



Computer Vision; Advanced Topics; Self-Supervised Learning

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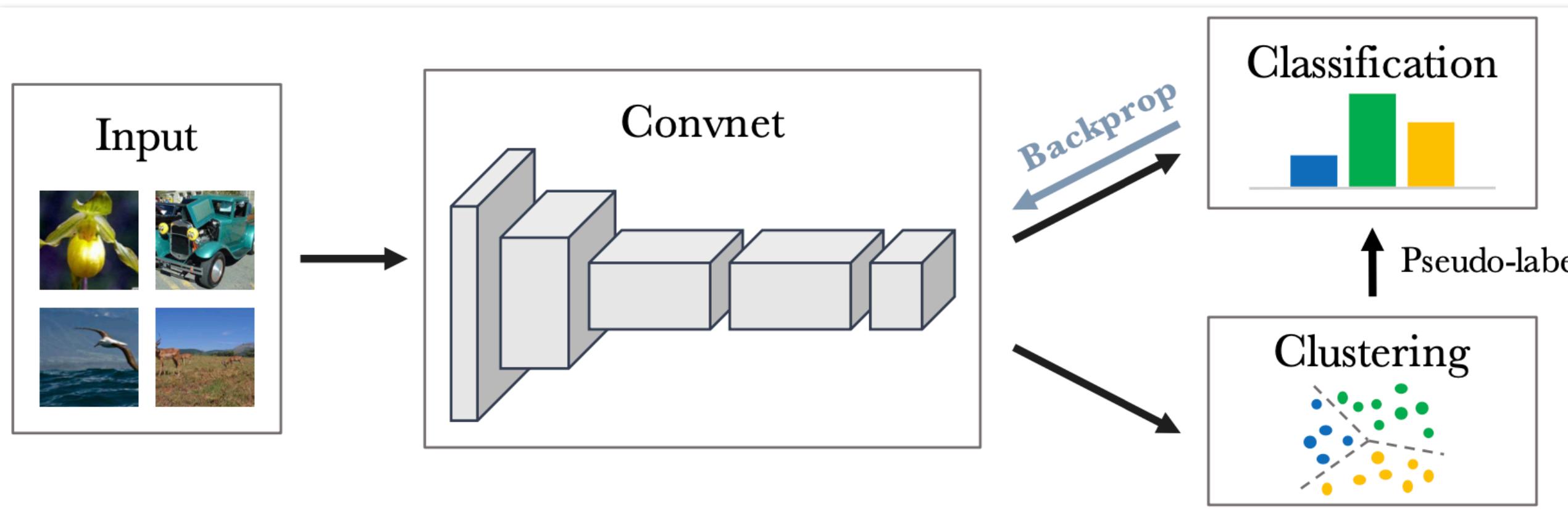
Deep Clustering for Unsupervised Learning of Visual Features

Key observation: A multilayer perceptron classifier on top of the last convolutional layer of a random AlexNet achieves 12% in accuracy on ImageNet while the chance is at 0.1%.

This is because a convolutional structure gives a strong prior.

$\{x_1, \dots, x_N\} \rightarrow$ training set of N images

Problem setup: Find parameters θ^* such that the convnet mapping f_{θ^*} produces good general-purpose features (representations).



k -means: cluster the features $f_{\theta}(x_n)$ into k distinct groups

$C \in \mathbb{R}^{d \times k} \rightarrow$ centroid matrix

$y_n \rightarrow$ cluster assignment of each image

$$\min_{C \in \mathbb{R}^{d \times k}} \frac{1}{N} \sum_{n=1}^N \min_{y_n \in \{0,1\}^k} \|f_{\theta}(x_n) - Cy_n\|_2^2 \quad \text{such that} \quad y_n^\top 1_k = 1.$$

$y_n^* \rightarrow$ optimal assignment (pseudo label)

$C^* \rightarrow$ optimal centroid matrix (not used)

$g_W \rightarrow$ parametrized classifier on top of the features $f_{\theta}(x_n)$

$$\min_{\theta, W} \frac{1}{N} \sum_{n=1}^N \ell(g_W(f_{\theta}(x_n)), y_n)$$

multinomial logistic loss

Avoiding Trivial Solutions

Empty clusters:

An optimal decision boundary is to assign all of the inputs to a single cluster.

When a cluster becomes empty, randomly select a non-empty cluster and use its centroid with a small random perturbation as the new centroid for the empty cluster. Then reassign the points belonging to the non-empty cluster to the two resulting clusters.

Trivial parametrization:

Unbalanced number of images per cluster

Sample images based on a uniform distribution over the classes, or pseudo-labels.

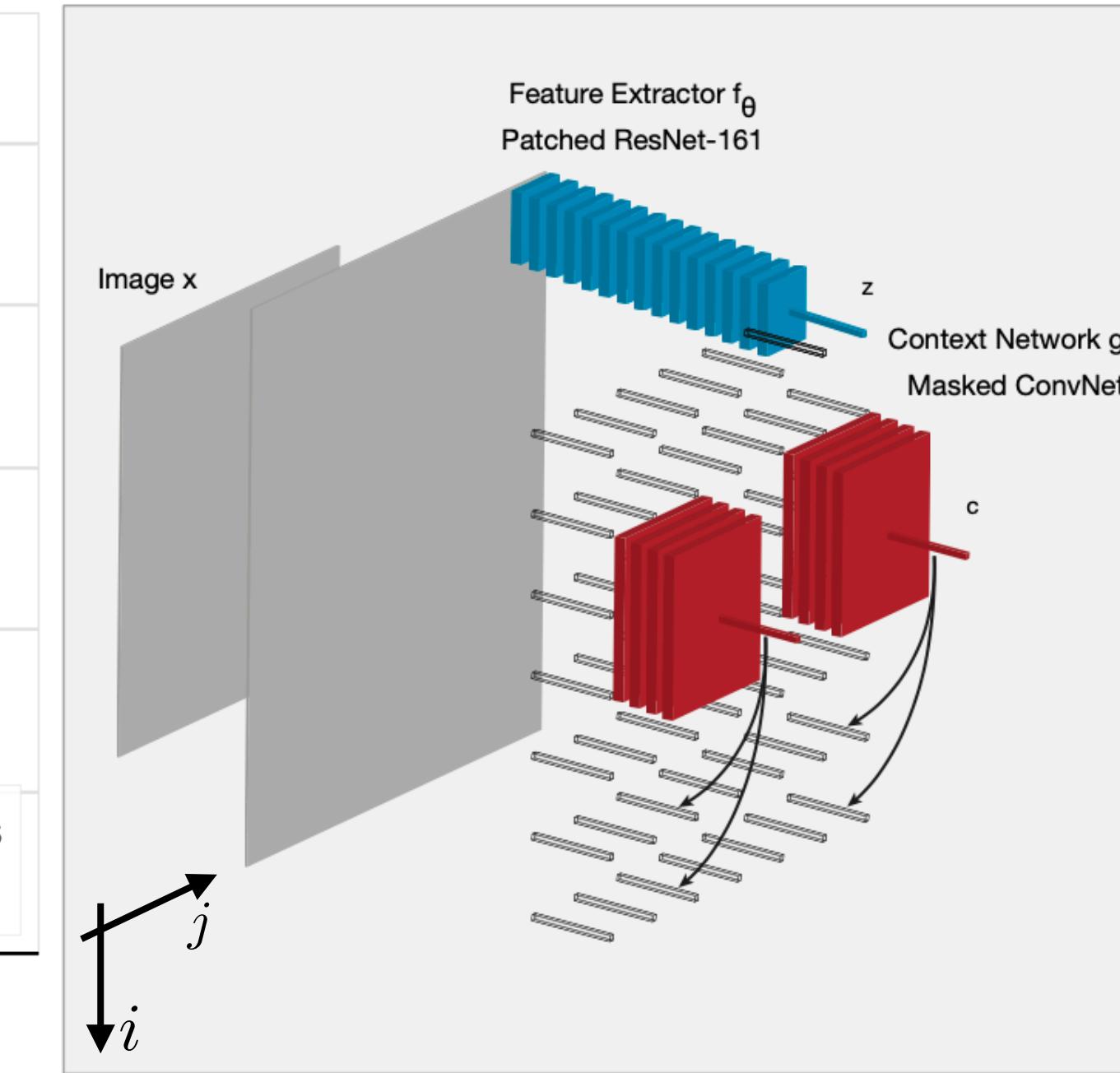
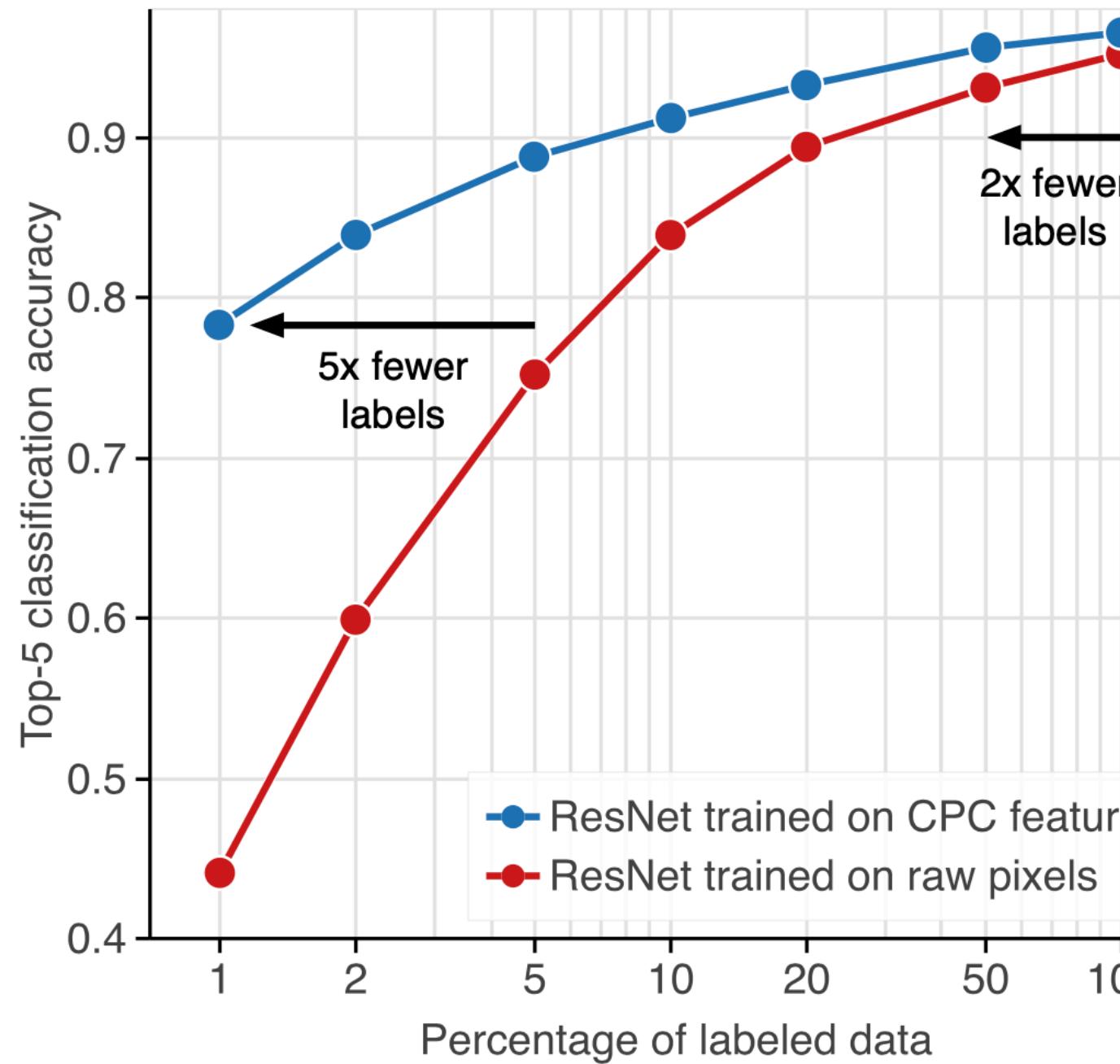
PASCAL VOC transfer tasks		Classification		Detection		Segmentation	
Method	Training set	FC6-8	ALL	FC6-8	ALL	FC6-8	ALL
Best competitor	ImageNet	63.0	67.7	43.4 [†]	53.2	35.8 [†]	37.7
DeepCluster	ImageNet	72.0	73.7	51.4	55.4	43.2	45.1
DeepCluster	YFCC100M	67.3	69.3	45.6	53.0	39.2	42.2

Pascal VOC 2007 object detection	Method	AlexNet		VGG-16		Method	Oxford5K		Paris6K	
		AlexNet	VGG-16	AlexNet	VGG-16		Oxford5K	Paris6K	Oxford5K	Paris6K
	ImageNet labels	56.8	67.3				72.4	81.5		
	Random	47.8	39.7				6.9	22.0		
	Doersch <i>et al.</i> [13]	51.1	61.5				35.4	53.1		
	Wang and Gupta [63]	47.2	60.2				42.3	58.0		
	Wang <i>et al.</i> [64]	–	63.2							
	DeepCluster	55.4	65.9				61.0	72.0		

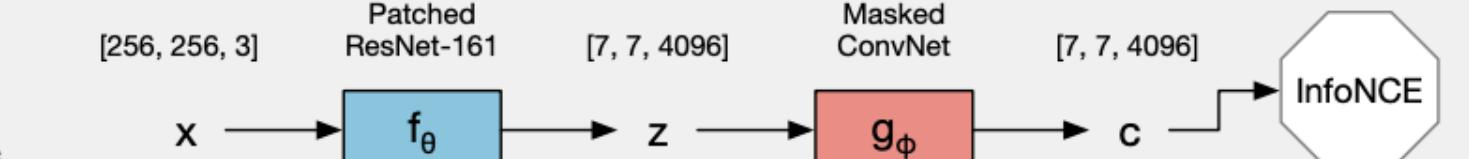
mAP on instance-level image retrieval on Oxford and Paris dataset with a VGG-16



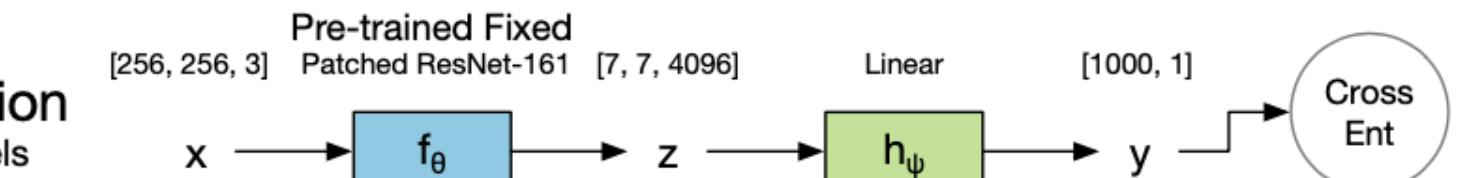
Data-Efficient Image Recognition with Contrastive Predictive Coding



