Metric learning: Knowledge transfer, data augmentation, and attention

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Athena Research Center

ICCV 2021 Tutorial: **Large-Scale Visual Localization**
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context

- representation learning for instance-level tasks like visual localization often reduces to metric learning
- ideas addressed most commonly in classification, less so in metric learning
  - knowedge transfer (from teacher to student models)
  - data augmentation (mixup)
  - attention (channel/spatial, local/global)

knowledge transfer

asymmetric metric learning for knowledge transfer

[CVPR 2021]

Mateusz Budnik

Yannis Avrithis

paper

https://arxiv.org/abs/2006.16331

code

https://github.com/budnikm/asymmetric_metric_learning

asymmetric metric learning (AML)

- instance-level image retrieval
- asymmetric testing: database represented by large network, queries by lightweight network on device, no re-indexing
- asymmetric metric learning: use asymmetric representations at training in teacher-student setup
- applies to both symmetric and asymmetric testing
- combines of knowledge transfer with supervised metric learning

Budnik and Avrithis. CVPR 2021. Asymmetric Metric Learning for Knowledge Transfer.

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Budnik and Avrithis. CVPR 2021. Asymmetric Metric Learning for Knowledge Transfer.

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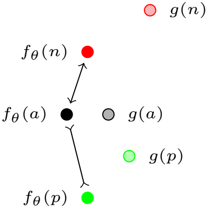
Budnik and Avrithis. CVPR 2021. Asymmetric Metric Learning for Knowledge Transfer.

metric learning and knowledge transfer



symmetric

- labels used, teacher not used
- positive pairs of examples mutually attracted and negative pairs are repulsed in student space

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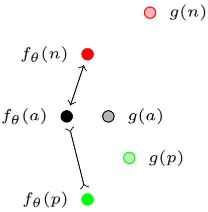
metric learning and knowledge transfer



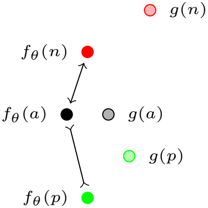
symmetric

- labels used, teacher not used (f_θ: student, g: teacher)
- contrastive $\ell_{\mathrm{C}}(a;\theta)$: independently, positive examples p close to anchor a, negative n farther from a by margin m in student space

$$\sum_{p \in P(a)} -s_\theta(a,p) + \sum_{n \in N(a)} [s_\theta(a,n) - m]_+$$

Hadsell, Chopra, Lecun. CVPR 2006. Dimensionality reduction by learning an invariant mapping.
Budnik and Avrithis. CVPR 2021. Asymmetric Metric Learning for Knowledge Transfer.

metric learning and knowledge transfer



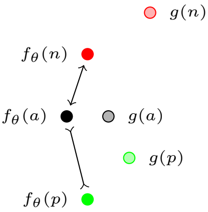
symmetric

- labels used, teacher not used (f_θ: student, g: teacher)
- triplet $\ell_{\mathrm{T}}(a;\theta)$: positive examples p closer to the anchor a than negative n by margin m in student space

$$\sum_{(p,n)\in L(a)} [s_\theta(a,n) - s_\theta(a,p) + m]_+$$

Wang, Song, Leung, Rosenberg, Wang, Philbin, Chen, Wu. CVPR 2014. Learning fine-grained image similarity with deep ranking.
Budnik and Avrithis. CVPR 2021. Asymmetric Metric Learning for Knowledge Transfer.

metric learning and knowledge transfer



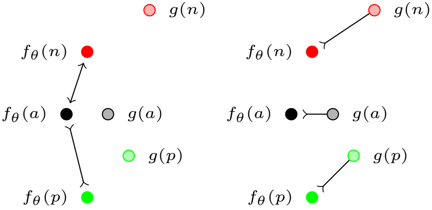
symmetric

- labels used, teacher not used (f_θ: student, g: teacher)
- multi-similarity $\ell_{\mathrm{MS}}(a;\theta)$: positives p (negatives n) farthest from (nearest to) anchor a receive the greatest relative weight

$$\frac{1}{\alpha}\log\left(1+\sum_{p\in P(a)} e^{-\alpha(s_\theta(a,p)-m)}\right)+\frac{1}{\beta}\log\left(1+\sum_{n\in N(a)} e^{\beta(s_\theta(a,n)-m)}\right)$$

Wang, Han, Huang, Dong, Scott. CVPR 2019. Multi-similarity loss with general pair weighting for deep metric learning.
Budnik and Avrithis. CVPR 2021. Asymmetric Metric Learning for Knowledge Transfer.

metric learning and knowledge transfer



symmetric **regression**

- labels not used, teacher used
- examples in student space attracted to corresponding examples in teacher space

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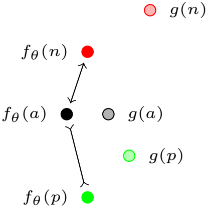
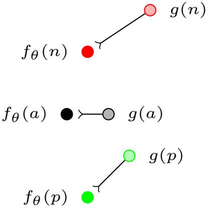
metric learning and knowledge transfer



symmetric



regression

- labels not used, teacher used (f_θ: student, g: teacher)
- regression $\ell_{\mathrm{R}}(a;\theta)$: representations of same example a by two models f_θ, g close to each other, where g is fixed

$$-s_\theta^{\mathrm{asym}}(a,a) = -\operatorname{sim}(f_\theta(a), g(a))$$

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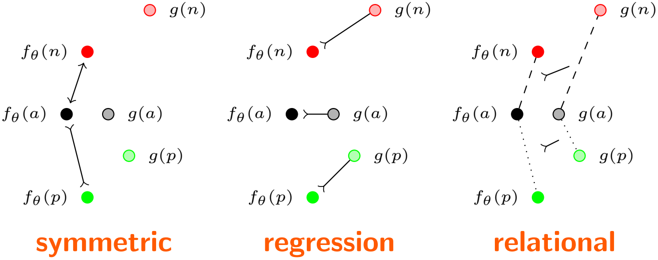
metric learning and knowledge transfer



