

# Theoretical Foundations of Pre-trained Models

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# A.I. is Everywhere



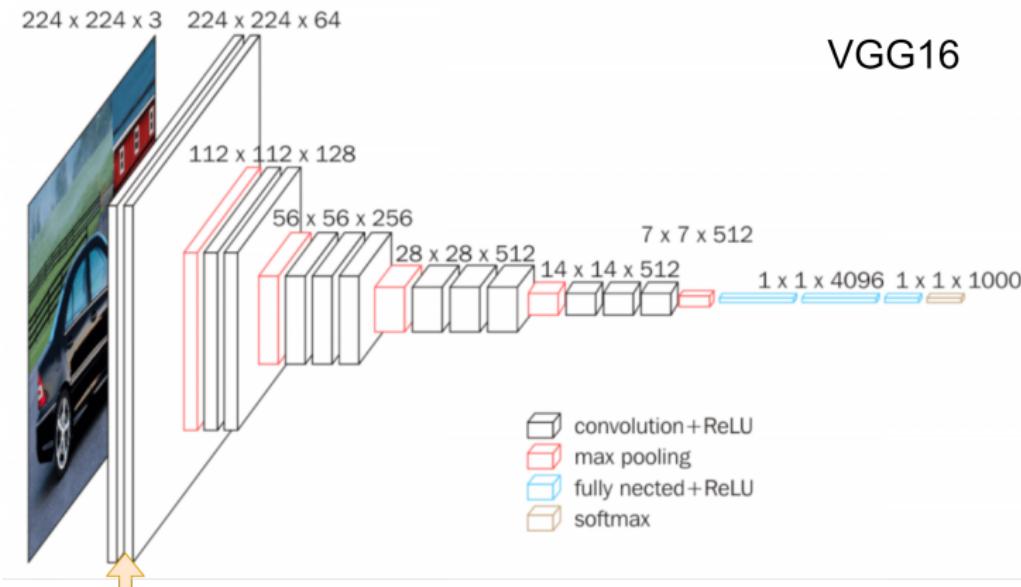
# A.I. is Everywhere



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# Deep Learning



- Deep learning succeeds with abundant labeled data.

# Emerging Application Domains



- Fundamental areas to our society
- Labeled data is lacking: significant costs in money and time
- Demands comprehensive domain knowledge

# Emerging Application Domains

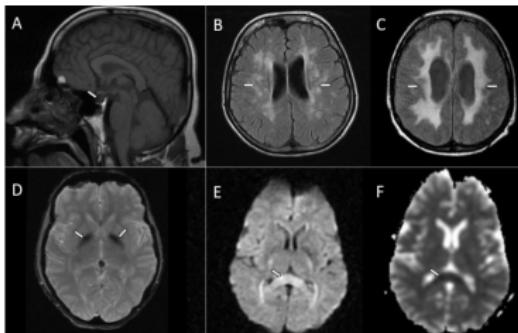


## Medical images

- X-ray



- MRI scan



# Pre-trained Models

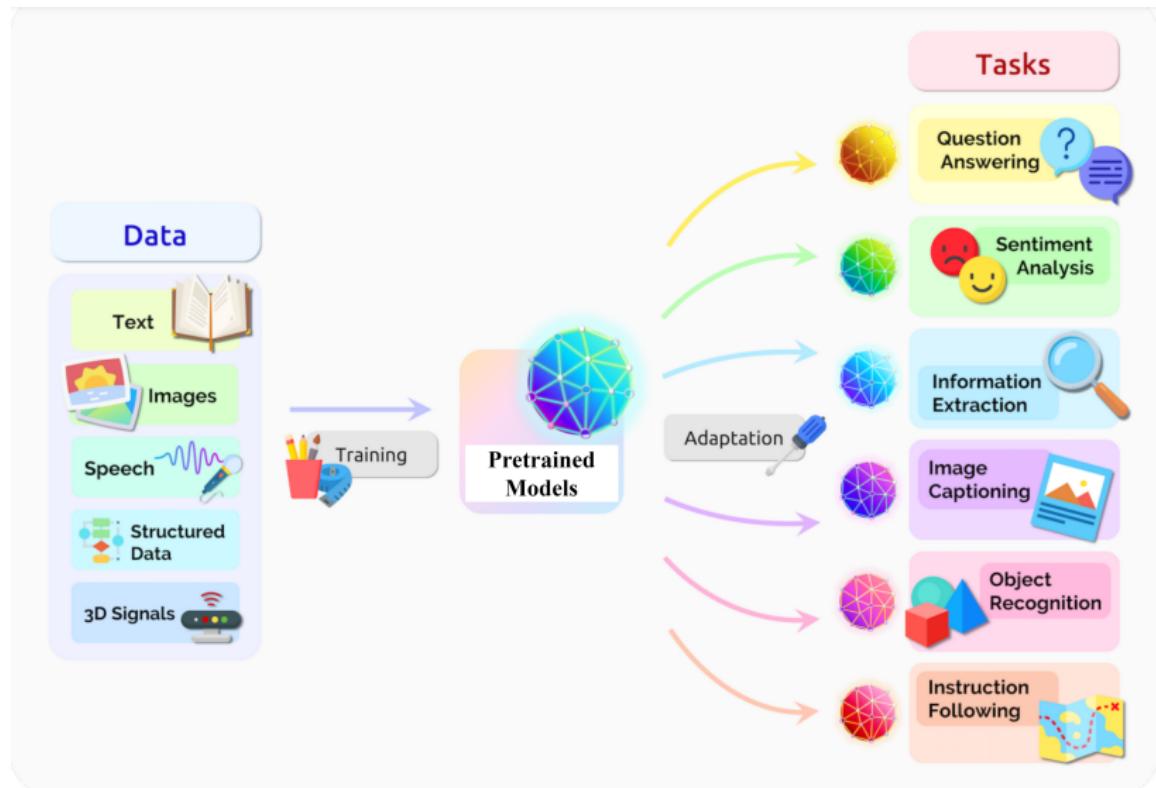
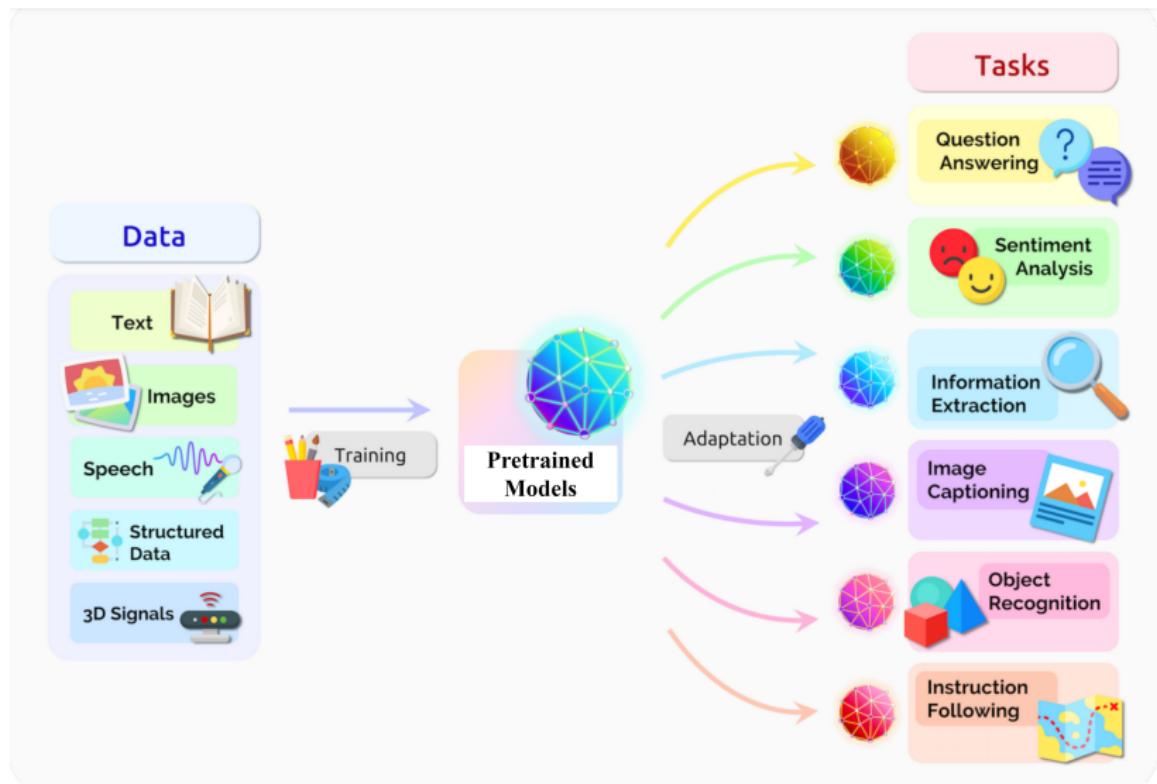


Figure credit to: "On the Opportunities and Risks of Foundation Models", CRFM, HAI, Stanford

# Pre-trained Models



BERT, GPT-3, Codex, AlphaCode, SimCLR, MAE, DALL-E, CLIP

# Example: DALL-E

DALL-E: create images from text captions

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DALL-E: create images from text captions

a pentagonal green clock. a green clock in the shape of a pentagon.



a cube made of porcupine. a cube with the texture of a porcupine.



a collection of glasses is sitting on a table



Figures source: OpenAI DALL-E playground

7/40

# Example: CLIP

Zero shot image classifier

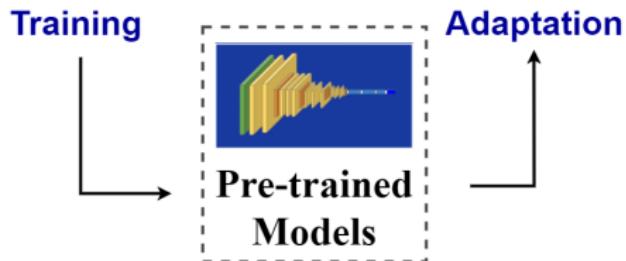
FOOD101

**guacamole** (90.1%) Ranked 1 out of 101 labels



- ✓ a photo of **guacamole**, a type of food.
- ✗ a photo of **ceviche**, a type of food.
- ✗ a photo of **edamame**, a type of food.
- ✗ a photo of **tuna tartare**, a type of food.
- ✗ a photo of **hummus**, a type of food.

Figure source: OpenAI, <https://clip.backprop.co/>



Theory's Role on  
Pre-trained models?



- What training tasks are useful for downstream tasks?
- What algorithm/architecture can identify the useful features?
- How many samples are required?

- guide technical decisions
- reduce trial and error
- forecast outcomes and risks
- inspire new methods

Current learning theory is relatively more mature in **supervised learning**.

- **Big labeled** dataset is necessary to fit deep learning.
- Training and testing data follow the **same distribution**.

