

Cross-domain and Cross-dimension Learning for Image-to-Graph Transformers

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Abstract

Direct image-to-graph transformation is a challenging task that involves solving object detection and relationship prediction in a single model. Due to this task’s complexity, large training datasets are rare in many domains, making the training of deep-learning methods challenging. This data sparsity necessitates transfer learning strategies akin to the state-of-the-art in general computer vision. In this work, we introduce a set of methods enabling cross-domain and cross-dimension learning for image-to-graph transformers. We propose (1) a regularized edge sampling loss to effectively learn object relations in multiple domains with different numbers of edges, (2) a domain adaptation framework for image-to-graph transformers aligning image- and graph-level features from different domains, and (3) a projection function that allows using 2D data for training 3D transformers. We demonstrate our method’s utility in cross-domain and cross-dimension experiments, where we utilize labeled data from 2D road networks for simultaneous learning in vastly different target domains. Our method consistently outperforms standard transfer learning and self-supervised pretraining on challenging benchmarks, such as retinal or whole-brain vessel graph extraction.¹

1. Introduction

Representing physical relationships via graph representations has proven to be an efficient and versatile concept with vast utility in machine learning. Prominent examples are road network graphs [2], neuron representations and connections in the brain [45], blood vessels [8], and cell interactions [55]. Here, typically used voxelized images

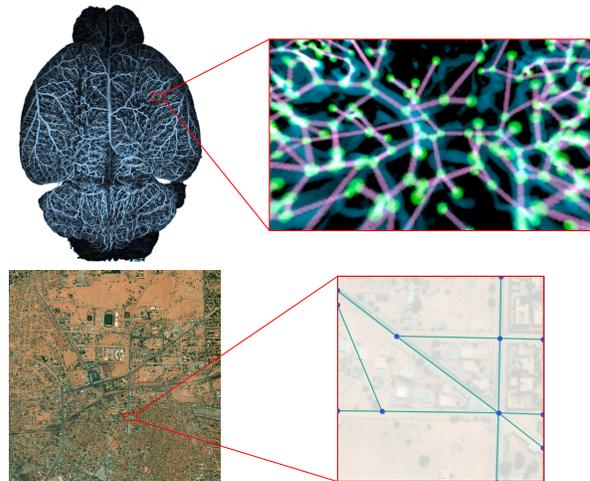


Figure 1. Direct image-to-graph transformation. Whole brain vessel (top) and Agadez road dataset (bottom). The predicted graph is visualized as an overlay on the real image.

disregard the physical structure’s semantic content. Hence, constructing graph representations from images (image-to-graph, see Fig. 1) is a critical challenge for unlocking the full potential in many real-world applications [27].

Traditionally, image-to-graph transformation involves a complex multi-stage process of segmentation, identification of physical structures and their relations, and iteratively pruning the constructed graph, which leads to inaccuracies and information loss at each step [14]. These disadvantages negatively impact prediction accuracy and limit the application to downstream tasks that require more information from the underlying image (e.g., [43, 44]). Hence, there is a clear need for machine learning solutions that facilitate accurate image-to-graph transformation in a single

