	relu	...	2	skip_cat	graph	BZR
...						
True	prelu	...	4	stack	graph	scale free
False	prelu	...	4	stack	graph	scale free

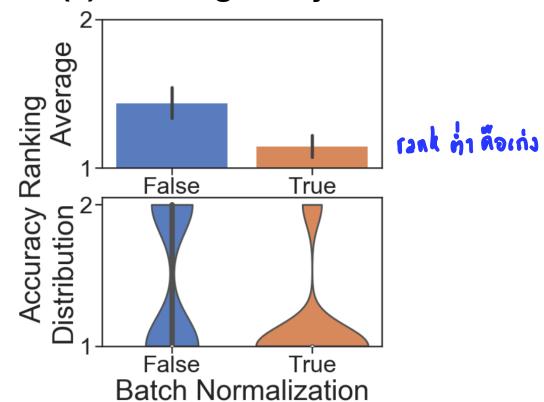
# Evaluating GNN Designs

- **b) Rank** BatchNorm = [True, False] by their performance (lower ranking is better)
- **c) Plot Average / Distribution of the ranking** of BatchNorm = [True, False]

(b) Rank Design Choices by Performance

GNN Design Space		Experimental Results	
BatchNorm		Val. Accuracy	Design Choice Ranking
True		0.75	1
False		0.54	2
True		0.88	1 (a tie)
False		0.88	1 (a tie)
True		0.89	1
False		0.36	2

(c) Ranking Analysis

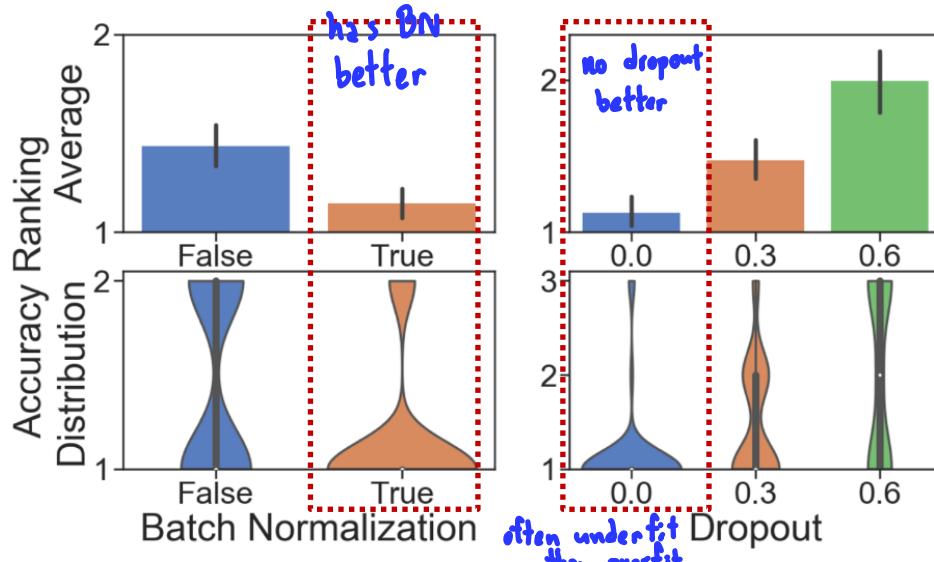


- **Summary:** Convincingly evaluate any new design dimension, e.g., a new GNN layer

