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# 流模型: 计算物理视角



# Physicists' gifts to Machine Learning

### **Mean Field Theory**



### **Monte Carlo Methods**



### **Tensor Networks**



### **Quantum Computing**



# Deep learning is more than fitting functions



### **Discriminative learning**

$$y = f(x)$$
  
or  $p(y|x)$ 



### **Generative learning**

 $p(\mathbf{x}, \mathbf{y})$ 



# Deep learning is more than fitting functions



What I cannot reate, I to not understand. Why const × Sort. PO Bethe Ansitz Prob. Know how to solve every problem that has been solved Non Linear Openical Hyper

### "What I can not create, I do not understand"



# Generated Arts



https://www.christies.com/Features/A-collaboration-between-two-artists-one-human-one-a-machine-9332-1.aspx

### \$432,500 25 October 2018 **Christie's New York**



# Generated Arts



https://www.christies.com/Features/A-collaboration-between-two-artists-one-human-one-a-machine-9332-1.aspx

### \$432,500 **25 October 2018 Christie's New York**



# Generating molecules

### Latent attributes

### Math behind: Simple Probability Distributions Transformation



### Generate

### Inference

### Complex Distribution

Sanchez-Lengeling & Aspuru-Guzik, Inverse molecular design using machine learning: Generative models for matter engineering, Science '18



# Probabilistic Generative Modeling

# How to express, learn, and sample from a high-dimensional probability distribution ?

CHAPTER 1. INTRODUCTION

CHAPTER 5. MACHINE LEARNING BASICS





Figure 5.12: Sampling images uniformly at random (by randomly picking each pixel Figure 1.9: Example inputs from the MNIST dataset. The "NIST" stands for National according to a uniform distribution) gives rise to noisy images. Although there is a non-Institute of Standards and Technology, the agency that originally collected this data. zero probability to generate an image of a face or any other object frequently encountered The "M" stands for "modified," since the data has been preprocessed for easier use with research. It remains popular despite being quite easy for ient to show that the data lies on a reasonably small number of manifolds. We must also Geoffrey Hinton has described it as "the drosophila of machine learning," meaning that establish that the examples we encounter are connected to each other by other it allows machine learning researchers to study their algorithms in controlled laboratory

conditions, much as biologists often study fruit flies.



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  9       2         5       6       7       8       9       0       1       2       3       4       5       6         7       8       9       9       1       0       5       5       1       9       2       6         7       8       9       8       1       0       5       3       4       6       0       4         7       8       9       9       4       5       3       4       5       6       7	4       7       8       9       0       1       2       3       4       5       6       7       8         5       4       7       8       9       2       9       3       9       3       8       2       0         5       4       7       8       9       2       9       3       9       3       8       2       0         5       3       5       3       8       0       0       3       4       1       5       3       0         1       8       1       7       1       3       8       9       7       6       7       4       1         8       0       6       9       4       9       9       3       7       1  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Images

# Proba

### Ian Goodfellow, Yoshua Bengio, and Aaron Courville

# How high-

### **Page 159**

"... the images encountered in Al applications occupy a negligible proportion of the volume of image space."

CHAPTER 5. MACHINE LEARNING B.



Figure 5.12: Sampling images uniformly according to a uniform distribution) give zero probability to generate an image of a in AI applications, we never actually obs that the images encountered in AI appl

ran 000 that the data lies on a reasonably establish that the examples we encou

# bdeling

# DEEP LEARNING

# from a bution ?

# Probabilistic Generative Modeling $p(\mathbf{x})$

# How to express, learn, and sample from a high-dimensional probability distribution ?



https://blog.openai.com/generative-models/





# Modern generative models for physics Physics of and for generative modeling

### Known: samples Unknown: generating distribution



### **Generative modeling**

### **Physics**



### Known: energy function Unknown: samples, partition function





![](_page_14_Figure_1.jpeg)

### Lecture Note <a href="http://wangleiphy.github.io/lectures/PILtutorial.pdf">http://wangleiphy.github.io/lectures/PILtutorial.pdf</a>

### **Generative Models for Physicists**

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Institute of Physics, Chinese Academy of Sciences Beijing 100190, China

October 28, 2018

### Abstract

Generative models generate unseen samples according to a learned joint probability distribution in the highdimensional space. They find wide applications in density estimation, variational inference, representation learning and more. Deep generative models and associated techniques (such as differentiable programing and representation learning) are cutting-edge technologies physicists can learn from deep learning.