¹Code: github.com/AlexanderHBerger/cross-dim_i2g

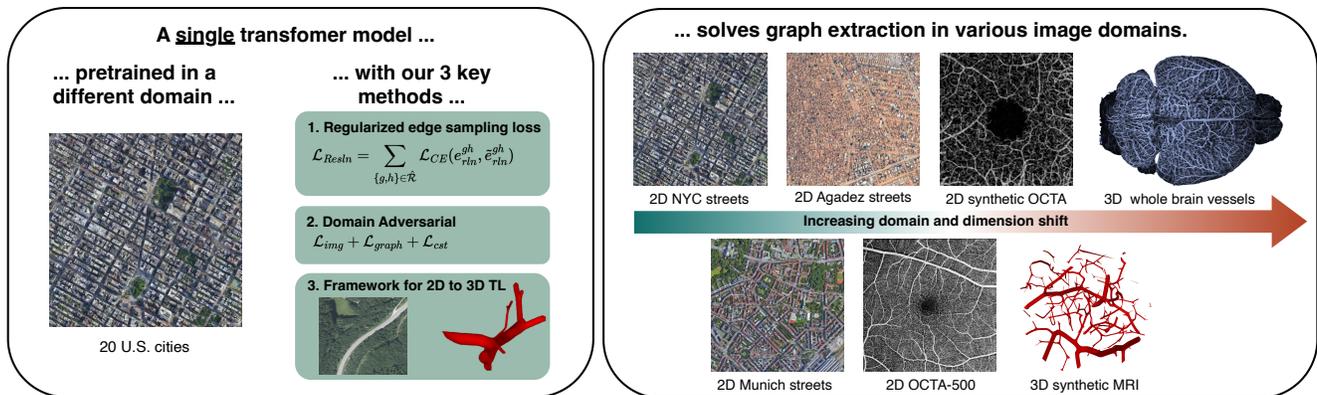


Figure 2. Conceptual overview of our framework. We use a transformer for single-stage image-to-graph transformation. Our three methodological contributions enable knowledge transfer between vastly different domains in 2D and 3D.

step [4, 22]. Recently, vision transformers have been proposed for this task and showed superior performance to traditional multi-stage approaches [42, 54]. However, these approaches require large sets of annotated 2D data and have not been shown to generalize to diverse 3D datasets where graph-level annotations are not widely available.

To address this challenge, we adopt and extend concepts from the field of inductive transfer learning (TL) (see taxonomy in [38]), which have not been explored for image-to-graph transformation. Inductive TL simultaneously uses large annotated datasets in the source domain (e.g., 2D satellite images) and a small set of labeled data in the target domain (e.g., 3D microscopy images of vascular networks).

Our contribution. Guided by the hypothesis that the *underlying graph representations of physical networks are similar across domains*, we introduce a set of methodological innovations for image-to-graph transformation:

1. We introduce a loss formulation that regularizes the number of sampled edges during training, allowing simultaneous learning in domains that differ in terms of the number of objects and relations (Sec. 3.1).
2. We propose a supervised domain adaptation framework for image-to-graph transformers that aligns features from different domains (Sec. 3.2).
3. We propose a framework for training 3D image-to-graph models with 2D data. Our framework introduces a projection function from the source representation to a space similar to the target domain (Sec. 3.4).

In extensive experiments on six datasets, we demonstrate our method’s utility and outperform all baselines, validating our initial hypothesis. Our method leads to *four main results*: 1) we show compelling improvements in image-to-graph transformation on existing datasets; 2) our method

enables image-to-graph transformation in previously unsolvable sparse data scenarios; 3) our method outperforms self-supervised pretraining by a margin and 4) our method bridges dimensions during training, i.e. we solve the previously unsolved direct image-to-graph inference for complex 3D vessel images by utilizing 2D road data in an additional training step. Further ablation studies highlight that each of our methodological contributions addresses a specific weakness in the state-of-the-art.

2. Related Works

Image-to-graph transformation. Image-to-graph transformation is an increasingly important field in computer vision with application to various domains, including road network extraction from satellite images [51] or 3D vessel graph extraction from microscopy images [1, 3]. Traditional methods solve this task through a multi-step approach involving input segmentation [2, 7, 11], skeletonization, and pruning to generate the graph [14, 51]. Deep learning-based approaches frequently use an object detector followed by relation prediction [1, 3] or require a segmentation map as input [54]. These approaches’ performances are determined by the performance of the pipeline’s intermediate stages. Furthermore, information loss at each stage limits performance and applicability to downstream tasks. Lastly, these methods are tailored to specific domains, rendering them unsuitable for cross-domain applications, including TL.

We select the *Relationformer* as our base concept because it is the most general single-stage transformer concept that can directly predict the graph from diverse image data in various domains [39, 42]. This generalizability makes it especially suitable for cross-domain TL.

