國立臺灣大學
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Structural Analysis with Graph Neural Network

圖神經網路於結構分析之應用

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2022/01/05

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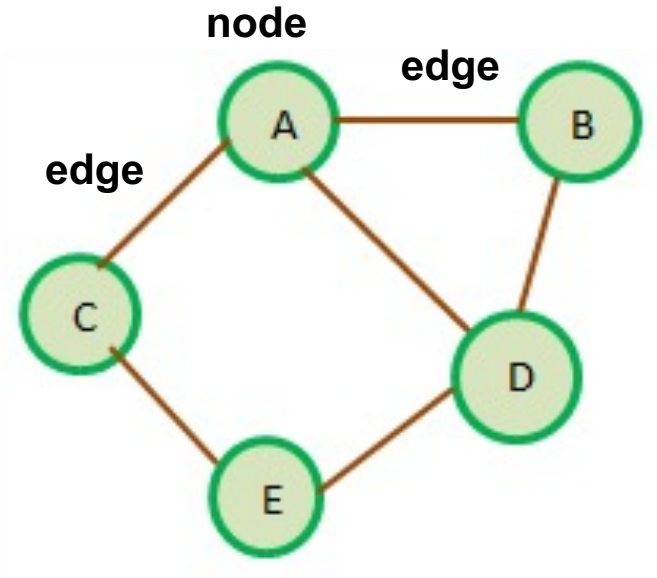
Outline

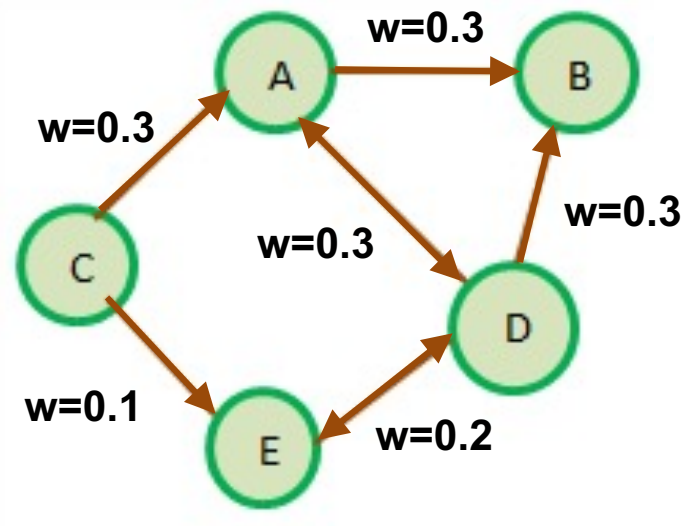
- **Graph Neural Network**
  - ✓ **What**
  - ✓ **Why**
  - ✓ **How**
- **Structural Analysis with GNN**
  - ✓ **What**
  - ✓ **Why**
  - ✓ **How**

What is graph?

- data structure

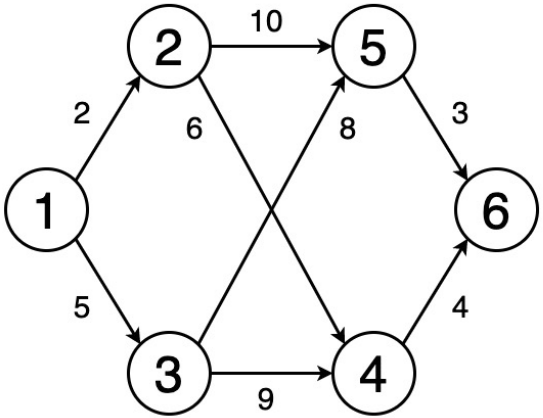


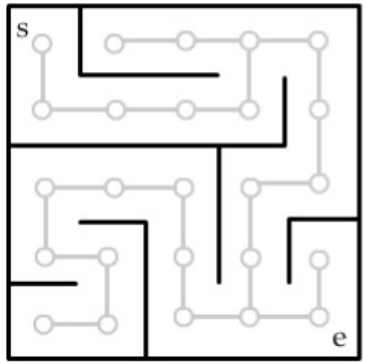
- **directed**
- **weighted**

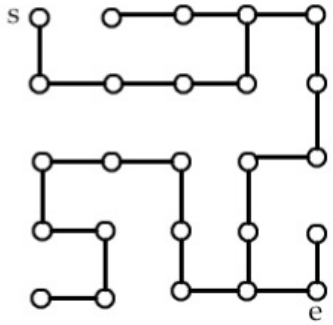


What is graph?

- Solve optimized problems
  - Travelling salesman problem (Dijkstra’s shortest path algorithm)
  - Mazes (depth-first search)

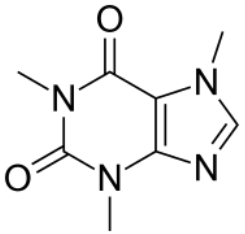




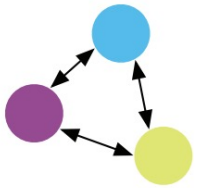


What is graph?

- These can also be graph!!!



n-body System

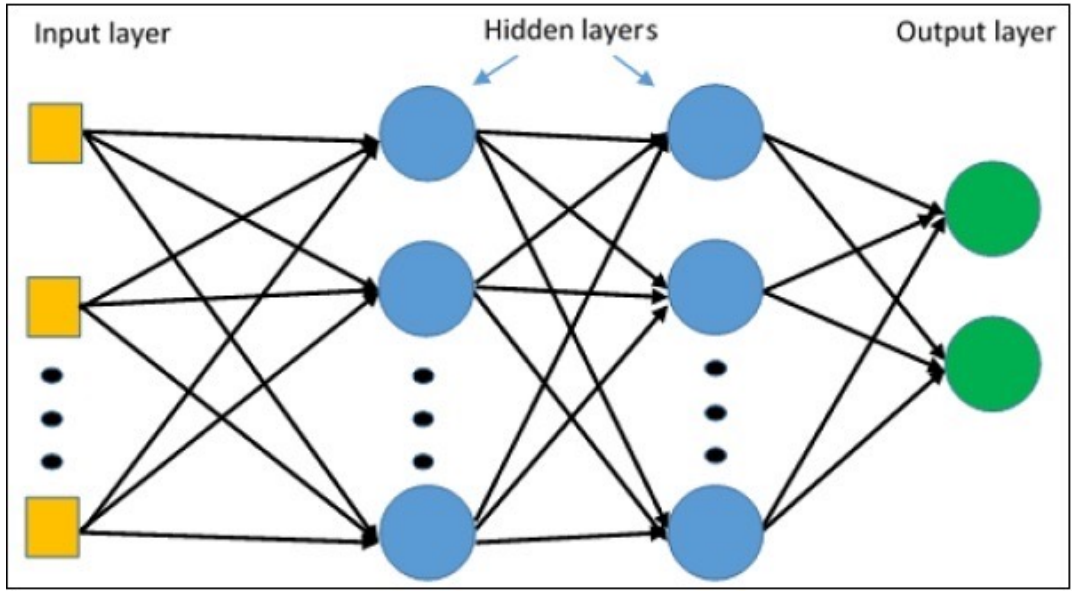


https://arxiv.org/pdf/1806.01261.pdf

Why need Graph Neural Network (GNN)?