# Results 1: A Guideline for GNN Design

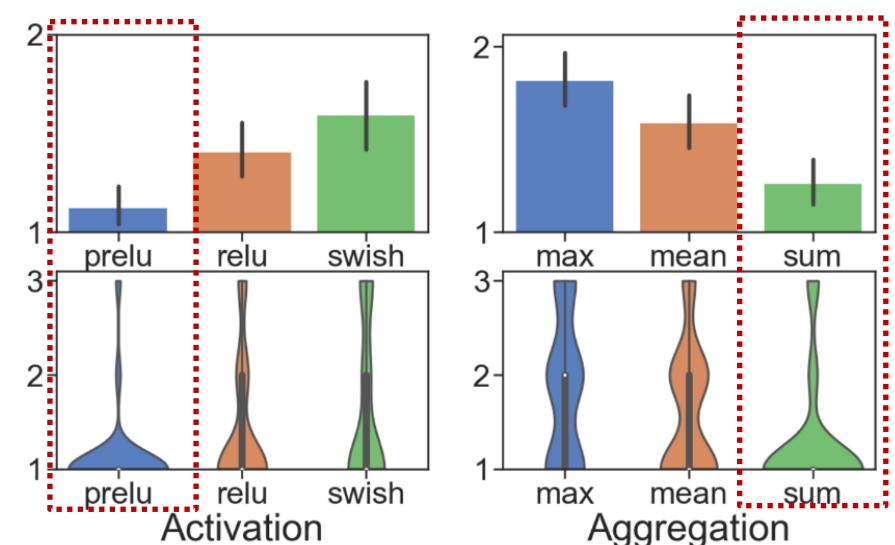
- Certain design choices exhibit **clear advantages**

Explanation:  
GNNs are hard to optimize



Explanation:  
GNNs experience  
underfitting more often

Explanation:  
This is our new finding!



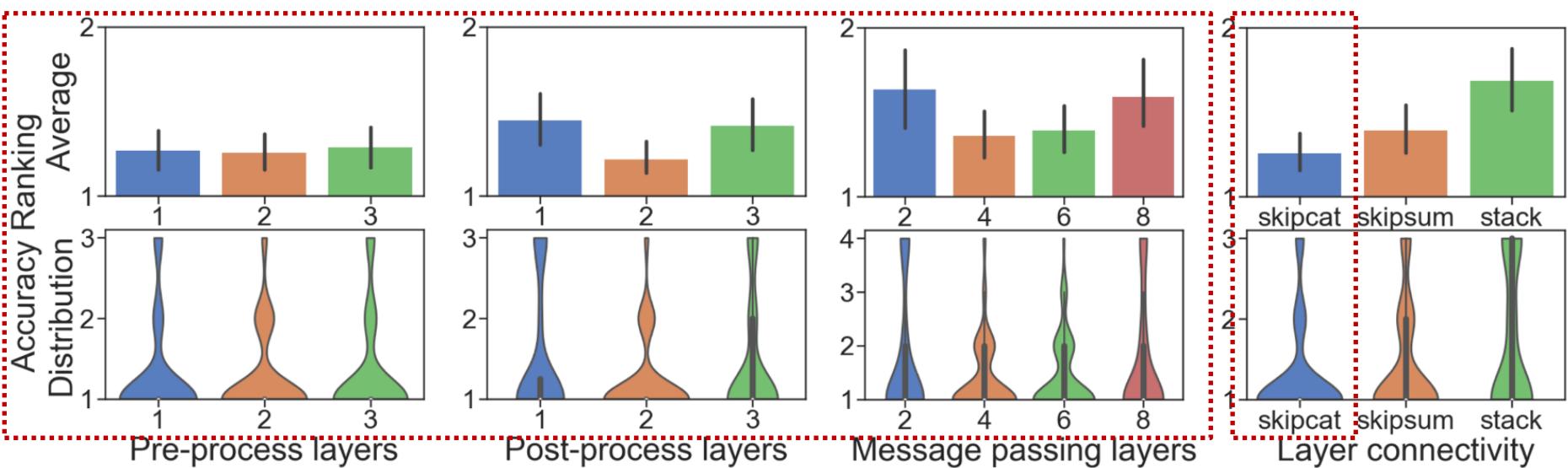
Explanation:  
Sum is the most  
expressive aggregator