This note introduces the concept and principles of generative modeling, together with applications of modern generative models (autoregressive models, normalizing flows, variational autoencoders etc) as well as the old ones (Boltzmann machines) to physics problems. As a bonus, this note puts some emphasize on physics-inspired generative models which take insights from statistical, quantum, and fluid mechanics.

The latest version of the note is at http://wangleiphy.github.io/. Please send comments, suggestions and corrections to the email address in below.

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# Generative modeling with normalizing flows

![](_page_16_Picture_1.jpeg)

![](_page_16_Picture_2.jpeg)

![](_page_16_Picture_3.jpeg)

https://blog.openai.com/glow/

![](_page_16_Picture_7.jpeg)

![](_page_16_Picture_8.jpeg)

![](_page_16_Picture_9.jpeg)

![](_page_16_Picture_10.jpeg)

![](_page_16_Picture_11.jpeg)

# Generative modeling with normalizing flows

![](_page_17_Picture_1.jpeg)

![](_page_17_Picture_2.jpeg)

![](_page_17_Picture_3.jpeg)

https://blog.openai.com/glow/

![](_page_17_Picture_7.jpeg)

![](_page_17_Picture_8.jpeg)

![](_page_17_Picture_9.jpeg)

![](_page_17_Picture_10.jpeg)

![](_page_17_Picture_11.jpeg)

# Normalizing flow in a nutshell

# $\mathcal{N}(z)$

### latent space

### "neural net" with 1 neuron

![](_page_18_Figure_4.jpeg)

![](_page_18_Figure_5.jpeg)

![](_page_18_Figure_6.jpeg)

# Normalizing Flows

$$p(\mathbf{x}) = \mathcal{N}(\mathbf{z}) \left| \det \left( \frac{\partial \mathbf{z}}{\partial \mathbf{x}} \right) \right|$$
 Review article 1912.02762  
Tutorial https://iclr.cc/virtual\_2020/speak

composable, differentiable, and invertible mapping between manifolds

![](_page_19_Figure_4.jpeg)

### Learn probability transformations with normalizing flows

Change of variables  $x \leftrightarrow z$  with deep neural nets

![](_page_19_Figure_7.jpeg)

Got this name in Tabak & Vanden-Eijnden, Commun. Math. Sci. '10

![](_page_19_Picture_9.jpeg)

# Training approaches

### **Density estimation**

"learn from data"

 $\mathscr{L} = -\mathbb{E}_{\mathbf{x} \sim \text{dataset}} \left[ \ln p(\mathbf{x}) \right]$ 

![](_page_20_Figure_4.jpeg)

Sample from dataset in the physical space

### Variational calculation

"learn from Hamiltonian"

$$\mathscr{L} = \int d\mathbf{x} \, p(\mathbf{x}) \Big[ \ln p(\mathbf{x}) + \beta \mathbf{H}(\mathbf{x}) \Big]$$

$$x$$
 **Herefore**  $z \sim \mathcal{N}(\mathbf{0}, \Sigma)$ 

Sample in the latent space

# Training approaches

# **Density estimation** "learn from data"

 $\mathscr{L} = -\mathbb{E}_{\mathbf{x} \sim \text{dataset}} \left[ \ln p(\mathbf{x}) \right]$ 

$$\mathbb{KL}(\pi | | p) = \sum_{x} \pi \ln \pi - \sum_{x} \pi \ln p$$

Sample from dataset in the physical space

### Variational calculation

"learn from Hamiltonian"

$$\mathscr{L} = \int d\mathbf{x} \, p(\mathbf{x}) \left[ \ln p(\mathbf{x}) + \beta \mathbf{H}(\mathbf{x}) \right]$$

$$\mathcal{L} + \ln Z = \mathbb{KL}\left(p \mid \mid \frac{e^{-\beta H}}{Z}\right) \ge$$

Sample in the latent space

![](_page_21_Picture_10.jpeg)

### **Maximum Likelihood Estimation**

![](_page_22_Figure_2.jpeg)

 ${\mathcal X}$ 

Fig. 3.6, Goodfellow, Bengio, Courville, http://www.deeplearningbook.org/

# Forward KL or Reverse KL?

### **Variational Free Energy**

 $q^* = \operatorname{argmin}_q D_{\mathrm{KL}}(q \| p)$ 

![](_page_22_Figure_9.jpeg)