# Challenge

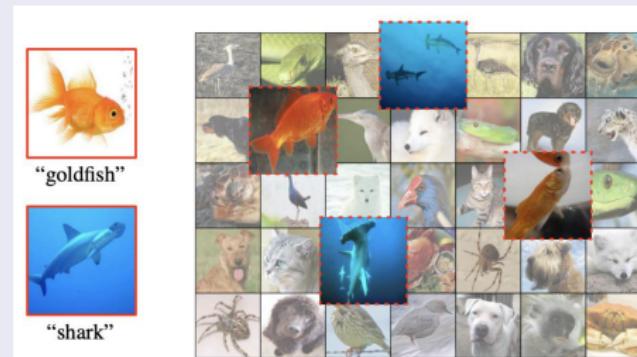
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We want to understand how pre-trained model can

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## Our target

We want to understand how pre-trained model can

- adapt to new tasks **quickly**,
- be learned from **unlabeled samples**,
- handle **distributional shift** from training to adaptation



Autonomous driving  
Trained on sunny weather



Tested on rainy weather

## 1 Meta-learning

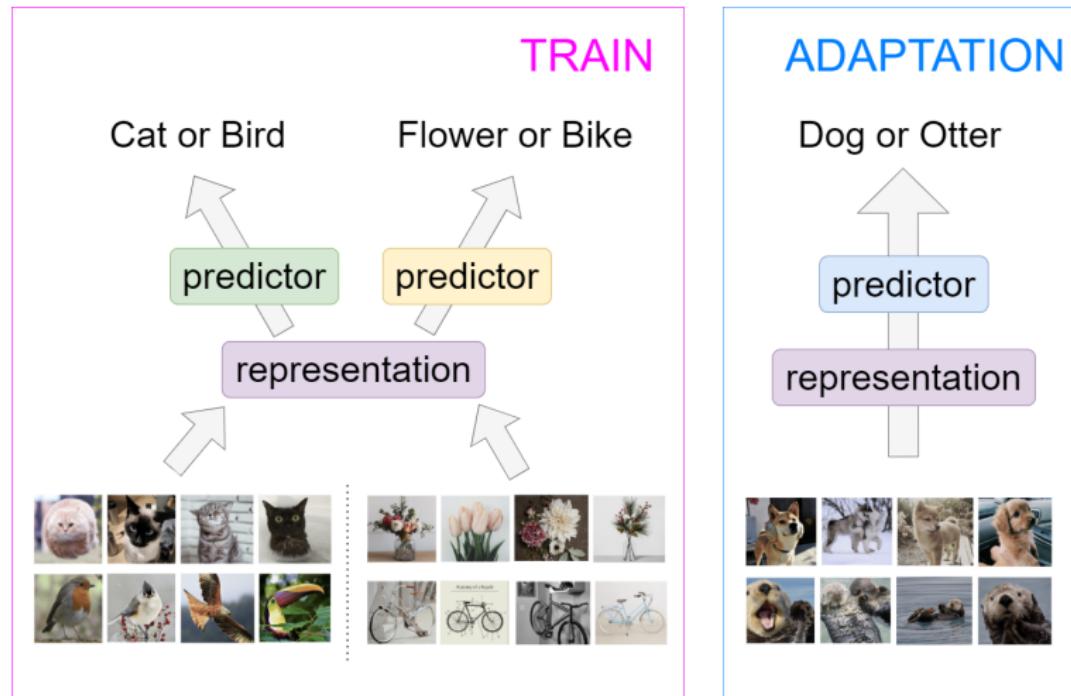
- Meta-Learning with Frozen Representation
- Meta-learning with Fine-tuned Representation

## 2 Self-Supervised Learning

## 3 Ongoing and Future Work

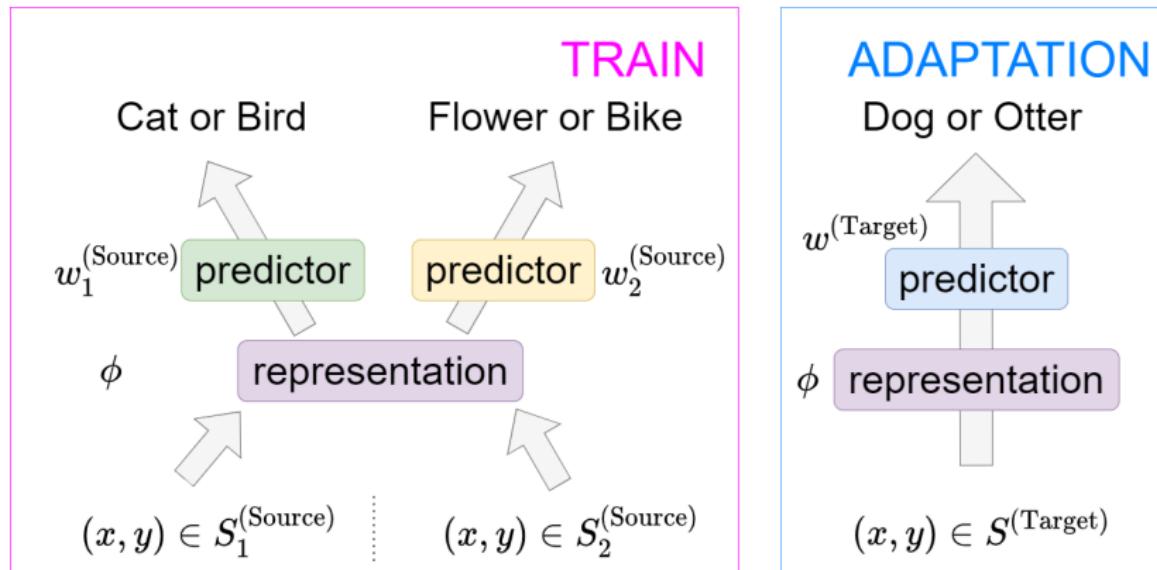
- Domain Adaptation
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# Learning the Meta-Representation

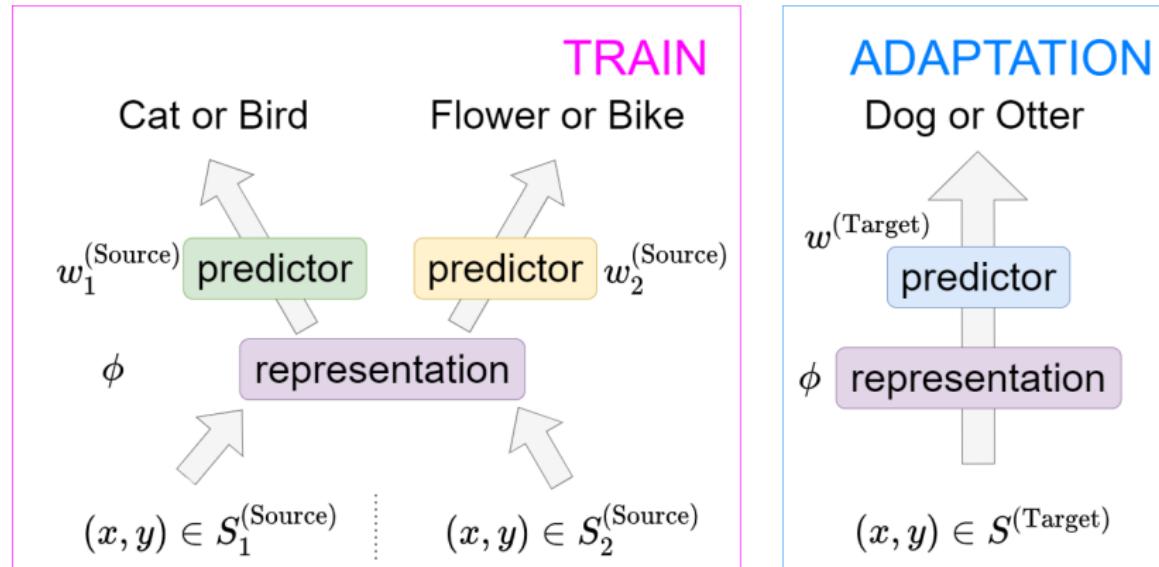


Prototypical network: (Snell et al. 2017), Meta-learning representation: (Javed and White, 2019)

# Algorithm



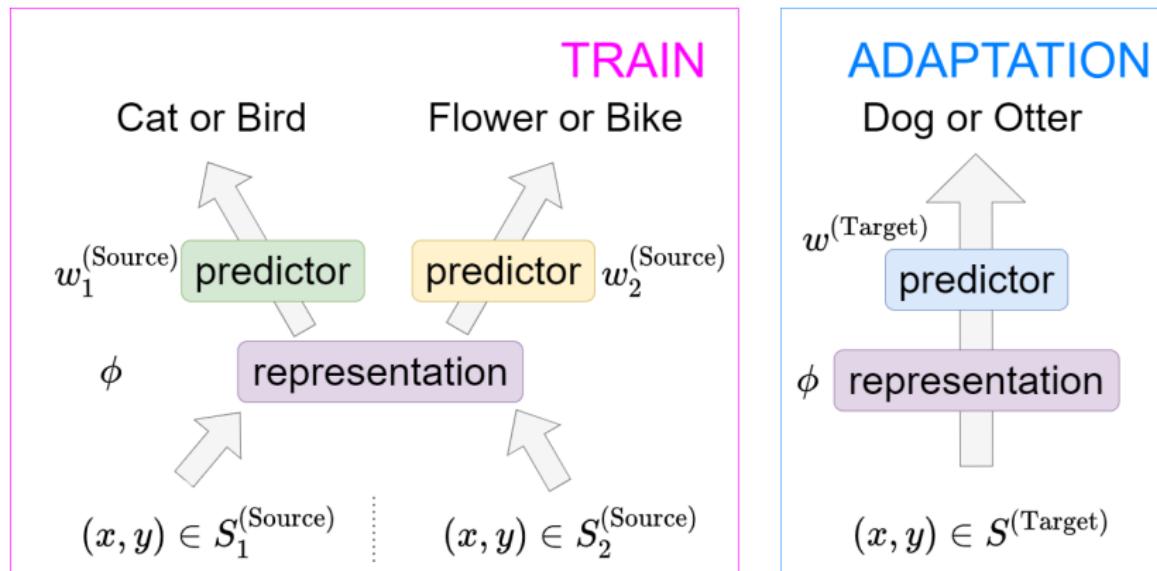
# Algorithm



On source tasks:

$$\hat{\phi} \leftarrow \arg \min_{\phi \in \Phi} \sum_{t=1}^{\#\text{source tasks}} \left\{ \min_{w_t} \sum_{(x,y) \in S_t^{(\text{Source})}} \text{loss}(y, w_t \circ \phi(x)) \right\}.$$

# Algorithm



On target task:

$$\hat{w}^{(\text{Target})} \leftarrow \arg \min_w \sum_{(x,y) \in S^{(\text{Target})}} \text{loss} \left( y, w \circ \hat{\phi}(x) \right).$$

# How to Quantify Task Similarities

Assumptions:

- ① Shared good representation across tasks:

There exist predictors  $w_t$ , representation function  $\phi$ ,  
 $y_t = (w_t)^\top \phi(x) + \text{noise}$ ,  $\phi \in \Phi$  for both source and target  
tasks.

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Behind the scenes

- ① Shared representation encodes what transfers across the tasks.
- ② Need source tasks  $\{w_t^{(\text{Source})}\}$  diverse enough to “cover”  
 $w^{(\text{Target})}$ .

- ➊ Shared representation encodes what transfers across the tasks.
- ➋ Diversity of source tasks  $\{w_t^{(\text{Source})}\}$  (at least needs to “cover” the target task.)