- We have just learned Neural Networks (MLP, CNN, ……)

Input
x_n



Output
y_n

Why GNN?

- Consider the case, who stole Nobita’s iPhone?

10歲
胖
成績普通
貪吃

10歲
瘦
成績很好
喜歡洗澡

10歲
瘦
成績超好
???

10歲
瘦
成績不錯
有錢

10歲
瘦
成績差
常被欺負

???歲
胖
成績???
機器貓

Why GNN?

- We can train a binary classifier

$f($  $) = False$

$f($  $) = False$

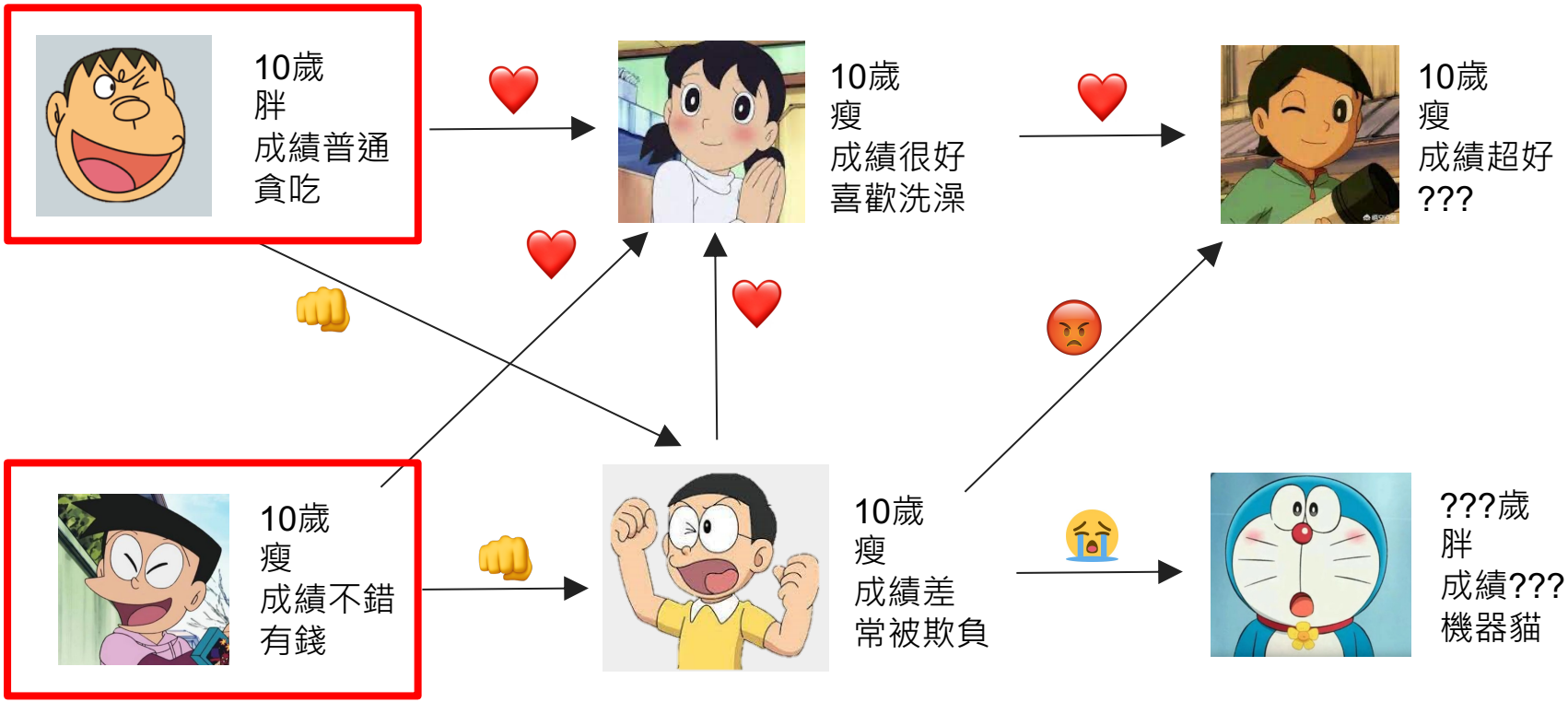
$f($  $) = False$

$f($  $) = ???$

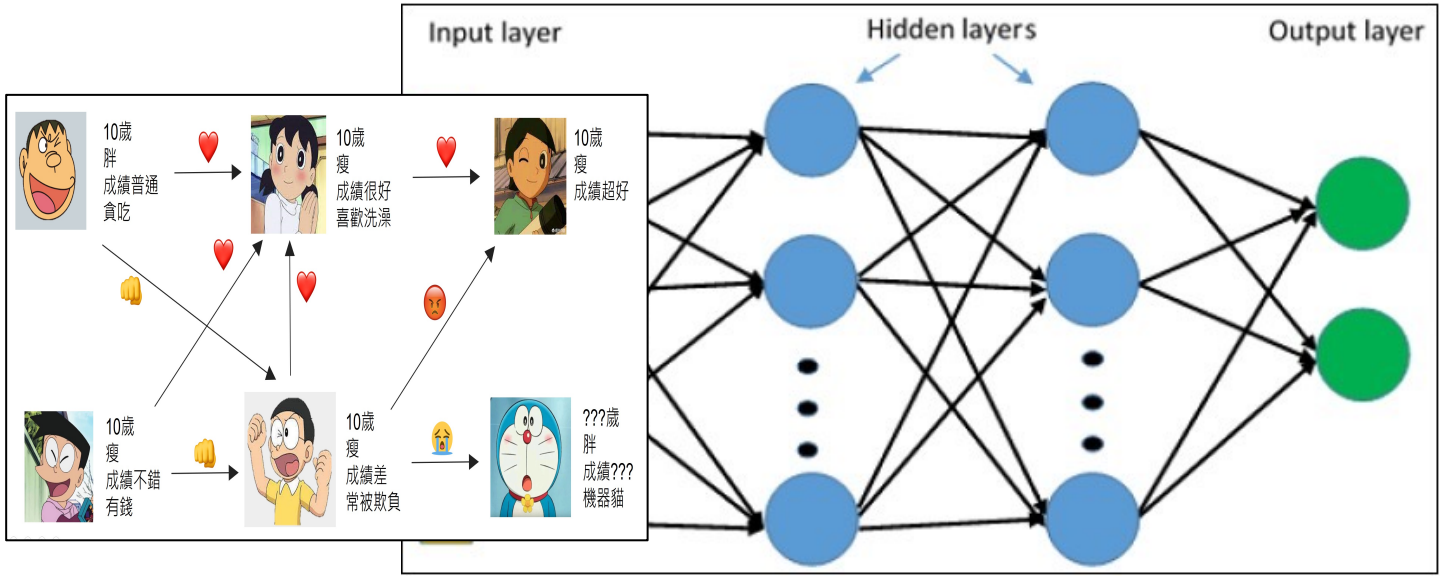
- It’s not easy to predict by only using their personal features

Why GNN?