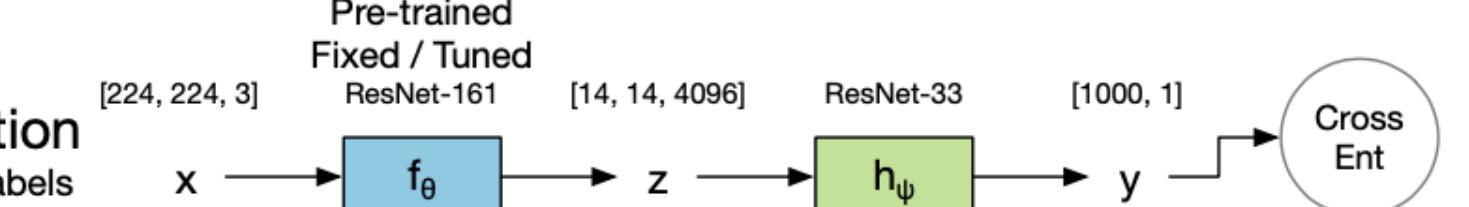
Self-supervised pre-training
100% images; 0% labels



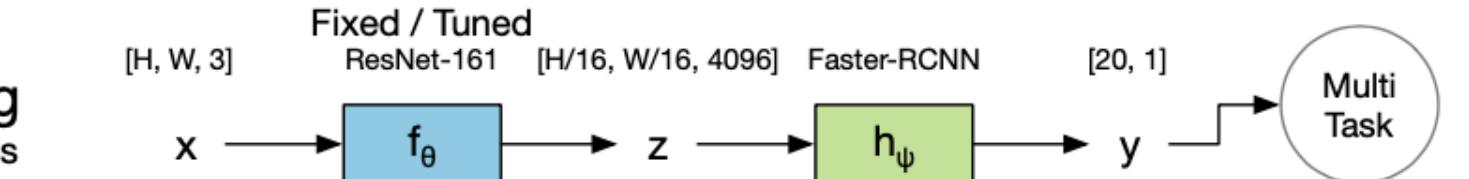
Linear classification
100% images and labels



Efficient classification
1% to 100% images and labels



Transfer learning
100% images and labels



Supervised training
1% to 100% images and labels



$\{x_{i,j}\} \rightarrow$ a grid of overlapping patches dividing each input image
 $i, j \rightarrow$ location of the patch

$z_{i,j} = f_\theta(x_{i,j}) \rightarrow$ encoded patch

↳ neural network

$g_\phi \rightarrow$ masked convolutional network (applied to the grid of feature vectors)

$c_{i,j} = g_\phi(\{z_{u,v}\}_{u \leq i, v}) \rightarrow$ context vector

↳ feature vectors that lie above i, j

$z_{i+k,j} \rightarrow$ “future” feature vectors to be predicted from current context vector $c_{i,j}$

$k \rightarrow$ prediction length

$\hat{z}_{i+k,j} = W_k c_{i,j}$
 ↳ prediction matrix

– increase depth & width – layer normalization – making predictions in all four directions – extensive patch-based data augmentation

Henaff, Olivier. "Data-efficient image recognition with contrastive predictive coding." *International Conference on Machine Learning*. PMLR, 2020.

InfoNCE (Noise Contrastive Estimation)

$$\mathcal{L}_{\text{CPC}} = - \sum_{i,j,k} \log p(z_{i+k,j} | \hat{z}_{i+k,j}, \{z_l\})$$

$$= - \sum_{i,j,k} \log \frac{\exp(\hat{z}_{i+k,j}^T z_{i+k,j})}{\exp(\hat{z}_{i+k,j}^T z_{i+k,j}) + \sum_l \exp(\hat{z}_{i+k,j}^T z_l)}$$



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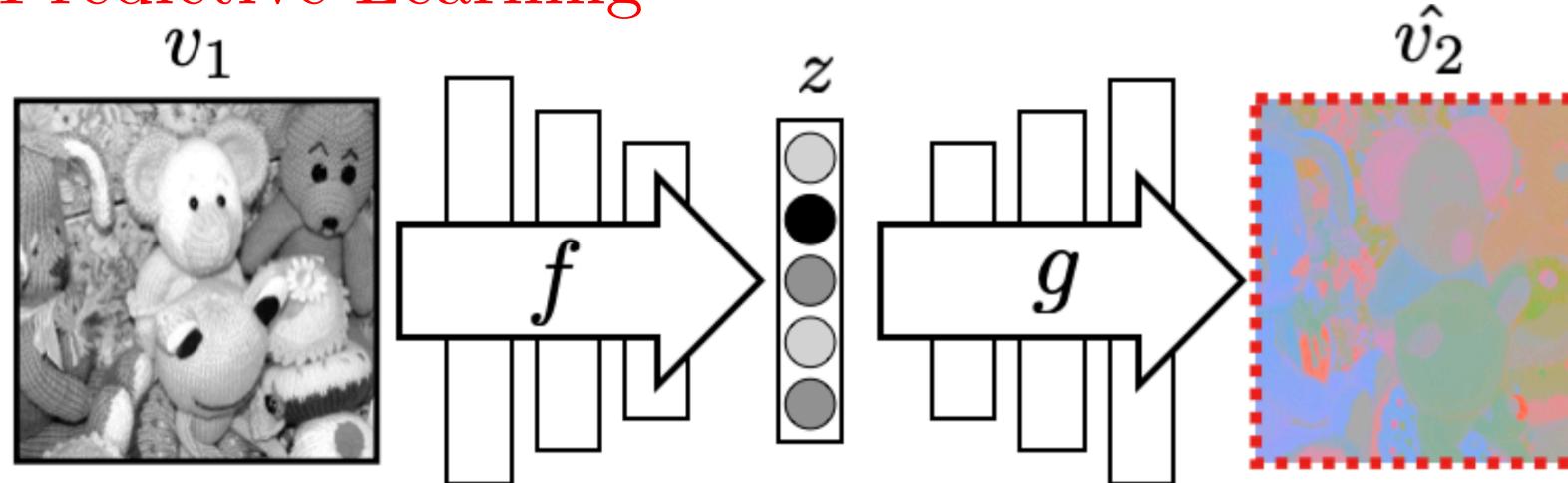
Contrastive Multiview Coding

A “dog” can be seen, heard and felt!

$V_1, V_2, \dots, V_M \rightarrow$ a collection of M views of the data

$v_i \sim \mathcal{P}(V_i) \rightarrow$ a random variable representing samples

Predictive Learning



$V_1, V_2 \rightarrow$ two views of a dataset
(e.g., luminance and chrominance)

$z = f(v_1) \rightarrow$ encoder

$\hat{v}_2 = g(z) \rightarrow$ decoder

↳ prediction of v_2 given v_1

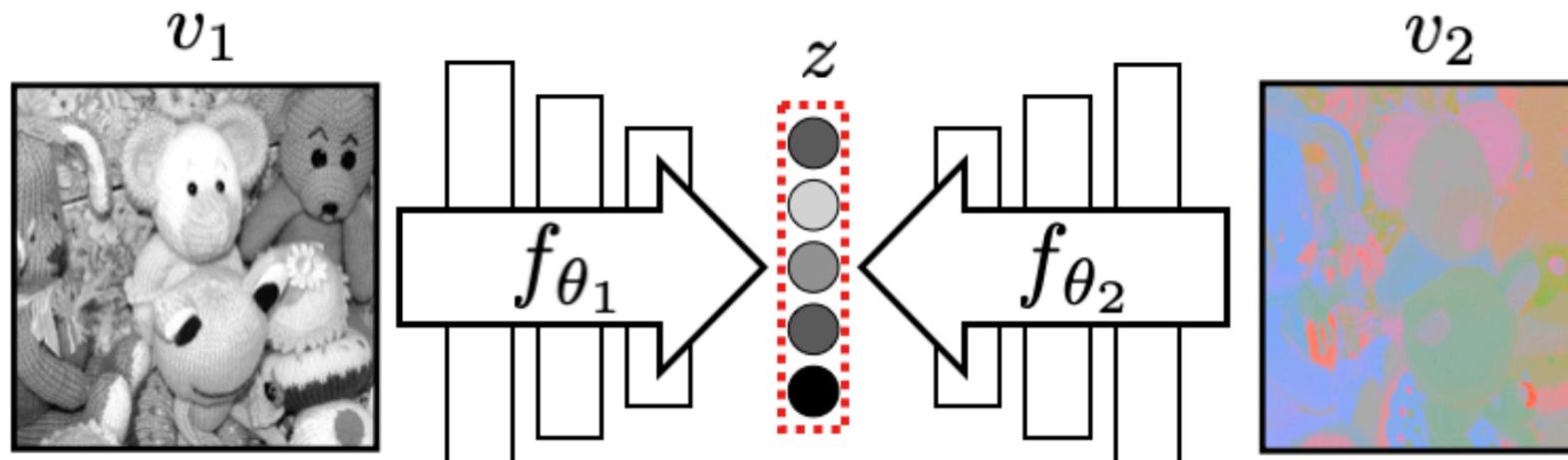
$z \rightarrow$ latent variables

Bring \hat{v}_2 close to $v_2 \rightarrow$ objective function (L_1 or L_2)

Independence assumption between elements or pixels

$p(v_2|v_1) = \prod_i p(v_{2i}|v_1)$ of v_2 given v_1 !

Contrastive Learning with Two Views



$\{v_1^i, v_2^i\}_{i=1}^N \rightarrow$ collection of samples from V_1 and V_2

$x = \{v_1^i, v_2^i\} \rightarrow$ positives (congruent pairs), $x \sim p(v_1, v_2) \rightarrow$ joint distribution

$y = \{v_1^i, v_2^j\} \rightarrow$ negatives (incongruent pairs), $y \sim p(v_1)p(v_2) \rightarrow$ product of marginals

Select a single positive sample x out of a set $S = \{x, y_1, y_2, \dots, y_k\}$ that contains k negative samples

$$\mathcal{L}_{contrast} = -\mathbb{E}_S \left[\log \frac{h_\theta(x)}{h_\theta(x) + \sum_{i=1}^k h_\theta(y_i)} \right]$$

$$h_\theta(\{v_1, v_2\}) = \exp\left(\frac{f_{\theta_1}(v_1) \cdot f_{\theta_2}(v_2)}{\|f_{\theta_1}(v_1)\| \cdot \|f_{\theta_2}(v_2)\|} \cdot \frac{1}{\tau}\right)$$

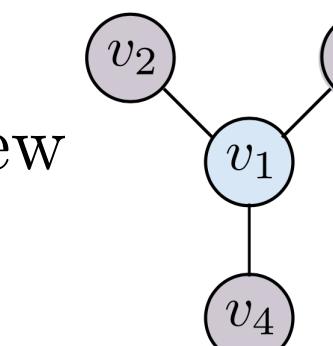
Connecting to Mutual Information

$$h_\theta^*(\{v_1, v_2\}) \propto \frac{p(z_1, z_2)}{p(z_1)p(z_2)} \propto \frac{p(z_1|z_2)}{p(z_1)} \rightarrow \text{point-wise mutual information}$$

$$I(v_i; v_j) \geq I(z_i; z_j) \geq \log(k) - \mathcal{L}_{contrast}$$

Contrastive Learning with More Than Two Views

$$\mathcal{L}_C = \sum_{j=2}^M \mathcal{L}(V_1, V_j) \rightarrow \text{core view}$$



$$\mathcal{L}_F = \sum_{1 \leq i < j \leq M} \mathcal{L}(V_i, V_j) \rightarrow \text{full graph}$$

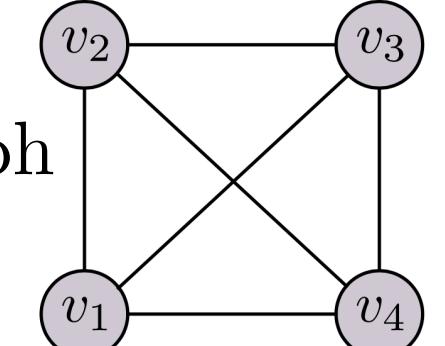


Image Views

luminance (L channel), chrominance (ab channel)

Video Views

$i_t \rightarrow$ image at time t , $i_{t+k} \rightarrow$ neighboring frame, $f_t \rightarrow$ optical flow (10 frames centered at time t)
 $(i_t, i_{t+k}), (i_t, f_t) \rightarrow$ two separate contrastive learning objectives

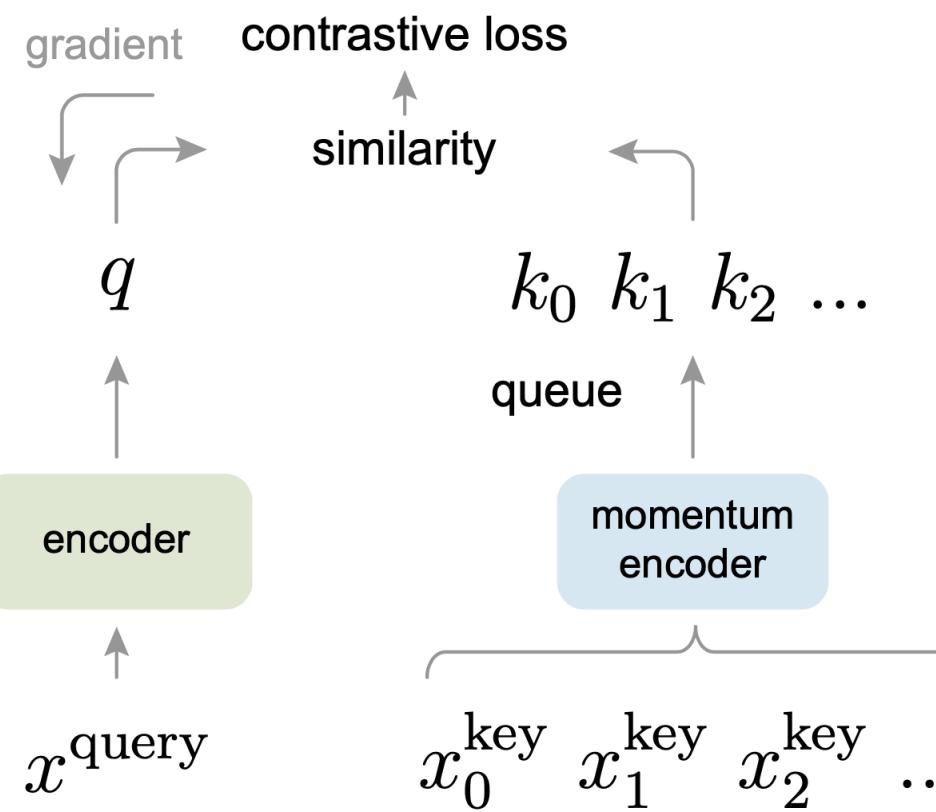
Multiple Image Views

luminance (L channel), chrominance (ab channel), depth, surface normal, and semantic labels