## Task diversity

Source tasks:  
Classify types of dogs

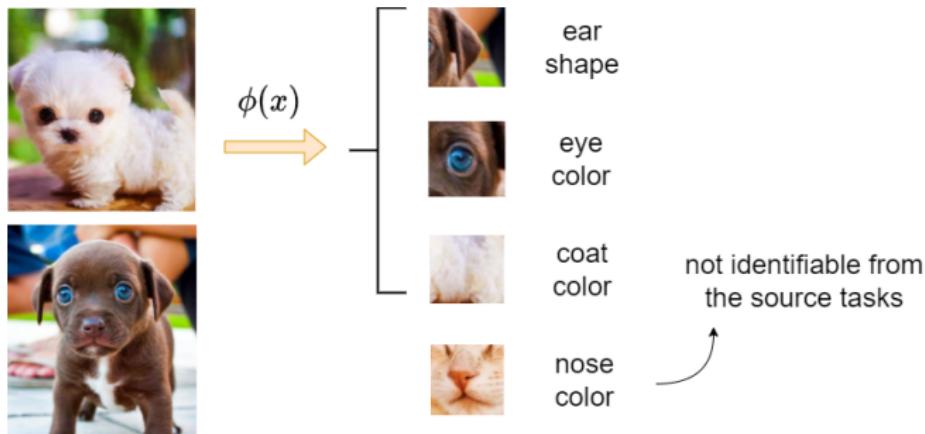


Target task:  
Cat or dog?



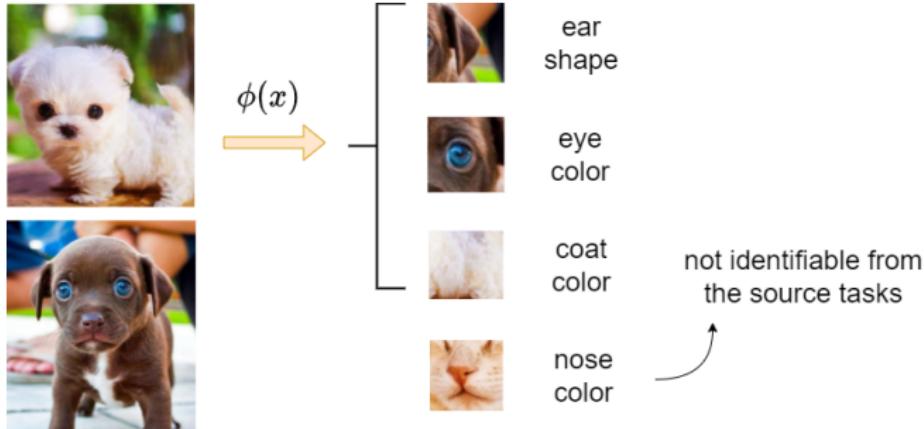
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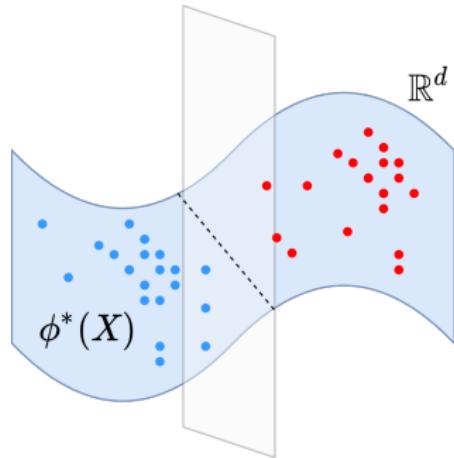
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Mathematically speaking,  $w^{(\text{Target})} \in \text{span}\{w_1^{(\text{Source})}, \dots, w_{ne}^{(\text{Source})}\}$ .

Setup:

- Shared representation:  
 $y_t = w_t^\top \phi(x_t) + \text{noise}$
- Representation layer is of dimension  $k$  (We assume  $k$  is small)



## Theorem 1 (Informal)

We only need  $O(k)$  labeled samples from target domain to get small **test error**.

In contrast, supervised learning requires samples up to the **complexity of the function class**. (500 vs.  $10^8$ .)

## Theorem 1

With shared representation and task diversity,

Test Error( $\hat{w}^{(\text{Target})} \circ \hat{\phi}$ )  $\leq$  Representation Error + Adaptation Error.

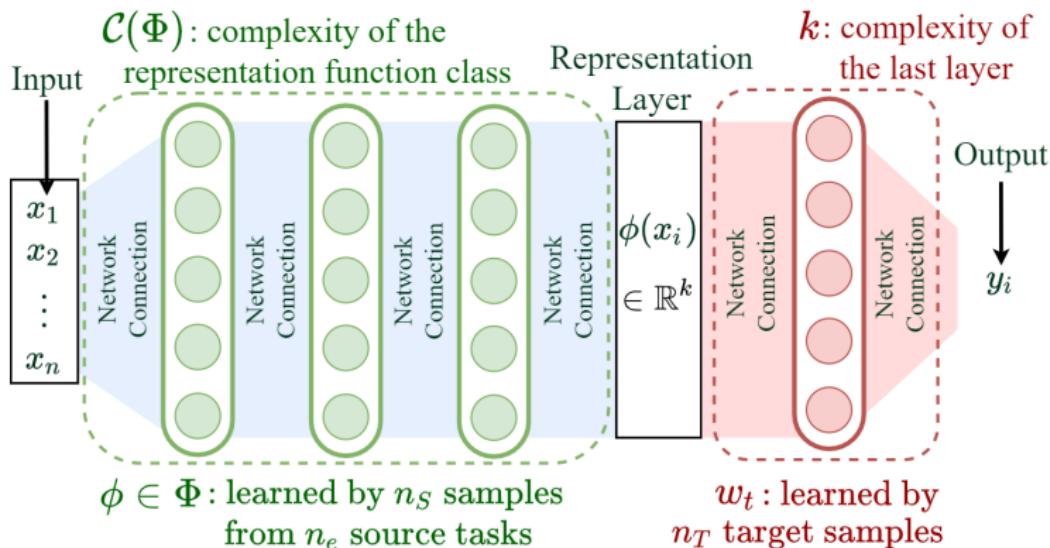
- Representation error: how well you learn representation layer  $\phi$
- Adaptation error: how well you learn target-task predictor  $w^{(\text{Target})}$

# Main Result on Meta Representation

## Theorem 1

With shared representation and task diversity,

$$\text{Test Error}(\hat{w}^{(\text{Target})} \circ \hat{\phi}) \lesssim \underbrace{\frac{\mathcal{C}(\Phi)}{n_S n_e}}_{\text{representation error}} + \underbrace{\frac{k}{n_T}}_{\text{adaptation error}}.$$



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Baselines:

- Supervised learning:

$$\text{Test error} \leq \frac{\mathcal{C}(w \circ \Phi)}{n_T}.$$

- Maurer et al. 2016:

$$\text{Test error} \leq \frac{\mathcal{C}(\Phi)}{\sqrt{n_e}} + \frac{k}{n_T}.$$

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Remark:

- Covariate shift is allowed: source and target data can come from different marginal distribution.
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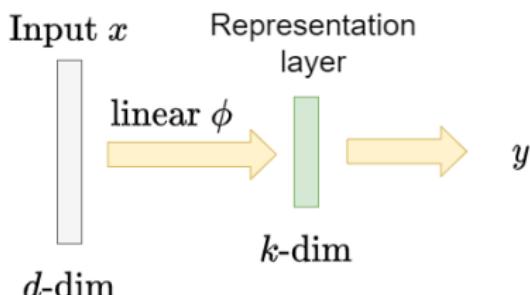
## Question

Does METAREP (previous algorithm) still work?

*If not, how should we modify the algorithm?*

# Failure with Previous Algorithm: METAREP

Instantiation in linear setting:



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Theorem: However, when  $\gamma > 0$ , METAREP requires at least  $\Omega(d)$  samples on the target task.

Remark: no improvement over traditional supervised learning that requires  $O(d)$  samples.

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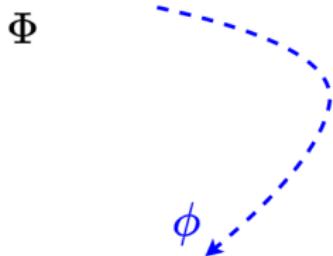
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$$\Phi$$

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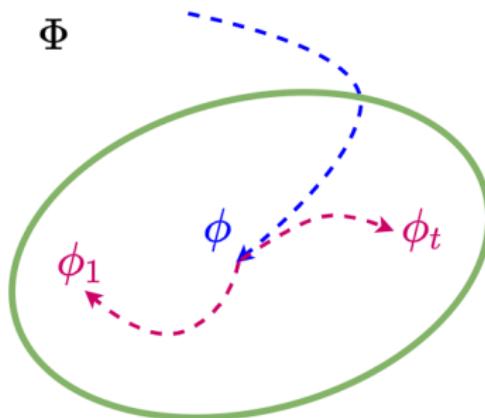
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# Modified Algorithm: FINE-TUNEDREP

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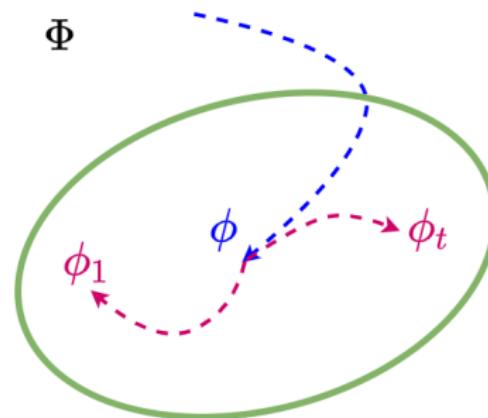
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### Theorem 2 (Informal)

When adapting  $\phi$  to target task, it requires  $O(k) + O(\gamma^2)$  training samples from target domain.

## Theorem 2

For **general function classes**, under similar settings,

$$\text{Test Error} \lesssim \text{METAREP Error (when } \gamma = 0) + O\left(\frac{\gamma}{\sqrt{n_T}}\right).$$

- $\gamma$  measures mis-specification in representation  $\phi$
- $n_T$ : number of samples from target training set

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Baselines:

- Supervised learning and METAREP need  $\mathcal{C}(w \circ \Phi)$  samples from target domain.
- $\mathcal{C}(w \circ \Phi)$ : Complexity of the function class for the whole network.

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Create your own labels

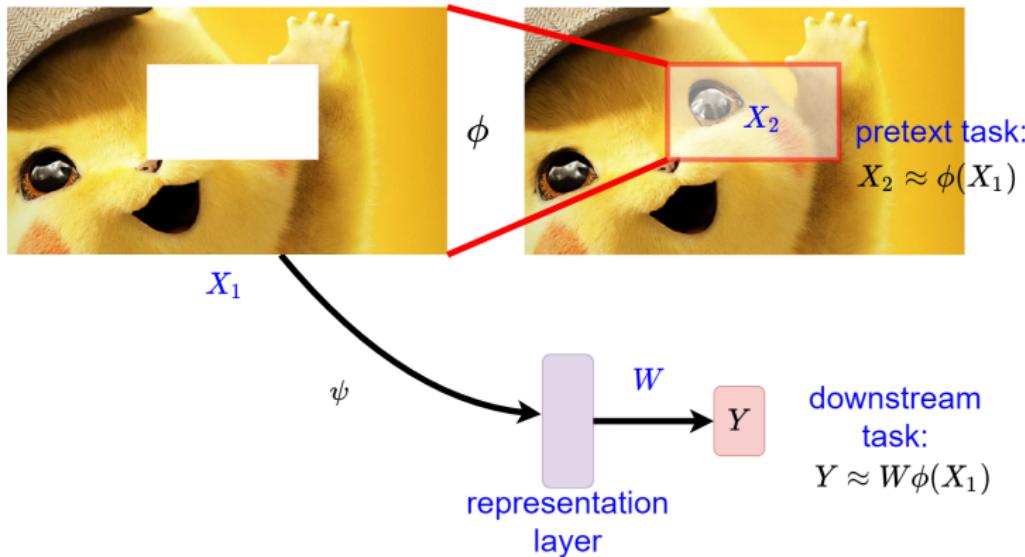
Supervised representation learning needs labels from related tasks.  
What if this isn't available?

