# Exercise1: examples of Schmidt decomposition

## 1-1: Random wave function

(Sample code: Ex1-1.ipynb)

- Make a random vector
- SVD it and see singular value spectrum and EE

## 1-2: Ground state of the transverse field Ising model

$$\mathcal{H} = -\sum_{i=1}^{L-1} S_{i,z} S_{i+1,z} - \Gamma \sum_{i=1}^{L} S_{i,x}$$

(Sample code: Ex1-2.ipynb)

- Calculate GS by diagonalizing Hamiltonian
- SVD it and see singular value spectrum and EE

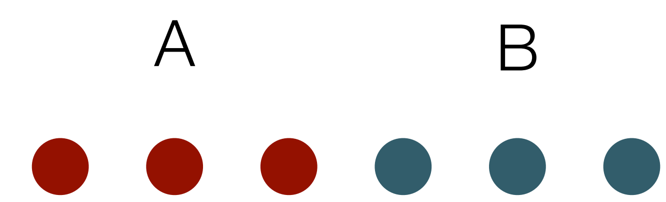
(Sample code: Ex1-3.ipynb)

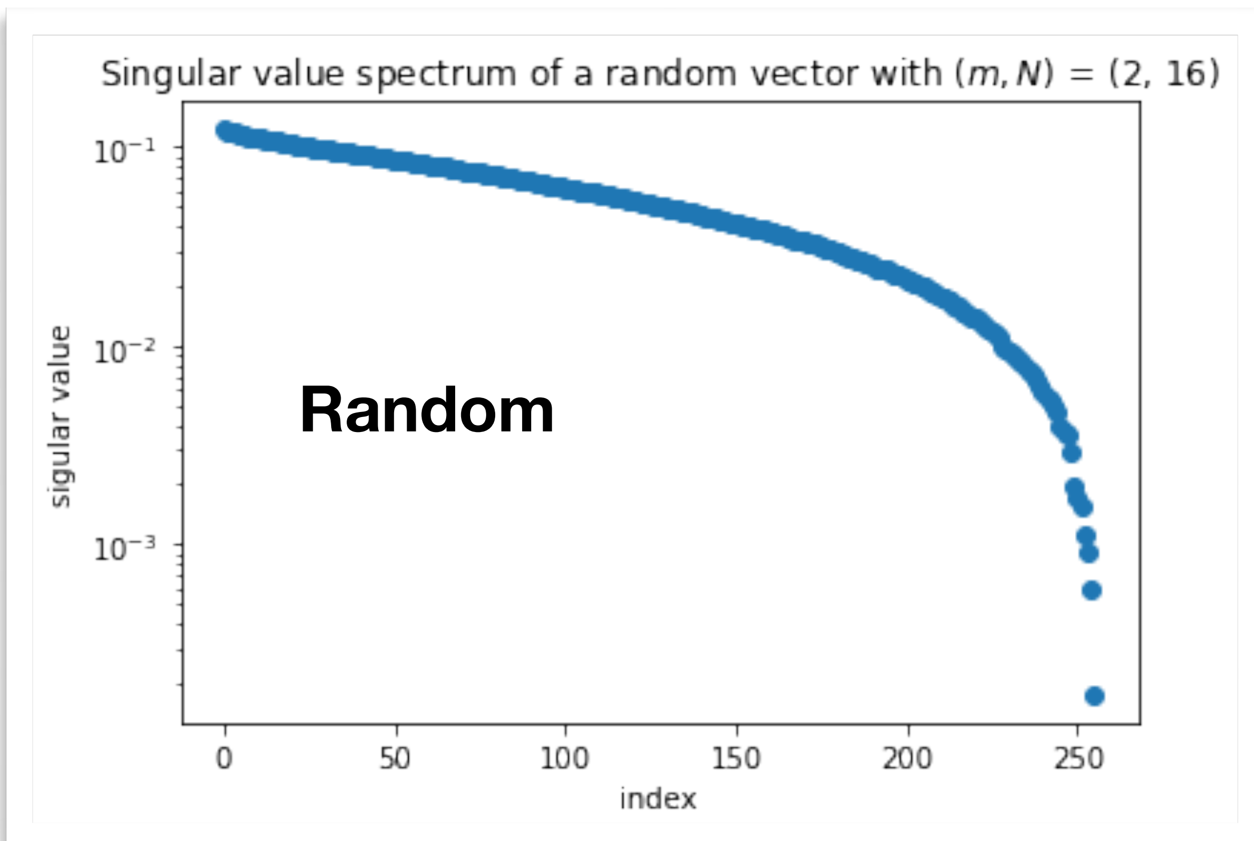
## 1-3: Picture image

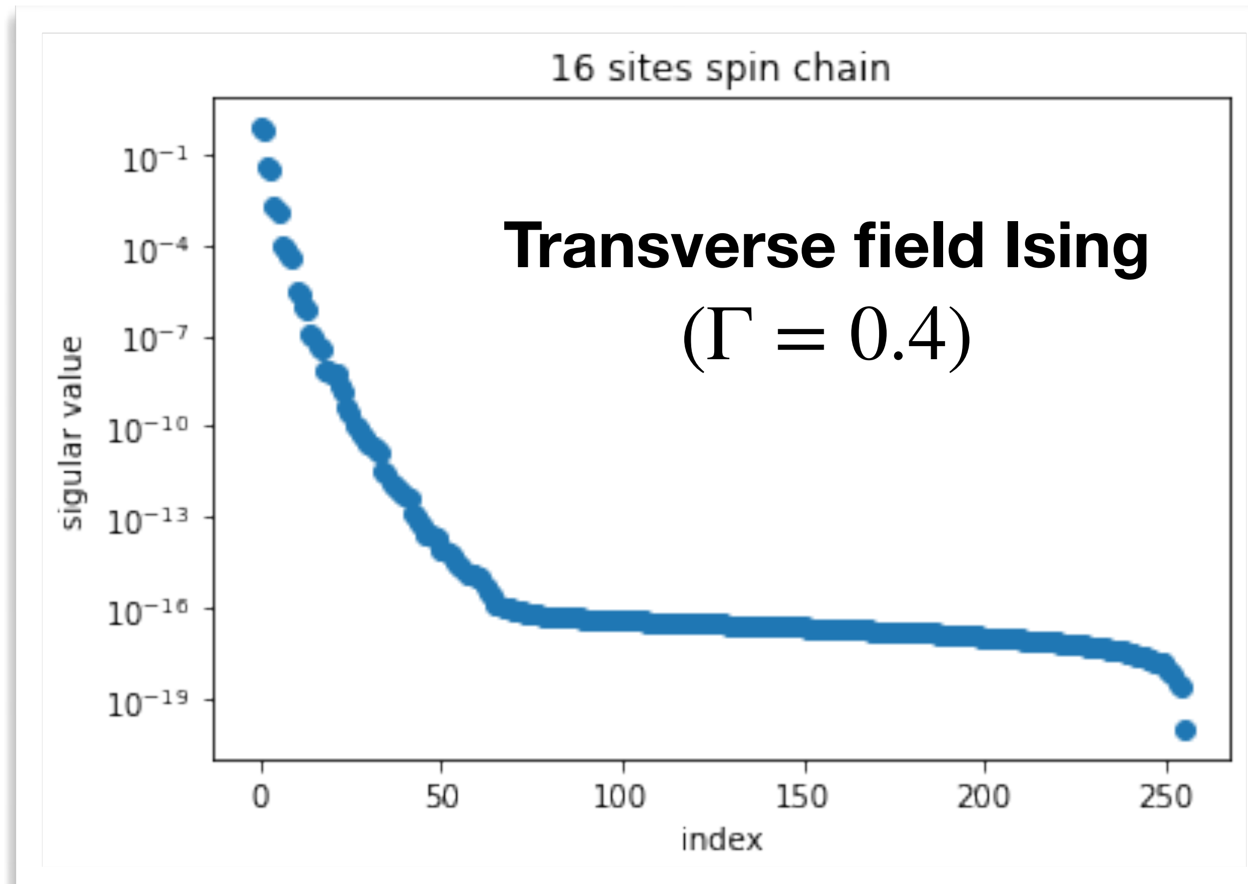
- Transform an image data to the vector in $m^N$ dimension.
- SVD it and see singular value spectrum and EE