 ${\mathcal X}$ 

# Monte Carlo Gradient Estimators

 $\nabla_{\boldsymbol{\theta}} \mathbb{E}_{\boldsymbol{x} \sim p_{\boldsymbol{\theta}}} \left| f(\boldsymbol{x}) \right|$ 

Score function estimator (REINFORCE)

$$\nabla_{\theta} \mathbb{E}_{\boldsymbol{x} \sim p_{\theta}} \left[ f(\boldsymbol{x}) \right] = \mathbb{E}$$

Pathwise estimator (Reparametrization trick)  $x = g_{\theta}(z)$  $\mathbb{E}_{z \sim \mathcal{N}(z)} \left[ \nabla_{\theta} f(g_{\theta}(z)) \right]$ 

$$\nabla_{\theta} \mathbb{E}_{\mathbf{x} \sim p_{\theta}} \left[ f(\mathbf{x}) \right] = \mathbb{E}$$

# **Choose the one with the lowest variance**

### **Review: 1906.10652**

Reinforcement learning Variational inference Variational Monte Carlo Variational quantum algorithms

 $\mathbb{E}_{\boldsymbol{x} \sim p_{\theta}} \left| f(\boldsymbol{x}) \nabla_{\theta} \ln p_{\theta}(\boldsymbol{x}) \right|$ 

. . .

### **Composability**

![](_page_24_Picture_2.jpeg)

# Design principles

![](_page_24_Figure_4.jpeg)

 $z = \mathcal{T}(x)$  $\mathcal{T} = \mathcal{T}_1 \circ \mathcal{T}_2 \circ \mathcal{T}_3 \circ \cdots$ 

![](_page_24_Picture_6.jpeg)

 $\frac{\partial \rho(\boldsymbol{x},t)}{\partial \boldsymbol{x}} + \nabla \cdot \left[ \rho(\boldsymbol{x},t) \boldsymbol{v} \right] = 0$  $\partial t$ 

Continuous flow

![](_page_24_Picture_9.jpeg)

Forward arbitrary  $\begin{cases} x_{<} = z_{<} \\ x_{>} = z_{>} \odot e^{s(z_{<})} + t(z_{<}) \end{cases}$ neural nets

Inverse

$$\begin{cases} z_{<} = x_{<} \\ z_{>} = (x_{>} - t(x_{<})) \odot d \end{cases}$$

Log-Abs-Jacobian-Det  $\ln \left| \det \left( \frac{\partial x}{\partial z} \right) \right| = \sum_{i} [s(z_{<})]_{i}$ 

Turns out to have surprising connection Störmer–Verlet integration (later)

# Example of a building block

![](_page_25_Figure_7.jpeg)

![](_page_25_Figure_8.jpeg)

Real NVP, Dinh et al, 1605.08803

![](_page_25_Picture_10.jpeg)

# How it can be useful in physics ? Relative Center-of-mass motion motion **Neural Net**

![](_page_26_Picture_1.jpeg)

![](_page_26_Picture_2.jpeg)

Coupled harmonic oscillator

![](_page_26_Picture_4.jpeg)

![](_page_26_Picture_5.jpeg)

![](_page_27_Picture_1.jpeg)

![](_page_27_Picture_2.jpeg)

Effective theory emerges upon transformation of the variables

# How it can be useful in physics?

![](_page_27_Picture_5.jpeg)

### Monte Carlo update

![](_page_27_Figure_7.jpeg)

Physics happens on a manifold Learn neural nets to unfold that manifold

![](_page_27_Figure_9.jpeg)

# Neural Network Renormalization Group

![](_page_28_Figure_1.jpeg)

![](_page_28_Picture_3.jpeg)

![](_page_29_Figure_1.jpeg)

![](_page_29_Picture_3.jpeg)

# Neural Network Renormalization Group

![](_page_30_Figure_1.jpeg)

![](_page_30_Picture_3.jpeg)

# Neural Network Renormalization Group

![](_page_31_Figure_1.jpeg)

Correlated classical variables

![](_page_31_Picture_3.jpeg)

# Neural Network Renormalization Group Li, LW, PRL '18 li012589/NeuralRG Collective variables Gener **Probability Transformation** Latent $\ln p(\mathbf{x}) = \ln \mathcal{N}(z) - \ln \left| \det \left( \frac{\partial x}{\partial z} \right) \right|$ variables ρ Bijective neural nets

![](_page_32_Figure_1.jpeg)

Correlated classical variables

![](_page_32_Picture_3.jpeg)

# Variational Loss

![](_page_33_Figure_1.jpeg)

Training = Variational free energy calculation

epochs

Latent space energy function  $E_{\text{eff}}(z) = E(g(z)) + \ln p(g(z)) - \ln \mathcal{N}(z)$ 

![](_page_34_Figure_2.jpeg)

Physical energy function  $E(\mathbf{x})$ 

### **HMC** thermalizes faster in the latent space

Other ways to de-bias: neural importance sampling, Metropolis rejection of flow proposal ...