Transfer learning for transformers. Recent studies showed effective pretraining for transformers on natural images. Prevailing architectures involve supervised pretrain-

ing of the model’s backbone on, e.g., ImageNet, coupled with random initialization of the encoder-decoder component [7, 33, 42]. Dai et al. [12] extend DETR [7] with a specific pretext task for object detection. Li et al. [28] compared self- and supervised pretraining methods with random initialization of a ViT-backbone [13]. They showed how self-supervised pretraining improves downstream object detection without a specific pretext task. Ma et al. [33] pretrained a transformer architecture on synthetic data and outperformed self-supervised methods for object detection. However, generating synthetic data, especially for specialized tasks, is typically domain-specific or requires expert knowledge [25]. Ma et al. [33] find that random weight initialization remains a robust baseline, often achieving competitive downstream performance. To this date, no study has explored TL for image-to-graph transformers.

Cross-domain transfer learning. Existing cross-domain TL approaches are generative or discriminative. Generative approaches translate images from source to target domain on a pixel-level using a generative network [56]. In restricted settings, they have shown promising results, e.g., object detection for day-/nighttime shifts in road scenes [23] or MRI to CT translation [21]. However, generative approaches require additional training of the translation network, which is computationally expensive and suffers from training instability [31]. Discriminative approaches train a single model to learn a general representation that is transferable between domains [50]. Some utilize a domain adversarial network that distinguishes whether a sample is from the source or target domain based on its feature representation. Combined with a gradient reversal layer (GRL) [17], this approach has proven effective in classification [17], segmentation [49], and object detection [10]. Chen et al. [10] introduced a domain adaptation (DA) framework for object detection using the GRL concept with two domain classifiers at the image and instance levels. Both are based on \mathcal{H} -divergence theory [5]. To reduce the bias towards the source domain, a consistency regularization penalizes the L_2 -distance between the domain classifiers [10]. To this day, all existing approaches are limited to a relatively small domain shift (e.g., from day to night scenes or synthetic to real images) instead of a *fundamental* domain shift, such as from satellite images to medical scans. Also, none of the existing approaches have been applied to the image-to-graph transformation problem.

Cross-dimension transfer learning. 2D to 3D TL is a highly challenging but promising research direction because of the abundance of labeled 2D data compared to the scarcity of 3D data. The few existing approaches [29, 41, 52, 53] address the challenge, either data-based or model-based. Data-based approaches augment and project

2D data into 3D space, while model-based approaches aim to adjust the model to work with multi-dimensional input. Shen et al. [41] introduced a method that projects 3D point clouds to pseudo-2D RGB images. Liu et al. [29] introduced a pixel-to-point knowledge transfer that pretrains a 3D model by generating 3D point cloud data from 2D images with a learned projection function. A model-based approach by Xie et al. [53] used dimension-specific feature extractors and a dimension-independent Transformer. Similarly, Wang et al. [52] proposed a special tokenizer that creates 2D-shaped patch embeddings in a standard 2D ViT-model. All existing approaches either require changes to the target model, which may limit performance, a specifically crafted projection function, or additional training (e.g., for learning an explicit projection function). In our approach, we seek simplicity in implementation and training as well as generalizability to new domains and tasks.

3. Methodology

In this section, we describe our three key contributions to efficiently transfer knowledge from a source domain with image and graph space denoted as a $(\mathcal{I}^S, \mathcal{G}^S)$ to a target domain with image and graph space denoted as $(\mathcal{I}^T, \mathcal{G}^T)$ for an image-to-graph transformer.

3.1. Regularized Edge Sampling Loss

A leading difference between the source and target domain in our cross-domain TL setting is the different node and edge distribution, which poses a challenge because they dictate the relation loss calculation. Previous works arbitrarily pick the number of ground truth edges and fix it for the relation loss calculation (\mathcal{L}_{rln}) for a specific dataset [42], which evidently generalizes poorly across varying domains. Generally, such a loss originates from object detection, where pair-wise relations are classified with a cross-entropy (CE) loss over a fixed number of edges m . This includes all active edges \mathcal{A} and an irregular number of randomly sampled background edges $\tilde{\mathcal{B}} \subseteq \mathcal{B}$. An active edge is defined as a pair of nodes g, h that is connected by an edge, i.e., $e_{\text{rln}}^{gh} = 1$. Similarly, for a background edge, $e_{\text{rln}}^{gh} = 0$ holds. Then, \mathcal{L}_{rln} is the CE loss on the set of sampled edges $\mathcal{R} = \mathcal{A} \cup \tilde{\mathcal{B}}$ with $|\mathcal{A}| + |\tilde{\mathcal{B}}| \leq m$:

$$\mathcal{L}_{\text{rln}} = \sum_{\{g,h\} \in \mathcal{R}} \mathcal{L}_{\text{CE}}(e_{\text{rln}}^{gh}, \tilde{e}_{\text{rln}}^{gh}) \quad (1)$$

where $\tilde{e}_{\text{rln}}^{gh} \in \{0, 1\}$ is the model’s relation prediction for the respective pair of nodes. Crucially, this formulation ignores the subset $\mathcal{B} \setminus \tilde{\mathcal{B}}$ when calculating the loss.

In previous works [42], m is a manually chosen global hyperparameter, strongly affecting the model’s performance. If m is too small, not enough background edges are sampled; hence, the loss does not penalize over-prediction.

If m is too large, background edges dominate the edge loss calculation because the edge space is sparse. In that case, the network under-predicts edges. Furthermore, with only a small subset of all edges being sampled, the loss gives a noisy signal regarding edge prediction, which worsens the learning process overall.

To address these limitations, we introduce our regularized edge sampling loss for transformers, short $\mathcal{L}_{\text{Reslt}}$. In simple terms, $\mathcal{L}_{\text{Reslt}}$ adaptively chooses the number of sampled edges. If necessary, $\mathcal{L}_{\text{Reslt}}$ upsamples the edges up to a fixed ratio between active and background edges. With our novel approach, we achieve a consistent loss across samples from different domains. Formally, we introduce our regularized edge sampling below:

$\hat{\mathcal{R}} = \hat{\mathcal{A}} \cup \hat{\mathcal{B}}$ is the set of a batch’s upsampled edges. The number of elements in the upsampled multisets $\hat{\mathcal{A}}$ and $\hat{\mathcal{B}}$ have the pre-defined ratio $r = \frac{|\hat{\mathcal{A}}|}{|\hat{\mathcal{B}}|}$ where $r \in [0, 1]$. Multisets are necessary because the ratio is achieved by duplicating random edges in \mathcal{A} or \mathcal{B} .

A batch’s labels consist of a ground-truth graph \mathcal{G}_n for each sample n . \mathcal{G}_n is defined as a tuple of the sample’s nodes and edges, $\mathcal{G}_n = (\mathcal{V}_n, \mathcal{E}_n)$. The set of a batch’s nodes \mathcal{V} and edges \mathcal{E} is thus defined as:

$$\mathcal{V} = \bigcup_{n=0}^N \mathcal{V}_n \quad \text{and} \quad \mathcal{E} = \bigcup_{n=0}^N \mathcal{E}_n \quad (2)$$

Each active edge $a \in \mathcal{A} = \mathcal{E}$ is a tuple of two nodes (g, h) that are connected by the respective edge:

$$a = (g, h) \in \mathcal{E} \quad \text{where} \quad g, h \in \mathcal{V} \quad (3)$$

Each background edge $b \in \mathcal{B}$ is a tuple of two nodes (j, k) that are not connected by an edge:

$$b = (j, k) \in (\mathcal{V} \times \mathcal{V}) \setminus \mathcal{E} = \mathcal{B} \quad (4)$$

Then, the upsampled multiset of active edges $\hat{\mathcal{A}}$ is:

$$\hat{\mathcal{A}} = \mathcal{E} \cup [x_i | x_i = a_{i \bmod |\mathcal{E}|}] \quad (5)$$

with $|\mathcal{E}| \leq i < |\mathcal{B}| * r$ and $i \in \mathbb{N}$. Similarly, we define the upsampled multiset of background edges $\hat{\mathcal{B}}$ as:

$$\hat{\mathcal{B}} = \mathcal{B} \cup [x_i | x_i = b_{i \bmod |\mathcal{B}|}] \quad (6)$$

with: $|\mathcal{B}| \leq i < \frac{|\mathcal{E}|}{r}$. Notably, only one of the sets is upsampled while the other stays the same because only one of the conditions in Eq. (5) or Eq. (6) can produce a valid i .