**Create pseudo-labels from the input data.**

# Self-supervised Learning

## Type I: reconstruction-based SSL

Reconstructing part of the input from the other part



Context encoder: (Pathak et al. 2016)

Other examples: Masked Autoencoder: (He et al., 2021), Colorization: (Zhang et al., 2016)

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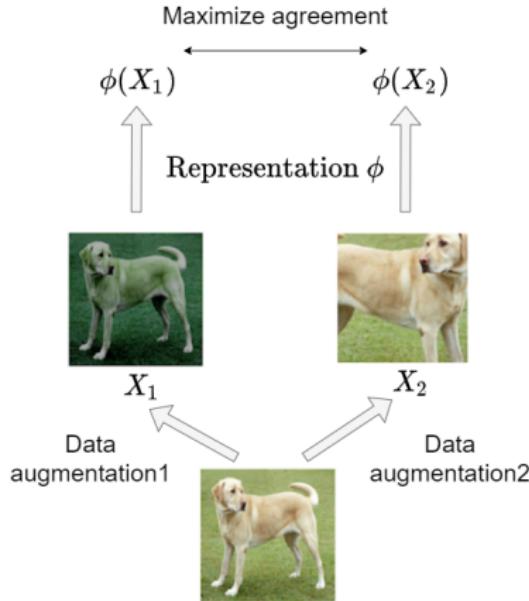


BERT: (Devlin et al., 2018)

Other examples: Masked Autoencoder: (He et al., 2021), Colorization: (Zhang et al., 2016)

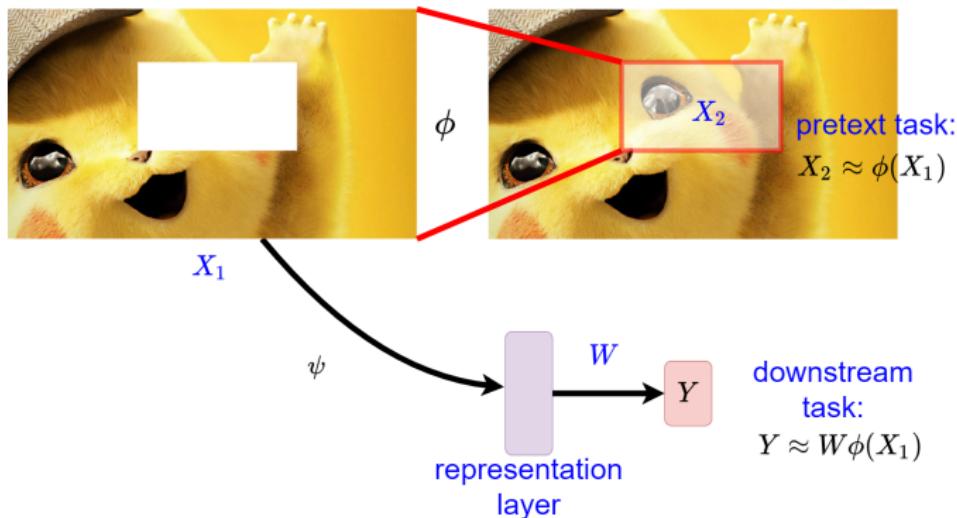
## Type II: similarity-based SSL

Enforcing two views of the same data to have similar representation

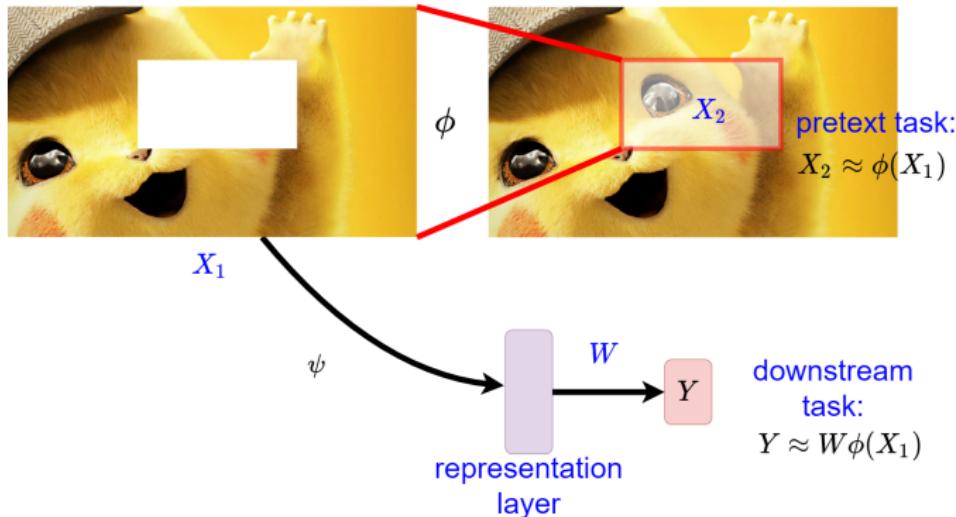


Examples: SimSiam: (Chen et al., 2021), CLIP: (Radford et al., 2021) ,  
SimCLR: (Chen et al., 2020)

- ① Label  $Y$  with  $k$  classes.
- ② Unmasked image  $X_1$  and masked image  $X_2$ .



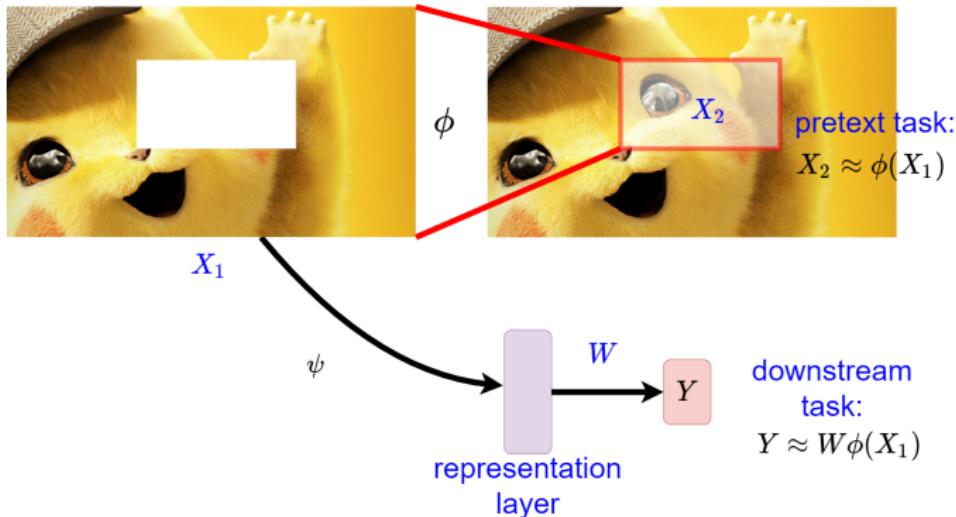
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- ③ Key intuition: Pretext tasks should help us reduce irrelevant features/forget information that is not necessary to predict  $Y$

# Ideal Scenario

- ① Label  $Y$  with  $k$  classes.
- ② Unmasked image  $X_1$  and masked image  $X_2$ .



- ③ Ideal scenario:  $X_1 \rightarrow Y \rightarrow X_2$   
 $\iff X_1 \perp X_2 | Y$

# Our Result: Ideal Scenario

Setting:

- ①  $k$ -class labels  $Y$ .
- ② Representation  $\phi$ , last layer  $W^*$ .

Compare this procedure to ground truth classifier  $f^*$ :

## Theorem 3

- ① (No representation error.) If  $X_1 \perp X_2 | Y$ ,

$$f^* = W^* \phi(X_1).$$

- ② Only need  $O(k)$  labeled samples.

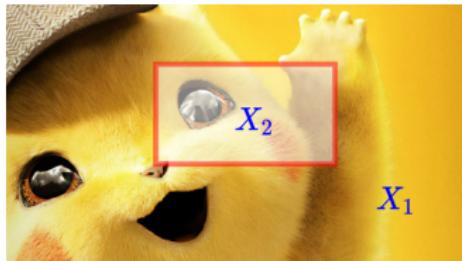
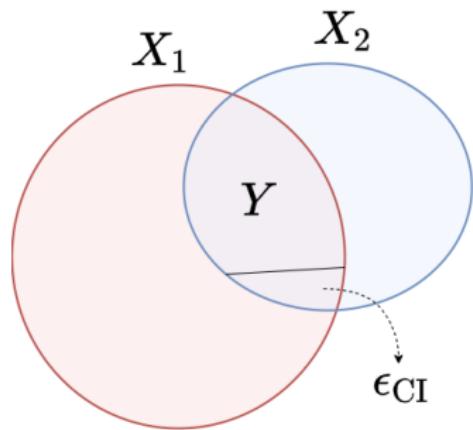
Remark: Only need  $k$  samples instead of Rademacher complexity of function class.

No representation error: if  $X_1 \rightarrow Y \rightarrow X_2$ , (i.e.,  $X_1 \perp X_2 | Y$ ),  
 then  $f^* = W^* \phi(X_1)$ .

$$\begin{aligned} \phi(\cdot) &:= \mathbb{E}[X_2|X_1] \quad \overbrace{\quad}^{\text{tower property}} \quad \mathbb{E}[\mathbb{E}[X_2|X_1, Y]|X_1] \overbrace{\quad}^{\text{CI}} \quad \mathbb{E}[\mathbb{E}[X_2|Y]|X_1] \\ &= \sum_{y=1}^k \mathbb{E}[X_2|Y=y] P(Y=y|X_1) =: \mathbf{A}^\top f(X_1), \end{aligned}$$

Here  $f(x_1)_y := P(Y=y|X_1=x_1), y=1 \cdots, k$   
 $\mathbf{A}$  satisfies  $\mathbf{A}_{y,:} = \mathbb{E}[X_2|Y=y]$ .

# Main Results on Reconstruction-based SSL



## Characterizing Approximate Conditional Independence

Define  $\epsilon_{CI} = \mathbb{E}_{X_1} \|\mathbb{E}[X_2|X_1] - \mathbb{E}_Y[\mathbb{E}[X_2|Y]|X_1]\|^2$ .