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Momentum Contrast for Unsupervised Visual Representation Learning



Keys (tokens): samples from the data (e.g., images or patches) represented by an encoder network

Unsupervised Learning:

dictionary look-up

An encoded "query" should be similar to its matching "key" and dissimilar to others

Instance discrimination task

A query matches a key if they are encoded views (e.g., different crops) of the same image

Contrastive learning

$q \rightarrow$ encoded query

$\{k_0, k_1, \dots\} \rightarrow$ set of encoded samples (keys of a dictionary)

$$k_+ \rightarrow \text{the single key in the dictionary that matches } q$$

$$\mathcal{L}_q = -\log \frac{\exp(q \cdot k_+ / \tau)}{\sum_{i=0}^K \exp(q \cdot k_i / \tau)}$$

InfoNCE (noise-contrastive estimation) loss

$\tau \rightarrow$ temperature hyper-parameter

$q = f_q(x^q)$ query sample

$k = f_k(x^k)$ encoder network

Momentum Contrast (MoCo)

- ① dynamic
 - ② large
 - ③ consistent dictionary
- dictionary as queue

The current mini-batch is enqueue to the dictionary, and the oldest mini-batch in the queue is removed

$\theta_k \rightarrow$ parameters of f_k

$\theta_q \rightarrow$ parameters of f_q

$\theta_k \leftarrow m\theta_k + (1-m)\theta_q, m \in [0, 1], m = 0.999$

$\theta_q \rightarrow$ updated by backprop

Object detection	fine-tuned on PASCAL VOC		
pre-train	AP ₅₀	AP	AP ₇₅
random init.	60.2	33.8	33.1
super. IN-1M	81.3	53.5	58.8
MoCo IN-1M	81.5 (+0.2)	55.9 (+2.4)	62.6 (+3.8)
MoCo IG-1B	82.2 (+0.9)	57.2 (+3.7)	63.7 (+4.9)

Faster R-CNN

ImageNet-1M (IN-1M), Instagram-1B (IG-1B), super. (supervised)

Algorithm 1 Pseudocode of MoCo in a PyTorch-like style.

```

# f_q, f_k: encoder networks for query and key
# queue: dictionary as a queue of K keys (CxK)
# m: momentum
# t: temperature

f_k.params = f_q.params # initialize
for x in loader: # load a minibatch x with N samples
    x_q = aug(x) # a randomly augmented version
    x_k = aug(x) # another randomly augmented version

    q = f_q.forward(x_q) # queries: Nx1
    k = f_k.forward(x_k) # keys: Nx1
    k = k.detach() # no gradient to keys

    # positive logits: Nx1
    l_pos = bmm(q.view(N,1,C), k.view(N,C,1))

    # negative logits: NxK
    l_neg = mm(q.view(N,C), queue.view(C,K))

    # logits: Nx(1+K)
    logits = cat([l_pos, l_neg], dim=1)

    # contrastive loss, Eqn. (1)
    labels = zeros(N) # positives are the 0-th
    loss = CrossEntropyLoss(logits/t, labels)

    # SGD update: query network
    loss.backward()
    update(f_q.params)

    # momentum update: key network
    f_k.params = m*f_k.params+(1-m)*f_q.params

    # update dictionary
    enqueue(queue, k) # enqueue the current minibatch
    dequeue(queue) # dequeue the earliest minibatch

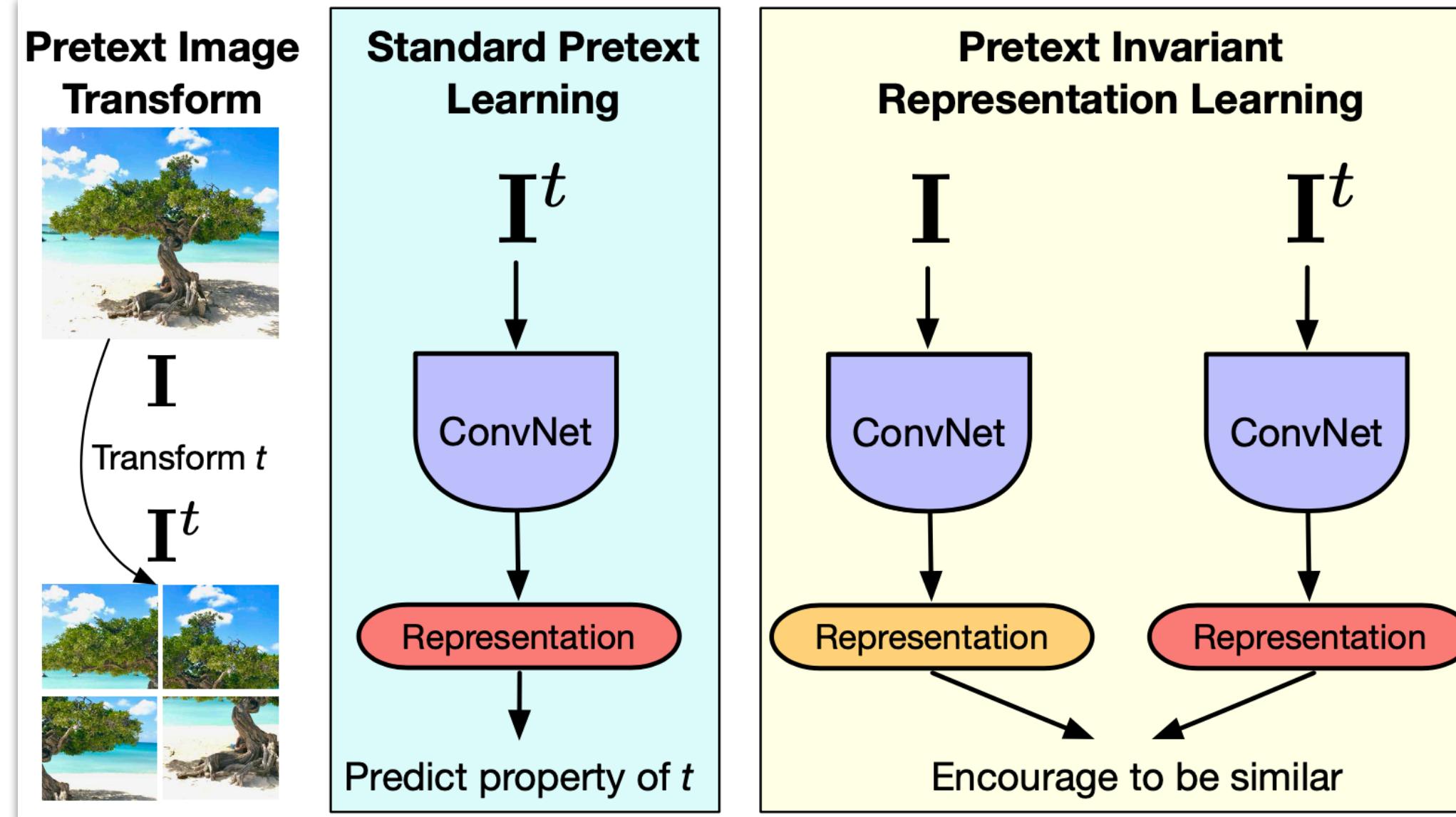
```

bmm: batch matrix multiplication; mm: matrix multiplication; cat: concatenation.



Self-Supervised Learning of Pretext-Invariant Representations

Pretext-Invariant Representation Learning (PIRL)



$\mathcal{D} = \{I_1, \dots, I_{|\mathcal{D}|}\}$ → image dataset

$I_n \in \mathbb{R}^{H \times W \times C}$

\mathcal{T} → set of image transformations (e.g., reshuffling of image patches, image rotation, etc.)

$\phi_\theta(\cdot)$ → CNN

$v_I = \phi_\theta(I)$ → image representation

$I^t = t(I)$ → image I after the transformation $t \in \mathcal{T}$

$\ell_{co}(\theta; \mathcal{D}) = \mathbb{E}_{t \sim p(\mathcal{T})} \left[\frac{1}{|\mathcal{D}|} \sum_{\mathbf{I} \in \mathcal{D}} L_{co}(\mathbf{v}_I, z(t)) \right]$ → Many pretext tasks (e.g., solving jigsaw puzzles) lead to representations that are covariant with image transformations
 $z \rightarrow$ a function that measures some properties of transformation t

Misra, Ishan, and Laurens van der Maaten. "Self-supervised learning of pretext-invariant representations."

Proceedings of the IEEE/CVF Conference on Computer Vision and Pattern Recognition. 2020.

Make representations invariant under transformations $t \in \mathcal{T}$

$$\ell_{inv}(\theta; \mathcal{D}) = \mathbb{E}_{t \sim p(\mathcal{T})} \left[\frac{1}{|\mathcal{D}|} \sum_{\mathbf{I} \in \mathcal{D}} L(\mathbf{v}_I, \mathbf{v}_{I^t}) \right]$$

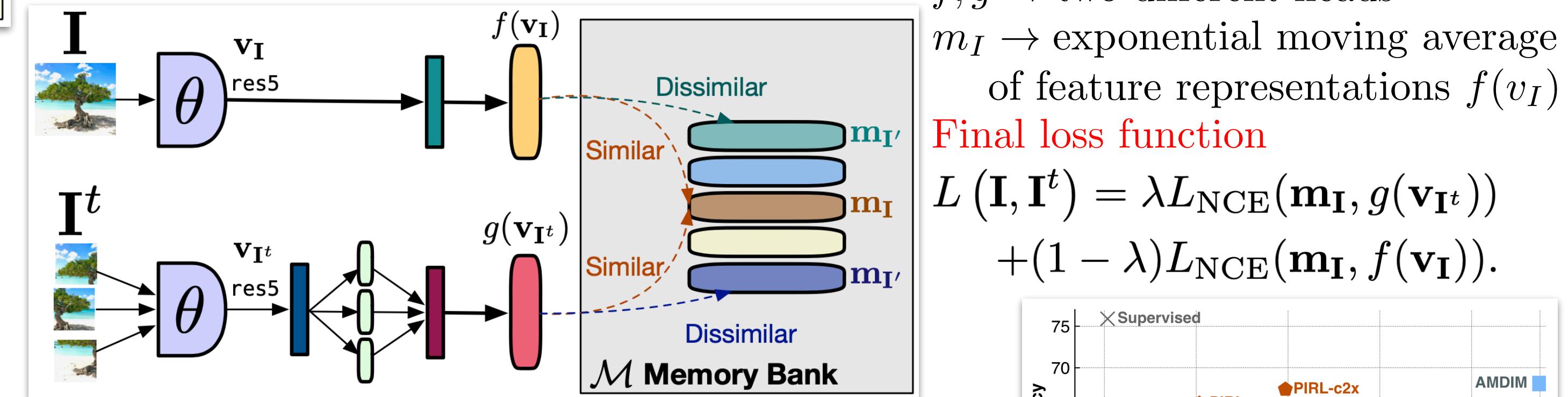
Loss Function
 $(I, I^t) \rightarrow$ “positive” pair
 $N \rightarrow$ number of corresponding “negative” pairs (computing features from other images $I' \neq I$)

$$h(\mathbf{v}_I, \mathbf{v}_{I^t}) = \frac{\exp \left(\frac{s(\mathbf{v}_I, \mathbf{v}_{I^t})}{\tau} \right)}{\exp \left(\frac{s(\mathbf{v}_I, \mathbf{v}_{I^t})}{\tau} \right) + |\mathcal{D}_N| / |\mathcal{D}|} \rightarrow$$

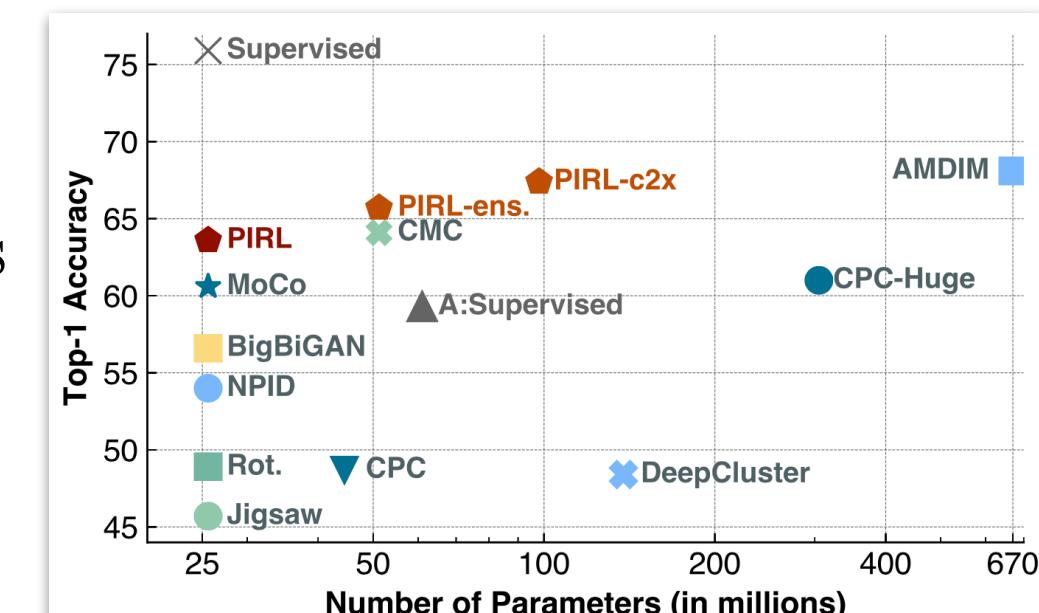
probability of the binary event that (I, I_t) originates from data distribution