Hence, we define our regularized edge sampling loss as:

$$\mathcal{L}_{\text{Reslt}} = \sum_{\{g,h\} \in \hat{\mathcal{R}}} \mathcal{L}_{\text{CE}}(e_{\text{rln}}^{gh}, \tilde{e}_{\text{rln}}^{gh}) \quad (7)$$

Although the edge ratio r is a hyperparameter, the model’s performance is relatively insensitive to its value. A

default value of 0.15 showed good results across all datasets (see Sec. 4 and Supplement), which makes $\mathcal{L}_{\text{Reslt}}$ beneficial compared to the previous works’ stochastic edge losses. Furthermore, $\mathcal{L}_{\text{Reslt}}$ gives a precise signal regarding edge prediction and increases convergence speed.

3.2. Supervised Domain Adaptation

In our setting, the stark differences between the source and target domain in image and graph features further amplify the TL challenge. Specifically, source and target domains significantly differ in image characteristics such as background and foreground intensities, signal-to-noise ratio, and background noise, as well as graph characteristics such as the structures’ radii or edge regularity. Edge regularity refers to the geometrical straightness of the underlying structure. While roads in the U.S. (e.g., highways) typically have a high edge regularity, vessels in microscopic images are highly irregular (i.e., the vessel does not follow a straight line and has high intra-edge curvature). To address this challenge, we utilize a domain adversarial network on the image and graph level, respectively. These adversarial networks are used when jointly pretraining in both domains. Similar to previous methods [17,30,48], the image-level adversarial network is a small neural network that classifies the domain based on a sample’s feature representation after the feature extractor. We treat each image patch $p^{u,v}$ at position u, v as an individual sample and compute the CE loss

$$\mathcal{L}_{\text{img}} = - \sum_{u,v} \left[D \log p^{u,v} + (1 - D) \log (1 - p^{u,v}) \right] \quad (8)$$

where $D \in \{0, 1\}$ denotes whether the respective sample is from the source or target domain [10].

To align graph-level features, we view the concatenated tokenized transformer output $T \in \mathbb{R}^{(\#o+\#r) \times d}$ as a sample’s abstract graph representation where $\#o$ and $\#r$ are the numbers of object and relation tokens, respectively, and d is the amount of the tokens’ hidden channels. We train a domain classifier on this abstract graph representation using the CE loss:

$$\mathcal{L}_{\text{graph}} = - \left[D \log T + (1 - D) \log (1 - T) \right] \quad (9)$$

Both domain classifiers are preceded by a GRL [17] reversing the gradient such that the main network is learning to maximize the domain loss. This framework forces the network to learn domain invariant representations and, thus, aligns the source and target domain. Furthermore, we apply a consistency regularization between both domain classifications to reduce the bias towards the source domain, as shown in [10]. This consistency regularization is expressed by an objective function minimizing the L_2 -distance between the domain classifiers’ predictions (i.e., the output

of the classification functions d_{img} and d_{graph} :

$$\mathcal{L}_{\text{cst}} = \left\| \frac{1}{|I|} \sum_{u,v} d_{\text{img}}(p^{u,v}) - d_{\text{graph}}(D) \right\|_2 \quad (10)$$

where we take the average over the image-level patch classifications of a sample consisting of $|I|$ patches.