# Sampling in the latent space

![](_page_34_Picture_7.jpeg)

![](_page_35_Figure_1.jpeg)

# Quantum origin of the architecture

![](_page_35_Figure_3.jpeg)

![](_page_35_Figure_4.jpeg)

![](_page_35_Figure_5.jpeg)

# Connection to wavelets

![](_page_36_Picture_1.jpeg)

### Nonlinear & adaptive generalizations of wavelets Guy, Wavelets & RG1999+ White, Evenbly, Qi, Wavelets, MERA, and holographic mapping 2013+

![](_page_36_Figure_3.jpeg)

# Continuous normalizing flows $\ln p(\mathbf{x}) = \ln \mathcal{N}(z) - \ln \left| \det \left( \frac{\partial x}{\partial z} \right) \right|$

### Consider infinitesimal change-of-variables Chen et al 1806.07366

 $\ln p(\mathbf{x})$  $x = z + \varepsilon v$ 

 $\varepsilon \to 0$ 

 $\frac{dx}{dt}$ = v

$$(x) - \ln \mathcal{N}(z) = -\ln \left| \det \left( 1 + \varepsilon \frac{\partial v}{\partial z} \right) \right|$$

$$\frac{d\ln\rho(\boldsymbol{x},t)}{dt} = -\nabla\cdot\boldsymbol{v}$$

![](_page_37_Picture_9.jpeg)

### **Residual network**

![](_page_38_Figure_2.jpeg)

$$\boldsymbol{x}_{t+1} = \boldsymbol{x}_t + f(\boldsymbol{x}_t)$$

### **ODE** integration

![](_page_38_Figure_6.jpeg)

 $d\mathbf{x}/dt = f(\mathbf{x})$ 

Chen et al, 1806.07366

Harbor el al 1705.03341 Lu et al 1710.10121, E Commun. Math. Stat 17'...

![](_page_38_Picture_10.jpeg)

### **Residual network**

![](_page_39_Figure_2.jpeg)

Chen et al, 1806.07366

**ODE integration** 

![](_page_39_Picture_5.jpeg)

 $d\boldsymbol{x}/dt = f(\boldsymbol{x})$ 

Harbor el al 1705.03341 Lu et al 1710.10121, E Commun. Math. Stat 17'...

![](_page_39_Picture_8.jpeg)

# Target

![](_page_40_Picture_3.jpeg)

# Density

![](_page_40_Picture_5.jpeg)

![](_page_40_Picture_6.jpeg)

### **Continuous normalizing flow have no structural** constraints on the transformation Jacobian

Chen et al, 1806.07366, Grathwohl et al 1810.01367

# Samples

![](_page_40_Picture_10.jpeg)

# Vector Field

![](_page_40_Picture_12.jpeg)

![](_page_40_Picture_13.jpeg)

# Target

![](_page_41_Picture_3.jpeg)

# Density

![](_page_41_Picture_5.jpeg)

![](_page_41_Picture_6.jpeg)

### **Continuous normalizing flow have no structural** constraints on the transformation Jacobian

Chen et al, 1806.07366, Grathwohl et al 1810.01367

# Samples

![](_page_41_Picture_10.jpeg)

# Vector Field

![](_page_41_Picture_12.jpeg)

![](_page_41_Picture_13.jpeg)

# Fluid physics behind flows

![](_page_42_Figure_1.jpeg)

Simple density

Zhang, E, LW 1809.10188 wangleiphy/MongeAmpereFlow

$$\nabla \cdot \mathbf{v} \qquad \frac{d}{dt} = \frac{\partial}{\partial t} + \mathbf{v} \cdot \nabla \qquad \text{``material} \\ \text{derivative''}$$

Complex density

![](_page_42_Figure_6.jpeg)

# **Optimal Transport Theory**

![](_page_43_Picture_2.jpeg)

Monge problem (1781): How to transport earth with optimal cost?