- labels not used, teacher used
- pairwise / groupwise relations like distances, angles or ranks encouraged to be compatible in both spaces

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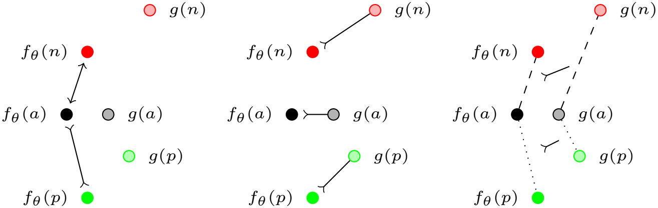
metric learning and knowledge transfer



symmetric **regression** **relational**

- labels not used, teacher used (f_θ: student, g: teacher)
- relational distillation $\ell_{\mathrm{RKD}}(a;\theta)$: measurements $\psi(\mathbf{a}, \mathbf{x}, \dots)$ of same examples $(a, x, \dots)$ by two models f_θ, g close to each other

$$\sum_{(x,\dots)\in U(a)^n} -\operatorname{sim}(\psi(f_\theta(a), f_\theta(x), \dots), \psi(g(a), g(x), \dots))$$

e.g. distance $\|\mathbf{a} - \mathbf{x}\|$, angle $\operatorname{sim}(\mathbf{a} - \mathbf{x}, \mathbf{a} - \mathbf{y})$; regression $\psi(\mathbf{a}) := \mathbf{a}$

Park, Kim, Lu, Cho. CVPR 2019. Relational knowledge distillation.
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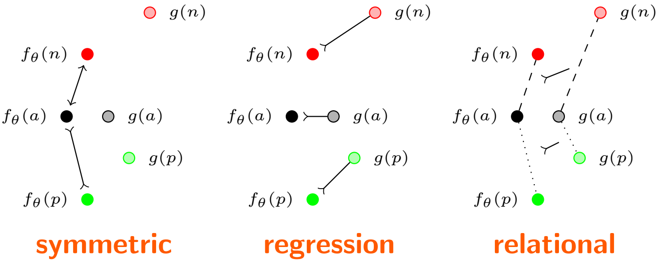
metric learning and knowledge transfer

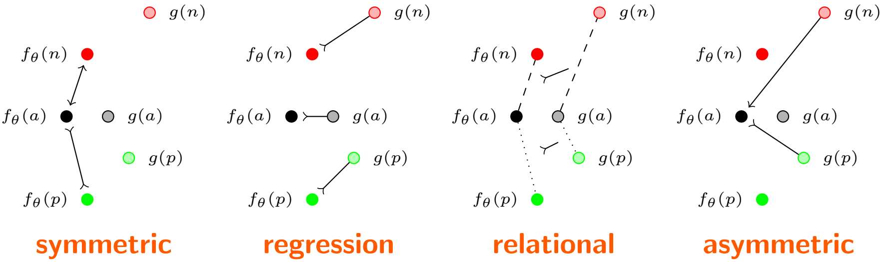


- labels not used, teacher used (f_θ: student, g: teacher)
- DarkRank $\ell_{\mathrm{DR}}(a;\theta)$: examples $y \in V(a,x)$ mapped farther from anchor a than x in teacher space do the same in student space:

$$-\sum_{x \in U(a)} \left(s_\theta^{\mathrm{sym}}(a,x) - \log \sum_{y \in V(a,x)} e^{s_\theta^{\mathrm{sym}}(a,y)} \right)$$

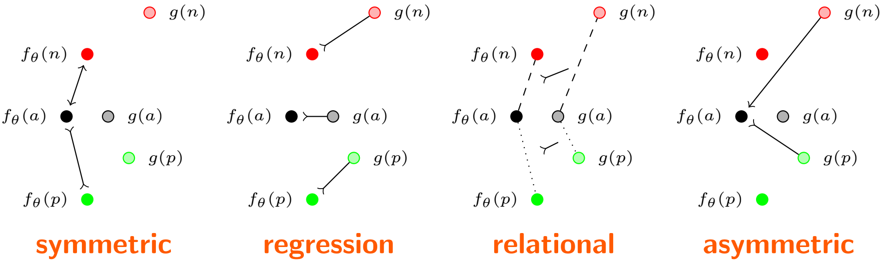
Chen, Wang, Zhang. AAAI 2018. DarkRank: Accelerating deep metric learning via cross sample similarities transfer.
Budnik and Avrithis. CVPR 2021. Asymmetric Metric Learning for Knowledge Transfer.

metric learning and knowledge transfer



- both labels and teacher used
- anchors in student space attracted to positives and repulsed from negatives in teacher space

metric learning and knowledge transfer



- both labels and teacher used (f_θ: student, g: teacher)
- Asymmetric Metric Learning (AML): simply use

$$s_\theta^{\mathrm{asym}}(a, x) := \mathrm{sim}(f_\theta(a), g(x))$$

with any supervised metric learning loss like ℓ_{C}, ℓ_{T}, ℓ_{MS}

Budnik and Avrithis. CVPR 2021. Asymmetric Metric Learning for Knowledge Transfer.