$s(\cdot, \cdot) \rightarrow$ cosine similarity

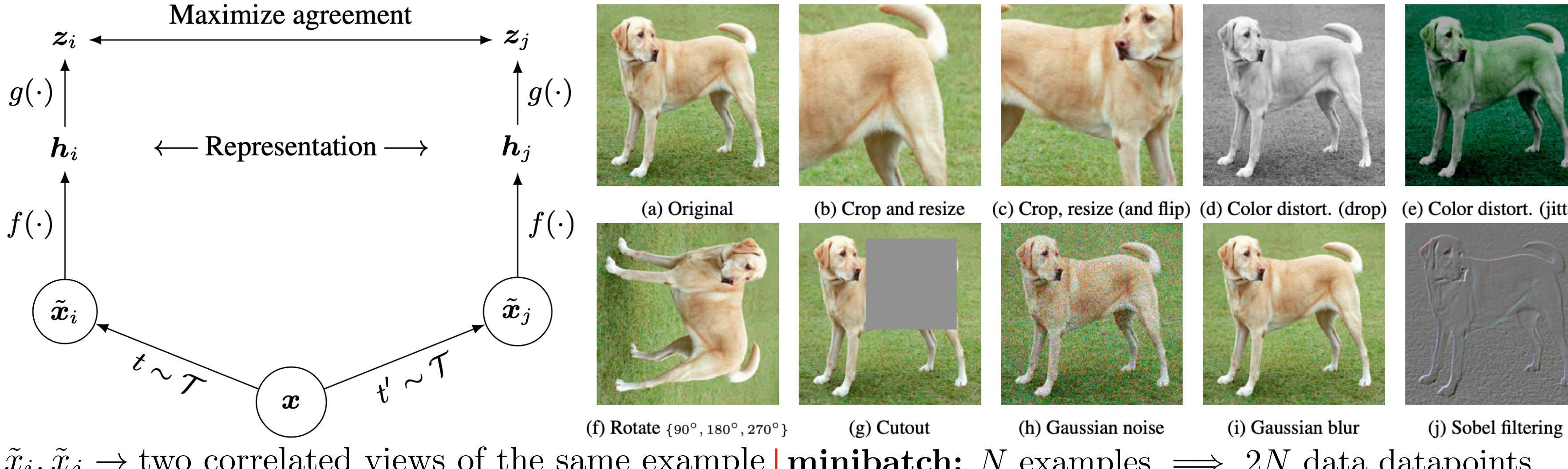
$$L_{NCE}(I, I^t) = -\log [h(f(\mathbf{v}_I), g(\mathbf{v}_{I^t}))] - \sum_{I' \in \mathcal{D}_N} \log [1 - h(g(\mathbf{v}_I^t), f(\mathbf{v}_{I'}))] \quad \text{noise contrastive estimator}$$



Final loss function

$$L(\mathbf{I}, \mathbf{I}^t) = \lambda L_{NCE}(\mathbf{m}_I, g(\mathbf{v}_{I^t})) + (1 - \lambda) L_{NCE}(\mathbf{m}_I, f(\mathbf{v}_I)).$$


A Simple Framework for Contrastive Learning of Visual Representations



Data Augmentation

Random cropping and resizing to the original size

Random color distortions

Random Gaussian blur

Base Encoder

$$h_i = f(\tilde{x}_i) = \text{ResNet}(\tilde{x}_i)$$

$h_i \in \mathbb{R}^d \rightarrow$ output after average pooling layer

Projection Head

$$z_i = g(h_i) = W^2 \sigma(W^1 h_i)$$

ReLU

Contrastive Loss

Contrastive Prediction Task: Given a set $\{\tilde{x}_k\}$ including a positive pair of examples \tilde{x}_i and \tilde{x}_j , identify \tilde{x}_j in $\{\tilde{x}_k\}_{k \neq i}$ for a given \tilde{x}_i .

minibatch: N examples $\implies 2N$ data datapoints

Given a positive pair, treat the other $2(N - 1)$ augmented examples as negatives

$$\text{sim}(u, v) = u^T v / \|u\| \|v\| \rightarrow \text{cosine similarity}$$

$$\ell_{i,j} = -\log \frac{\exp(\text{sim}(z_i, z_j)/\tau)}{\sum_{k=1}^{2N} \mathbb{1}_{[k \neq i]} \exp(\text{sim}(z_i, z_k)/\tau)}$$

NT-Xent Loss (normalized temperature-scaled cross entropy loss)

$\tau \rightarrow$ temperature

The final loss is computed over all positive pairs (i, j) & (j, i) .

Transfer learning performance

	Food	CIFAR10	CIFAR100	Birdsnap	SUN397	Cars	Aircraft	VOC2007	DTD	Pets	Caltech-101	Flowers
<i>Linear evaluation:</i>												
SimCLR (ours)	76.9	95.3	80.2	48.4	65.9	60.0	61.2	84.2	78.9	89.2	93.9	95.0
Supervised	75.2	95.7	81.2	56.4	64.9	68.8	63.8	83.8	78.7	92.3	94.1	94.2
<i>Fine-tuned:</i>												
SimCLR (ours)	89.4	98.6	89.0	78.2	68.1	92.1	87.0	86.6	77.8	92.1	94.1	97.6
Supervised	88.7	98.3	88.7	77.8	67.0	91.4	88.0	86.5	78.8	93.2	94.2	98.0
Random init	88.3	96.0	81.9	77.0	53.7	91.3	84.8	69.4	64.1	82.7	72.5	92.5

Self-supervised learning on ImageNet

Method	Architecture	Param (M)	Top 1	Top 5
<i>Methods using ResNet-50:</i>				
Local Agg.	ResNet-50	24	60.2	-
MoCo	ResNet-50	24	60.6	-
PIRL	ResNet-50	24	63.6	-
CPC v2	ResNet-50	24	63.8	85.3
SimCLR (ours)	ResNet-50	24	69.3	89.0

Methods using other architectures:

Rotation	RevNet-50 (4×)	86	55.4	-
BigBiGAN	RevNet-50 (4×)	86	61.3	81.9
AMDIM	Custom-ResNet	626	68.1	-
CMC	ResNet-50 (2×)	188	68.4	88.2
MoCo	ResNet-50 (4×)	375	68.6	-
CPC v2	ResNet-161 (*)	305	71.5	90.1
SimCLR (ours)	ResNet-50 (2×)	94	74.2	92.0
SimCLR (ours)	ResNet-50 (4×)	375	76.5	93.2

Semi-supervised learning on ImageNet

Method	Architecture	Label fraction	
		1%	10%
Supervised baseline	ResNet-50	48.4	80.4
Top 5			

Methods using other label-propagation:

Pseudo-label	ResNet-50	51.6	82.4
VAT+Entropy Min.	ResNet-50	47.0	83.4
UDA (w. RandAug)	ResNet-50	-	88.5
FixMatch (w. RandAug)	ResNet-50	-	89.1
S4L (Rot+VAT+En. M.)	ResNet-50 (4×)	-	91.2

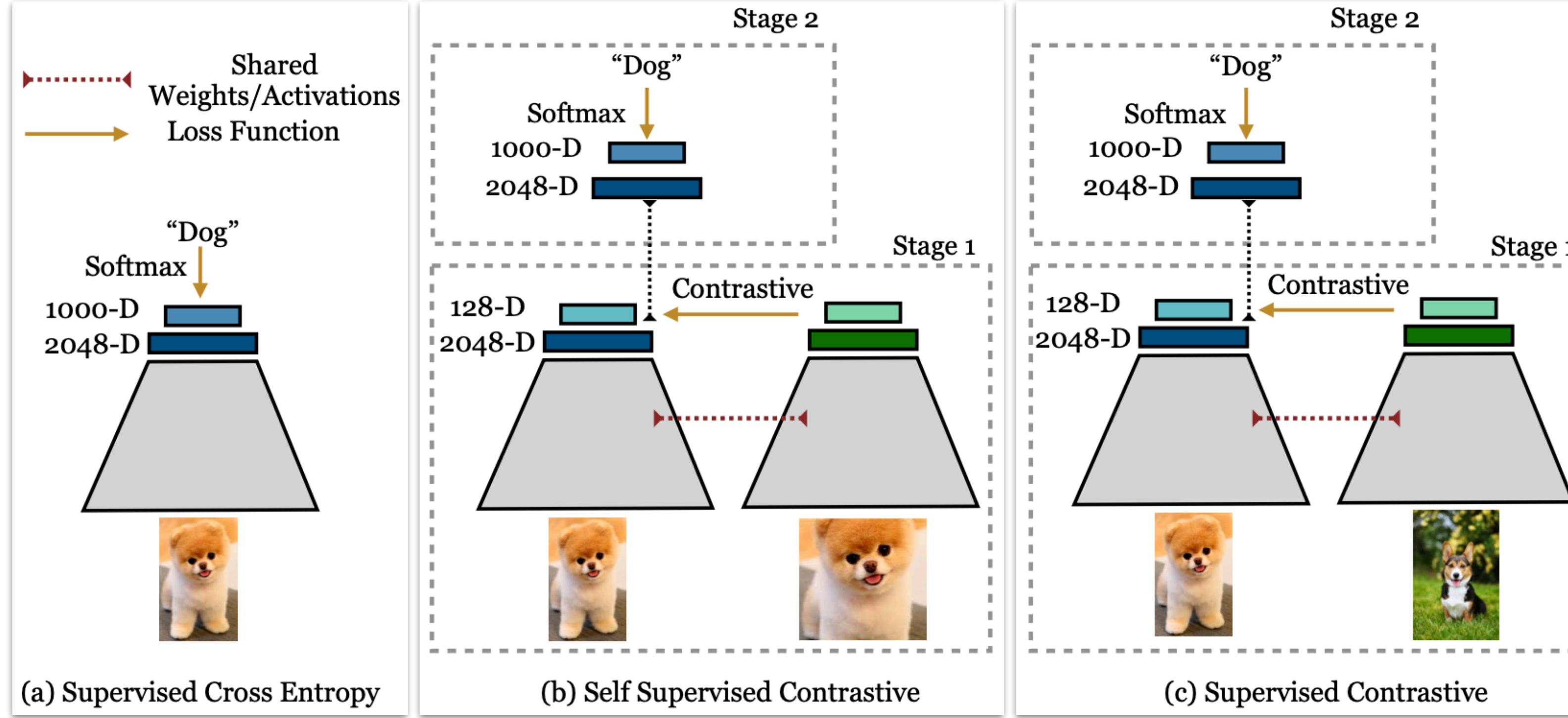
Methods using representation learning only:

InstDisc	ResNet-50	39.2	77.4
BigBiGAN	RevNet-50 (4×)	55.2	78.8
PIRL	ResNet-50	57.2	83.8
CPC v2	ResNet-161(*)	77.9	91.2
SimCLR (ours)	ResNet-50	75.5	87.8
SimCLR (ours)	ResNet-50 (2×)	83.0	91.2
SimCLR (ours)	ResNet-50 (4×)	85.8	92.6



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Supervised Contrastive Learning



Supervised Contrastive (SupCon) Loss

$\text{Aug}(\cdot)$ → data augmentation module

$\tilde{x} = \text{Aug}(x)$ → for each sample x generate two random augmentations

$\text{Enc}(\cdot)$ → encoder network

$r = \text{Enc}(x) \in \mathbb{R}^{D_E}$ → maps x to a representation vector

↳ normalized to the unit hyper-sphere ($D_E = 2048$)

$\text{Proj}(\cdot)$ → projection network – MLP (to be discarded)

$z = \text{Proj}(r) \in \mathbb{R}^{D_P}$ → maps r to a vector z ($D_P = 128$)

↳ normalized to the unit hyper-sphere

$\{x_k, y_k\}_{k=1}^N \rightarrow$ a set of N randomly sampled example/label pairs (batch)

$\{\tilde{x}_\ell, \tilde{y}_\ell\}_{\ell=1}^{2N} \rightarrow$ corresponding batch used for training (multi-viewed batch)

$\tilde{x}_{2k}, \tilde{x}_{2k-1} \rightarrow$ two random augmentations (a.k.a “views”) of x_k for $k = 1, \dots, N$

$\tilde{y}_{2k} = \tilde{y}_{2k-1} = y_k$

Self-Supervised Contrastive Loss

$i \in I := \{1, \dots, 2N\} \rightarrow$ index of an arbitrary augmented sample

$j(i) \rightarrow$ index of the other augmented sample originating from the same source sample

$$\mathcal{L}^{self} = \sum_{i \in I} \mathcal{L}_i^{self} = - \sum_{i \in I} \log \frac{\exp(z_i \cdot z_{j(i)}/\tau)}{\sum_{a \in A(i)} \exp(z_i \cdot z_a/\tau)}$$

$$z_\ell = \text{Proj}(\text{Enc}(\tilde{x}_\ell)) \in \mathbb{R}^{D_P}$$

$$A(i) = I \setminus \{i\}$$

$i \rightarrow$ anchor, $j(i) \rightarrow$ positive, $k \in A(i) \setminus \{j(i)\} \rightarrow$ negatives
one positive and $2(N - 1)$ negatives

Supervised Contrastive Loss

$P(i) \equiv \{p \in A(i) : \tilde{y}_p = \tilde{y}_i\} \rightarrow$ set of indices of all positives in the multi-viewed batch distinct from i

$$\mathcal{L}_{out}^{sup} = \sum_{i \in I} \mathcal{L}_{out,i}^{sup} = \sum_{i \in I} \frac{-1}{|P(i)|} \sum_{p \in P(i)} \log \frac{\exp(z_i \cdot z_p/\tau)}{\sum_{a \in A(i)} \exp(z_i \cdot z_a/\tau)}$$

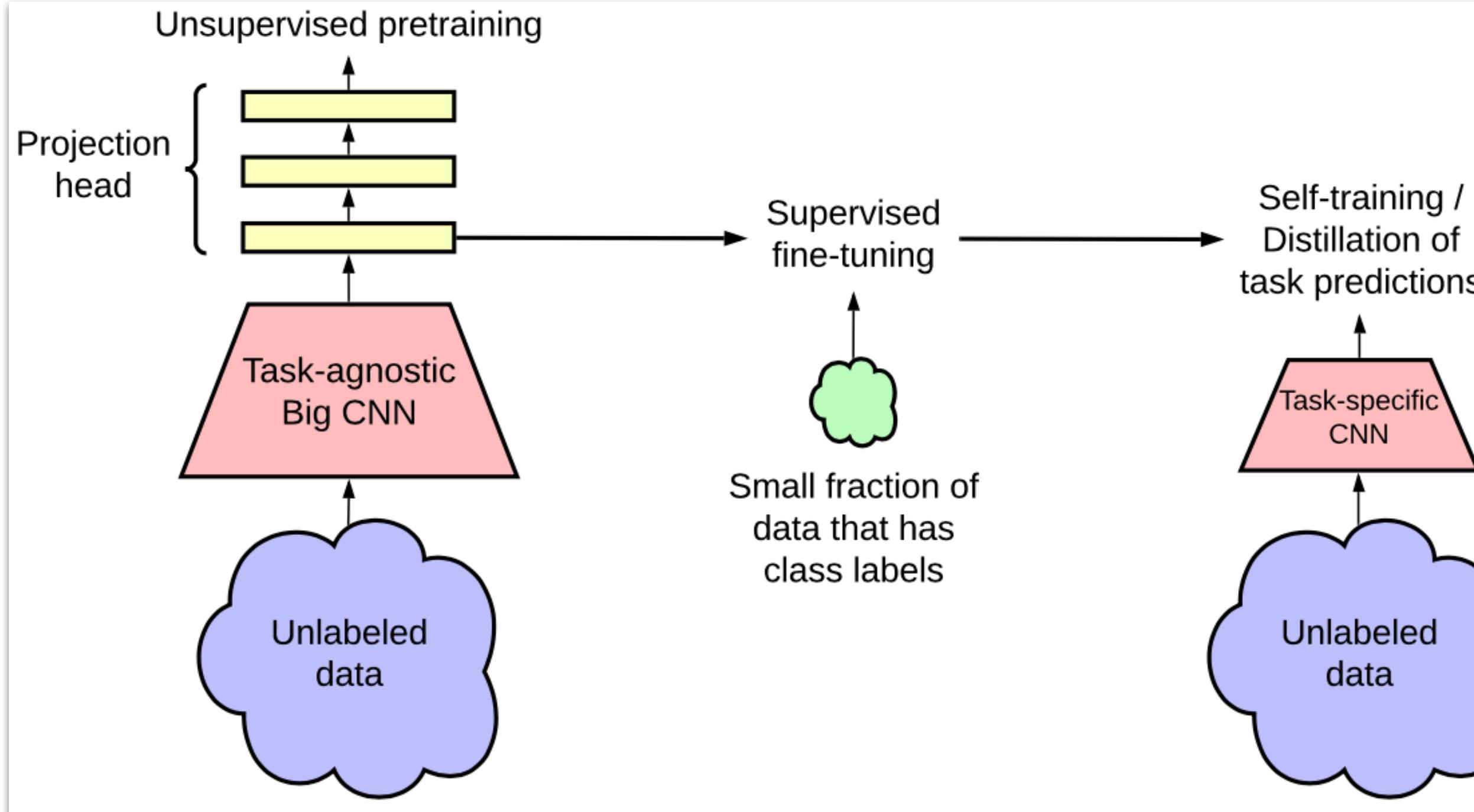
– Generalization to an arbitrary number of positives