# Results 1: A Guideline for GNN Design

- Certain design choices exhibit **clear advantages**

Optimal number of layers is hard to decide

Highly dependent on the task



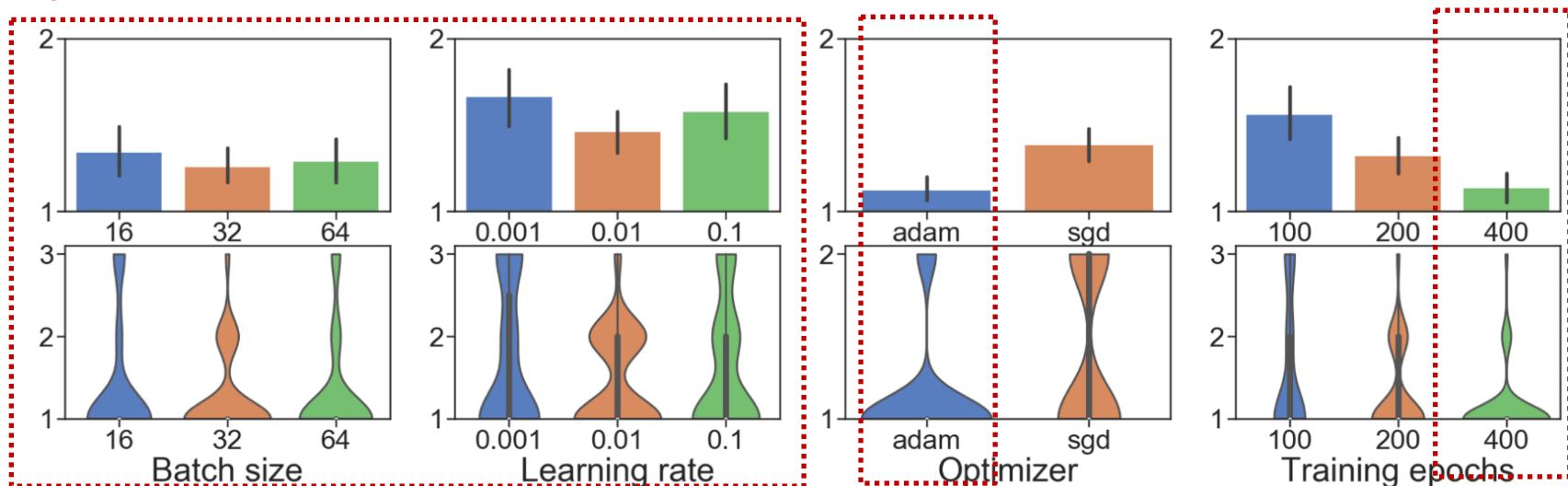
Explanation:  
Skip connection enable  
hierarchical node  
representation