best loss functions

- regression (Reg)

$$\ell_{\mathrm{R}}(a;\theta) := -s_\theta^{\mathrm{asym}}(a,a) = -\operatorname{sim}(f_\theta(a), g(a))$$

- asymmetric contrastive (Contr)

$$\ell_{\mathrm{C}}(a;\theta) := \sum_{n \in N(a)} [s_\theta(a,n) - m]_+ - \sum_{p \in P(a)} s_\theta(a,p)$$

- asymmetric contrastive + regression (Contr$^+$)

$$\ell_{\mathrm{C}^+}(a;\theta) := \sum_{n \in N(a)} [s_\theta(a,n) - m]_+ - \sum_{p \in P(a)} s_\theta(a,p) \quad - s_\theta(a,a)$$

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best loss functions

- regression (Reg)

$$\ell_{\mathrm{R}}(a;\theta) := \boxed{-s_\theta^{\mathrm{asym}}(a,a)} = -\operatorname{sim}(f_\theta(a), g(a))$$

- asymmetric contrastive (Contr)

$$\ell_{\mathrm{C}}(a;\theta) := \boxed{\sum_{n \in N(a)} [s_\theta(a,n) - m]_+ - \sum_{p \in P(a)} s_\theta(a,p)}$$

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test set: revisited Oxford and Paris

- 11 + 11 landmarks, 70 + 70 queries, 5k + 6k images, easy/hard
- 1M distractor images
- performance measured by mAP: positive ranked first

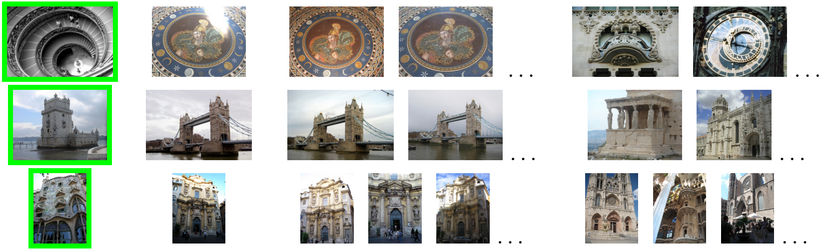
Radenovic, Iscen, Tolias, Avrithis, Chum. CVPR 2018. Revisiting Oxford and Paris: Large-Scale Image Retrieval Benchmarking.
Budnik and Avrithis. CVPR 2021. Asymmetric Metric Learning for Knowledge Transfer.

training set: SfM120k (positives)

- camera position (closest to query)
- number of inliers (co-observed 3D points with query)
- according to SIFT descriptors

Radenovic, Tolias, Chum. ECCV 2016. CNN Image Retrieval Learns From BoW: Unsupervised Fine-Tuning with Hard Examples.
Budnik and Avrithis. CVPR 2021. Asymmetric Metric Learning for Knowledge Transfer.

training set: SfM120k (negatives)



- k-nearest neighbors from non-matching clusters
- at most one image per cluster
- according to learned descriptors

Radenovic, Tolias, Chum. ECCV 2016. CNN Image Retrieval Learns From BoW: Unsupervised Fine-Tuning with Hard Examples.
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network models

Network	Teacher	d	GFLOPS	Param(M)
ResNet101		2048	42.85	42.50
EfficientNet-B3		1536	5.36	10.70
	ResNet101	2048	6.26	13.84

- teacher: ResNet101 (RN101)
- student: EfficientNet-B3 (EN-B3), dimensions d adapted to teacher
- $7\times$ less FLOPS
- $3\times$ less parameters

Tan and Le. ICML 2019. EfficientNet: Rethinking model scaling for convolutional neural networks.
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symmetric testing

Stu	d	Tea	Lab	Mining	Asym	Loss	Medium $\mathcal{R}$Oxf	Medium $\mathcal{R}$Par	Hard $\mathcal{R}$Oxf	Hard $\mathcal{R}$Par
RN101	2048		✓	hard		Contr	65.4	76.7	40.1	55.2
EN-B3	512		✓	hard		Contr	53.8	70.9	26.2	46.0
	2048		✓	hard		Contr	59.6	75.1	33.3	51.9
EN-B3	2048	RN101	✓	hard	✓	Contr^+	**66.8**	77.1	**42.5**	**55.5**
			✓	hard	✓	Contr	66.3	**77.4**	41.3	**55.5**
			✓	hard	✓	Triplet	39.5	69.4	11.6	45.8
			✓	hard	✓	MS	39.9	69.7	11.7	46.2
				–	✓	Reg	64.9	74.4	40.5	52.4
				random		RKD	56.3	73.0	30.5	50.4
				random		DR	40.3	69.9	11.8	46.4

- Contr, Contr^+: student beats teacher
- Reg: second best, slightly below teacher
- everything else fails (worse than student alone)

Budnik and Avrithis. CVPR 2021. Asymmetric Metric Learning for Knowledge Transfer.