– Intrinsic ability to perform hard positive/negative mining



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Big Self-Supervised Models are Strong Semi-Supervised Learners



Learning from few labeled examples

- (1) unsupervised or self-supervised pretraining
- (2) supervised fine-tuning, and
- (3) distillation using unlabeled data

Self-supervised pretraining with SimCLRv2

$x_{2k-1}, x_{2k} \rightarrow$ two views of the same example augmented twice in a randomly sampled mini-batch of images

augmented twice using random crop, color distortion and Gaussian blur

$$h_{2k-1}, h_{2k} = f(x_{2k-1}), f(x_{2k})$$

$f \rightarrow$ encoder network (e.g., ResNet)

Chen, Ting, et al. "Big self-supervised models are strong semi-supervised learners." *arXiv preprint arXiv:2006.10029* (2020).

$z_{2k-1}, z_{2k} = g(h_{2k-1}), g(h_{2k}) \rightarrow$ used for contrastive loss
 $g \rightarrow$ non-linear transformation network (MLP projection head)
 $i, j \rightarrow$ positive examples (i.e., augmented from the same image)

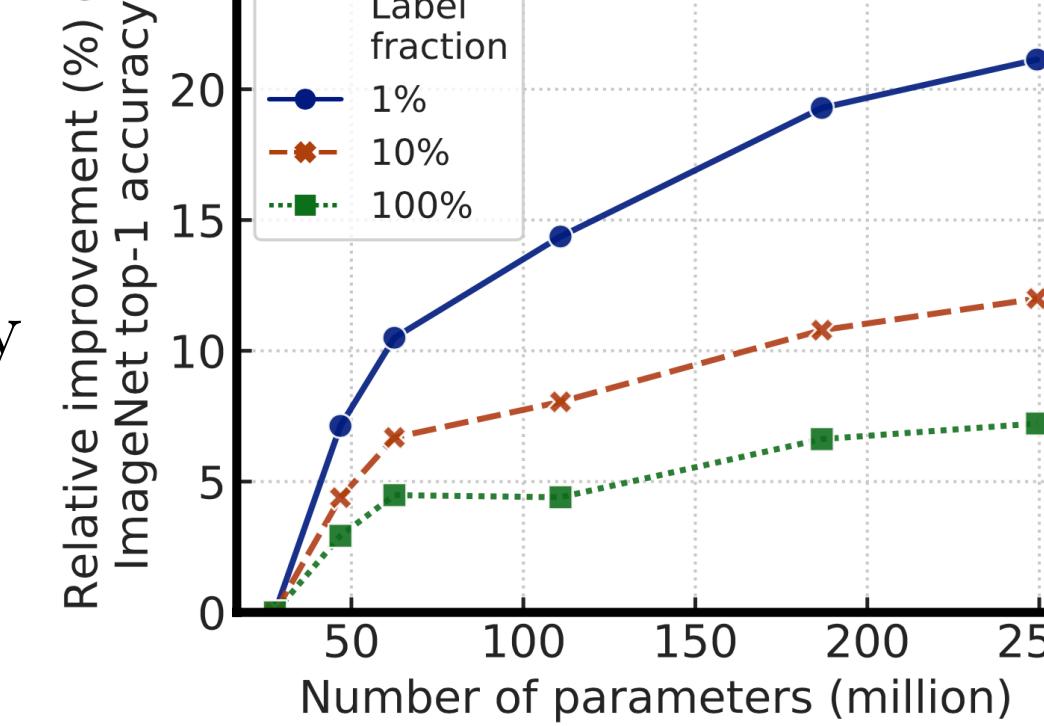
$$\ell_{i,j}^{\text{NT-Xent}} = -\log \frac{\exp(\text{sim}(z_i, z_j)/\tau)}{\sum_{k=1}^{2N} \mathbb{1}_{[k \neq i]} \exp(\text{sim}(z_i, z_k)/\tau)}$$

Improvements

- (1) Larger ResNet models
ResNet-152(3×+SK)
SK → selective kernels (a channel-wise attention mechanism)
- (2) Making g deeper and fine-tuning from a middle layer of g (instead of discarding g entirely)
- (3) Incorporate the memory mechanism from MOCO
A memory network (with a moving average of weights for stabilization) whose output will be buffered as negative examples

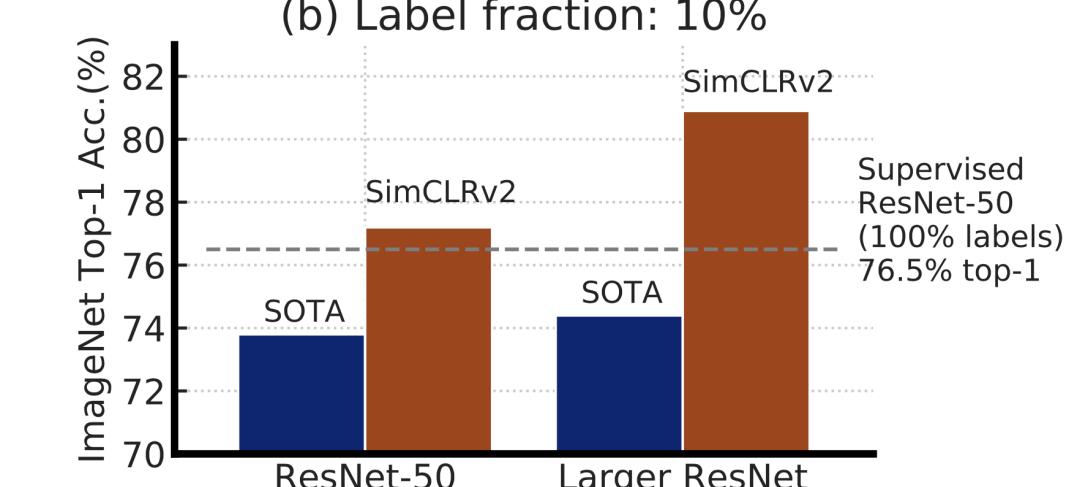
Bigger models yield larger gains when fine-tuning with fewer labeled examples

Self-training / knowledge distillation via unlabeled examples



Teacher: Fine-tuned network

$$\mathcal{L}^{\text{distill}} = - \sum_{x_i \in \mathcal{D}} \left[\sum_y P^T(y|x_i; \tau) \log P^S(y|x_i; \tau) \right]$$





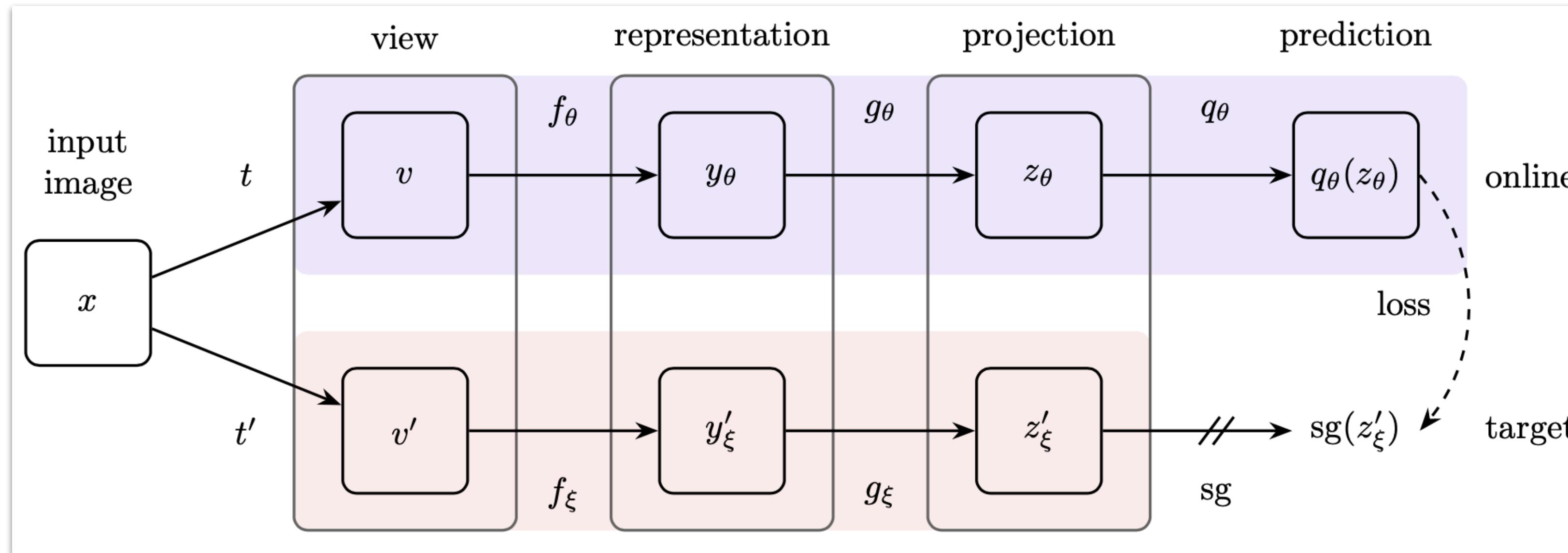
Boulder

Bootstrap your own latent: A new approach to self-supervised Learning

Bootstrap Your Own Latent (BYOL)

Self-supervised image representation learning without using negative pairs! (★)

Learn a representation y_θ which can be used for downstream tasks!



Three stages of the online network:

1. $f_\theta \rightarrow$ encoder
2. $g_\theta \rightarrow$ projector
3. $q_\theta \rightarrow$ predictor (★)

$\theta \rightarrow$ online parameters

$\xi \rightarrow$ parameters of the target network

$\xi \leftarrow \tau\xi + (1 - \tau)\theta$ (★)

$\mathcal{D} \rightarrow$ set of images

$x \sim \mathcal{D} \rightarrow$ an image sampled uniformly from \mathcal{D}

$\mathcal{T}, \mathcal{T}' \rightarrow$ two distributions of image augmentations

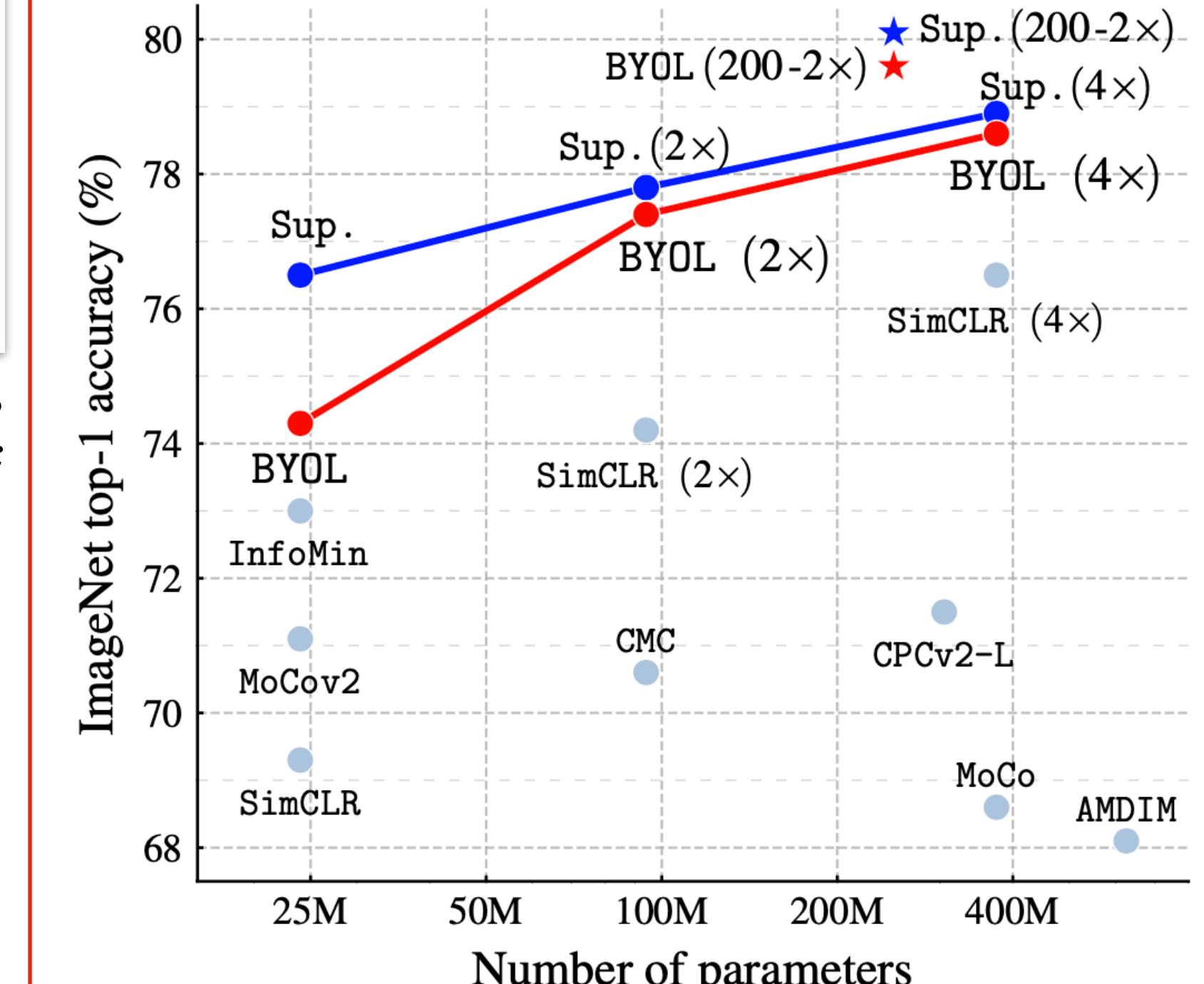
$v = t(x), v' = t'(x) \rightarrow$ two augmented views from x
 $t \sim \mathcal{T}, t' \sim \mathcal{T}'$
 $y_\theta = f_\theta(v) \rightarrow$ representation
 $z_\theta = g_\theta(y_\theta) \rightarrow$ projection
 $y'_\xi = f'_\xi(v') \rightarrow$ target representation
 $z'_\xi = g'_\xi(y'_\xi) \rightarrow$ target projection
 $q_\theta(z_\theta) \rightarrow$ prediction of z'_ξ
 $\bar{q}_\theta(z_\theta), \bar{z}'_\xi \rightarrow l_2$ normalized