*** Try to simulate different system size "*N*"**
*** You can simulate other S by changing "*m*"**

# Spectrum for N=16 $\vec{v} \in \mathbb{C}^{2^{16}}$



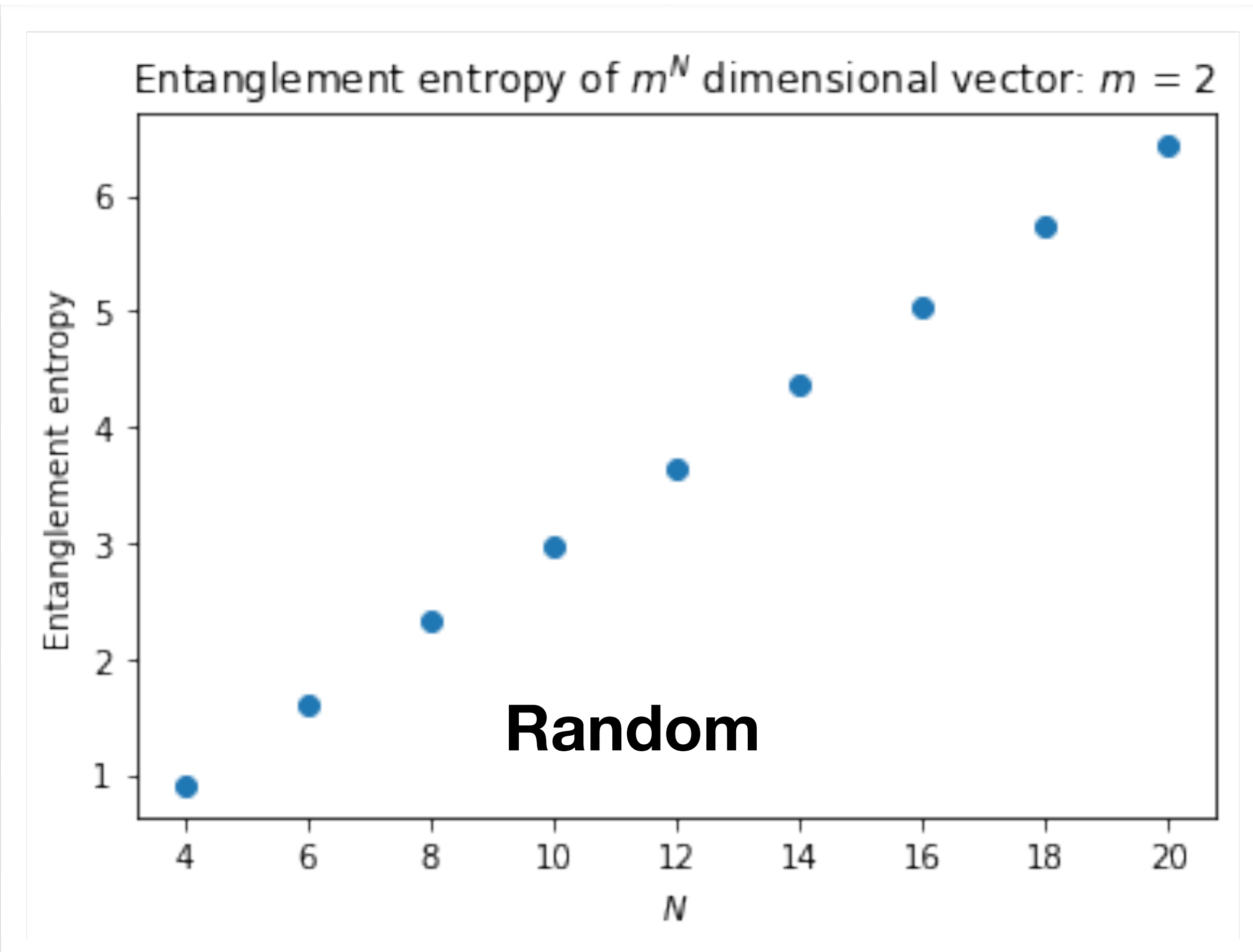



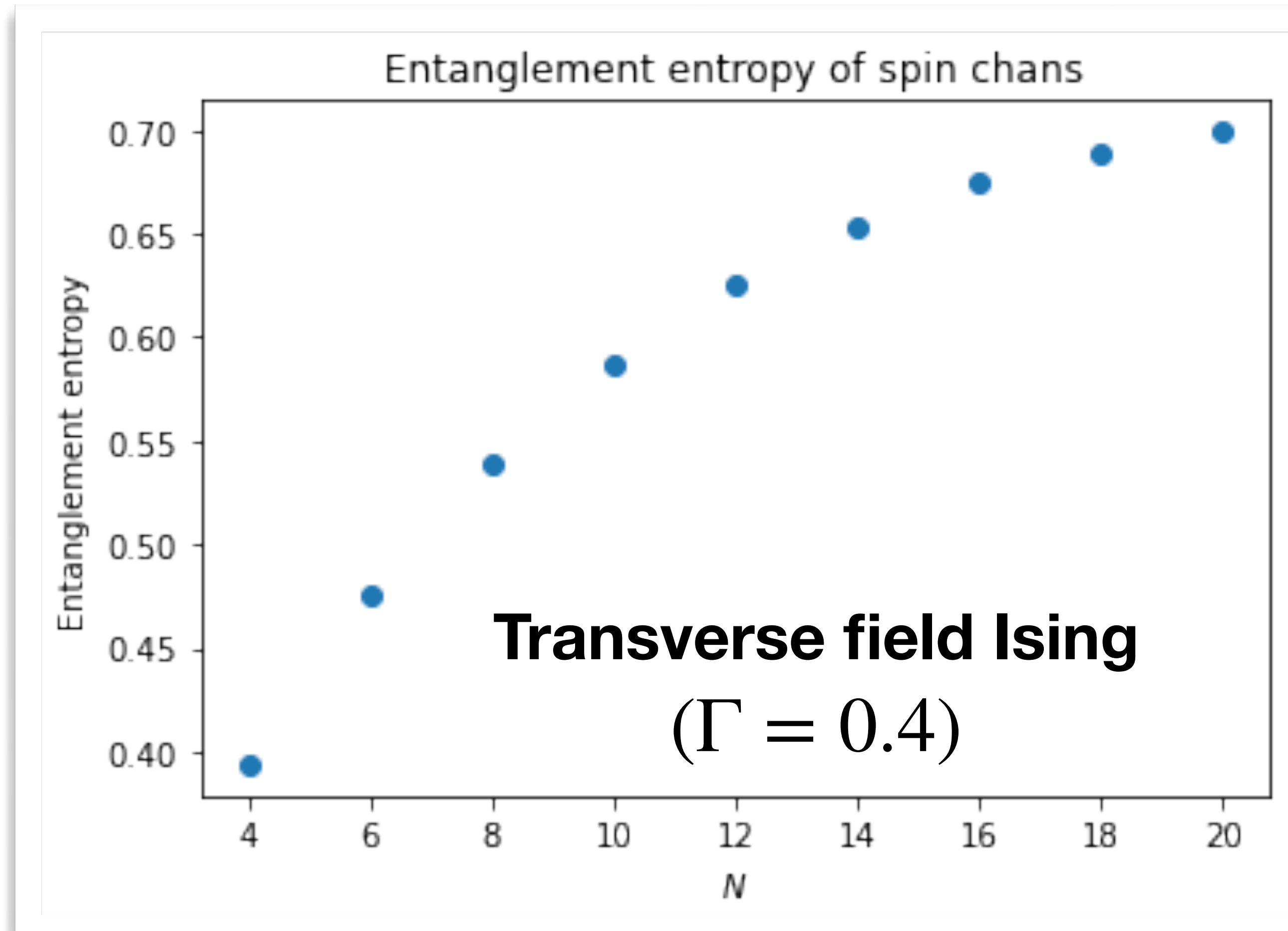




Ground state wave function has lower entanglement!