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				–	✓	Reg	**52.9**	**65.2**	**27.8**	**42.4**
				random		RKD	1.6	3.8	0.7	2.4
				random		DR	1.5	4.0	0.7	2.5

- Reg: best, but significantly lower than student alone
- Contr$^+$ / Contr: second / third best, significantly lower than Reg
-

asymmetric testing

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EN-B3	512		✓	hard		Contr	53.8	70.9	26.2	46.0
	2048		✓	hard		Contr	59.6	75.1	33.3	51.9
EN-B3	2048	RN101	✓	hard	✓	Contr^{+}	45.2	63.7	19.6	40.9
			✓	hard	✓	Contr	37.4	57.4	10.9	33.7
			✓	hard	✓	Triplet	1.5	4.0	0.7	2.5
			✓	hard	✓	MS	1.5	4.0	0.7	2.4
				–	✓	Reg	52.9	65.2	27.8	42.4
				random		RKD	1.6	3.8	0.7	2.4
				random		DR	1.5	4.0	0.7	2.5

- Reg: best, but significantly lower than student alone
- Contr^{+} / Contr: second / third best, significantly lower than Reg

asymmetric testing

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Budnik and Avrithis. CVPR 2021. Asymmetric Metric Learning for Knowledge Transfer.

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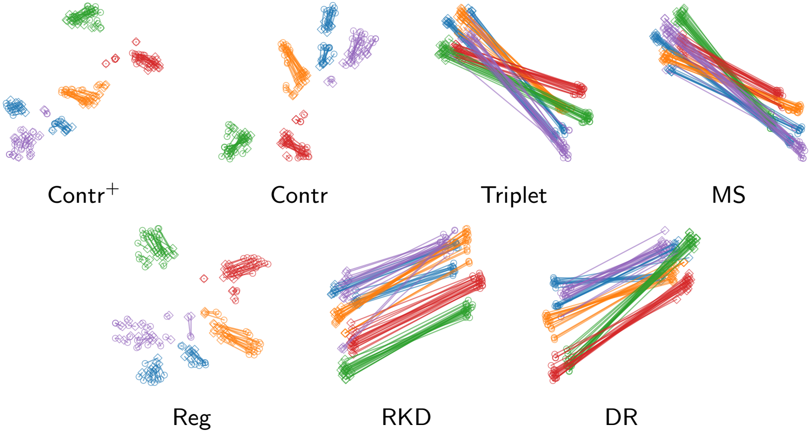
asymmetric testing: T-SNE embeddings



- 5 Oxford classes, 20 “easy” examples per class
- Triplet, MS, RKD, DR fail completely

Budnik and Avrithis. CVPR 2021. Asymmetric Metric Learning for Knowledge Transfer.

data augmentation

mixup for deep metric learning

Shashanka Venkataramanan

Ewa Kijak

Laurent Amsaleg

Yannis Avrithis

paper

https://arxiv.org/abs/2106.04990

code

upon publication

data augmentation and mixup

- data augmentation increases the amount and diversity of data, improving the generalization performance at almost no cost
- operates on one image at a time, limited to label-preserving transformations: hard to explore beyond the image manifold
- mixup operates on two or more examples at a time, interpolating examples and labels
- in classification, smooths decision boundaries far away from training data and reduces overly confident predictions
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input mixup and manifold mixup

- standard mixup operation: linear interpolation

$$\text{mix}_\lambda(x, x') := \lambda x + (1 - \lambda)x'$$

  where $\lambda \in [0, 1]$: interpolation factor, drawn from Beta distribution

- interpolation of examples: decomposing model as $f = f_m \circ g_m$,

$$f_\lambda(x, x') := \begin{cases} f(\text{mix}_\lambda(x, x')), & \text{input mixup} \\ f_m(\text{mix}_\lambda(g_m(x), g_m(x'))), & \text{feature mixup} \\ \text{mix}_\lambda(f(x), f(x')), & \text{embedding mixup} \end{cases}$$

- interpolation of labels: $\text{mix}_\lambda(y, y')$
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Zhang, Cisse, Dauphin and Lopez-Paz. ICLR 2018. mixup: Beyond empirical risk minimization.
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existing approaches

Method	DML	Stoch	Pairs	Proxy	Labels > 1	Labels Mix	Anc-Neg
Hardness-Aware DML	✓		✓				
Embedding Expansion	✓		✓				
Symmetrical Synthesis	✓		✓				
Proxy Synthesis	✓	✓		✓	✓		✓
MoCHi		✓	✓		✓		✓
i-Mix		✓	✓		✓	✓	
MixCo		✓	✓		✓	✓	
Metrix (ours)	✓	✓	✓	✓	✓	✓	✓

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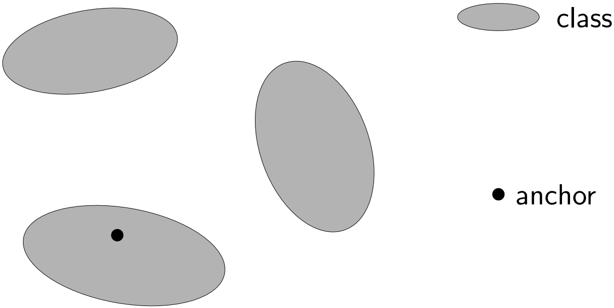
metrix (= metric mix)



- allow anchor to interact with positive examples (same class), negative examples (different class), and interpolated examples, which also have interpolated labels

Venkataraman *et al.* 2021. It Takes Two to Tango: Mixup for Deep Metric Learning.