# Results 1: A Guideline for GNN Design

- Certain design choices exhibit **clear advantages**

Optimal batch size and learning rate is hard to decide

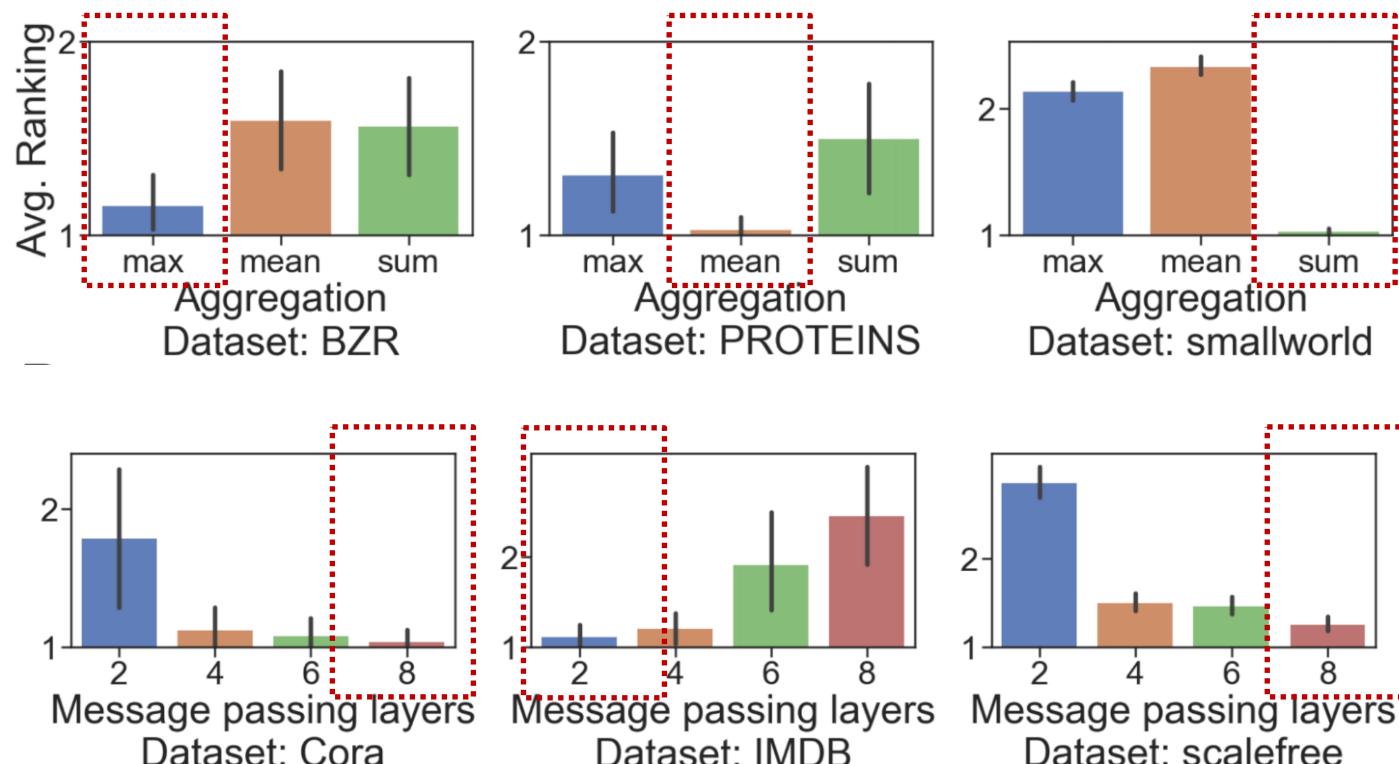
Highly dependent on the task



Explanation:  
Adam is more robust  
More training epochs is better

# Results 2: Understanding GNN Tasks

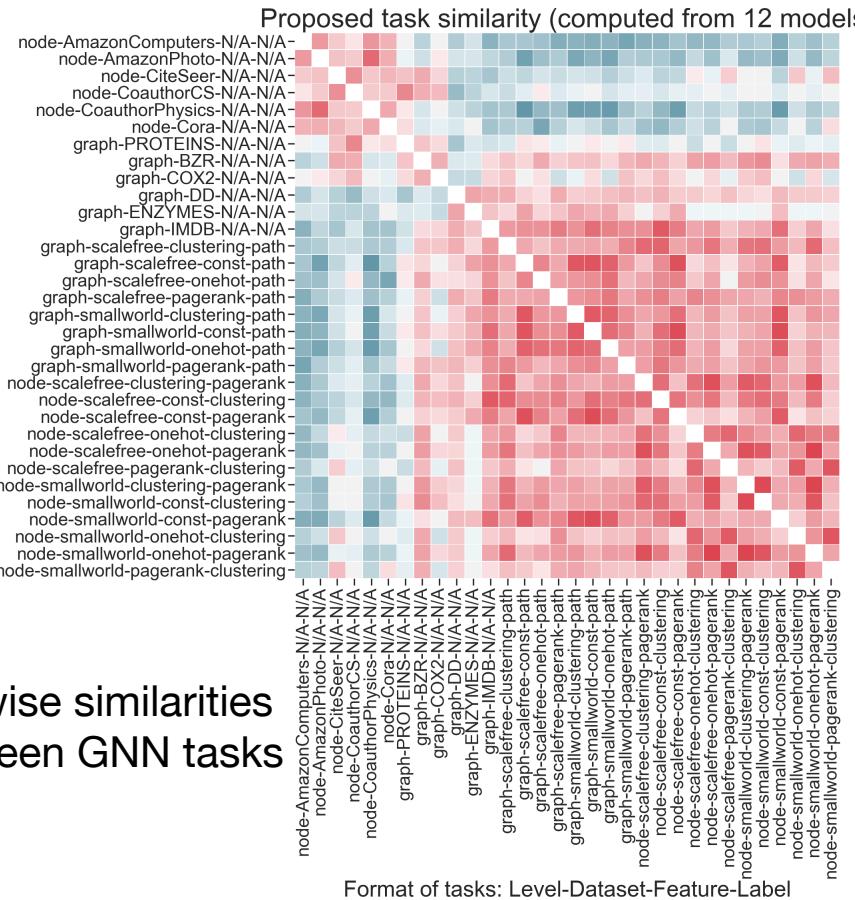
- Best GNN designs in different tasks **vary significantly**
  - Motivate that **studying a task space is crucial**