# Scaling of the entanglement entropy

$\vec{v} \in \mathbb{C}^{2^N}$




Random vector: Volume low
Ground state: Area low

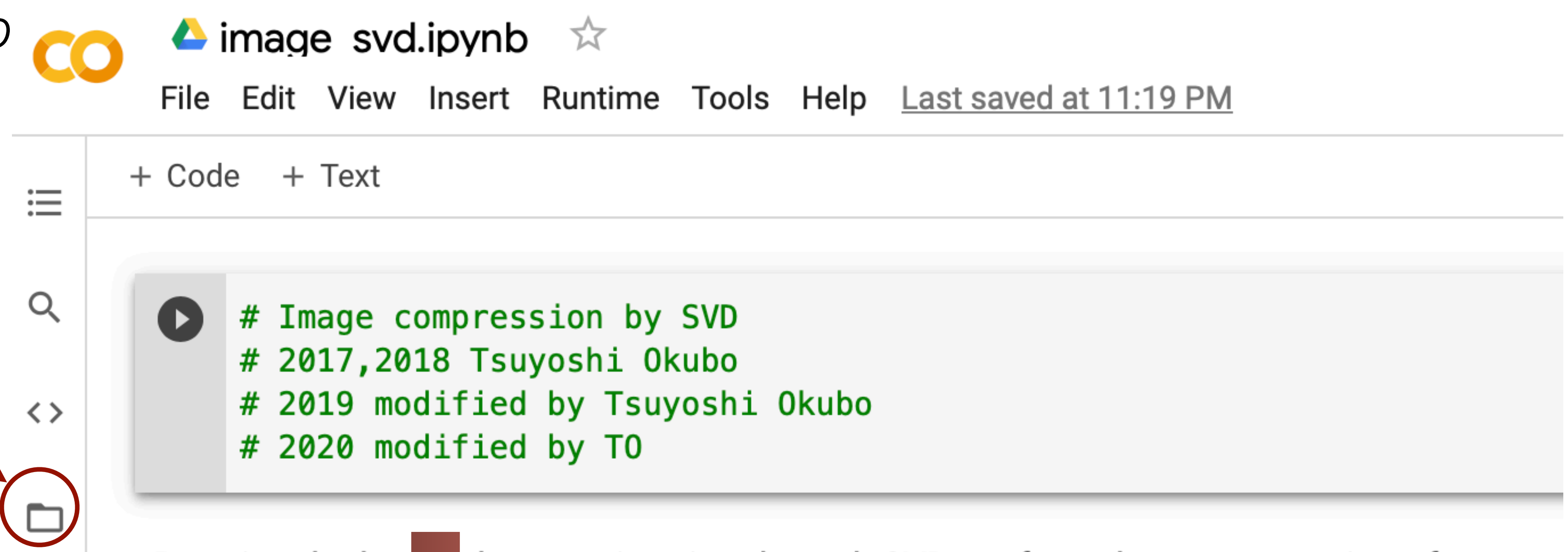
# Exercises with Google Colab

I recommend you to use google colaboratory,
https://colab.research.google.com
where you can run .ipynb from your web browser.

When you use Google Colab, you need to also upload
**"ED.py"**
for the case of "Ex1-2.ipynb", and
**your image file (sample.jpg)**,
for the case of "Ex1-3.ipynb".

# How to use Google Colab

1. Open Ex1-3.ipynb in Google colab
   - Select "**File/upload notebook**" and upload Ex1-3.*ipynb*

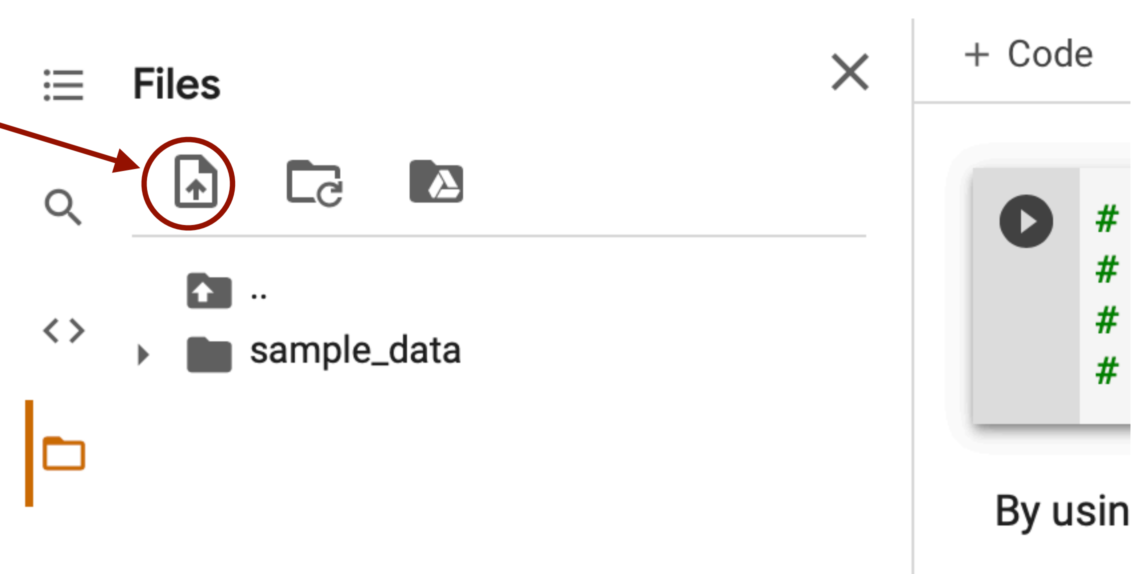



2. Click here

   (Wait a moment for the connection)

3. Click here and upload your image file (e.g. sample.jpg).

   (Uploaded file will be deleted after the session finishes.)