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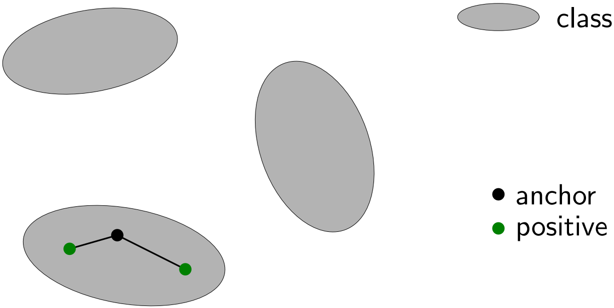

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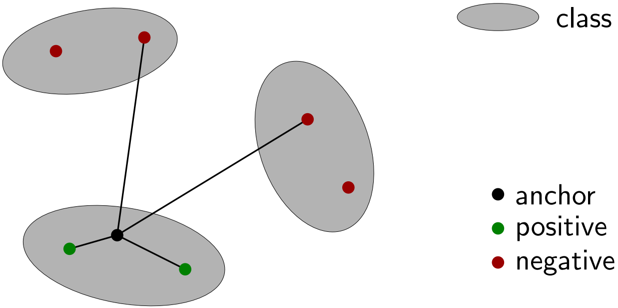

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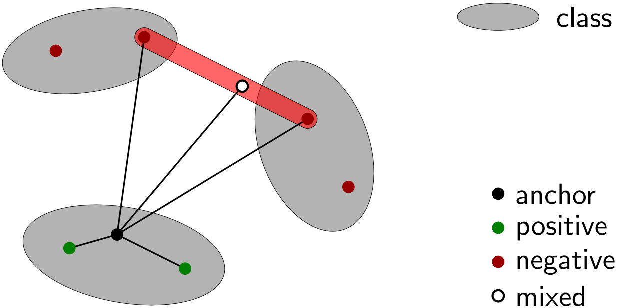

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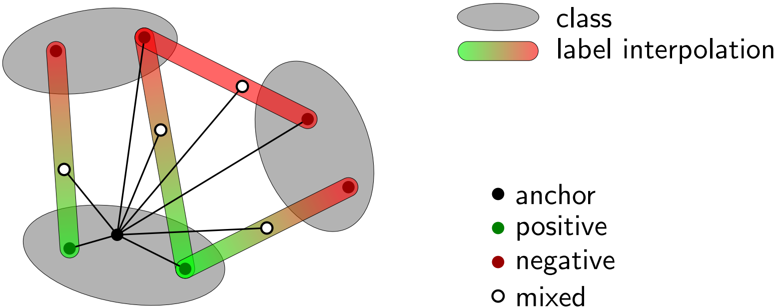

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generic loss formulation

- contrastive loss $\ell_{\mathrm{C}}(a;\theta)$

$$\sum_{p\in P(a)} -s(a,p) + \sum_{n\in N(a)} [s(a,n)-m]_+$$

- multi-similarity loss $\ell_{\mathrm{MS}}(a;\theta)$

$$\frac{1}{\alpha}\log\left(1+\sum_{p\in P(a)} e^{-\alpha(s(a,p)-m)}\right)+\frac{1}{\beta}\log\left(1+\sum_{n\in N(a)} e^{\beta(s(a,n)-m)}\right)$$

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generic loss formulation

- generic loss $\ell(a;\theta)$

$$\sigma^+\left(\sum_{p\in P(a)}\rho^+(s(a,p))\right)+\sigma^-\left(\sum_{n\in N(a)}\rho^-(s(a,n))\right)$$

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generic loss formulation

- generic loss $\ell(a;\theta)$

$$\sigma^{+}\left(\sum_{p\in P(a)} \rho^{+}(s(a,p))\right) + \sigma^{-}\left(\sum_{n\in N(a)} \rho^{-}(s(a,n))\right)$$

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- multi-similarity loss $\ell_{\mathrm{MS}}(a;\theta)$

$$\frac{1}{\alpha}\log\left(1+\sum_{p\in P(a)} e^{-\alpha(s(a,p)-m)}\right) + \frac{1}{\beta}\log\left(1+\sum_{n\in N(a)} e^{\beta(s(a,n)-m)}\right)$$

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generic loss formulation

- generic loss $\ell(a;\theta)$

$$\sigma^{+}\left(\sum_{p\in P(a)} \rho^{+}(s(a,p))\right) + \sigma^{-}\left(\sum_{n\in N(a)} \rho^{-}(s(a,n))\right)$$

- different loss functions in the generic formulation

Loss	Anchor	Pos/Neg	$\sigma^{+}(x)$	$\sigma^{-}(x)$	$\rho^{+}(x)$	$\rho^{-}(x)$
Contrastive	X	X	x	x	$-x$	$[x-m]_{+}$
Binomial deviance	X	X	$\log(1+x)$	$\log(1+x)$	$e^{-\beta(x-m)}$	$e^{\gamma(x-m)}$
Multi-similarity	X	X	$\frac{1}{\beta}\log(1+x)$	$\frac{1}{\gamma}\log(1+x)$	$e^{-\beta(x-m)}$	$e^{\gamma(x-m)}$
Proxy anchor	proxy	X	$\frac{1}{\beta}\log(1+x)$	$\frac{1}{\gamma}\log(1+x)$	$e^{-\beta(x-m)}$	$e^{\gamma(x-m)}$
NCA	X	X	$-\log(x)$	$\log(x)$	e^{x}	e^{x}
ProxyNCA	X	proxy	$-\log(x)$	$\log(x)$	e^{x}	e^{x}
ProxyNCA++	X	proxy	$-\log(x)$	$\log(x)$	$e^{x/T}$	$e^{x/T}$

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mixing examples and labels

- generic loss $\ell(a;\theta)$

$$\sigma^+\left(\sum_{p\in P(a)} \rho^+(s(a,p))\right) + \sigma^-\left(\sum_{n\in N(a)} \rho^-(s(a,n))\right)$$