3.3. Combined Training Loss

Our new regularized edge loss is combined with the other essential loss components to a final optimization function. The final loss consists of the L_1 regression loss (\mathcal{L}_{reg}), the scale-invariant, generalized intersection over union loss ($\mathcal{L}_{\text{gIoU}}$) for the box predictions (with predicted boxes \tilde{v}_{box} and ground truth v_{box}), and a CE classification loss (\mathcal{L}_{cls}) for object classification [42]. Further, our new regularized edge sampling loss $\mathcal{L}_{\text{Reslt}}$ and our three DA losses (\mathcal{L}_{img} , $\mathcal{L}_{\text{graph}}$, and \mathcal{L}_{cst}) are included. Furthermore, in order to achieve unique predictions, we compute a bipartite matching between the ground truth and predicted objects utilizing the Hungarian algorithm [42]. \mathcal{L}_{reg} , $\mathcal{L}_{\text{gIoU}}$, and $\mathcal{L}_{\text{Reslt}}$ are calculated over all object predictions v that are matched to a ground truth, i.e. where $v_{\text{cls}}^i = 1$, whereas \mathcal{L}_{cls} is calculated over all object predictions. The combined loss term for our N object tokens in a batch is defined as:

$$\begin{aligned} \mathcal{L} = & \sum_{i=1, [v_{\text{cls}}^i=1]}^N \left[\lambda_{\text{reg}} \mathcal{L}_{\text{reg}}(v_{\text{box}}^i, \tilde{v}_{\text{box}}^i) \right. \\ & \left. + \lambda_{\text{gIoU}} \mathcal{L}_{\text{gIoU}}(v_{\text{box}}^i, \tilde{v}_{\text{box}}^i) \right] \\ & + \lambda_{\text{cls}} \sum_{i=1}^N \mathcal{L}_{\text{cls}}(v_{\text{box}}^i, \tilde{v}_{\text{box}}^i) \quad (11) \\ & + \lambda_{\text{DA}} (\mathcal{L}_{\text{img}} + \mathcal{L}_{\text{graph}} + \mathcal{L}_{\text{cst}}) \\ & + \lambda_{\text{Reslt}} \underbrace{\sum_{\{g,h\} \in \hat{\mathcal{R}}} \mathcal{L}_{\text{CE}}(e_{\text{rln}}^{gh}, \tilde{e}_{\text{rln}}^{gh})}_{\mathcal{L}_{\text{Reslt}}} \end{aligned}$$

with λ_{reg} , λ_{gIoU} , λ_{cls} , λ_{Reslt} , and λ_{DA} as weights.

3.4. Framework for 2D-to-3D Transfer Learning

This section describes our framework for the challenging setting of a 2D source domain and a 3D target domain. This setting is especially relevant given the scarcity of completely annotated 3D image datasets. At the core of our framework is a simple projection function Π that transforms source instances into a space similar to the target space, i.e., $\Pi : (\mathcal{I}^S, \mathcal{G}^S) \rightarrow (\tilde{\mathcal{I}}, \tilde{\mathcal{G}})$. Since our regularized edge sampling loss (Sec. 3.1) and domain adaptation framework (Sec. 3.2) automatically optimize the alignment of source and target domain characteristics, we do not need to engineer our projection to resemble the target domain characteristics (e.g., signal-to-noise ratio or the structures' radiuses).

Thus, we can design our projection function in the most simple and generalizable form. Intuitively, Π projects 2D data to a 3D space by simply creating an empty 3D volume, placing the 2D image as a frame in it, and randomly rotating the entire volume. Formally, Π is described by:

1. Resize \mathcal{I}^S from $(H^{\mathcal{I}^S} \times W^{\mathcal{I}^S})$ to the target domain's spatial patch size $(H^T \times W^T)$ by a linear down-sampling operator $D : \mathcal{I}^S \rightarrow \tilde{\mathcal{I}}^{S'}$, where $D \in \mathbb{R}^{H^T W^T \times H^{\mathcal{I}^S} W^{\mathcal{I}^S}}$. G remains unchanged as we use normalized coordinates.
2. We initialize I in 3D with $I = \mathbf{0}^{H^T W^T D^T}$ and place $\tilde{\mathcal{I}}^{S'}$ in I at slice location $z = 0.5$. We also augment the node coordinates of $G := V, E$ by $V' = \{[v, 0.5] : v \in V\}$. New graph $G' := (V', E)$.
3. We apply a random three dimensional rotation matrix R on I and obtain $\tilde{I} \in \tilde{\mathcal{I}}$. We apply the same R on the nodes of G' and obtain $V'' = \{Rv : v \in V'\}$. New graph $\tilde{G} := (V'', E) \in \tilde{\mathcal{G}}$.