4. Select "**Runtime/Restart and Run all**".

# Exercise 2: Make MPS and approximate it

## 2: Make exact MPS and approximate it by truncating singular values

Try MPS approximation for a random vector, GS of spin model, or a picture image.
Let's see how the approximation efficiency depends on the bond dimensions and vectors.

Sample code: Ex2-1, Ex2-2, Ex2-3. ipynb

These codes correspond to random vector, spin model and picture image, respectively.

*If you run them at Goole Colab, please upload MPS.py in addition to the *.ipynb.

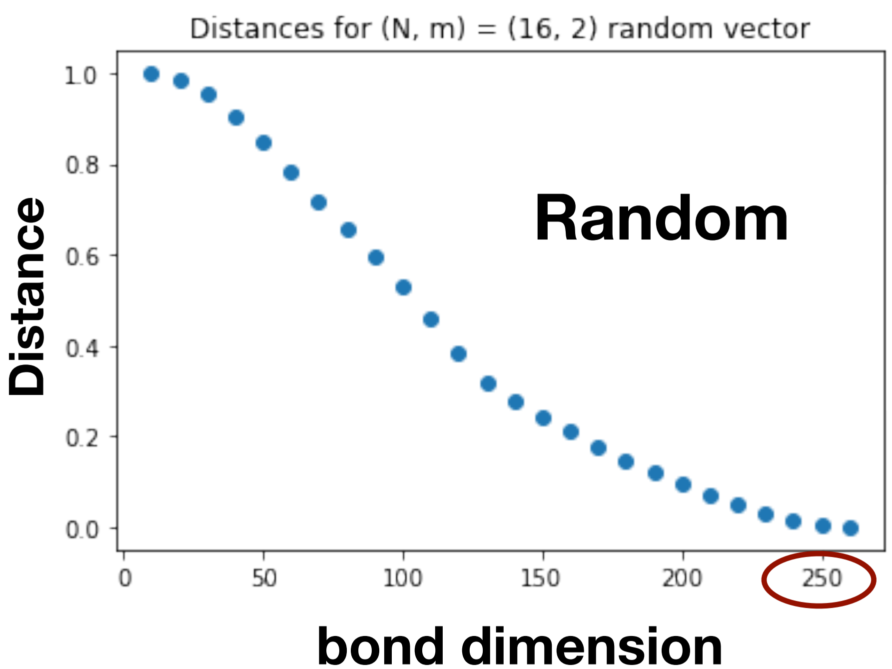
*In the case of Ex2-2 you also need ED.py.

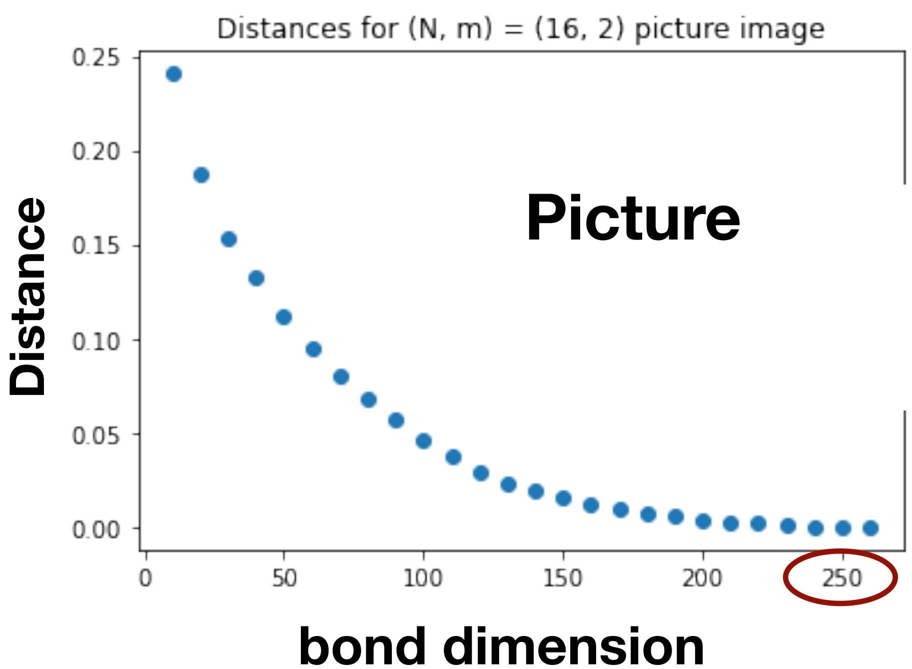
*In the case of Ex2-3 you also need picture file.