- defining $U(a) := \{(p,1) : p \in P(a)\} \cup \{(n,0) : n \in N(a)\}$,

$$\sigma^+\left(\sum_{(x,y)\in U(a)} y\rho^+(s(a,x))\right) + \sigma^-\left(\sum_{(x,y)\in U(a)} (1-y)\rho^-(s(a,x))\right)$$

- defining $V(a) := \{(f_\lambda(x,x'), \mathrm{mix}_\lambda(y,y')) : ((x,y),(x',y')) \in U(a)^2\}$,

$$\sigma^+\left(\sum_{(v,y)\in V(a)} y\rho^+(s(a,v))\right) + \sigma^-\left(\sum_{(v,y)\in V(a)} (1-y)\rho^-(s(a,v))\right)$$

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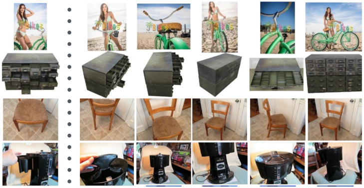
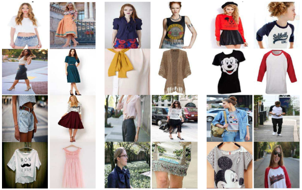
datasets

CUB

Cars



SOP



InShop

Wah, Branson, Welinder, Perona and Belongie. Caltech, 2011. The Caltech-UCSD Birds-200-2011 Dataset.
Krause, Stark, Deng and Fei-Fei. ICCVW 2013. 3D object representations for fine-grained categorization.
Song, Xiang, Jegelka and Savarese. CVPR 2016. Deep metric learning via lifted structured feature embedding.
Liu, Luo, Qiu, Wang and Tang. CVPR 2016. Deepfashion: Powering robust clothes recognition and retrieval with rich annotations.

R@k results with ResNet-50, $d = 512$

	CUB200		CARS196		SOP		IN-SHOP	
METHOD	R@1	R@2	R@1	R@2	R@1	R@10	R@1	R@10
Contrastive	64.7	75.9	81.6	88.2	74.9	87.0	86.4	94.7
+Metrix	67.4	77.9	85.1	91.1	77.5	89.1	89.1	95.7
	+2.7	+2.0	+3.5	+2.9	+2.6	+2.1	+2.7	+1.0
Multi-similarity	67.8	77.8	**87.8**	**92.7**	76.9	89.8	90.1	**97.6**
+Metrix	**71.4**	80.6	**89.6**	**94.2**	81.0	92.0	**92.2**	**98.5**
	+3.6	+2.8	+1.8	+1.5	+4.1	+2.2	+2.1	+0.9
Proxy anchor	**69.5**	79.3	87.6	92.3	79.1	90.8	90.0	97.4
+Metrix	71.0	**81.8**	89.1	93.6	**81.3**	91.7	91.9	98.2
	+1.3	+1.8	+1.4	+0.7	+2.2	+0.9	+1.9	+0.8
ProxyNCA++	69.1	**79.5**	86.6	92.1	**80.4**	**91.7**	**90.2**	**97.6**
+Metrix	70.4	80.6	88.5	93.4	**81.3**	**92.7**	91.9	98.1
	+1.3	+0.8	+1.9	+0.9	+0.6	+0.7	+1.5	+0.0
Gain over SOTA	+1.7	+1.8	+1.8	+1.3	+0.6	+0.0	+1.2	+0.4

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Kim, Kim, Cho and Kwak. CVPR 2020. Proxy anchor loss for deep metric learning.
Teh, DeVries and Taylor. ECCV 2020. ProxyNCA++: Revisiting and revitalizing proxy neighborhood component analysis.
Venkataramanan *et al.* 2021. It Takes Two to Tango: Mixup for Deep Metric Learning.

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Hadsell, Chopra and LeCun. CVPR 2006. Dimensionality reduction by learning an invariant mapping.
Wang, Han, Huang, Dong, Scott. CVPR 2019. Multi-similarity loss with general pair weighting for deep metric learning.
Venkataramanan *et al.* 2021. It Takes Two to Tango: Mixup for Deep Metric Learning.

"positivity"

- $\text{Pos}(a, v)$: a mixed embedding v behaves as "positive" for anchor a: $\partial \ell(a; \theta) / \partial s(a, v) \leq 0$
- under certain assuptions, estimate the probability of $\text{Pos}(a, v)$ for a single mixed embedding v as a function of λ

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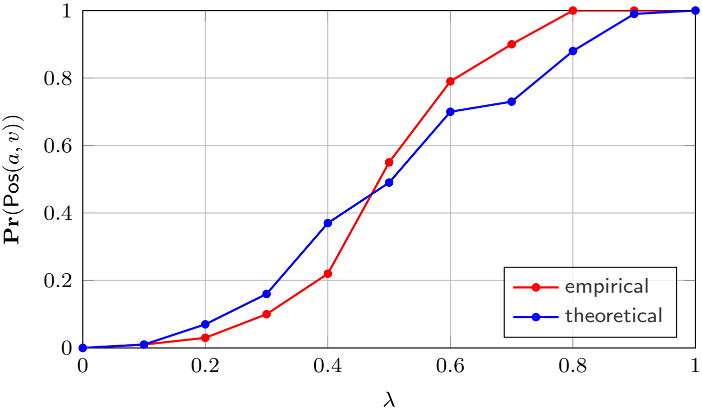
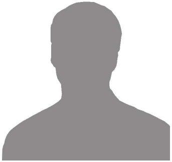


attention

global-local, spatial-channel attention for image retrieval

[WACV 2022]