![](_page_43_Picture_4.jpeg)

![](_page_43_Picture_5.jpeg)

![](_page_43_Picture_6.jpeg)

![](_page_43_Picture_7.jpeg)

![](_page_43_Picture_8.jpeg)

![](_page_43_Picture_9.jpeg)

Brenier

Otto

McCann

Villani

Figalli

![](_page_43_Picture_15.jpeg)

Fields Metal '18

from Cuturi, Solomon NISP 2017 tutorial

# **Optimal Transport Theory**

![](_page_44_Picture_2.jpeg)

Monge problem (1781): How to transport earth with optimal cost ?

![](_page_44_Figure_4.jpeg)

![](_page_44_Picture_5.jpeg)

![](_page_44_Picture_6.jpeg)

![](_page_44_Picture_7.jpeg)

![](_page_44_Picture_8.jpeg)

![](_page_44_Picture_9.jpeg)

Brenier

Otto

McCann

Villani

Figalli

![](_page_44_Picture_15.jpeg)

Fields Metal '18

from Cuturi, Solomon NISP 2017 tutorial

# **Optimal Transport Theory**

![](_page_45_Figure_2.jpeg)

![](_page_45_Picture_3.jpeg)

Monge problem (1781): How to transport earth with optimal cost?

Under certain conditions the optimal map is

 $z \mapsto x = \nabla u(z)$ 

# Optimal Transport Theory Monge problem (1781): How to transport earth with optimal cost?

![](_page_46_Figure_1.jpeg)

![](_page_46_Picture_2.jpeg)

### Monge-Ampère Equation

![](_page_46_Picture_5.jpeg)

# Monge-Ampère Flow Zhang, E, LW 1809.10188 wangleiphy/MongeAmpereFlow

 $\frac{\partial \rho(\boldsymbol{x},t)}{\partial t} + \nabla$ 

![](_page_47_Picture_2.jpeg)

![](_page_47_Picture_4.jpeg)

# symmetric generative model

 $\varphi(g\mathbf{x}) = \varphi(\mathbf{x})$ 

$$\cdot \left[ \rho(\boldsymbol{x}, t) \, \nabla \boldsymbol{\varphi} \right] = 0$$

- Drive the flow with an "irrotational" velocity field
- Impose symmetry to the scalar valued potential for

$$\Rightarrow \rho(g x) = \rho(x)$$

### Hamiltonian equations

$$\begin{cases} \dot{p} = -\frac{\partial H}{\partial q} \\ \dot{q} = +\frac{\partial H}{\partial p} \end{cases}$$

![](_page_48_Picture_12.jpeg)

### Hamiltonian equations Phase space variables

 $\begin{cases}
 \dot{p} = -\frac{\partial H}{\partial q} \\
 \dot{q} = +\frac{\partial H}{\partial p}
 \end{cases}$ 

J = (

- $\boldsymbol{x} = (p, q)$
- Symplectic metric

![](_page_49_Picture_9.jpeg)

### Hamiltonian equations

 $\dot{p} = -\frac{\partial H}{\partial q}$  $\dot{q} = +\frac{\partial H}{\partial p}$ 

Phase space variables

Symplectic gradient flow

 $\mathbf{x} = (p, q)$ 

Symplectic metric

 $J = \begin{pmatrix} I \\ I \end{pmatrix}$ 

![](_page_50_Picture_11.jpeg)

 $\dot{\mathbf{x}} = \nabla_{\mathbf{x}} H(\mathbf{x}) J$ 

![](_page_50_Picture_12.jpeg)

![](_page_50_Picture_13.jpeg)

### Hamiltonian ec

![](_page_51_Picture_2.jpeg)

![](_page_51_Picture_3.jpeg)

V.I. Arnold

Mathematical **Methods of** Classical **Mechanics** 

Second Edition

 $1815 \times 2646$ 

![](_page_51_Picture_8.jpeg)

![](_page_51_Picture_9.jpeg)

![](_page_51_Picture_10.jpeg)

![](_page_51_Picture_11.jpeg)

# Symplectic Integrators

![](_page_52_Figure_1.jpeg)

![](_page_52_Figure_2.jpeg)

from Hairer et al, Geometric Numerical Integration

![](_page_52_Picture_4.jpeg)

# Canonical Transformations Change of variables $\boldsymbol{x} = (p,q) \quad \boldsymbol{\leftarrow} \quad \boldsymbol{z} = (P,Q)$