- Missing something? Their relationship!



Why GNN?



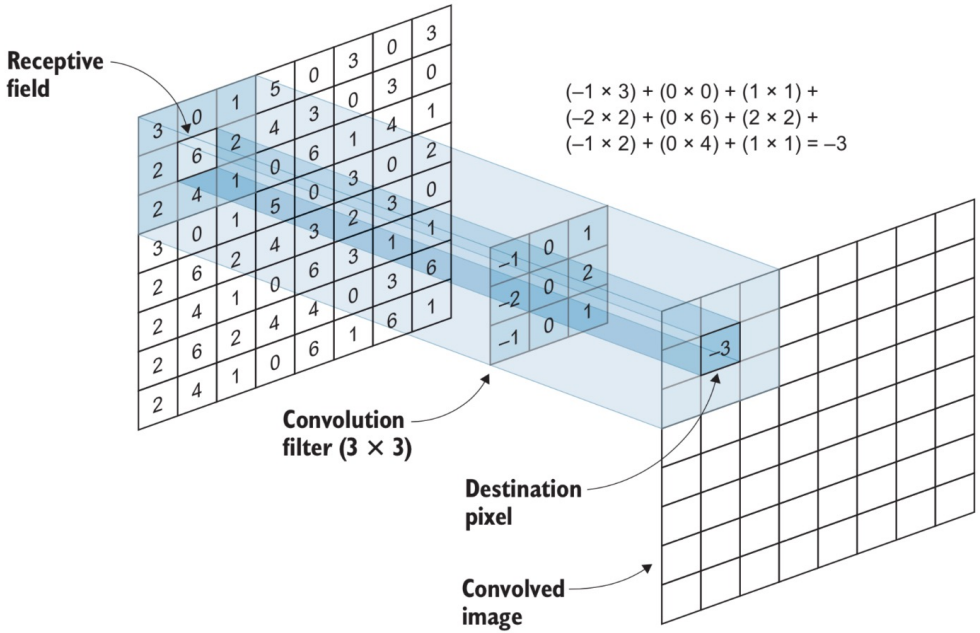
- Node clf
- Node reg

- Edge clf
- Edge reg

- Graph clf
- Graph reg
- Graph gen

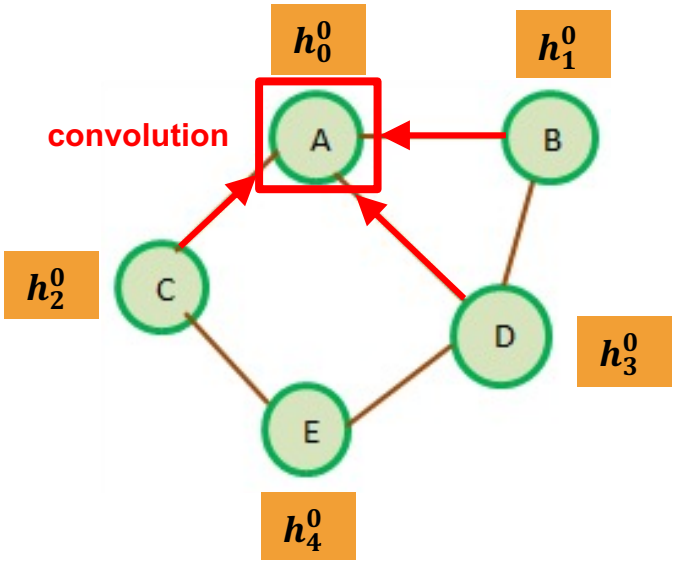
How to consider relationship between nodes??

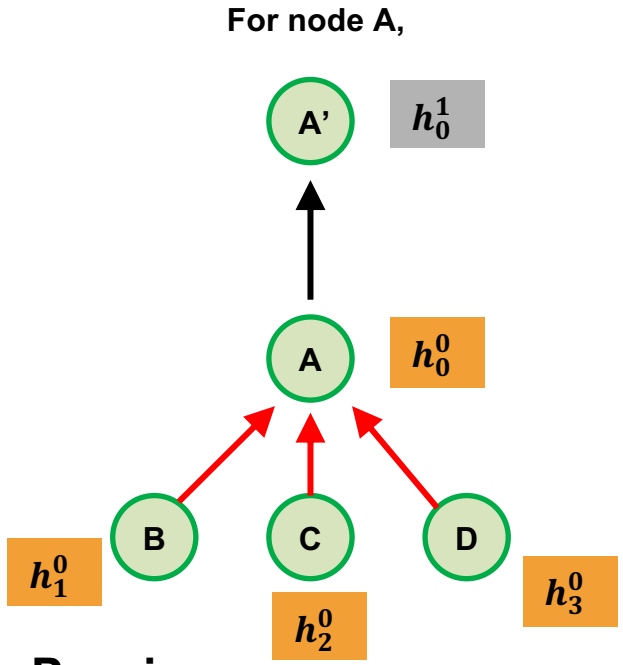
- In CNN, we use convolution to get the local feature



How to consider relationship between nodes??

- In graph, we can also use convolution!

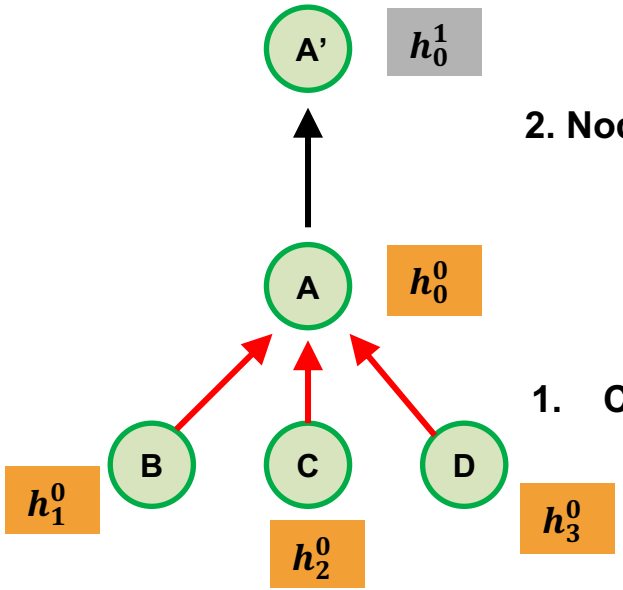




Convolution ⟶ Message Passing

How to consider relationship between nodes??