Chull Hwan Song

Hye Joo Han

Yannis Avrithis

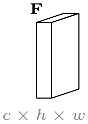
paper

`https://arxiv.org/abs/2107.08000`

code

by WACV (January)

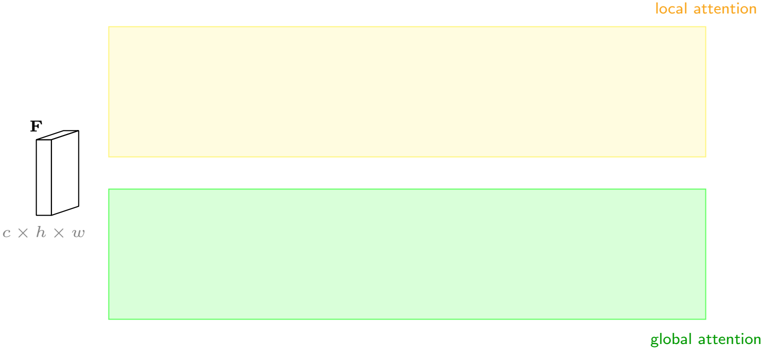
global-local attention module (GLAM)



- input feature tensor: c feature maps (channels), $h \times w$ spatial resolution

Song, Han and Avrithis. WACV 2022. All the attention you need: Global-local, spatial-channel attention for image retrieval.

global-local attention module (GLAM)



- local (1st order) attention: elements of the feature tensor (channels / spatial locations) weighted independently, by pooling or learning
- global (2nd order) attention: pairwise interaction between elements of the tensor

Song, Han and Avrithis. WACV 2022. All the attention you need: Global-local, spatial-channel attention for image retrieval.

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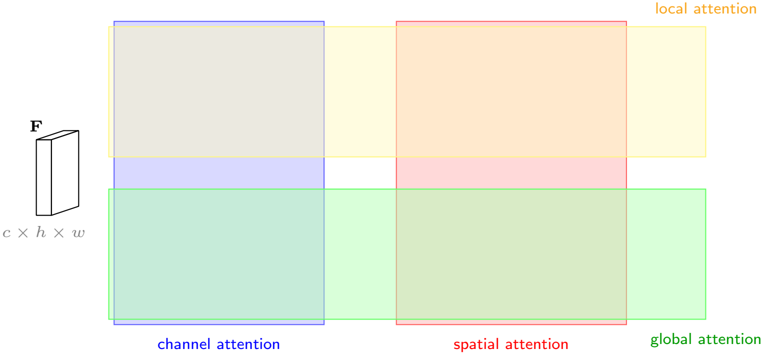

- channel attention: channels weighted independently or interact pairwise
- spatial attention: spatial locations weighted independently or interact pairwise

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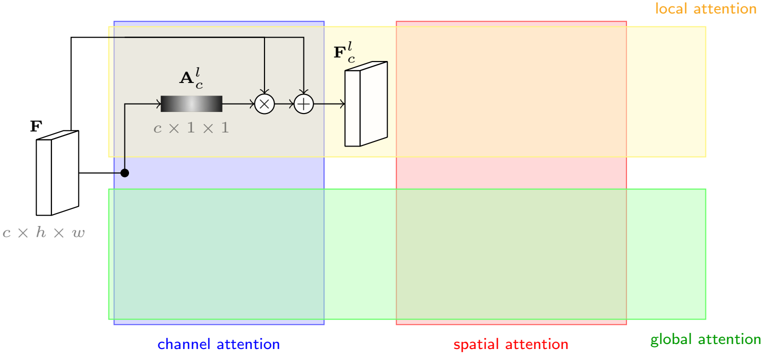
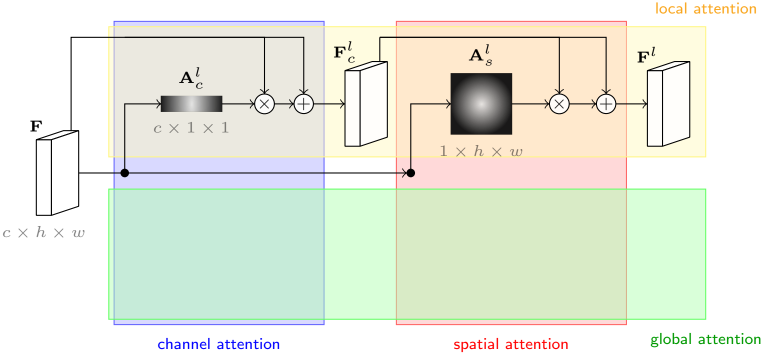
global-local attention module (GLAM)



- local channel attention: pooling over locations yields $c \times 1 \times 1$ attention map
-

Song, Han and Avrithis. WACV 2022. All the attention you need: Global-local, spatial-channel attention for image retrieval.

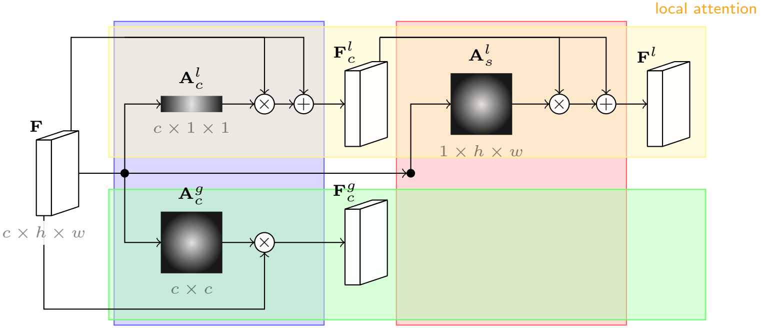
global-local attention module (GLAM)