- This is 0 if  $X_1 \perp X_2 | Y$ .
- $\epsilon_{CI}$  can be viewed as quantification of extra shared features between  $X_1$  and  $X_2$  are not captured by  $Y$  (spurious feature not reducible by SSL)

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- Also applies to similarity-based SSL

## Implications on pretext selection

- Design pretext tasks such that  $X_1$  and  $X_2$  have smaller dependence (given  $Y$ )

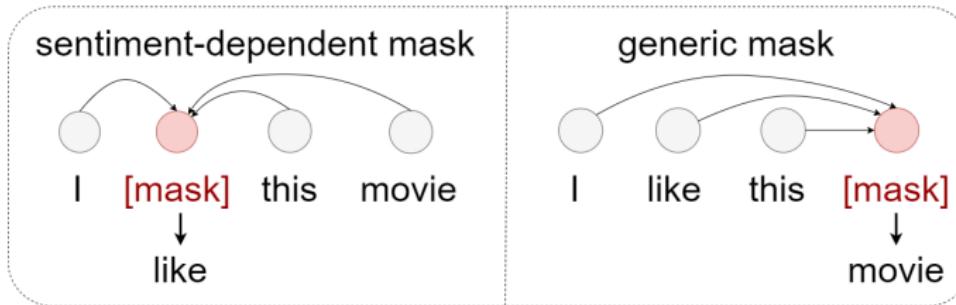
# Empirical Implications

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## Applications:

- Image: image classification [He et al. 2021]
- Text: sentiment analysis [Zhang and Hashimoto, 2021]

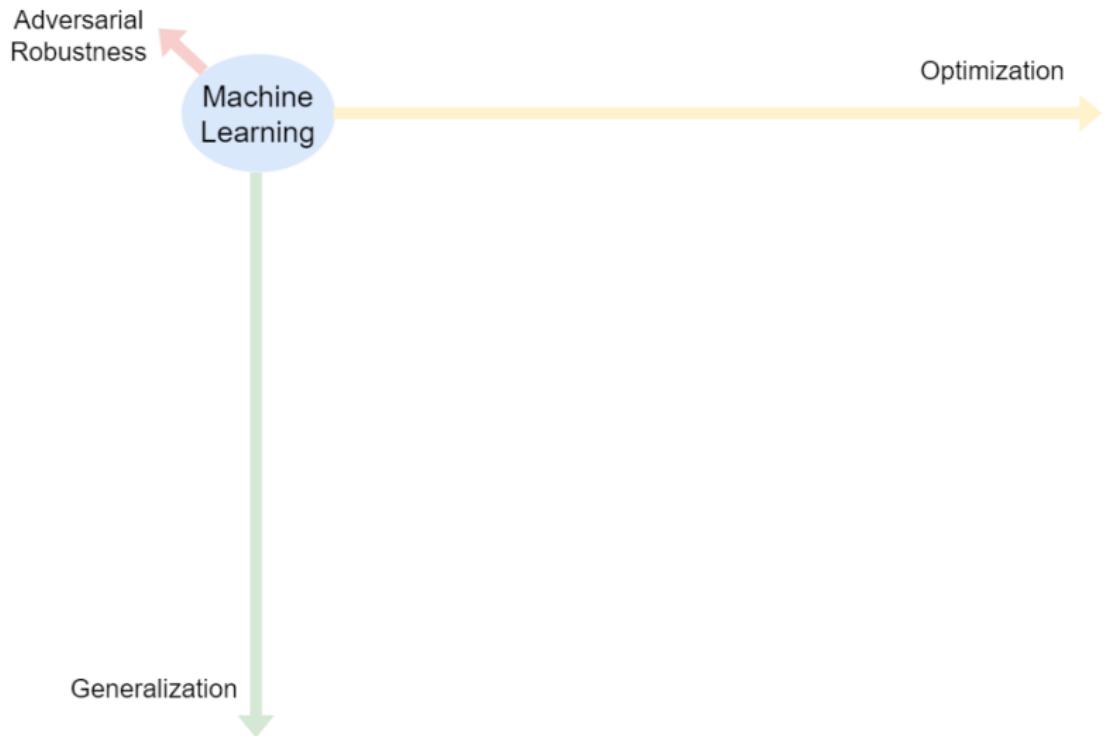


- Audio: speech recognition [Zaiem et al., 2021]

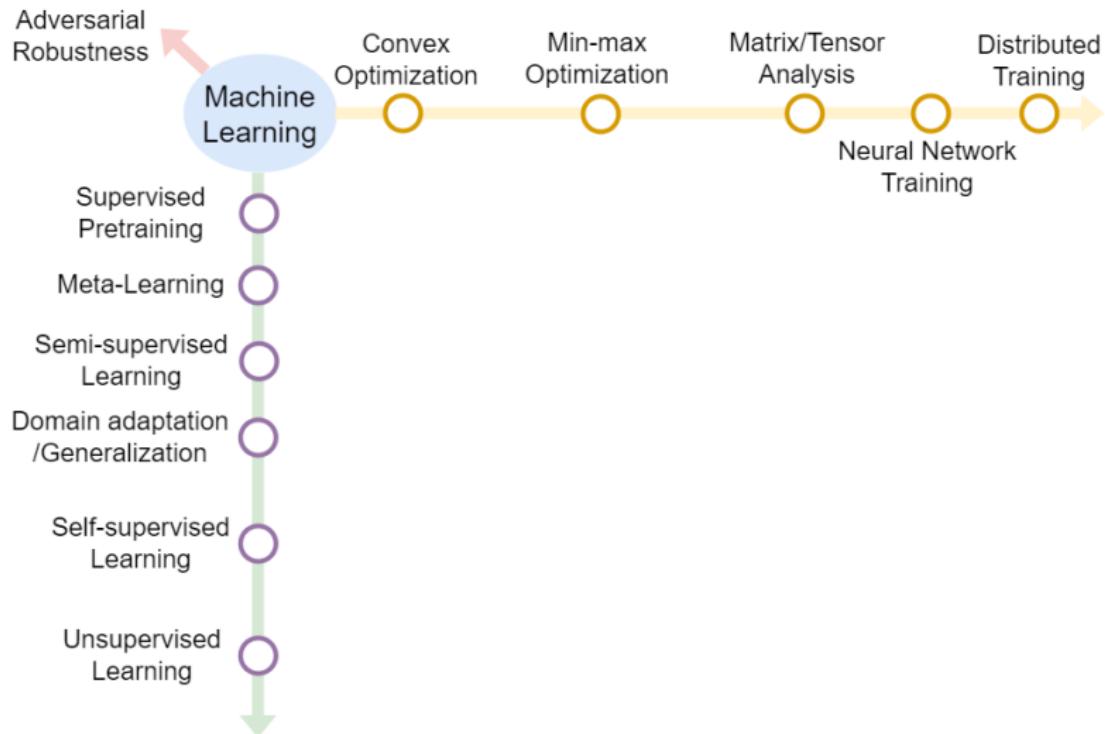
Predicting what you already know helps: Provable self-supervised learning,  
NeurIPS 2021

# wrap-up

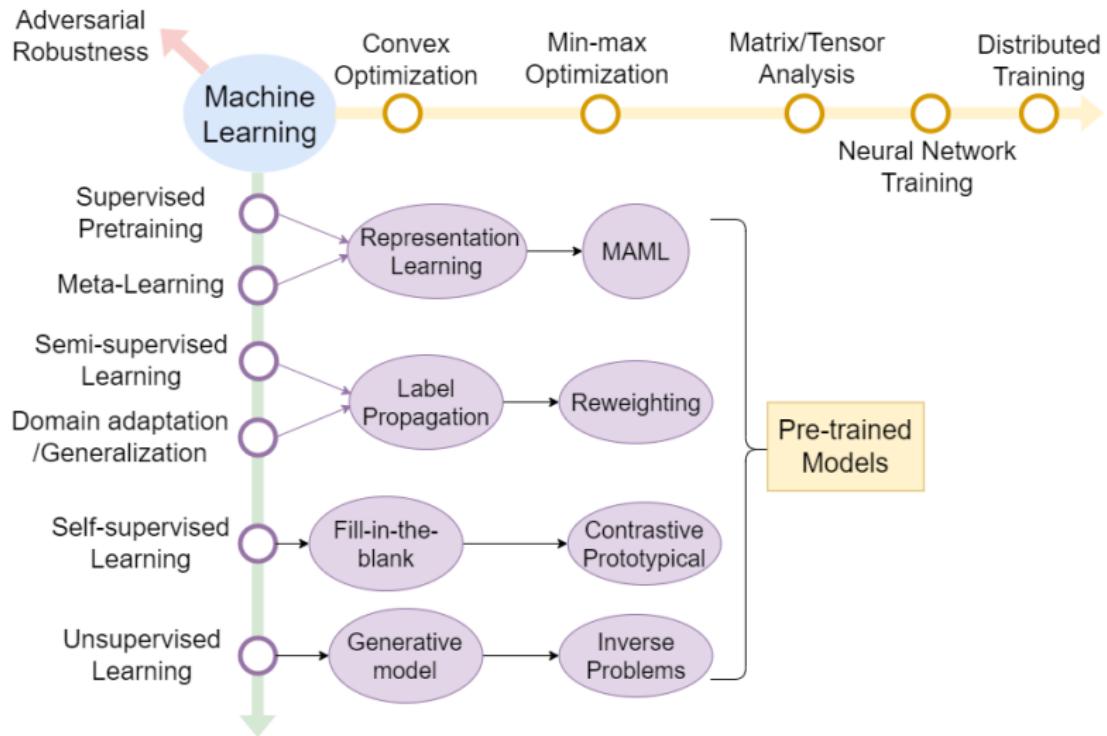
# Overview of My Research Contributions



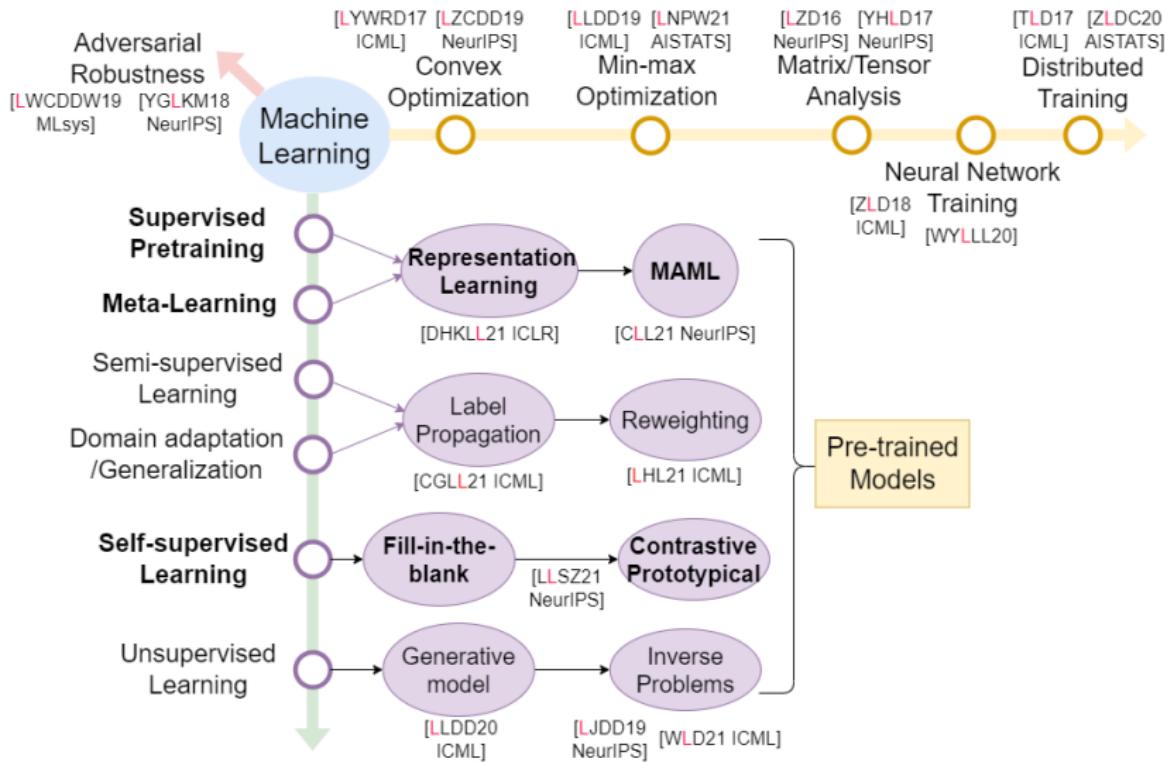
# Overview of My Research Contributions



# Overview of My Research Contributions



# Overview of My Research Contributions





- Our ultimate goal is to expand the capability of AI to broader disciplines
- Pre-trained model is a big step towards that direction
- I will work towards accelerating us to their “ImageNet” moment