- Message passing is done in two stages:



2. Nodal update (w2)

1. Create message (w1)

1.

$$m_{0,1}^0 = w_1 (h_0^0 + h_1^0)$$

$$m_{0,2}^0 = w_1 (h_0^0 + h_2^0)$$

$$m_{0,2}^0 = w_1 (h_0^0 + h_2^0)$$

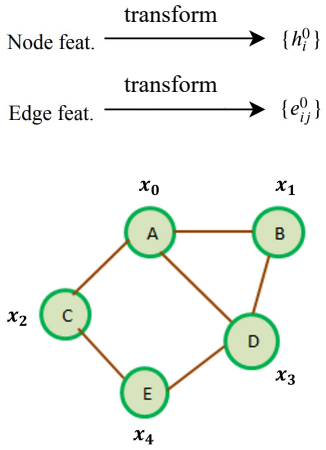
$$m_0^0 = aggr (m_{0,1}^0, m_{0,2}^0, m_{0,3}^0)$$

$$aggr = \{max, add, mean\}$$

2.

$$h_0^1 = w_2 (h_0^0 + m_0^0)$$

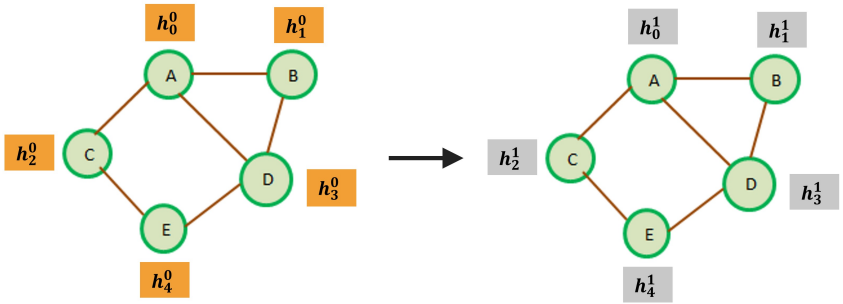
Graph Neural Networks



$$m_{i,j}^t = \varphi_{message}(h_i^t, h_j^t)$$

$$m_i^t = aggr(m_{i,0}^t, m_{i,1}^t, \cdots, m_{i,N}^t)$$

$$h_i^{t+1} = \varphi_{update}(h_i^t, m_i^t)$$



$\times k$

h_i^L MLP → Node Predictions

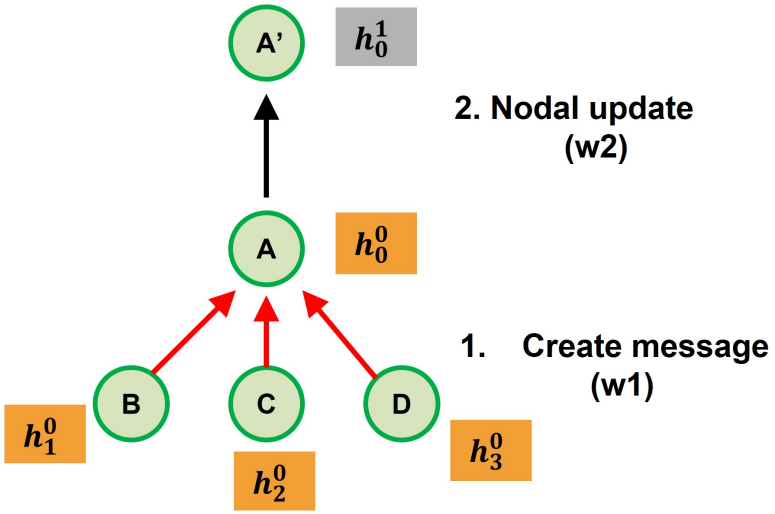
$\frac{1}{\mathcal{V}} \sum_{i=0}^{\mathcal{V}} h_i^L$ MLP → Graph Prediction

$\text{Concat}(h_i^L, h_j^L)$ MLP → Edge Predictions

Input | **Message Passing Layers** | **Output**

https://arxiv.org/pdf/2003.00982.pdf

What is the message, update function?



Different message passing mechanism

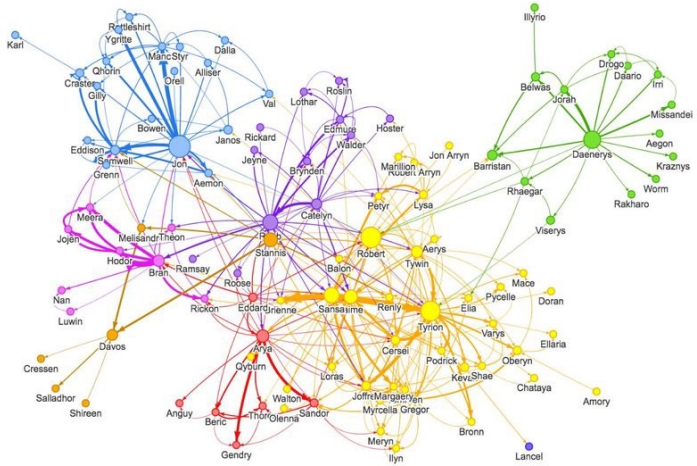
- GCN (Graph Convolution Network)
- GAT (Graph Attention Network)
- GIN (Graph Isomorphism Network)
- GN (Graph Network)

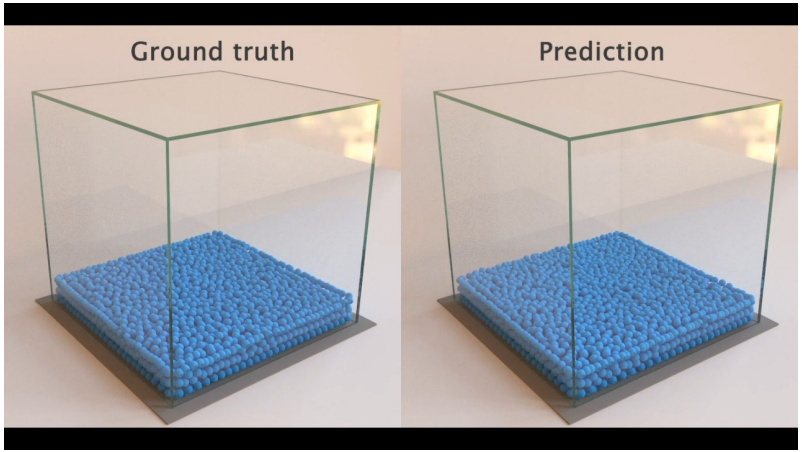
⋮

https://arxiv.org/pdf/1609.02907.pdf
https://arxiv.org/pdf/1710.10903.pdf
https://arxiv.org/pdf/1810.00826.pdf
https://arxiv.org/pdf/1806.01261.pdf

What can message passing do?