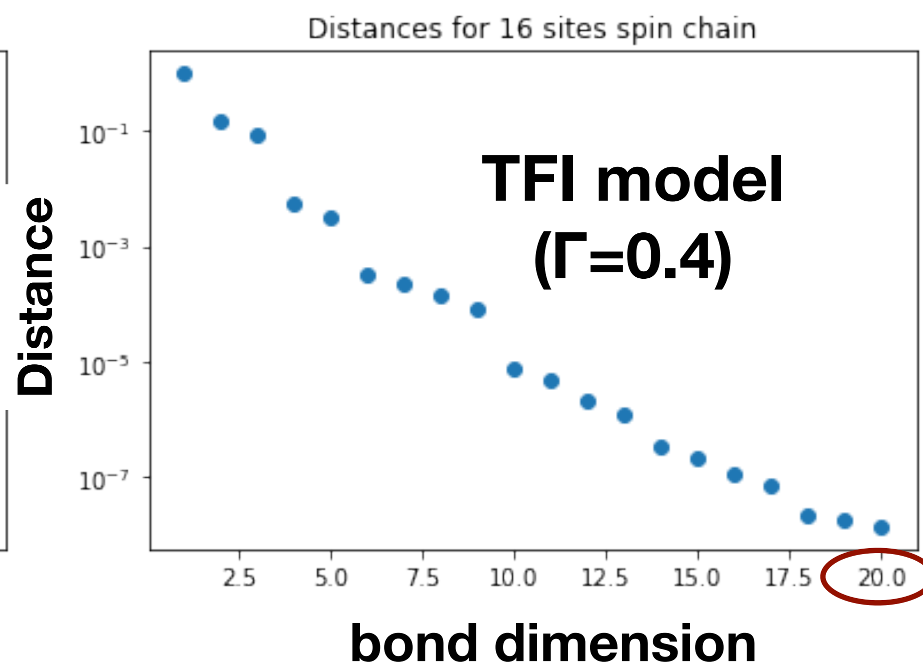
# Exercise 2: Make MPS and approximate it

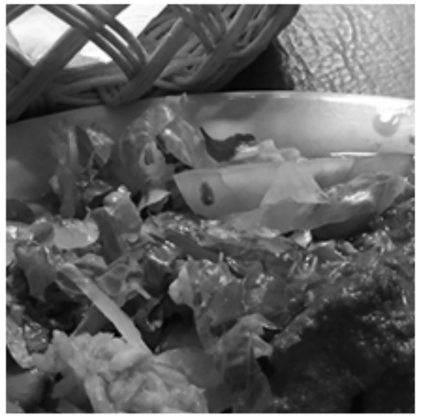
$2^{16}$ dimensional vectors (=16-leg tensors)

Distance between the original and approximated vectors: $||\vec{v}_{ex} - \vec{v}_{ap}||$



$$\mathcal{H} = -\sum_{i=1}^{L-1} S_{i,z} S_{i+1,z} - \Gamma \sum_{i=1}^{L} S_{i,x}$$

# Exercise 3: (TEBD and) iTEBD simulation (ITE)

## 3-1: TEBD simulation

Simulate small finite size system and compare energy with ED

Sample code: Ex3-1.py or Ex3-1.ipynb

## 3-2: iTEBD simulation

Simulate infinite system and calculate energy

Sample code: Ex3-2.py or Ex3-2.ipynb

*** Try simulation with different "chi_max", "T_step"**

*If you run them at Goole Colab, please upload ED.py and TEBD.py for Ex3-1.ipynb, and please upload TEBD.py and iTEBD.py for Ex3-2.ipynb.

# 3-1: Energy dynamics in TEBD