# Remaining challenges:



- Understanding the optimization part
- From making predictions to making decisions
- Handle different types of distribution shift
- Training and testing time speed up
- More reliable: security, privacy, AI safety
- Fairness
- Interpretability
- How to evaluate the model without target data
- Other technical details

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## 1 Meta-learning

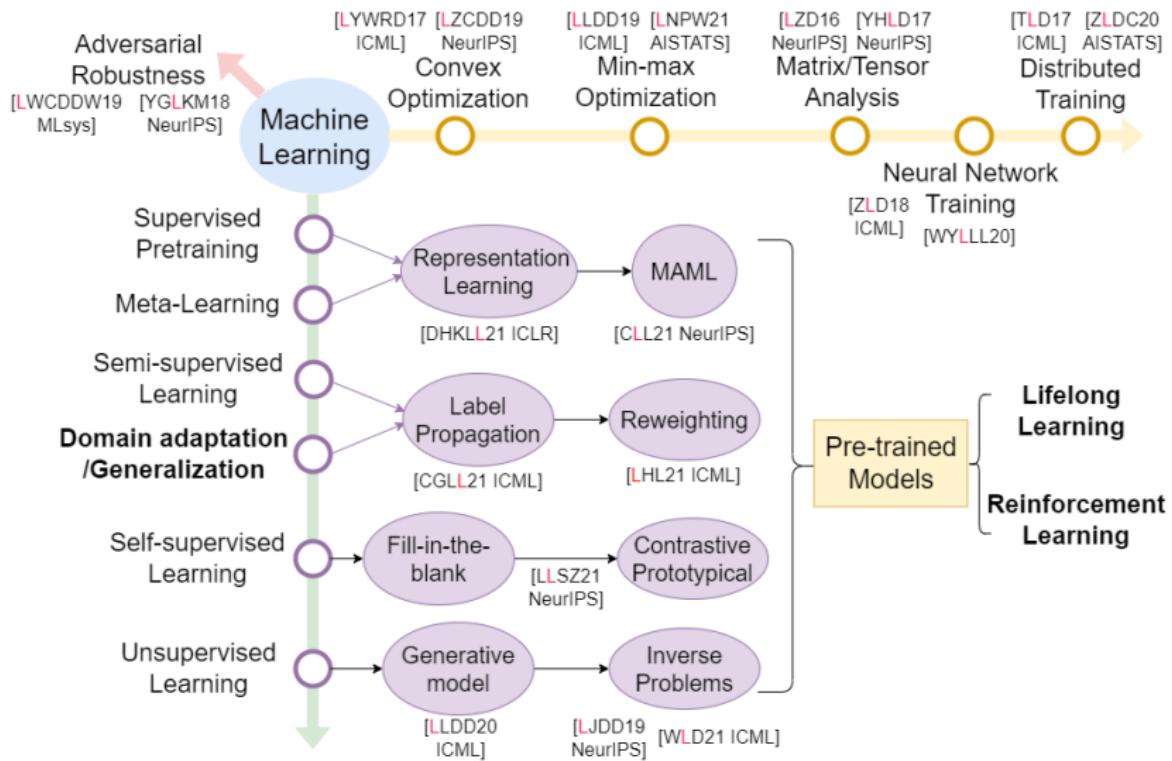
- Meta-Learning with Frozen Representation
- Meta-learning with Fine-tuned Representation

## 2 Self-Supervised Learning

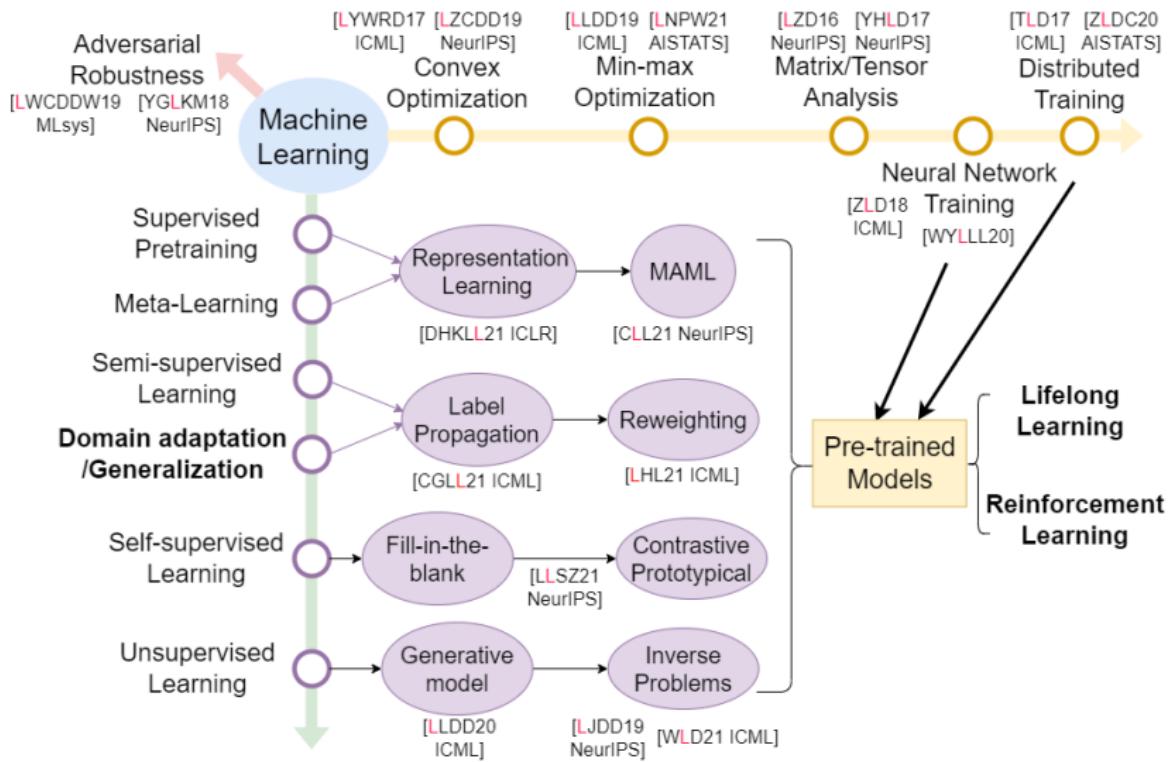
## 3 Ongoing and Future Work

- Domain Adaptation
- Lifelong Learning
- Meta Reinforcement Learning

# Future Work



# Future Work



We investigate sufficient conditions that guarantee:

- Deep networks **learn a good pre-trained model**.
- Good pre-trained models drastically **reduce sample complexity**.
- Pre-trained models can be **learned on unlabeled data**.
- Pre-trained models **transfer to other tasks/domains with covariate shift**.

We investigate sufficient conditions that guarantee:

- Deep networks **learn a good pre-trained model**.
- Good pre-trained models drastically **reduce sample complexity**.
- Pre-trained models can be **learned on unlabeled data**.
- Pre-trained models **transfer to other tasks/domains with covariate shift**.

In the future, I will explore other aspects of pre-trained model:

- How to handle different types of **distribution shift** for domain adaptation?
- How to utilize **latent structure** for meta reinforcement learning?
- How to improve the training algorithms?

# Thank you!

# Thank you!

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Link back to:

METAREP

FINETUNEDREP

SSL

Back-up slides:

FINETUNEDREP

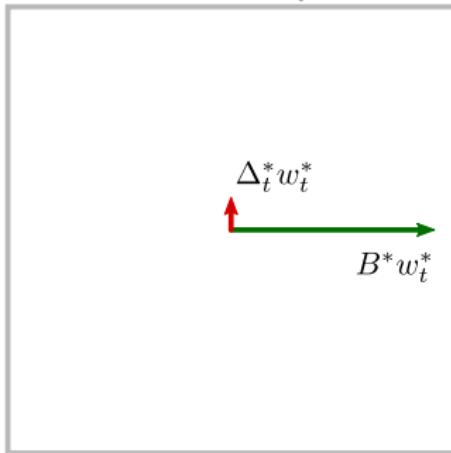
SSL Example

Experiments

METAREP (Fixed feature) has  $\Omega\left(\frac{d}{n_T}\right)$  minimax rate on  
the target task

METAREP chooses representation based on prediction space norm, not parameter space norm!

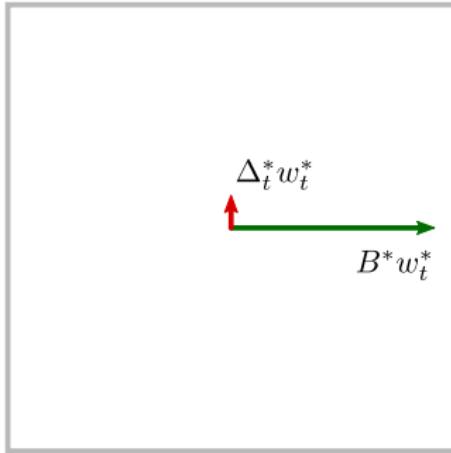
Parameter space ( $L_2$ -norm)



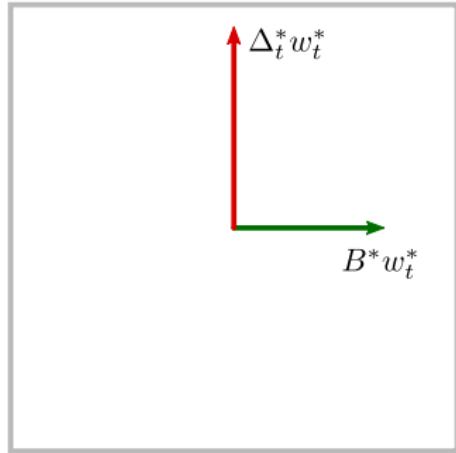
# Failure with Previous Algorithm: METAREP

METAREP chooses representation based on prediction space norm, not parameter space norm!