![](_page_53_Picture_2.jpeg)

$$\left(\nabla_{x}z\right)^{T}=J$$

symplectic condition

![](_page_54_Figure_0.jpeg)

which satisfies  $\left(\nabla_x z\right) J\left(\nabla_x z\right)$ 

one has

**Preserves Hamiltonian dynamics in the "latent phase space"** 

# Canonical Transformations

# Change of variables z = (P, Q)

$$(\nabla_{\mathbf{x}} z)^T = J$$

symplectic condition

# $\dot{z} = \nabla_{\tau} K(z) J$ where $K(z) = H \circ x(z)$

# Canonical transformation for Gutzwiller, RMP, '98 Moon-Earth-Sun 3-body problem

640

+ 12

THÉORIE DU MOUVEMENT DE LA LUNE.  $+\left(\frac{13}{64}+\frac{187}{32}\gamma^{3}-\frac{237}{128}\epsilon^{3}+\frac{195}{128}\epsilon^{\prime\prime}-\frac{1389}{32}\gamma^{\prime}-\frac{599}{64}\gamma^{3}\epsilon^{3}+\frac{2805}{64}\gamma^{3}\epsilon^{\prime2}\right)$  $-\frac{103173}{1006}e^{4}-\frac{3105}{356}e^{3}e^{4}$  $+\left(\frac{79}{16}+\frac{55}{48}\gamma^2-\frac{1063}{48}\epsilon^3+\frac{2133}{32}\epsilon^{\prime 2}\right)\frac{\pi^3}{\pi^3}+\left(\frac{153}{8}+\frac{3245}{96}\gamma^2-\frac{73159}{768}\epsilon^3+\frac{246085}{512}\epsilon^{\prime 2}\right)\frac{\pi^3}{\pi^3}$  $+\frac{22441}{288}\frac{n''}{n'}+\frac{99916415}{442368}\frac{n''}{n'}+\frac{4431}{2048}\frac{n''}{n'}\cdot\frac{a'}{a'}$ De ces valeurs de L, G, H, on déduit  $\frac{da}{dL} = \frac{1}{a\pi} \left\{ 2 + \left( \frac{1960}{32} - \frac{1629}{8} \gamma^2 + \frac{34985}{128} \epsilon^2 + \frac{28635}{64} \epsilon'^2 \right) \frac{\pi'}{\pi'} \right\}$  $+\left(\frac{415}{2}-\frac{2745}{4}7^{2}+\frac{31449}{16}6^{2}+\frac{43299}{16}6^{2}\right)\frac{n^{2}}{n^{3}}+\frac{61185}{64}\frac{n^{4}}{n^{4}}+\frac{1532167}{576}\frac{n^{2}}{n^{4}}\right)$ 

 $\frac{da}{dt_{3}} = -\frac{1}{an} \left\{ \left( \frac{5a7}{8} - \frac{3633}{16}\gamma^{2} - \frac{9091}{128}e^{2} + 480e^{2} \right) \frac{n^{2}}{n^{2}} \right\}$  $+\left(\frac{2757}{8}-\frac{2493}{2}\gamma^{1}-\frac{7161}{16}\epsilon^{2}+\frac{36459}{8}\epsilon^{2}\right)\frac{n^{2}}{n^{2}}+\frac{104117}{64}\frac{n^{2}}{n^{2}}+\frac{277537}{48}\frac{n^{2}}{n^{2}}\right)$  $\frac{da}{dH} = -\frac{1}{an} \left\{ \left( \frac{15}{16} + \frac{15}{16} \gamma^2 - \frac{1809}{32} e^2 + \frac{225}{32} e^{\prime 2} \right) \frac{\pi^6}{\pi^4} \right\}$  $+\left(\frac{167}{8}-66\gamma^{2}-\frac{2625}{8}c^{2}+\frac{4509}{16}c^{2}\right)\frac{\pi^{2}}{\pi^{2}}+\frac{895}{16}\frac{\pi^{2}}{\pi^{2}}+\frac{176531}{576}\frac{\pi^{2}}{\pi^{2}}\right)$  $\frac{de}{dL} = \frac{1}{a^3 n^2} \left\{ 1 - e^3 + \left( \frac{1901}{64} - \frac{1113}{16} \gamma^3 - \frac{40571}{128} e^3 + \frac{28065}{128} e^n \right) \frac{n^2}{n^4} + \frac{3323}{24} \frac{n^5}{n^5} + \frac{62483}{96} \frac{n^n}{n^4} \right\},$  $\frac{dc}{dG} = -\frac{1}{a^{2}ae} \left\{ 1 - \frac{1}{2}e^{2} - \frac{1}{8}e^{4} - \frac{1}{16}e^{4} \right.$  $+\left(\frac{1907}{64}-\frac{1113}{16}\gamma^2-\frac{3831}{8}e^2+\frac{28065}{128}e^2\right)\frac{n^{\prime\prime}}{n^{\prime}}+\frac{3323}{24}\frac{n^{\prime\prime}}{n^{\prime}}+\frac{62483}{95}\frac{n^{\prime\prime}}{n^{\prime}}\right)$  $\frac{de}{d\Pi} = \frac{1}{a^2 n e} \cdot \frac{141}{8} e^3 \frac{n^4}{n^2},$  $\frac{d\gamma}{dL} = \frac{1}{a^2 a \gamma} \frac{183}{3a} \gamma^2 \frac{a^n}{a^2},$ 