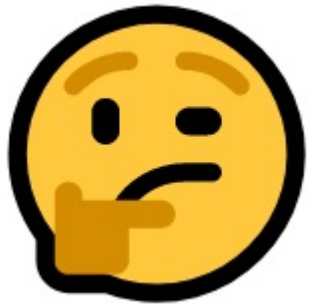
- Pass k-hop by using k layers
- Interaction between nodes
  - ➢ Simulate physics





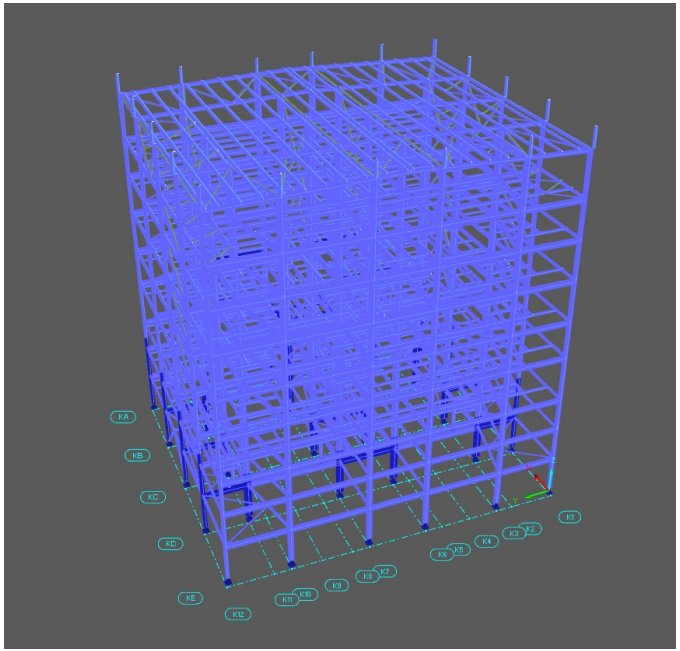
https://arxiv.org/pdf/2002.09405.pdf

Structural Analysis with GNN?



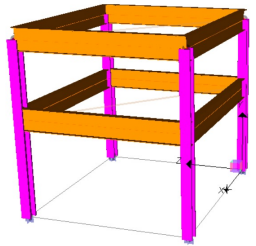
Why ML in structural analysis?

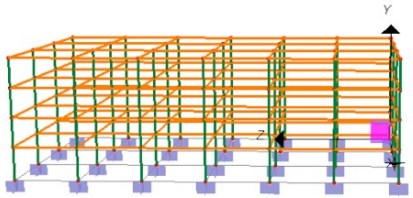
- It’s time-consuming
- Have to wait several hours to know the output response



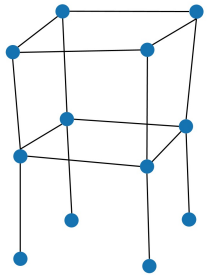
Represent structure as graph

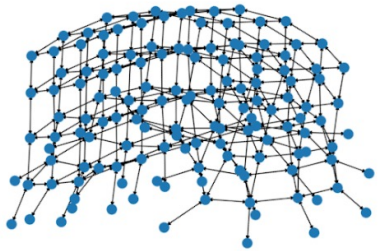
- Structure



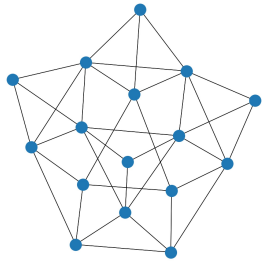


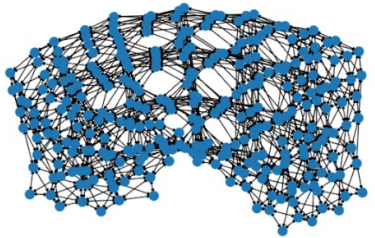
- NodeAsNode



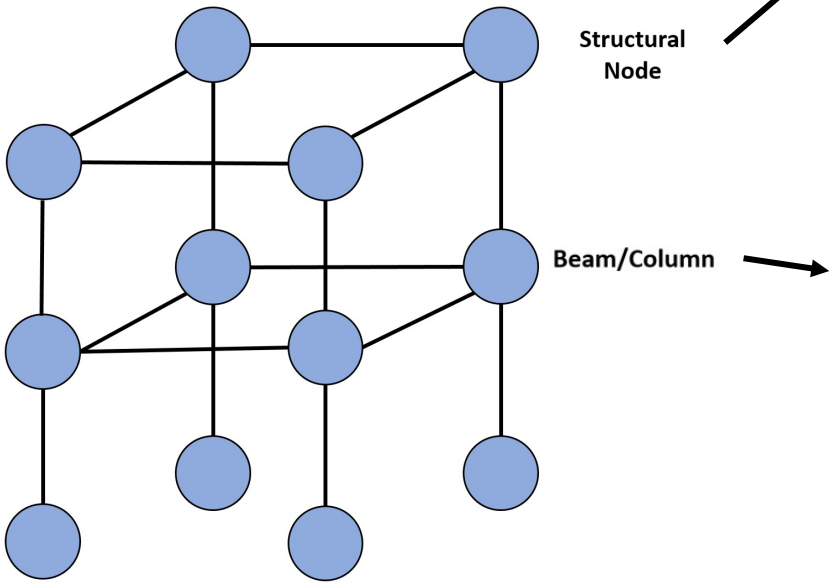


- ElemAsNode





Node feature and output labels



Node Features:

- span/story number of structure
- nodal gird coordinates (x, y, z)
- degree of freedom
- nodal mass
- load

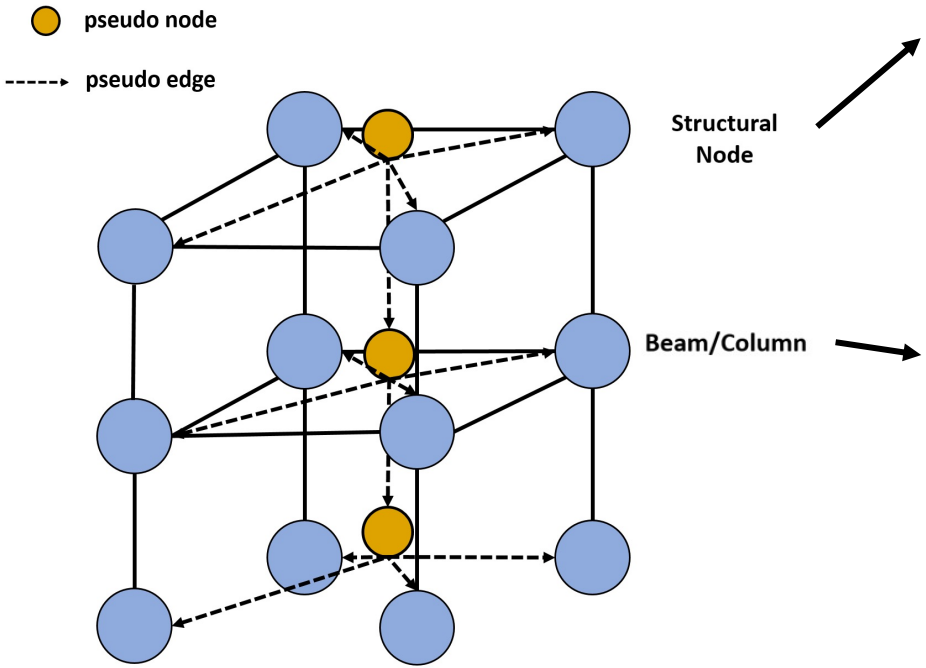
Edge Attributes:

- beam or column
- beam/column length

Node Outputs:

- displacement
- bending moment
- shear force

Node feature and output labels



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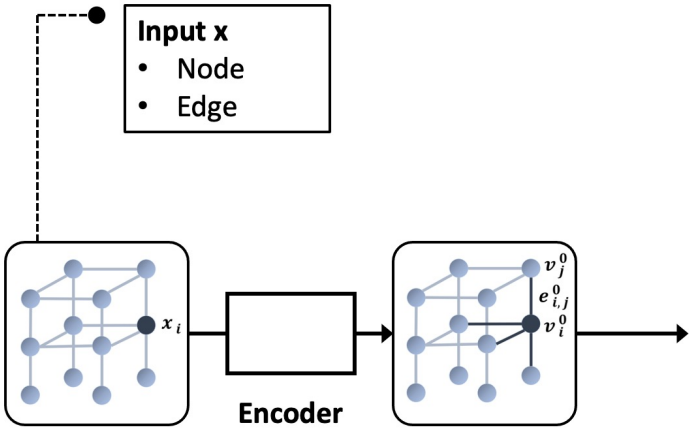
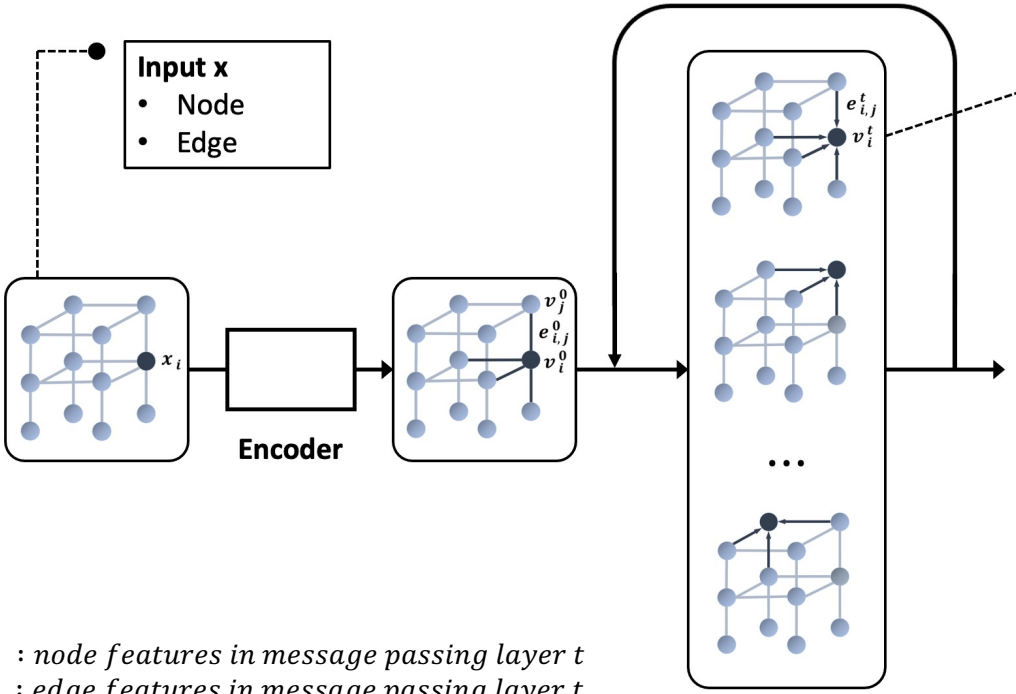
GNN Architecture