Parameter space ( $L_2$ -norm)



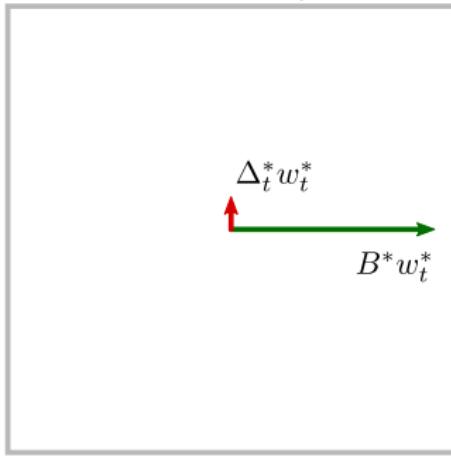
Prediction space ( $\Sigma$ -norm)



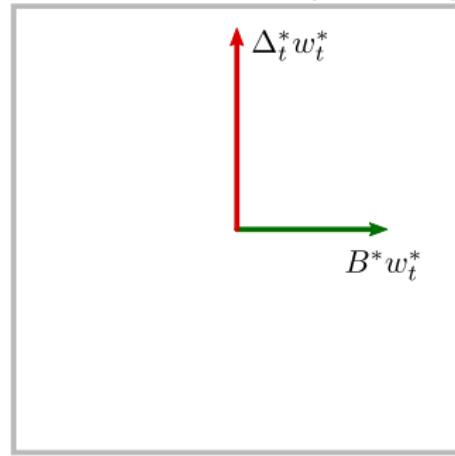
# Failure with Previous Algorithm: METAREP

METAREP *chooses representation based on prediction space norm, not parameter space norm!*

Parameter space ( $L_2$ -norm)



Prediction space ( $\Sigma$ -norm)



Intuition: Trick METAREP into learning subspace of  $\delta_t^*$ 's, and pay cost of having to fine-tune to learn large-norm  $B^*w_{test}^*$ .

Theoretical results:

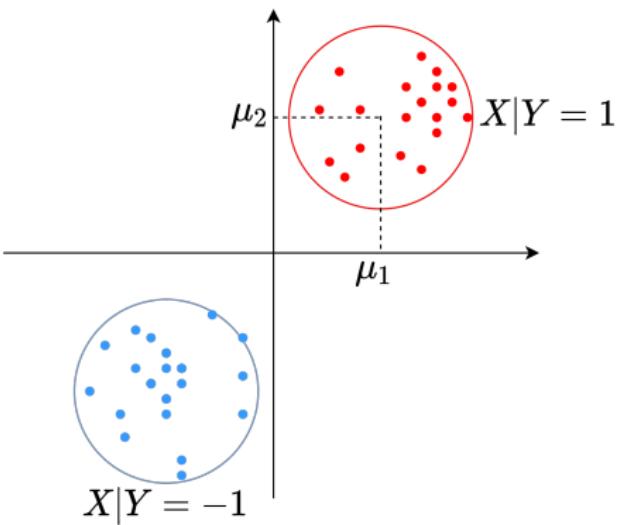
- ① If  $X_1 \perp X_2|Y$ ,

$$f^* = W^* \phi(X_1).$$

- ② Only need  $k$  (dimension of  $Y$ ) samples.

How can  $\phi(X_1)$  be better than  $X_2$  to predict  $Y$ ?

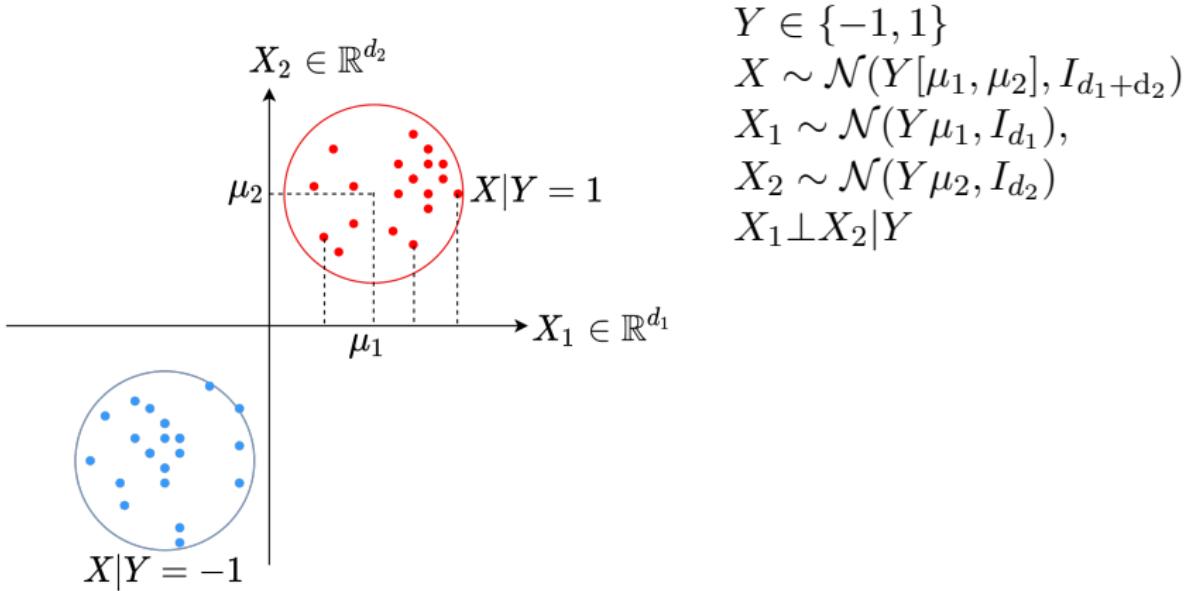
# Example: Gaussian Mixture



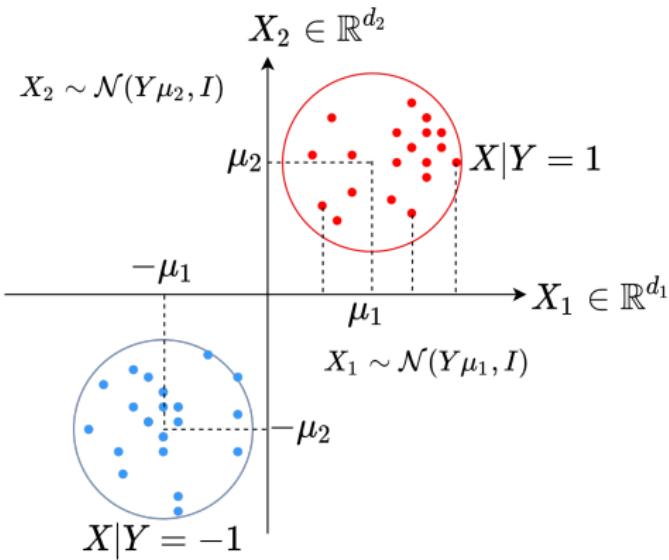
$$Y \in \{-1, 1\}$$

$$X \sim \mathcal{N}(Y[\mu_1, \mu_2], I_{d_1+d_2})$$

# Example: Gaussian Mixture

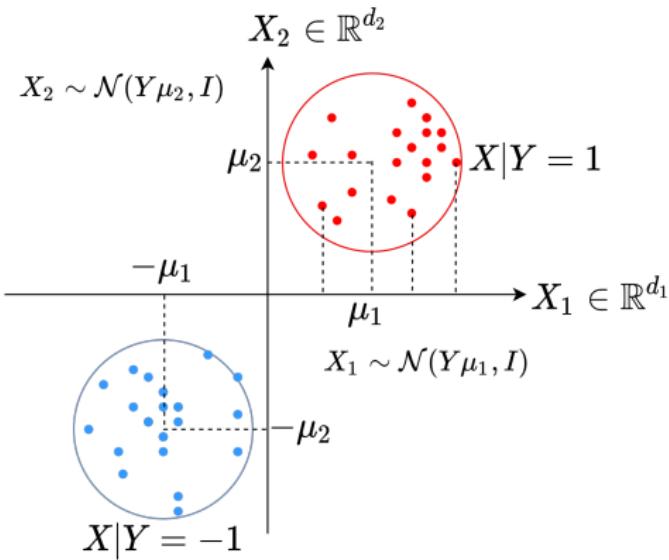


# Example: Gaussian Mixture



$Y \in \{-1, 1\}$   
 $X \sim \mathcal{N}(Y[\mu_1, \mu_2], I_{d_1+d_2})$   
 $X_1 \sim \mathcal{N}(Y\mu_1, I_{d_1})$ ,  
 $X_2 \sim \mathcal{N}(Y\mu_2, I_{d_2})$   
 $X_1 \perp X_2 | Y$   
 $\mathbb{E}[Y|X_2]$  is not linear, but  
 $\mathbb{E}[Y|\phi]$  is linear:

# Example: Gaussian Mixture



$Y \in \{-1, 1\}$   
 $X \sim \mathcal{N}(Y[\mu_1, \mu_2], I_{d_1+d_2})$   
 $X_1 \sim \mathcal{N}(Y\mu_1, I_{d_1}),$   
 $X_2 \sim \mathcal{N}(Y\mu_2, I_{d_2})$   
 $X_1 \perp X_2 | Y$   
 $\mathbb{E}[Y|X_2]$  is not linear, but  
 $\mathbb{E}[Y|\phi]$  is linear:

- $\phi(x_1) = \mathbb{E}[X_2 | X_1 = x_1] = p_1(x_1)\mu_2 + p_{-1}(x_1)(-\mu_2)$
- $\mathbb{E}[Y|X_1] = p_1(x_1) - p_{-1}(x_1) = \mu_2^\top \phi(X_1) / \|\mu_2\|^2.$
- $p_y(x_1) := P(Y = y | X_1 = x_1)$

# Connection to SimSiam method

- Before, we learn  $\phi(x_1) = \mathbb{E}[X_2|X_1 = x_1]$ , which naturally requires  $X_2$  and  $Y$  to be linearly correlated
- We can actually predict any  $g(X_2)|X_1$ , or even  $p(X_2|X_1)$

## ACE and nonlinear CCA

- Alternating conditional expectation (ACE):

$$\min_{\phi, \eta} L_{ACE}(\phi, \eta) = \mathbb{E}_{X_1, X_2} \left[ \|\phi(X_1) - \eta(X_2)\|^2 \right],$$

s.t.  $\Sigma_{\phi, \phi} = \Sigma_{\eta, \eta} = I_k.$

- This is equivalent to the following canonical correlation analysis (CCA):

$$\max_{\phi, \eta} L_{CCA}(\phi, \eta) = \mathbb{E}_{X_1, X_2} \left[ \phi(X_1)^\top \eta(X_2) \right],$$

s.t.  $\Sigma_{\phi, \phi} = \Sigma_{\eta, \eta} = I_k.$

Algorithm (SimSiam):

$$\max_{\phi, \eta, \text{normalized}} \mathbb{E}[\phi(X_1)^\top \eta(X_2)]$$

New measure of conditional independence:

$$\epsilon_{CI} := \max_{\|g\|_{L^2(X_2)} = 1} \mathbb{E}_{X_1} (\mathbb{E}[g(X_2)|X_1] - \mathbb{E}[\mathbb{E}[g(X_2)|Y]|X_1])^2.$$