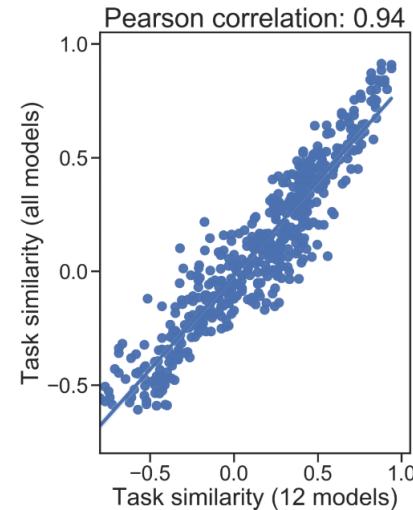
# Results 2: Understanding GNN Tasks

## ■ Build a GNN task space

Recall how we **compute task similarity**



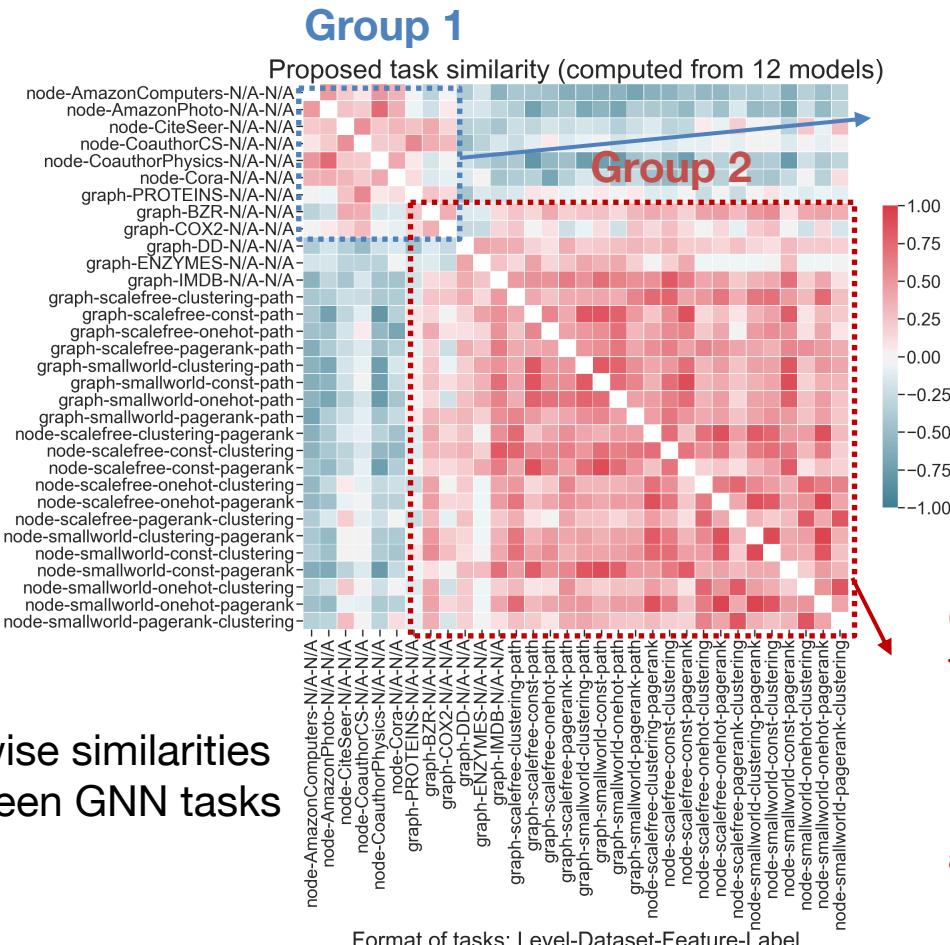
	Anchor Model Performance ranking					Similarity to Task A	
	Task A	$M_1$	$M_2$	$M_3$	$M_4$	$M_5$	
Task A		1.0					1.0
Task B		$M_1$	$M_3$	$M_2$	$M_4$	$M_5$	0.8
Task C		$M_5$	$M_1$	$M_4$	$M_3$	$M_2$	-0.4