Notably, our approach works out of the box without requiring segmentation masks, handcrafted augmentations, specifically engineered projections, or changes to the target model. Furthermore, it naturally extends to new domains and is trainable end-to-end together with the target task.

4. Experiments and Results

Datasets. We validate our method on a diverse set of six public image datasets capturing physical networks. We choose two 2D road datasets, namely a dataset from Munich (a European city with green vegetation-dominated land cover) and from Agadez (a historic Tuareg city in Niger in the Sahara desert). The appearance in satellite images of these cities and their network structure substantially differ from the pretraining set as well as from each other; see Fig. 2. Accurately extracting road graphs is a highly important task for traffic forecasting and traffic flow modeling [15, 34]. Next, we choose a synthetic OCTA retina dataset [35] and a real OCTA dataset [26]. Additionally, we present experiments on two 3D datasets, namely a synthetic vessel dataset [40] and a real whole-brain microscopy vessel dataset [47]. Details on the datasets and data generation can be found in the Supplement.

Training. We pretrain our method on the 20 U.S. cities dataset [22] jointly with the target dataset. We crop the source images to overlapping patches, in which we eliminate redundant nodes (i.e., nodes of degree 2 with a curvature of fewer than 160 degrees) to train our model on meaningful nodes [4]. After pretraining, we finetune the model on the target dataset for 100 epochs. For more details, please refer to the Supplement and our repository.

Table 1. Main results. Quantitative Results for our cross-domain and cross-dimensional image-to-graph transfer learning framework. The domain shift increases from top to bottom. We outperform the baselines across all datasets. The best scores per respective metric across all models for a dataset are highlighted in bold. * Results for supervised pretraining on D) and E) (3D data) are not reported because it is technically not possible. Additional metrics and standard deviations are given in the Supplement.

Fine Tuning Training Set	(Pre-)Training Strategy	Node-mAP↑	Node-mAR↑	Edge-mAP↑	Edge-mAR↑	SMD ↓	Topo-Prec.↑	Topo-Rec.↑
A) TL from roads (2D) to roads (2D)								
Agadez [20]	No Pretraining [18]	0.067	0.122	0.021	0.043	0.062	0.369	0.261
	Self-supervised [9]	0.083	0.156	0.030	0.071	0.030	0.471	0.459
	Supervised	0.161	0.237	0.115	0.177	0.023	0.783	0.711
	Ours	0.163	0.244	0.116	0.172	0.022	0.816	0.614
Munich [20]	No Pretraining [18]	0.083	0.120	0.034	0.054	0.235	0.260	0.247
	Self-supervised [9]	0.088	0.145	0.060	0.097	0.155	0.339	0.384
	Supervised	0.277	0.336	0.207	0.272	0.091	0.682	0.660
	Ours	0.285	0.344	0.224	0.277	0.090	0.726	0.655
B) TL from roads (2D) to synthetic retinal vessels (2D)								
Synthetic OCTA [35]	No Pretraining [18]	0.273	0.375	0.140	0.339	0.005	0.181	0.948
	Self-supervised [9]	0.136	0.260	0.069	0.223	0.031	0.093	0.927
	Supervised	0.291	0.384	0.170	0.338	0.004	0.211	0.957
	Ours	0.415	0.493	0.250	0.415	0.002	0.401	0.890
C) TL from roads (2D) to real retinal vessels (2D)								
OCTA-500 [26]	No Pretraining [18]	0.189	0.282	0.108	0.169	0.017	0.737	0.634
	Self-supervised [9]	0.214	0.305	0.135	0.213	0.016	0.763	0.706
	Supervised	0.366	0.447	0.276	0.354	0.014	0.862	0.775
	Ours	0.491	0.571	0.366	0.489	0.012	0.877	0.817
D) TL from roads (2D) to brain vessels (3D)								
Synthetic MRI [40]	No Pretraining [18]	0.162	0.250	0.125	0.201	0.013	-	-
	Self-supervised [9]	0.162	0.252	0.120	0.193	0.014	-	-
	Supervised	*	*	*	*	*	*	*
	Ours	0.356	0.450	0.221	0.322	0.013	-	-
E) TL from roads (2D) to real whole-brain vessel data (3D)								
Microscopic images [47]	No Pretraining [18]	0.231	0.308	0.249	0.329	0.017	-	-
	Self-supervised [9]	0.344	0.404	0.363	0.425	0.017	-	-
	Supervised	*	*	*	*	*	*	*
	Ours	0.483	0.535	0.523	0.566	0.017	-	-