- local channel attention: pooling over locations yields $c \times 1 \times 1$ attention map
- local spatial attention: pooling over channels yields $1 \times h \times w$ attention map

Song, Han and Avrithis. WACV 2022. All the attention you need: Global-local, spatial-channel attention for image retrieval.

global-local attention module (GLAM)



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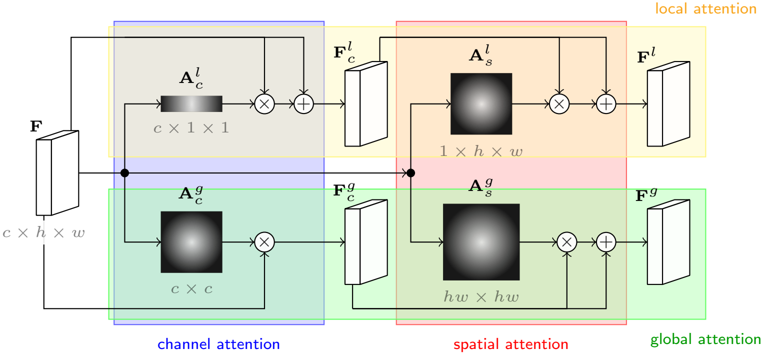

- global channel attention: pairwise interaction of channels yields $c \times c$ attention map
- global spatial attention: pairwise interaction of locations yields $hw \times hw$ attention map

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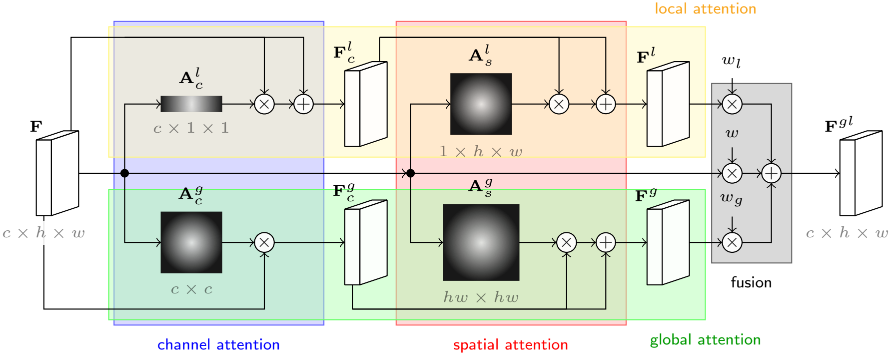

- fusion: local and global attention streams fused with original feature tensor

Song, Han and Avrithis. WACV 2022. All the attention you need: Global-local, spatial-channel attention for image retrieval.

image retrieval study

- ResNet101 backbone, GeM pooling
- global descriptor only, $d = 512$
- train by Arcface loss on Google Landmarks v2 clean (1.5M images)
- mini-batch examples with similar aspect ratios resized jointly
- at inference, multi-resolution representation to queries and database
- test on Revisited Oxford ($\mathcal{R}$Oxf) and Paris ($\mathcal{R}$Par)
- ablate local/global, channel/spatial attention components

Radenović, Iscen, Tolias, Avrithis and Chum. CVPR 2018. Revisiting Oxford and Paris: Large-Scale Image Retrieval Benchmarking.
Yokoo, Ozaki, Simo-Serra and Iizuka. CVPRW 2020. Two-stage Discriminative Re-ranking for Large-scale Landmark Retrieval.
Weyand, Araujo, Cao and Sim. CVPR 2020. Google Landmarks Dataset v2 - A Large-Scale Benchmark for Instance-Level Recognition and Retrieval.
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ablation

Method	Oxf5k	Par6k	$\mathcal{R}$Medium		$\mathcal{R}$Hard	
			$\mathcal{R}$Oxf	$\mathcal{R}$Par	$\mathcal{R}$Oxf	$\mathcal{R}$Par
GLAM baseline	91.9	94.5	72.8	84.2	49.9	69.7
+local-channel	91.3	95.3	72.2	85.8	48.3	73.1
+local-spatial	91.0	95.1	72.1	85.3	48.3	71.9
+local	91.2	95.4	73.7	86.5	52.6	75.0
+global-channel	92.5	94.4	73.3	84.4	49.8	70.1
+global-spatial	92.4	95.1	73.2	86.3	50.0	72.7
+global	92.3	95.3	77.2	86.7	57.4	75.0
+global+local	**94.2**	**95.6**	**78.6**	**88.5**	**60.2**	**76.8**

- channel/spatial attention: may be harmful when used alone, but complementary and surprisingly beneficial when used together
- local/global attention: clearly complementary, their gain nearly additive

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+global-channel	92.5	94.4	73.3	84.4	49.8	70.1
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+global-channel	92.5	94.4	73.3	84.4	49.8	70.1
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+local-channel	91.3	95.3	72.2	85.8	48.3	73.1
+local-spatial	91.0	95.1	72.1	85.3	48.3	71.9
+local	91.2	95.4	73.7	86.5	52.6	75.0
+global-channel	92.5	94.4	73.3	84.4	49.8	70.1
+global-spatial	92.4	95.1	73.2	86.3	50.0	72.7
+global	92.3	95.3	77.2	86.7	57.4	75.0
+global+local	**94.2**	**95.6**	**78.6**	**88.5**	**60.2**	**76.8**

- channel/spatial attention: may be harmful when used alone, but complementary and surprisingly beneficial when used together
- local/global attention: clearly complementary, their gain nearly additive

thank you!

more

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