**Task similarity computation is cheap:  
Using 12 anchor models is a good approximation!**

# Results 2: Understanding GNN Tasks

## ■ Proposed GNN task space is **informative**



**Group 1:**  
Tasks rely on **feature information**  
Node/graph classification tasks,  
where **input graphs have high-dimensional features**

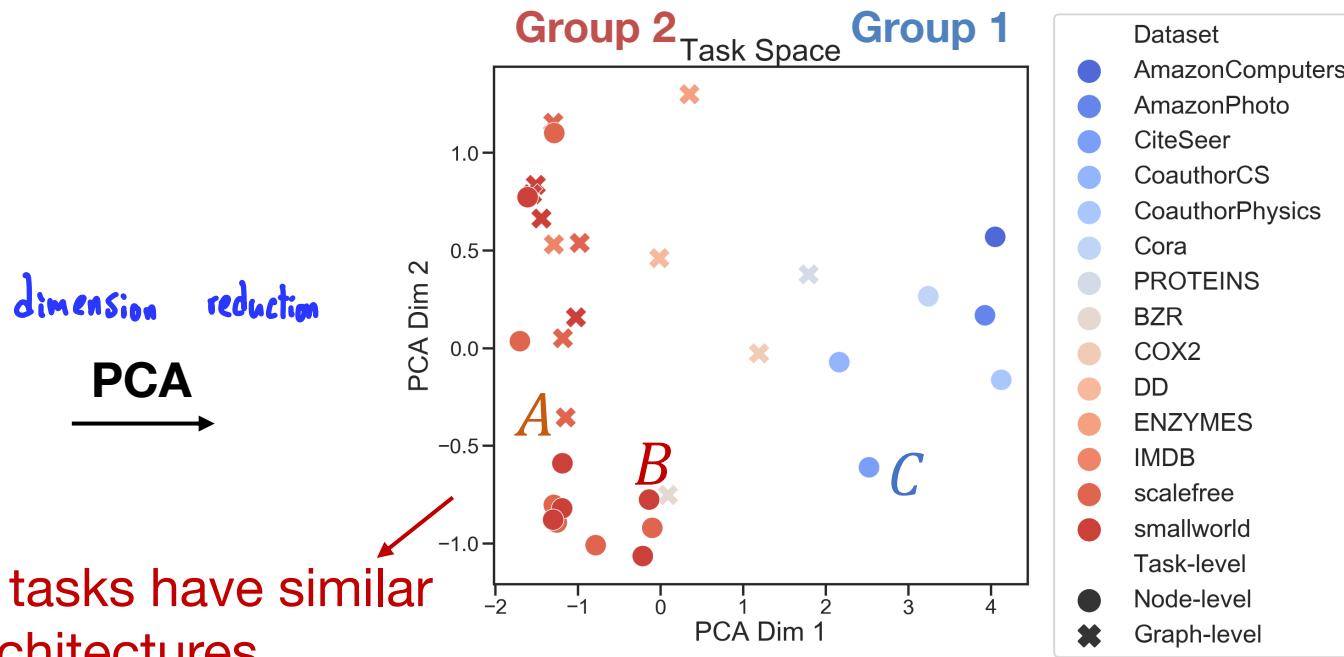
- Cora graph has 1000+ dim node feature

**Group 2:**  
Tasks rely on **structural information**  
Nodes have few features  
Predictions are highly **dependent on graph structure**

- Predicting clustering coefficients

# Results 2: Understanding GNN Tasks

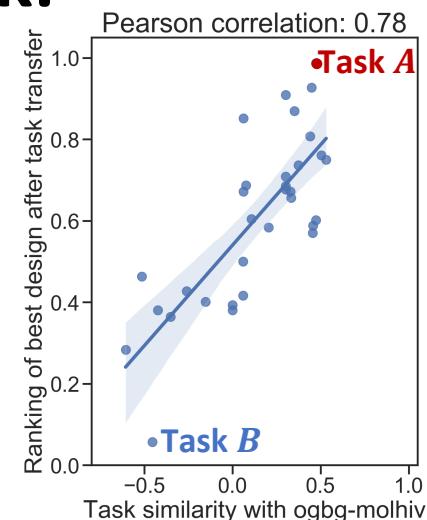
- Proposed GNN task space is informative



	Best GNN Designs Found in Different Tasks					
	Pre layers	MP layers	Post layers	Connectivity	AGG	
Task A	2	8	2	skip-sum	sum	
Task B	1	8	2	skip-sum	sum	
Task C	2	6	2	skip-cat	mean	

# Results 3: Transfer to Novel Tasks

- **Case study:** generalize best models to **unseen** OGB ogbg-molhiv task
  - **ogbg-molhiv is unique from other tasks:** 20x larger, imbalanced (1.4% positive) and requires out-of-distribution generalization