$$\mathcal{L}_{\theta, \xi} \triangleq \|\bar{q}_\theta(z_\theta) - \bar{z}'_\xi\|_2^2 = 2 - 2 \cdot \frac{\langle q_\theta(z_\theta), z'_\xi \rangle}{\|q_\theta(z_\theta)\|_2 \cdot \|z'_\xi\|_2}$$

$$\mathcal{L}_{\text{BYOL}} = \mathcal{L}_{\theta, \xi} + \tilde{\mathcal{L}}_{\theta, \xi}$$

feeding v' to the online network and v to the target network

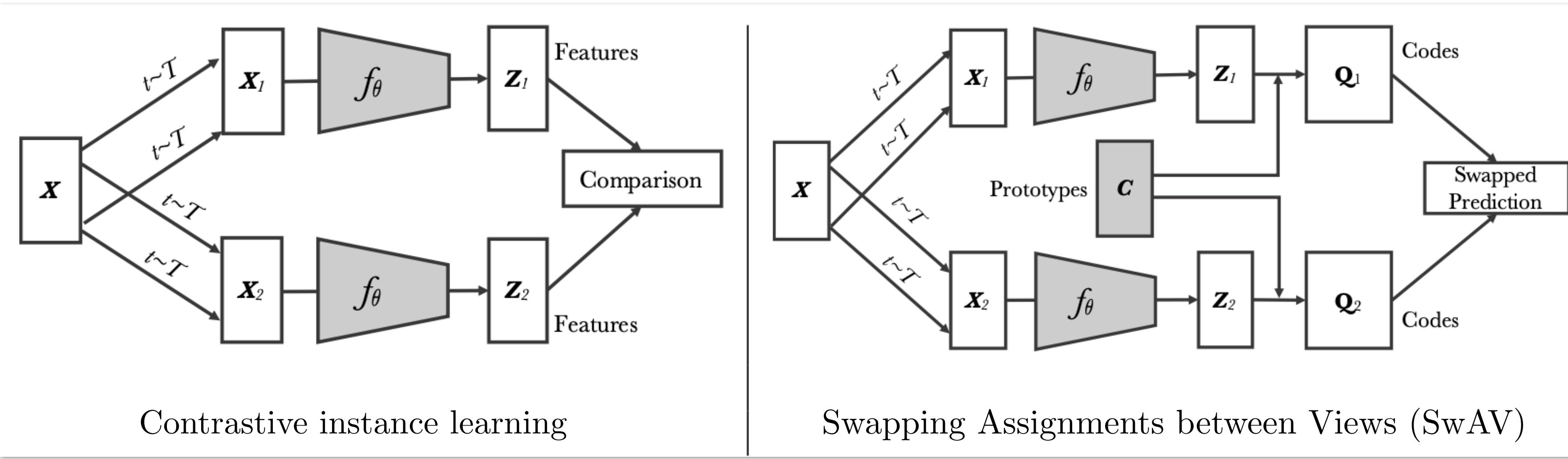
While this objective admits collapsed solutions, e.g., outputting the same vector for all images, the paper empirically shows that BYOL does not converge to such solutions. It hypothesizes (see Section 3.2) that the combination of (i) the addition of a predictor to the online network and (ii) the use of a slow-moving average of the online parameters as the target network encourages encoding more and more information within the online projection and avoids collapsed solutions.





Boulder

Unsupervised Learning of Visual Features by Contrasting Cluster Assignments



Contrastive instance learning

Swapping Assignments between Views (SwAV)

DeepCluster (offline) v.s. SwAV (online)

Offline: requires a pass over the entire dataset to form image “codes” (i.e., cluster assignments)

$z_t, z_s \rightarrow$ two image features from two different augmentations of the same image

$\{c_1, \dots, c_K\} \rightarrow$ set of K prototypes

$q_t, q_s \rightarrow$ codes (matching z_t, z_s to the set of K prototypes)

$L(z_t, z_s) = \ell(z_t, q_s) + \ell(z_s, q_t) \rightarrow$ “swapped” prediction problem

$\ell(z, q) \rightarrow$ measures the fit between features z and a code q

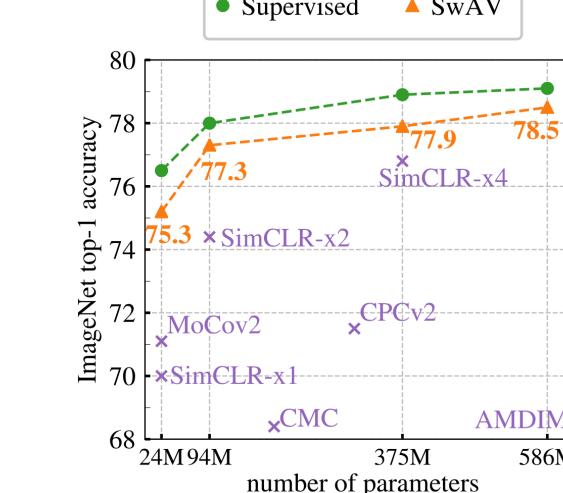
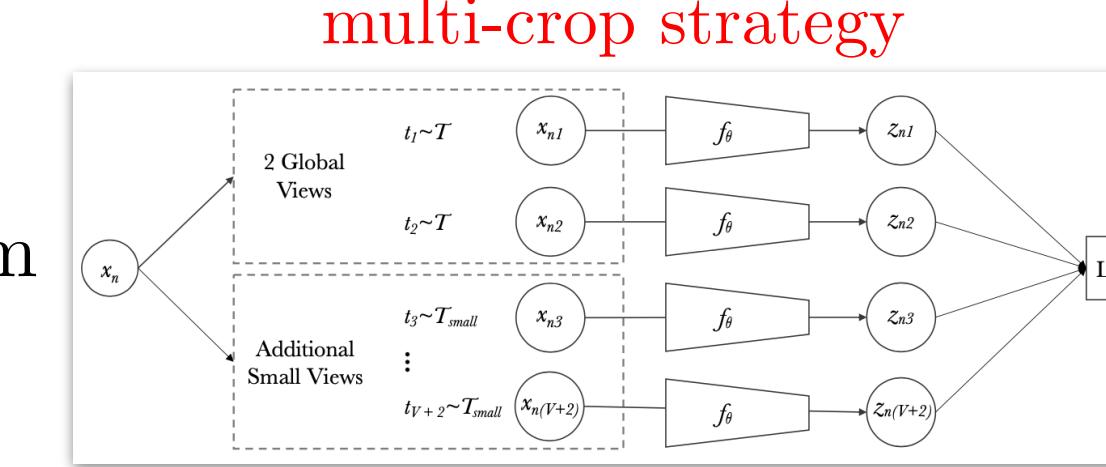
Online Clustering

$t \sim \mathcal{T} \rightarrow$ transformation t sampled from the set of image augmentations \mathcal{T}

$x_{nt} \rightarrow$ augmented view of image x_n transformed by t

$z_{nt} = \frac{f_\theta(x_{nt})}{\|f_\theta(x_{nt})\|_2} \rightarrow$ image features

$q_{nt} \rightarrow$ code computed by mapping z_{nt} to a set of K trainable prototype vectors



Swapped prediction problem

$$\ell(\mathbf{z}_t, \mathbf{q}_s) = - \sum_k \mathbf{q}_s^{(k)} \log \mathbf{p}_t^{(k)}$$

$$\mathbf{p}_t^{(k)} = \frac{\exp\left(\frac{1}{\tau} \mathbf{z}_t^\top \mathbf{c}_k\right)}{\sum_{k'} \exp\left(\frac{1}{\tau} \mathbf{z}_t^\top \mathbf{c}_{k'}\right)}$$

$$-\frac{1}{N} \sum_{n=1}^N \sum_{s,t \sim \mathcal{T}} \left[\frac{1}{\tau} \mathbf{z}_{nt}^\top \mathbf{C} \mathbf{q}_{ns} + \frac{1}{\tau} \mathbf{z}_{ns}^\top \mathbf{C} \mathbf{q}_{nt} \right]$$

$$- \log \sum_{k=1}^K \exp\left(\frac{\mathbf{z}_{nt}^\top \mathbf{c}_k}{\tau}\right) - \log \sum_{k=1}^K \exp\left(\frac{\mathbf{z}_{ns}^\top \mathbf{c}_k}{\tau}\right)$$

Minimized with respect to the prototypes C and the parameters θ

Computing codes online

Trivial solution: every image having the same code
 $Z = [z_1, \dots, z_B] \rightarrow B$ feature vectors

$B \rightarrow$ mini-batch size

$Q = [q_1, \dots, q_B] \rightarrow$ codes

$$\max_{\mathbf{Q} \in \mathcal{Q}} \text{Tr}(\mathbf{Q}^\top \mathbf{C}^\top \mathbf{Z}) + \varepsilon H(\mathbf{Q})$$

$$H(\mathbf{Q}) = - \sum_{ij} \mathbf{Q}_{ij} \log \mathbf{Q}_{ij} \rightarrow \text{entropy}$$

$$\mathcal{Q} = \left\{ \mathbf{Q} \in \mathbb{R}_+^{K \times B} \mid \mathbf{Q} \mathbf{1}_B = \frac{1}{K} \mathbf{1}_K, \mathbf{Q}^\top \mathbf{1}_K = \frac{1}{B} \mathbf{1}_B \right\}$$

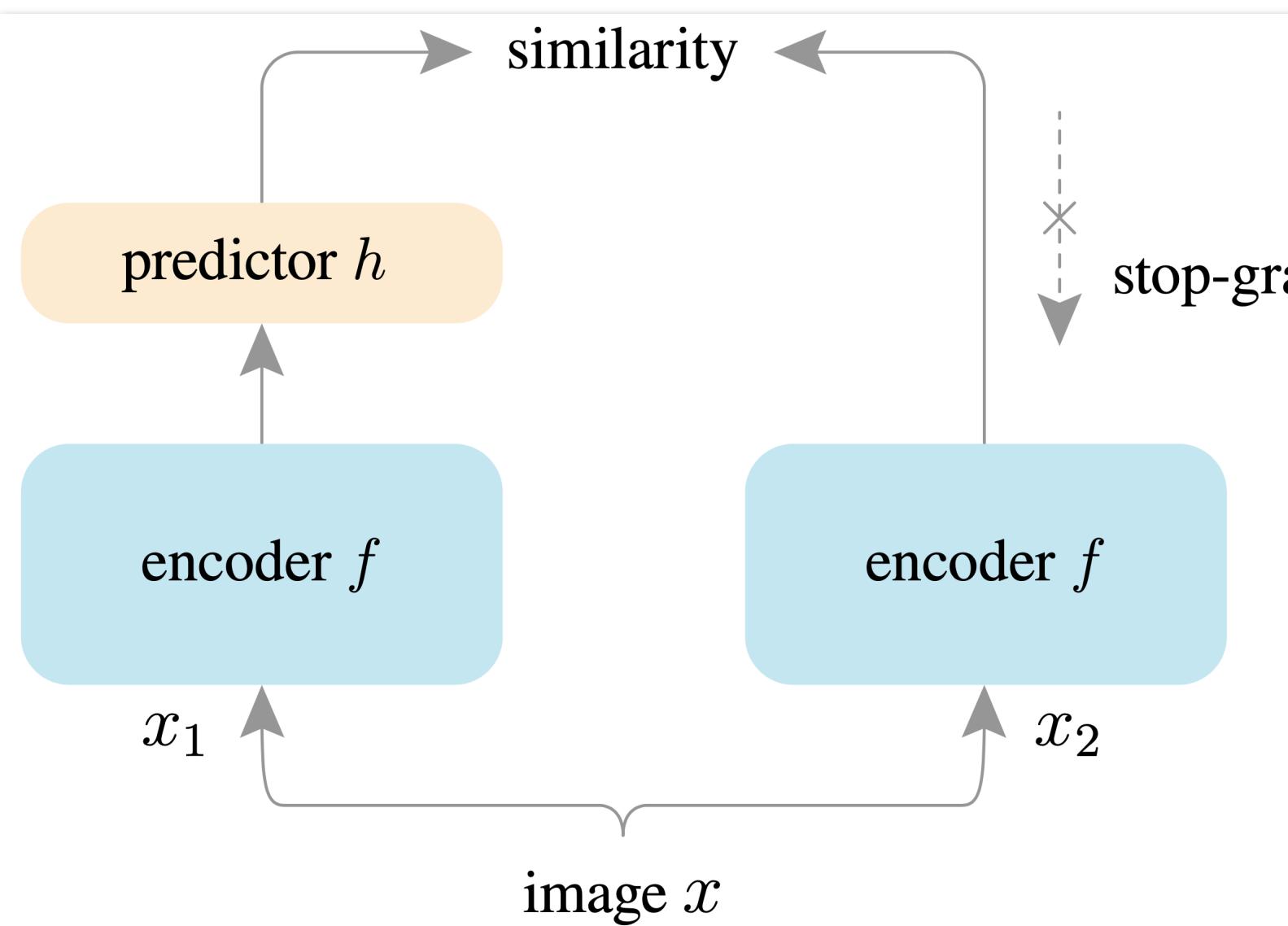
Enforce that on average each prototype is selected at least B/K times in the batch

Three iterations of iterative Sinkhorn-Knopp algorithm!