GNN Architecture

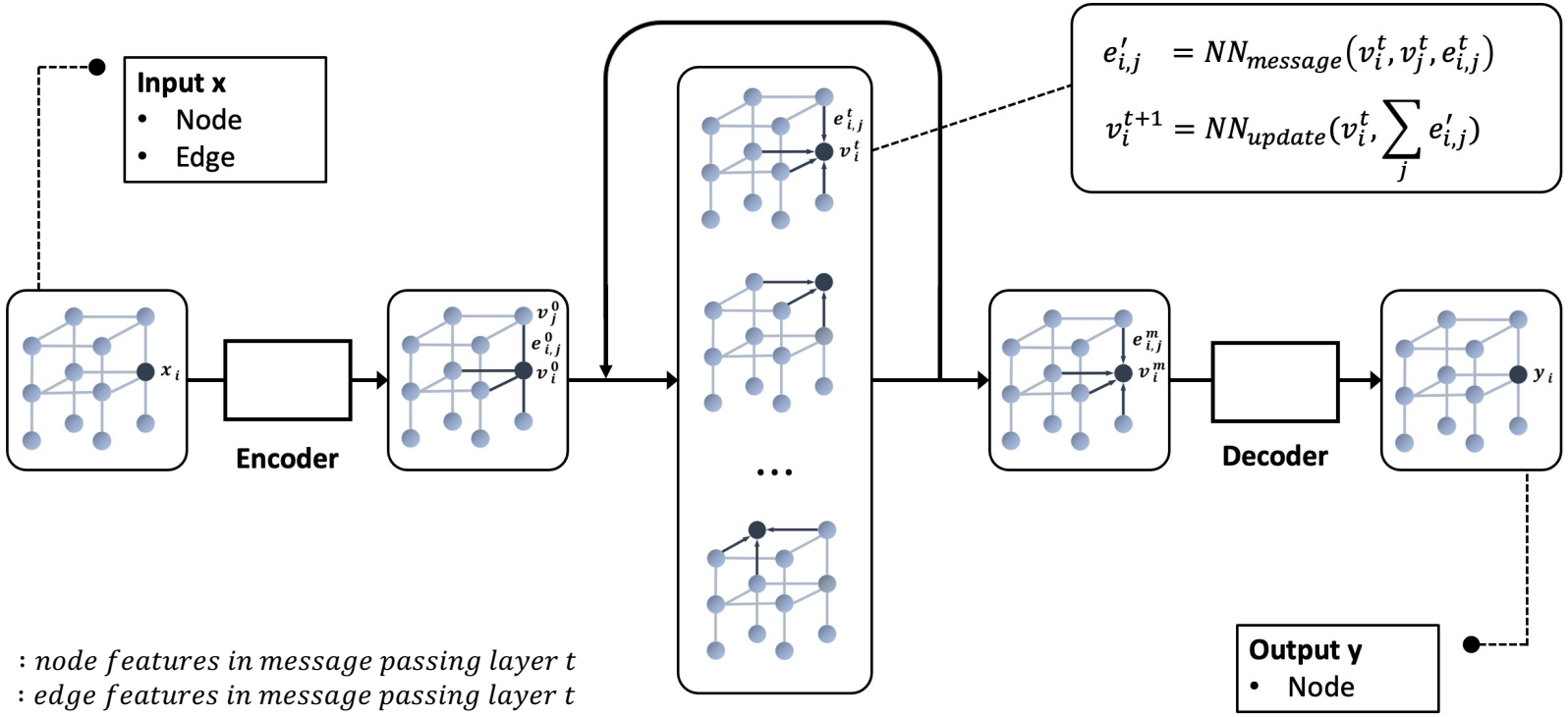


$$e'_{i,j} = NN_{message}(v_i^t, v_j^t, e_{i,j}^t)$$

$$v_i^{t+1} = NN_{update}(v_i^t, \sum_j e'_{i,j})$$

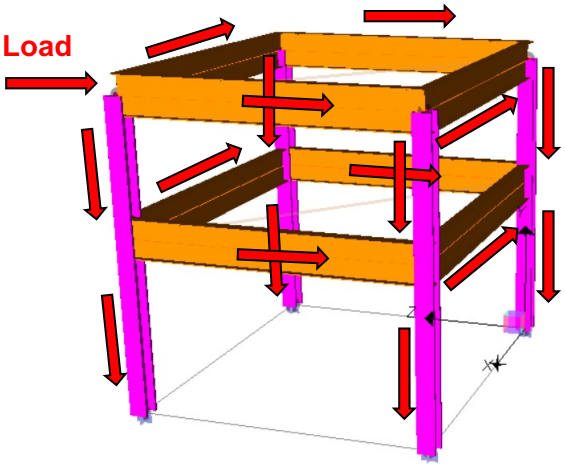
v^t : *node features in message passing layer t*
e^t : *edge features in message passing layer t*
NN : *neural network*

GNN Architecture

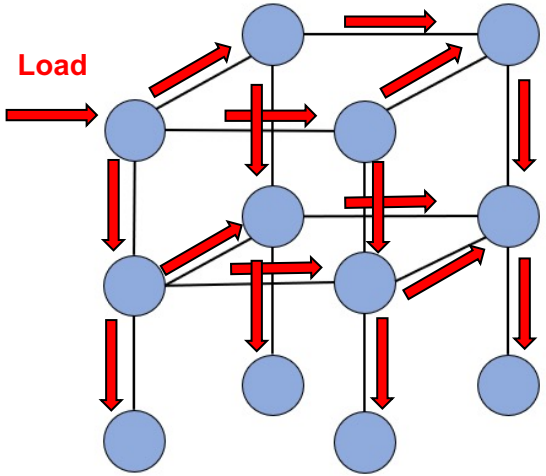


v^t : *node features in message passing layer t*
e^t : *edge features in message passing layer t*
NN : *neural network*

Force Transmission vs. Message Passing



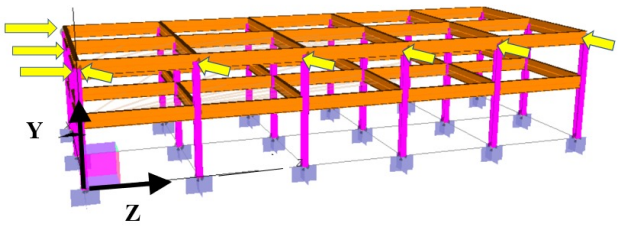
Structure

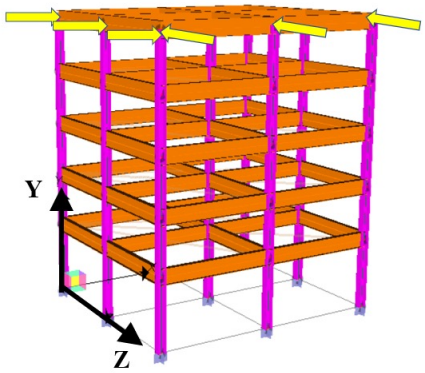


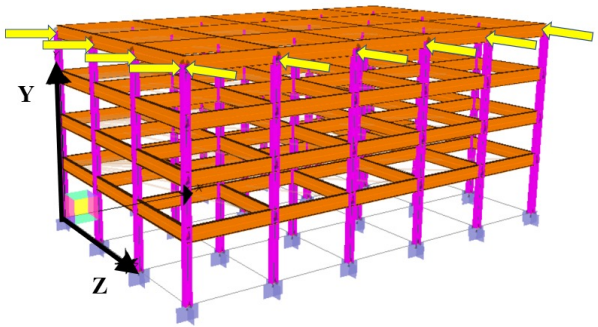
Graph

Data Generation

- random structure







Linear Static Analysis

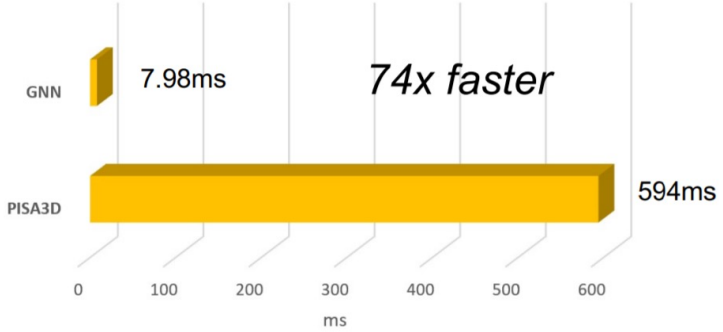
$$Structural\ Load \rightarrow Displacement, Bending\ Moment, Shear\ Force$$

Model	Pseudo Nodes	δ_X	δ_Y	M_Y	M_Z	V_Y	V_Z
GCN	True	97.04	96.82	90.80	90.18	87.42	90.83
GAT	True	97.94	98.26	92.12	91.18	90.02	92.22
GIN	True	98.73	98.44	98.93	98.66	96.92	98.90
StrucGNN	**True**	**99.31**	**99.42**	**99.40**	**99.29**	**99.19**	**99.43**

Table 3: Training performance on 2-6 story (relative accuracy, %)