- **Concrete steps for applying to a novel task:**
  - **Step 1:** Run 12 anchor models on the new task
  - **Step 2:** Compute **similarity between the new task and existing tasks**
  - **Step 3:** Recommend the **best designs from existing tasks with high similarity**



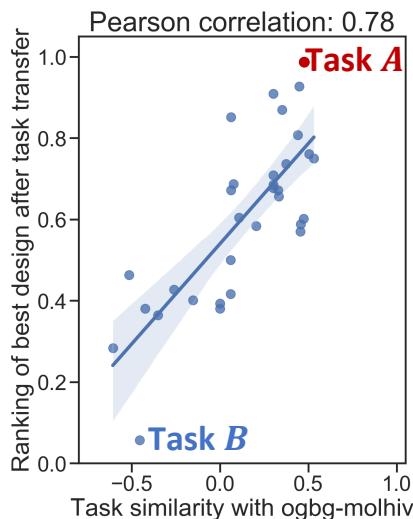
# Results 3: Transfer to Novel Tasks

- Our task space can guide best model transfer to novel tasks!

We pick 2 tasks:

Task A: Similar to OGB

Task B: Not similar to OGB



## Findings:

Transfer the best model from Task A achieves SOTA on OGB

Transfer the best model from Task B performs badly on OGB

	Task A: graph-scalefree-const-path	Task B: node-CoauthorPhysics
Best design in our design space	(1, 8, 3, skipcat, sum)	(1, 4, 2, skipcat, max)
Task Similarity with ogbg-molhiv	0.47	-0.61
Performance after transfer to ogbg-molhiv	0.785	0.736

**Previous SOTA: 0.771**

# GNN Design Space: Summary

- The first systematic investigation of:
  - General guidelines for GNN design
  - Understandings of GNN tasks
  - Transferring best GNN designs across tasks
  - **GraphGym:** Easy-to-use **code platform for GNN**