![](_page_55_Picture_5.jpeg)

More than 1800 pages of this, ~20 years of efforts (1846-1867)

![](_page_55_Picture_7.jpeg)

![](_page_55_Picture_8.jpeg)

![](_page_56_Picture_2.jpeg)

### Learn the network parameter and the latent harmonic frequency

![](_page_56_Picture_5.jpeg)

![](_page_57_Figure_1.jpeg)

### **Neural canonical transformation identifies nonlinear slow modes!**

![](_page_57_Picture_3.jpeg)

![](_page_57_Picture_4.jpeg)

![](_page_58_Figure_1.jpeg)

### **Neural canonical transformation identifies nonlinear slow modes!**

![](_page_58_Picture_3.jpeg)

![](_page_58_Picture_4.jpeg)

![](_page_59_Picture_0.jpeg)

### slow motion of the two torsion angles

![](_page_59_Picture_2.jpeg)

### **Dimensional reduction to slow collective variables** useful for control, prediction, enhanced sampling...

check the paper 1910.00024, PRX '20 for more examples & applications

![](_page_59_Figure_5.jpeg)

Ramachandran plot of stable conformations

![](_page_59_Picture_8.jpeg)

# Symplectic primitives

- Linear transformation: Symplectic Lie algebra
- Continuous-time flow: Symplectic generating functions

Symplectic integrator of neural ODE, Chen et al 1806.07366

Neural point transformation

![](_page_60_Figure_5.jpeg)

neural net

![](_page_60_Picture_9.jpeg)

# "A Hamiltonian Extravaganza"

- Sep 25 ICLR 2020 paper submission deadline
- Sep 26 Symplectic ODE-Net, 1909.12077 😴 SIEMENS
- Sep 27 Hamiltonian Graph Networks with ODE Integrators, 1909.12790
- Sep 29 Symplectic RNN, 1909.13334
- Sep 30 Equivariant Hamiltonian Flows, 1909.13739
  - Hamiltonian Generative Network, 1909.13789

—Danilo J. Rezende@DeepMind

![](_page_61_Picture_9.jpeg)

![](_page_61_Picture_10.jpeg)

![](_page_61_Picture_11.jpeg)

![](_page_61_Picture_12.jpeg)

- http://tinv.cc/hgn
- Neural Canonical Transformation with Symplectic Flows, 1910.00024 🐼 🐬
- See also Bondesan & Lamacraft, Learning Symmetries of Classical Integrable Systems, 1906.04645

![](_page_61_Figure_16.jpeg)

![](_page_61_Picture_17.jpeg)

![](_page_61_Picture_18.jpeg)

# Killer application in science ?

### **Renormalization group** Lattice field theory

![](_page_62_Picture_2.jpeg)

![](_page_62_Picture_3.jpeg)

Li and LW, PRL '18 Hu et al, PRResearch '20 Albergo et al, PRD '19 Kanwar et al, PRL '20

### **Molecular simulation**

![](_page_62_Picture_7.jpeg)

Noe et al, Science '19 Wirnsberger et al, JCP '20

![](_page_62_Picture_9.jpeg)

![](_page_63_Picture_1.jpeg)

# Invariance $\rho(g\mathbf{x}) = \rho(\mathbf{x})$

Spatial symmetries, permutation symmetries, gauge symmetries...