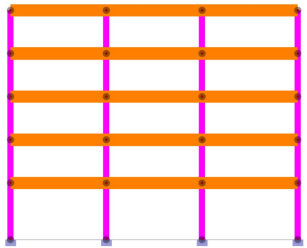
Method	Total Time	Total Iterations	Time / Iteration
PISA3D	9m54s	1000	0.594s
GNN	7.98s	1000	0.00798s

Table 2: Time comparison using PISA3D and GNN



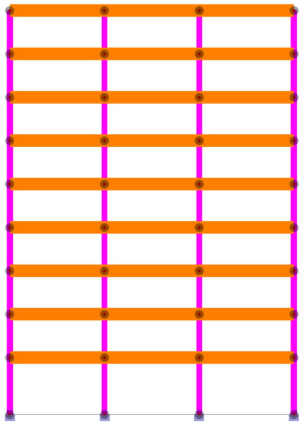
Generalizability

2-6F



Training Structure

7-9F

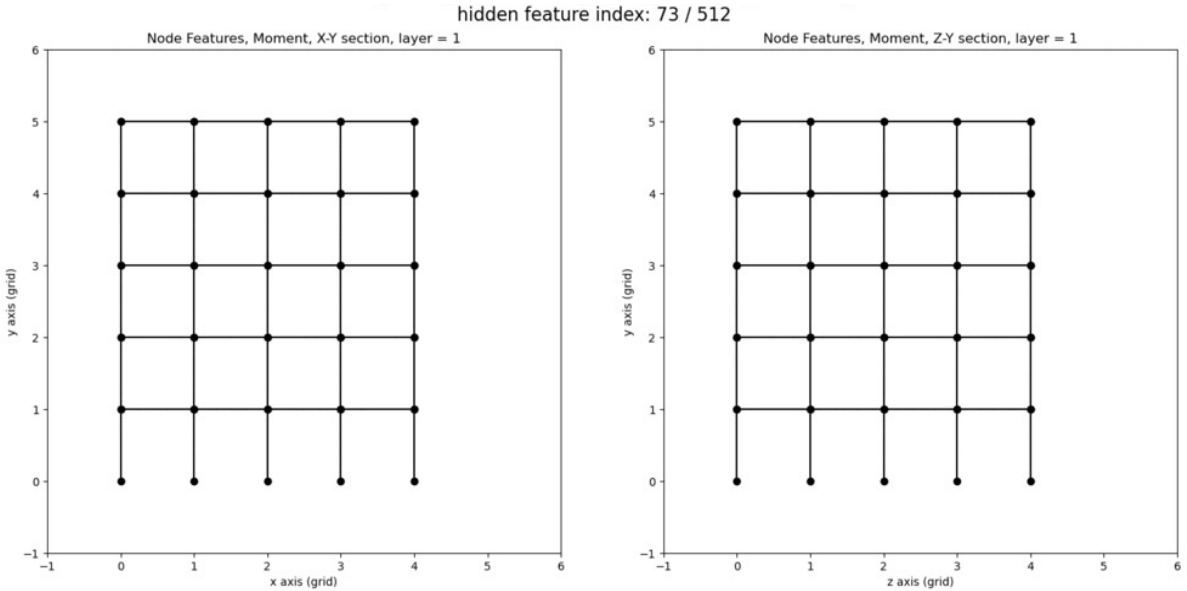


Testing Structure

Model	Pseudo Nodes	δ_X	δ_Y	M_Y	M_Z	V_Y	V_Z
GCN	True	85.92	85.01	77.42	76.98	75.03	77.37
GAT	True	89.81	91.24	79.28	81.88	77.03	79.38
GIN	True	93.58	93.12	88.81	90.42	86.01	89.53
StrucGNN	**True**	**97.41**	**97.62**	**96.19**	**95.14**	**95.13**	**96.50**

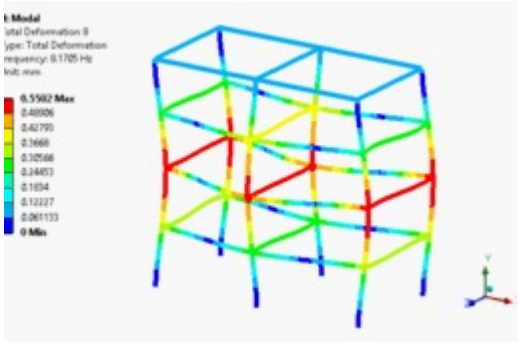
Table 5: Generalizability performance on 7-9 story (relative accuracy, %)

GNN: An Iterative Method



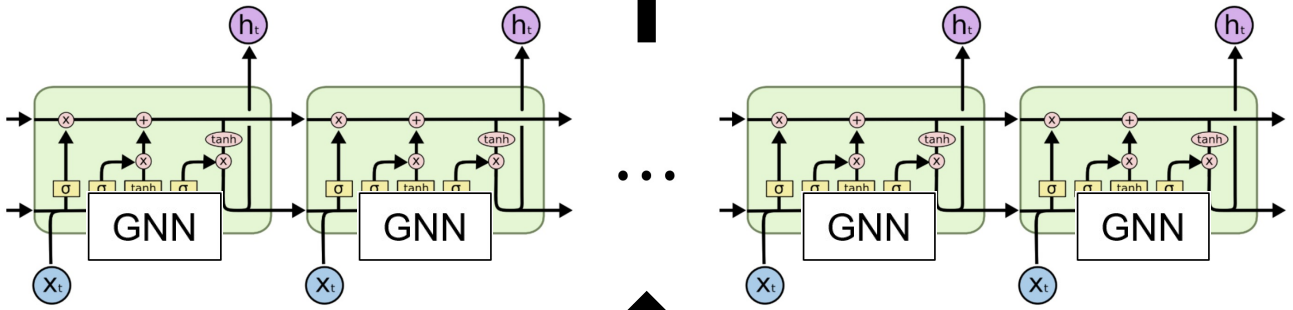
What else?

Response

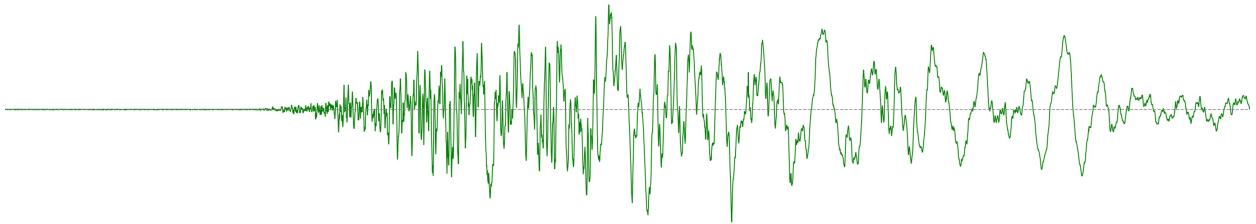


LSTM

GNN



Ground Motion



Summary

GNN is

- mature
- widely used in many field
- straightforward and explainable
- Fun!

Thanks for your attention!

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