Boulder

Exploring Simple Siamese Representation Learning



$x_1, x_2 \rightarrow$ two randomly augmented views of an image x

$f \rightarrow$ encoder network (ResNet backbone and a projection MLP head)

$h \rightarrow$ prediction MLP head

$$p_1 = h(\underbrace{f(x_1)}_{z_1})$$

$$p_2 = h(\underbrace{f(x_2)}_{z_2})$$

$$\mathcal{L} = \frac{1}{2}\mathcal{D}(p_1, z_2) + \frac{1}{2}\mathcal{D}(p_2, z_1) \rightarrow \text{symmetrized loss}$$

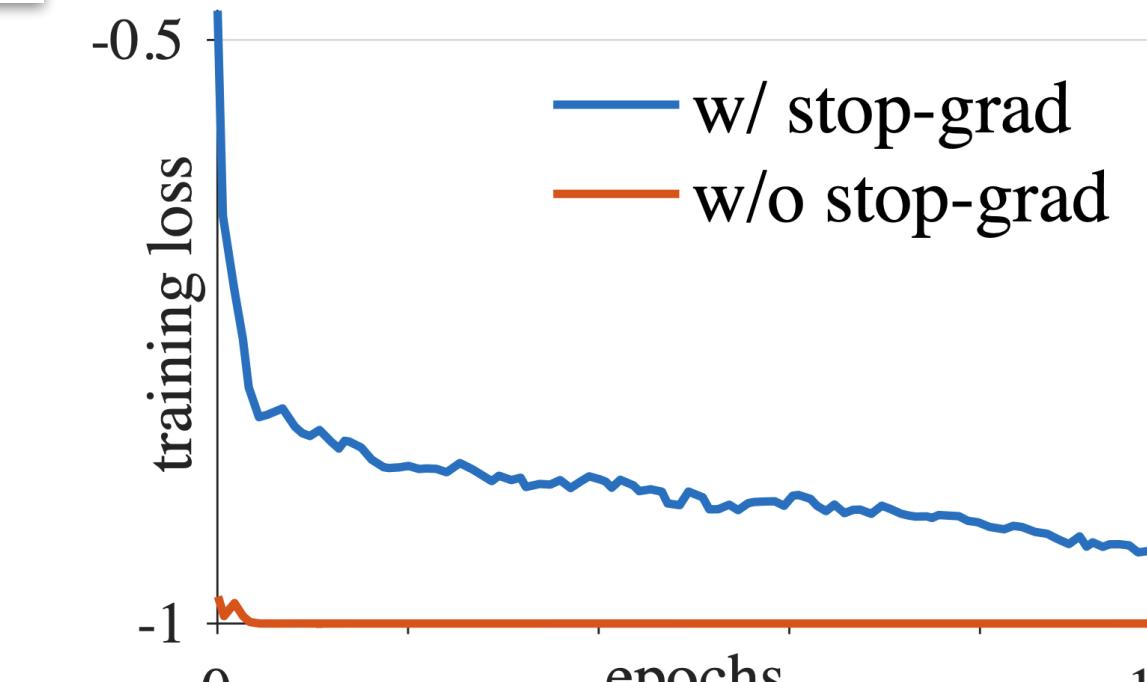
stop gradients

$$\mathcal{D}(p_1, z_2) = -\frac{p_1}{\|p_1\|_2} \frac{z_2}{\|z_2\|_2}$$

\rightarrow negative cosine similarity (to be minimized)
equivalent to the mean squared error of l_2 -normalized vectors, up to a scale of 2

SimSiam uses none of the following:

- 1) negative sample pairs
- 2) large batches
- 3) momentum encoders



method	batch size	negative pairs	momentum encoder	100 ep	200 ep	400 ep	800 ep
SimCLR (repro.+)	4096	✓		66.5	68.3	69.8	70.4
MoCo v2 (repro.+)	256	✓	✓	67.4	69.9	71.0	72.2
BYOL (repro.)	4096		✓	66.5	70.6	73.2	74.3
SwAV (repro.+)	4096			66.5	69.1	70.7	71.8
SimSiam	256			68.1	70.0	70.8	71.3

Effect of batch sizes

	batch size	64	128	256	512	1024	2048	4096
	acc. (%)	66.1	67.3	68.1	68.1	68.0	67.9	64.0

Effect of batch normalization on MLP heads

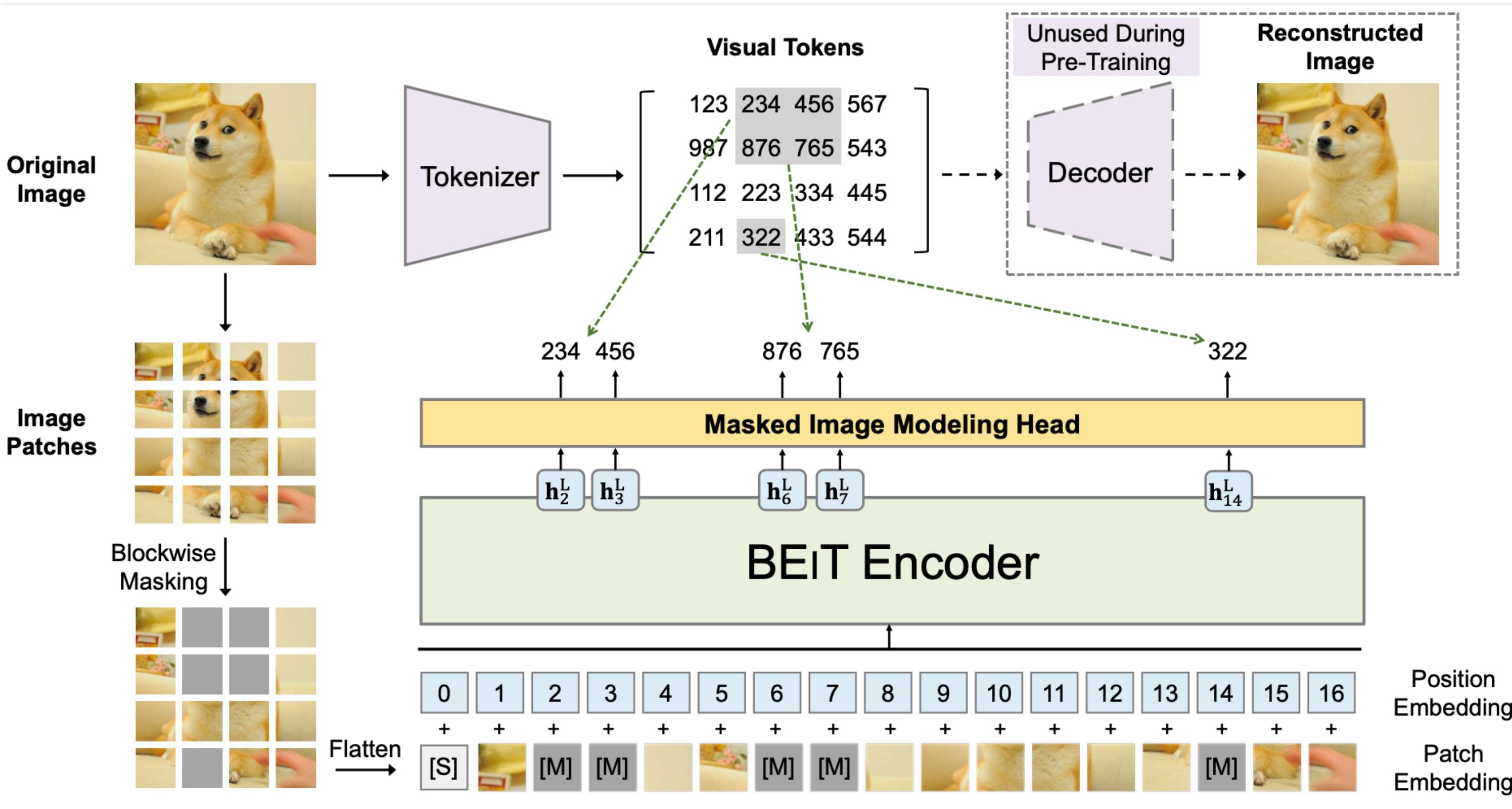
	case	proj. MLP's BN hidden	proj. MLP's BN output	pred. MLP's BN hidden	pred. MLP's BN output	acc. (%)
(a)	none	-	-	-	-	34.6
(b)	hidden-only	✓	-	✓	-	67.4
(c)	default	✓	✓	✓	-	68.1
(d)	all	✓	✓	✓	✓	unstable



Boulder

BEiT: BERT Pre-Training of Image Transformers

Bidirectional Encoder representation from Image Transformers



Visual Token

image tokenizer (discrete variational autoencoder)

tokenize $x \in \mathbb{R}^{H \times W \times C}$ into $z \in \mathcal{V}^{h \times w}$

$\mathcal{V} = \{1, \dots, |\mathcal{V}|\} \rightarrow$ vocabulary containing discrete token indices

<https://github.com/openai/DALL-E>

$q_\phi(z|x) \rightarrow$ tokenizer (maps image x into discrete tokens z according to a visual codebook/vocabulary)

Bao, Hangbo, Li Dong, and Furu Wei. "BEiT: BERT Pre-Training of Image Transformers." *arXiv preprint arXiv:2106.08254* (2021).

$p_\psi(x|z) \rightarrow$ decoder (reconstruct the input image x based on the visual tokens z)

$$\max_{\phi, \psi} \mathbb{E}_{z \sim q_\phi(z|x)} [\log p_\psi(x|z)] - \text{KL}[q_\phi(z|x) \parallel p(z)]$$

Gumbel-softmax relaxation

Algorithm 1 Blockwise Masking

Input: $N (= h \times w)$ image patches

Output: Masked positions \mathcal{M}

$$\mathcal{M} \leftarrow \{\}$$

repeat

$$s \leftarrow \text{Rand}(16, 0.4N - |\mathcal{M}|)$$

$$r \leftarrow \text{Rand}(0.3, \frac{1}{0.3})$$

$$a \leftarrow \sqrt{s \cdot r}; b \leftarrow \sqrt{s/r}$$

$$t \leftarrow \text{Rand}(0, h - a); l \leftarrow \text{Rand}(0, w - b)$$

$$\mathcal{M} \leftarrow \mathcal{M} \cup \{(i, j) : i \in [t, t + a], j \in [l, l + b]\}$$

until $|\mathcal{M}| > 0.4N$

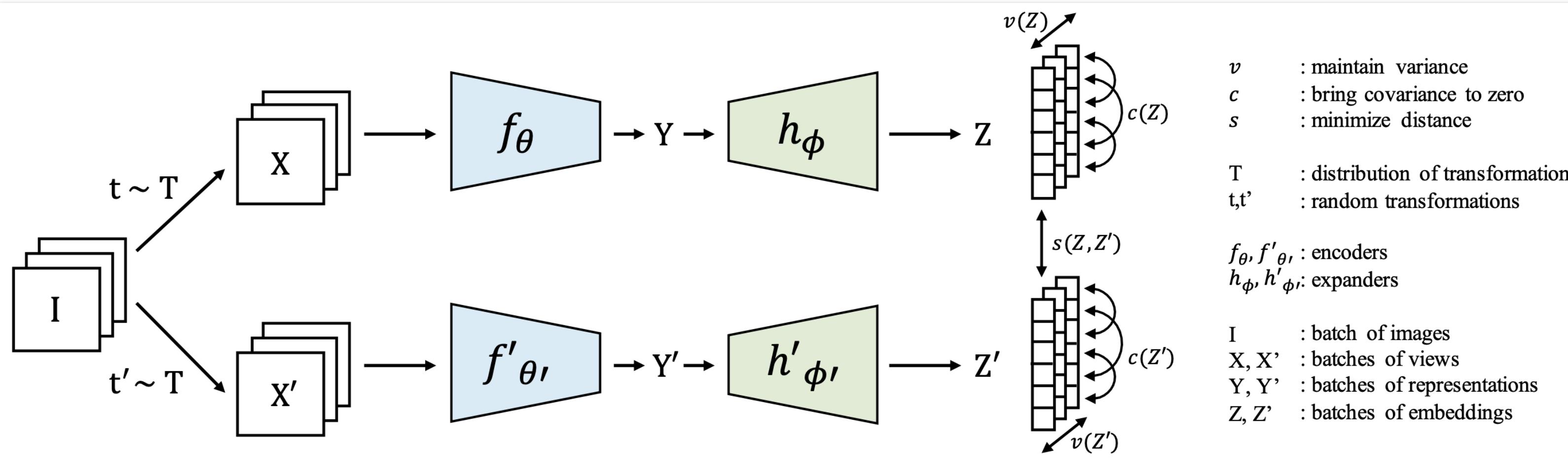
\triangleright Masking ratio is 40%

return \mathcal{M}

Models	CIFAR-100	ImageNet
<i>Training from scratch (i.e., random initialization)</i>		
ViT ₃₈₄ (Dosovitskiy et al., 2020)	48.5*	77.9
DeiT (Touvron et al., 2020)	n/a	81.8
<i>Supervised Pre-Training on ImageNet-1K (using labeled data)</i>		
ViT ₃₈₄ (Dosovitskiy et al., 2020)	87.1	77.9
DeiT (Touvron et al., 2020)	90.8	81.8
<i>Self-Supervised Pre-Training on ImageNet-1K (without labeled data)</i>		
iGPT-1.36B [†] (Chen et al., 2020a)	n/a	66.5
ViT ₃₈₄ -JFT300M [‡] (Dosovitskiy et al., 2020)	n/a	79.9
DINO (Caron et al., 2021)	91.7	82.8
MoCo v3 (Chen et al., 2021)	87.1	n/a
BEiT (ours)	90.1	83.2
<i>Self-Supervised Pre-Training, and Intermediate Fine-Tuning on ImageNet-1K</i>		
BEiT (ours)	91.8	83.2

Top-1 accuracy of image classification

VICReg: Variance-Invariance-Covariance Regularization for Self-Supervised Learning



Method	Linear	
	Top-1	Top-5
Supervised	76.5	-
MoCo He et al. (2020)	60.6	-
PIRL Misra & Maaten (2020)	63.6	-
CPC v2 Hénaff et al. (2019)	63.8	-
CMC Tian et al. (2019)	66.2	-
SimCLR Chen et al. (2020a)	69.3	89.0
MoCo v2 Chen et al. (2020c)	71.1	-
SimSiam Chen & He (2020)	71.3	-
SwAV Caron et al. (2020)	71.8	-
InfoMin Aug Tian et al. (2020)	73.0	91.1
OBoW Gidaris et al. (2021)	73.8	-
BYOL Grill et al. (2020)	74.3	91.6
SwAV (w/ multi-crop) Caron et al. (2020)	75.3	-
Barlow Twins Zbontar et al. (2021)	73.2	91.0
VICReg (ours)	73.2	91.1

$i \sim \mathcal{D} \rightarrow$ an image sampled from a dataset

$t, t' \sim \mathcal{T} \rightarrow$ two transformations sampled from a distribution

$x = t(i), x' = t'(i) \rightarrow$ two different views of i

random crops of the image, followed by color distortions

$y = f_\theta(x), y' = f_\theta(x') \rightarrow$ representations

$f_\theta \rightarrow$ encoder (outputs the representations used for downstream tasks)

$z = h_\phi(y), z' = h_\phi(y') \rightarrow$ embeddings

$h_\phi \rightarrow$ expander (maps the representations into an embedding space

where the loss function will be computed)