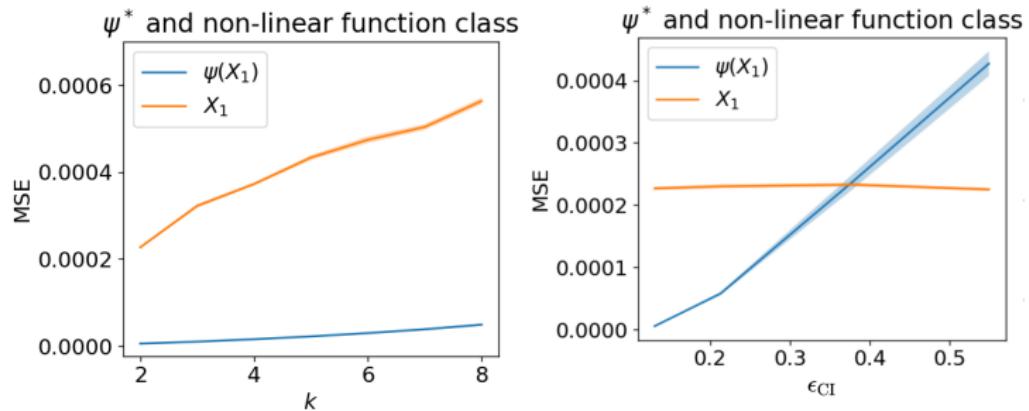
- Extension of previous result:

$$\text{test error} \lesssim \epsilon_{CI} + \frac{k}{n_L}.$$

- If both  $X_2$  and  $X_1$  can well predict  $Y$ , i.e.,  $P_{X_1,Y}(g^*(x_1) \neq y) \leq \alpha$  (same for  $X_2$ ), we have:

$$\text{test error} \lesssim \frac{\alpha}{1-\epsilon_{CI}} + \frac{k}{n_L}.$$

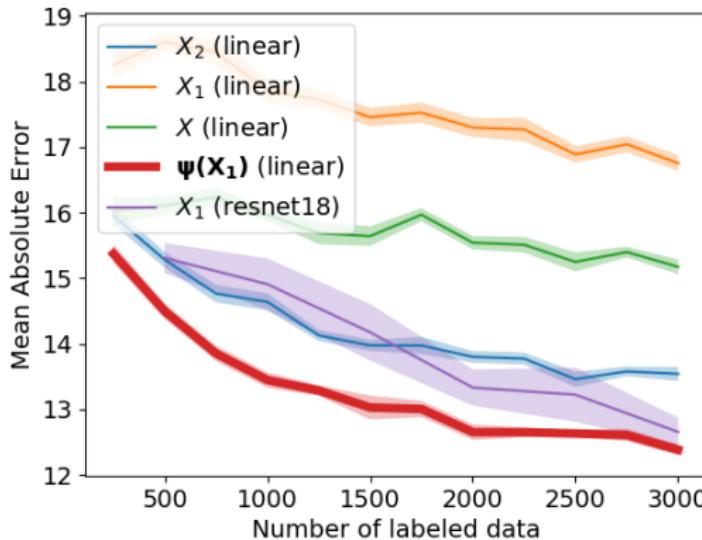
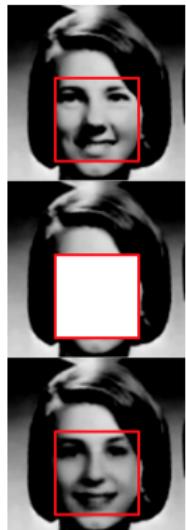
# Simulations: Both Terms Tight in $\frac{k}{n_L} + \epsilon_{\text{CI}}$



**Left:** Class Conditional Gaussian  $X \sim \mathcal{N}(\mu_Y, I)$ ,  $\mu_Y \in \mathbb{R}^{90}$ ,  $Y \in \{1, 2, \dots, k\}$ ,  $X_1 = X_{1:50}$ ,  $X_2 = X_{51:90}$ .  $X_1 \perp X_2 | Y$

**Right:** Similar mixture of Gaussian:  $X \sim \mathcal{N}(\mu_Y, \Sigma_{\epsilon_{\text{CI}}})$ ,  $\alpha \propto \epsilon_{\text{CI}}$  controls the dependence of  $X_1$  and  $X_2$ :  $\epsilon_{\text{CI}} = 0 \Rightarrow$  exact CI, and  $\epsilon_{\text{CI}} = 1 \Rightarrow X_2$  fully depends on  $X_1$ .

# Experiments



- Yearbook: portraits date from 1905 to 2013.

# Ongoing Work: Distribution Shift



Entity30 - Passerine

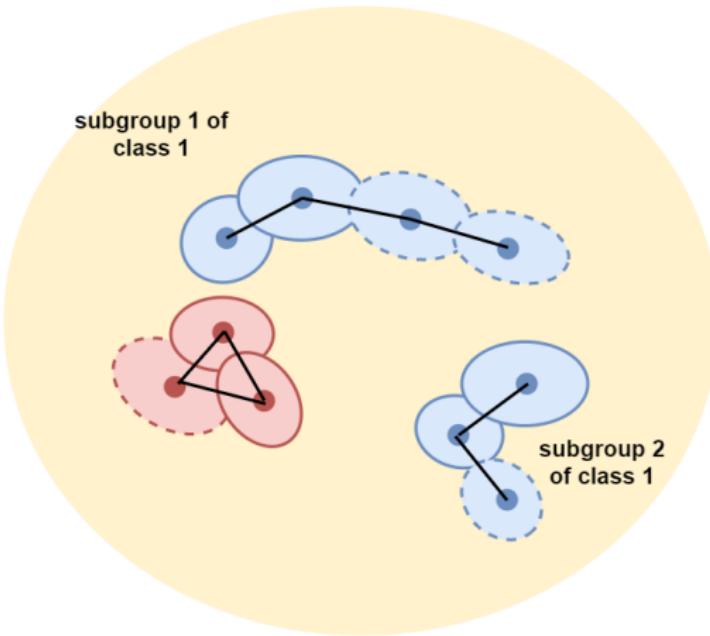
Entity30 - Tableware

# Our New Framework: Subpopulation Shift

	Class 1	Class -1
Source		
Target		

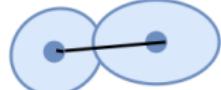


Components connected  
through data augmentation

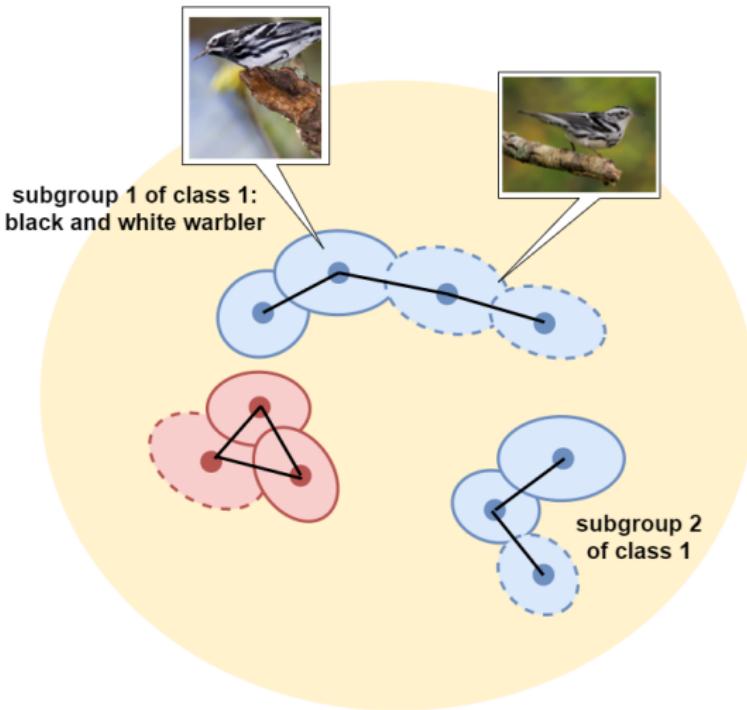


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Source		
Target		

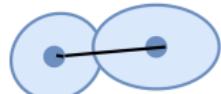


Components connected  
through data augmentation

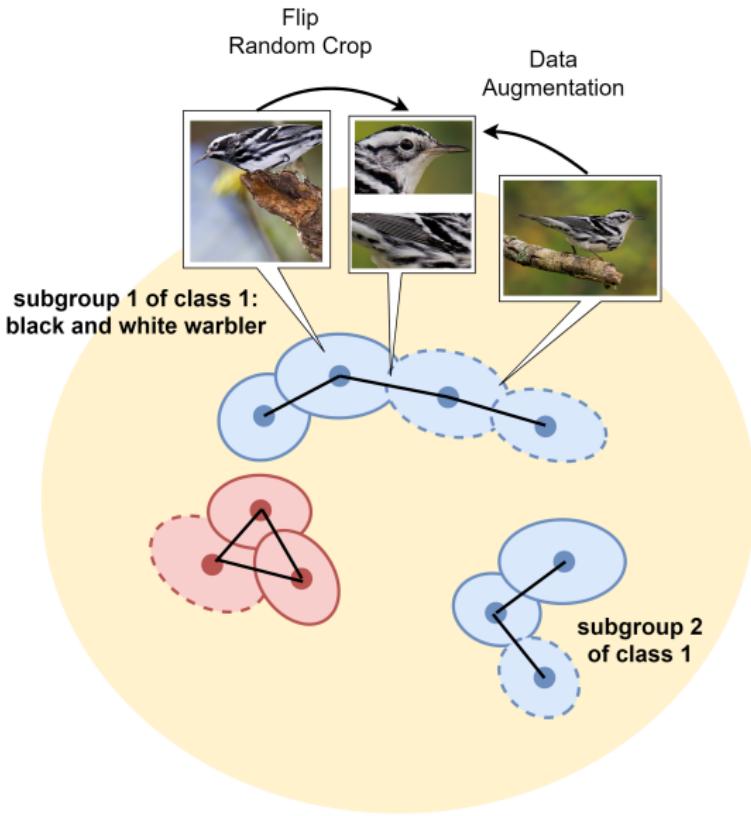


# Our New Framework: Subpopulation Shift

	Class 1	Class -1
Source		
Target		



Components connected  
through data augmentation



# Experiments

Method	A → W	D → W	W → D	A → D	D → A	W → A	Average
MDD	94.97±0.70	98.78±0.07	100±0	92.77±0.72	75.64±1.53	72.82±0.52	89.16
Ours	95.47±0.95	98.32±0.19	100±0	93.71±0.23	76.64±1.91	74.93±1.15	<b>89.84</b>

Performance of MDD<sup>1</sup> and our method on Office-31 dataset.

Method	Ar → Cl	Ar → Pr	Ar → Rw	Cl → Ar	Cl → Pr	Cl → Rw	Pr → Ar
MDD	54.9±0.7	74.0±0.3	77.7±0.3	60.6±0.4	70.9±0.7	72.1±0.6	60.7±0.8
Ours	55.1±0.9	74.7±0.8	78.7±0.5	63.2±1.3	74.1±1.8	75.3±0.1	63.0±0.6
Method	Pr → Cl	Pr → Rw	Rw → Ar	Rw → Cl	Rw → Pr	Average	
MDD	53.0±1.0	78.0±0.2	71.8±0.4	59.6±0.4	82.9±0.3	68.0	
Ours	53.0±0.6	80.8±0.4	73.4±0.1	59.4±0.7	84.0±0.5	<b>69.6</b>	

Performance of MDD and our method on Office-Home dataset.

<sup>1</sup>MDD: (Zhang et al. 2019)

# Experiments: Subpopulation Shift Dataset

- ENTITY-30 task from BREEDS tasks.
- We use FixMatch, an existing consistency regularization method. We also leverage SwAV, an existing unsupervised representation learned from ImageNet, where there can be a better structure of subpopulation shift. We compare with popular distribution matching methods like DANN and MDD.

Method	Source Acc	Target Acc
Train on Source	$91.91 \pm 0.23$	$56.73 \pm 0.32$
DANN (Ganin et al., 2016)	$92.81 \pm 0.50$	$61.03 \pm 4.63$
MDD (Zhang et al., 2019)	$92.67 \pm 0.54$	$63.95 \pm 0.28$
FixMatch (Sohn et al., 2020)	$90.87 \pm 0.15$	$72.60 \pm 0.51$