# Symmetries

# Equivariance $\mathcal{T}(gz) = g\mathcal{T}(z)$

![](_page_64_Picture_1.jpeg)

Gemici et al 1611.02304, Rezende et al, 2002.02428, Boyda et al, 2008.05456 Neural ODE on manifolds, Falorsi et al, 2006.06663, Lou et al, 2006.10254, Mathieu et al, 2006.10605

Periodic variables, gauge fields, ...

![](_page_64_Picture_6.jpeg)

Regular Homoboly Euses of Burfaces

**Theorem** (Pinkall). For a surface of genus *g*, there are  $2^{2g}$  regular homotopy classes of immersions into  $\mathbb{R}^3$ .

![](_page_65_Figure_2.jpeg)

Dupont et al 1904.01681, Cornish et al, 1909.13833, Zhang et al, 1907.12998, Zhong et al, 2006.00392...

![](_page_65_Picture_4.jpeg)

# $\underset{\lambda = 0}{\text{Mix with other approaches}} \underset{\lambda = 0.33}{\text{min other approaches}} \underset{\lambda = 0.66}{\text{min other approaches}} \underset{\lambda = 1}{\text{min other approaches}}$

![](_page_66_Figure_1.jpeg)

 $u_{\lambda}(\mathbf{y})$ 

![](_page_66_Figure_3.jpeg)

![](_page_66_Figure_6.jpeg)

Kingma et al, 1606.04934,...

Levy et al, 1711.09268, Wu et al 2002.06707, ...

# Discrete flows

![](_page_67_Picture_2.jpeg)

 $p(\mathbf{x}) = p(\mathbf{y} = \mathcal{T}(\mathbf{x}))$ 

![](_page_67_Figure_5.jpeg)

Tran et al, 1905.10347, Hoogeboom et al, 1905.07376, van den Berg 2006.12459

# Representation learning: what and how ?

.02230

1812.

### What is a good representation ?

# Generative Pre-Training appears to be a successful way in learning good representations

### Towards a Definition of Disentangled Representations

Irina Higgins<sup>\*</sup>, David Amos<sup>\*</sup>, David Pfau, Sebastien Racaniere, Loic Matthey, Danilo Rezende, Alexander Lerchner DeepMind

![](_page_68_Figure_5.jpeg)

![](_page_68_Figure_6.jpeg)

# Thank You!

# Explore more in the interface of machine learning & physics

### 量子纠缠:从量子物质态到深度学习

程嵩<sup>1,2</sup> 陈靖<sup>1,2</sup> 王磊<sup>1,†</sup>

中国科学院物理研究所 北京 100190) (1

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《物理》2017年7月

### 微分万物:深度学习的启示\*

- 王磊<sup>1,2,†</sup> 刘金国<sup>3</sup>
- (1 中国科学院物理研究所 北京 100190)
- (2 松山湖材料实验室 东莞 523808)
- (3 哈佛大学物理系 剑桥 02138)

### 《物理》2021年2月

![](_page_69_Picture_14.jpeg)

# 

### 王磊 深度学习:从理论到实践

以微分编程和表示学习为重点 介绍深度学习技术,并讲解它们在 统计物理和量子多体计算中的应用实例

### 张潘

### 从机器学习角度理解张量网络

从表述,优化,学习与泛化这 四个角度介绍张量网络及其 在应用数学和机器学习中的应用

### 罗秀哲

### 面向物理学家的Julia编程实践

以量子物理的工程实践为重点介绍 Julia语言,量子计算的基础概念, Julia 语言中的CUDA编程和量子物理工具链

### 刘金国

### 量子编程实践

介绍量子机器学习。量子优化算法和 量子化学中的研究前沿,基于Julia量子 计算库Yao.jl实现这些算法,介绍自动 微分与GPU编程在量子编程中的应用

Yao Framework

![](_page_69_Picture_27.jpeg)

### 授课形式: 中文授课+程序演示+Hackathon (有奖品)

时间: 2019年5月6-10日 地点: 广东东莞 松山湖材料实验室 粤港澳交叉科学中心

### **Quantum Hackathon:**

学员将通过组队的形式,完成 一个量子物理相关的编程挑战。 我们将评出表现突出的团队, 给予奖励。

### Contact: wanglei@iphy.ac.cn

![](_page_69_Picture_33.jpeg)

![](_page_69_Picture_34.jpeg)

![](_page_69_Picture_35.jpeg)

![](_page_69_Picture_36.jpeg)

![](_page_69_Picture_37.jpeg)

![](_page_69_Picture_40.jpeg)

SONGSHAN LAKE MATERIALS LABORATORY 松山湖材料实验室