$Z = [z_1, \dots, z_n], Z' = [z'_1, \dots, z'_n] \rightarrow$ two batches composed of n vectors of dimension d

$v(Z) = \frac{1}{d} \sum_{j=1}^d \max(0, \gamma - S(z^j, \epsilon)) \rightarrow$ variance regularization term

(hinge function on the standard deviation of the embeddings along the batch dimension)

$S(x, \epsilon) = \sqrt{\text{Var}(x) + \epsilon} \rightarrow$ regularized standard deviation

$$\text{covariance matrix of } Z = \frac{1}{n-1} \sum_{i=1}^n (z_i - \bar{z})(z_i - \bar{z})^T, \quad \text{where } \bar{z} = \frac{1}{n} \sum_{i=1}^n z_i$$

$$\text{covariance regularization} \leftarrow c(Z) = \frac{1}{d} \sum_{i \neq j} [C(Z)]_{i,j}^2$$

encourages the off-diagonal terms to be close to zero (decorrelating the different dimensions of the embeddings and preventing them from encoding similar information)

$$s(Z, Z') = \frac{1}{n} \sum_i \|z_i - z'_i\|_2^2$$

$$\ell(Z, Z') = \lambda s(Z, Z') + \mu [v(Z) + v(Z')] + \nu [c(Z) + c(Z')]$$

$$\mathcal{L} = \sum_{I \in \mathcal{D}} \sum_{t, t' \sim \mathcal{T}} \ell(Z^I, Z'^I)$$

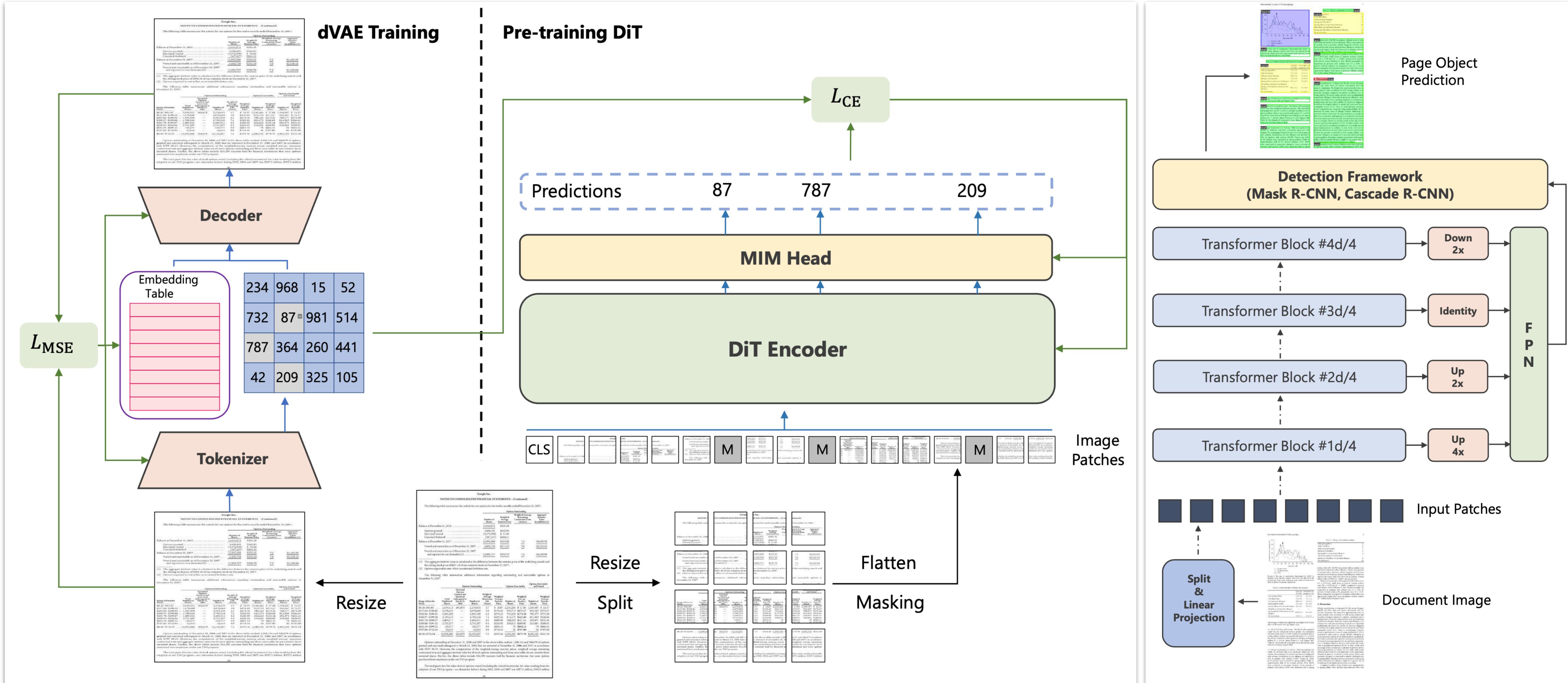


Boulder

DiT: Self-supervised Pre-training for Document Image Transformer

forms, invoice/receipts, reports, etc.

document image classification, document layout analysis, as well as table detection





Boulder

Unsupervised Semantic Segmentation by Distilling Feature Correspondences

separate feature learning from cluster compactification

STEGO (Self-supervised Transformer with Energy-based Graph Optimization)

- CocoStuff
- Cityscapes

Feature Correspondences Predict Class Co-occurrence

$f \in \mathbb{R}^{CWH}, g \in \mathbb{R}^{CIJ} \rightarrow$ feature tensors for two different images

$$F_{hwij} := \sum_c \frac{f_{chw}}{|f_{hw}|} \frac{g_{cij}}{|g_{ij}|} \rightarrow \text{feature correspondence tensor}$$

$k \in \mathcal{C}^{HW}, l \in \mathcal{C}^{IJ} \rightarrow$ ground-truth semantic segmentation labels

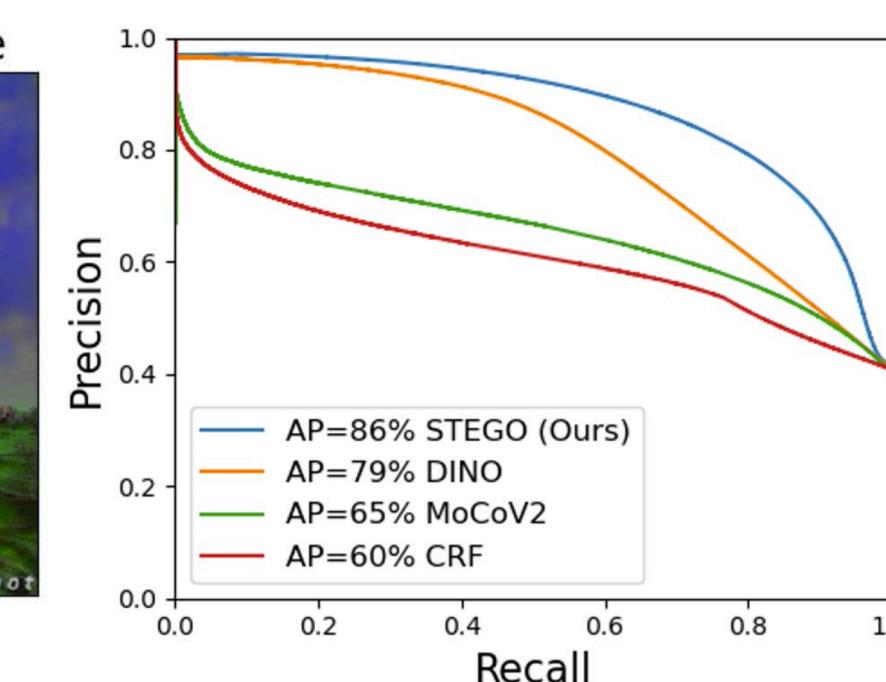
$\mathcal{C} \rightarrow$ set of possible classes

$$L_{hwij} := \begin{cases} 1, & \text{if } l_{hw} = k_{ij} \\ 0, & \text{if } l_{hw} \neq k_{ij} \end{cases} \rightarrow \text{label co-occurrence tensor}$$

examine how well F (logits) predicts L



Feature correspondences from DINO.



Distilling Feature Correspondences

$S \rightarrow$ segmentation head (MLP)

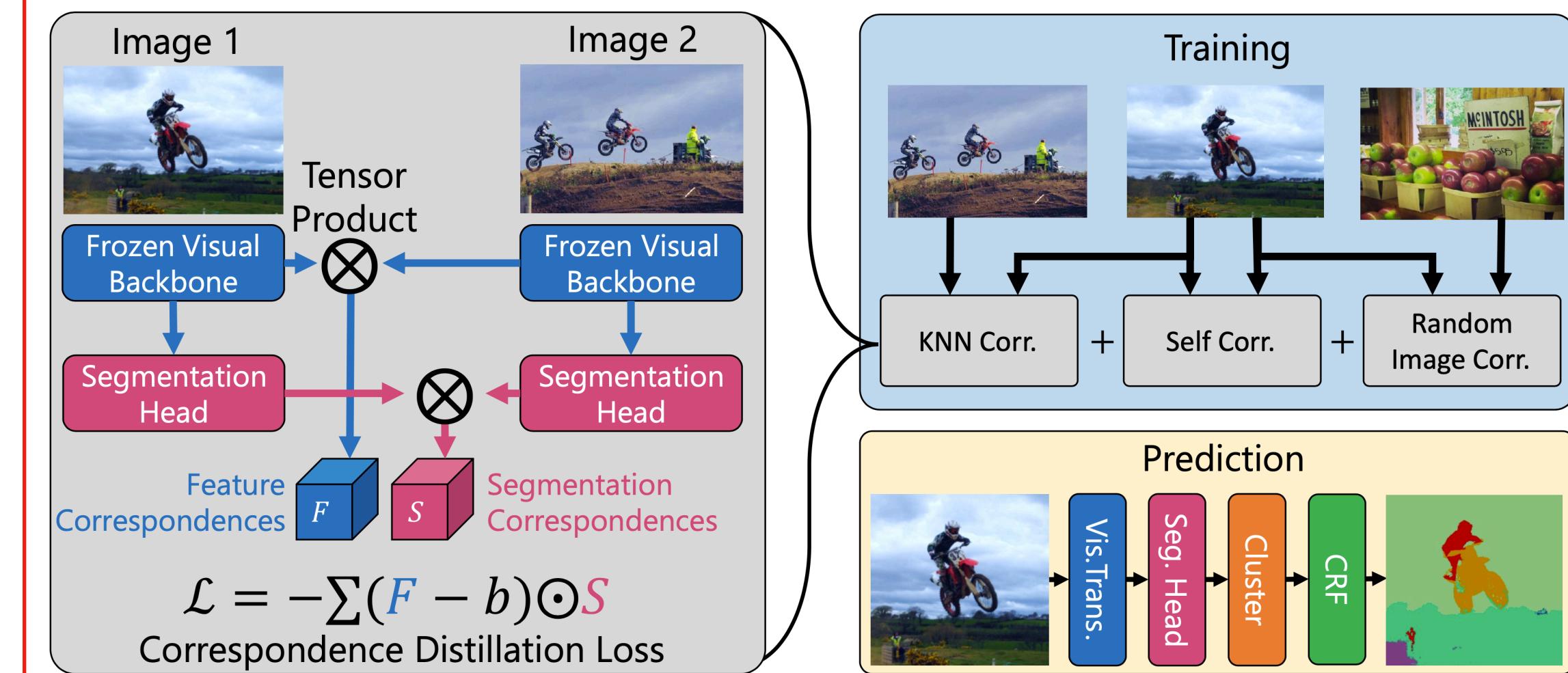
$s := S(f), t := S(g) \rightarrow$ semantic feature of two feature tensors f, g from a pair of images x, y

$S \rightarrow$ segmentation correlation tensor from s and t

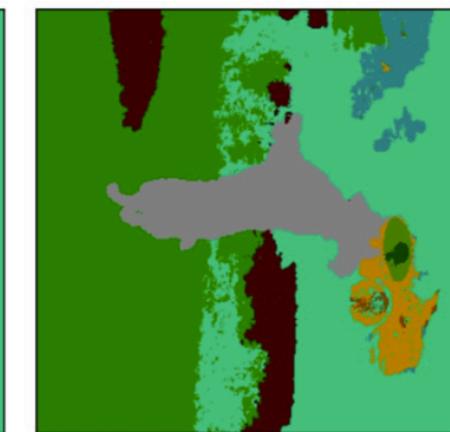
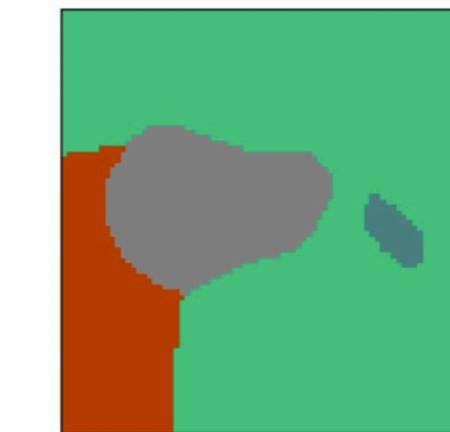
$$\mathcal{L}_{\text{simple-corr}}(x, y, b) := - \sum_{hwij} (F_{hwij} - b) S_{hwij}$$

$$F_{hwij}^{SC} := F_{hwij} - \frac{1}{IJ} \sum_{i'j'} F_{hwi'j'}$$

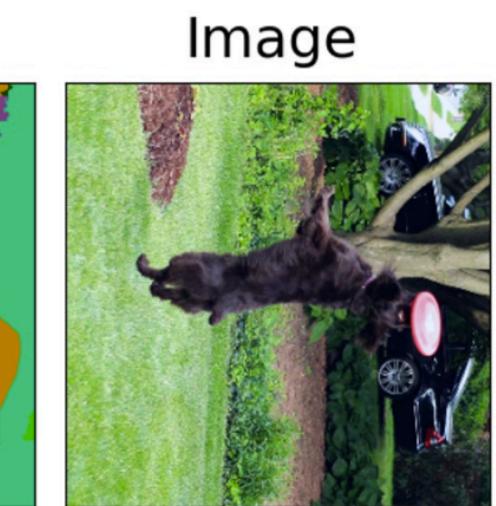
$$\mathcal{L}_{\text{corr}}(x, y, b) := - \sum_{hwij} (F_{hwij}^{SC} - b) \max(S_{hwij}, 0)$$



PiCIE (Baseline) STEGO (Ours)



Label



Image

■ Ground ■ Sky ■ Building ■ Plant ■ Vehicle ■ Person ■ Animal ■ Wall ■ Floor ■ Furniture ■ Water ■ Structural



Boulder

Questions?