Metrics. We evaluate our method on six metrics from object detection and graph similarity tasks. For graph similarity, we report the 2D TOPO-score [6] and the street mover distance (SMD), which approximates the Wasserstein distance of the graph [4]. From object detection, we report mean average recall (mAR) and mean average precision (mAP) for node- and edge-detection. For more implementation details, please refer to the Supplement.

Baselines. No prior work has developed transfer learning techniques for the structural image-to-graph transformation problem. To evaluate the significance of our proposed methods, we compare the downstream task performance against three competing approaches with varying pretraining and initialization methods. Our first baseline, *no pretraining*, is random weight initialization [18], which is considered standard practice for model initialization when no suitable

pretraining is available. Second, we benchmark against a state-of-the-art method for *self-supervised pretraining*, MoCo v3 [9], which even outperformed supervised pretraining in some tasks [9]. Self-supervised pretraining is typically used when the amount of unlabeled data significantly exceeds that of labeled data in the same (or very similar) domain. Hence, we pretrain on a large set of unlabeled data from the same domain in each experiment for the self-supervised baseline. For more details regarding the unlabeled dataset, please refer to the Supplement. Third, *supervised pretraining*, where we pretrain the target model on the source data without using our methodological contributions. This approach has been successfully applied for various vision transformers, including the relationformer [42]. Note that the *supervised pretraining* baseline is impossible in 3D scenarios; only a projection function enables the use of 2D data for pretraining 3D models.

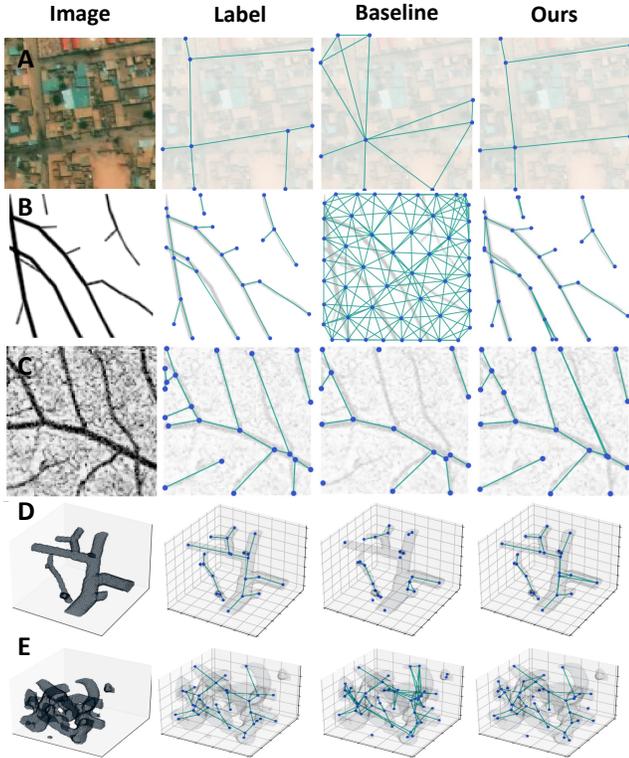


Figure 3. Qualitative results. From left to right: Image, ground truth graph, *no pretraining*-baseline, and our method. Datasets in each row are indicated by the letters for the datasets as in Tab. 1. Our method consistently outperforms the *no pretraining* baseline, which overpredicts the edges and nodes in all datasets but the OCTA-500, where the fine-tuning set is uncharacteristically large.

4.1. Results on Cross-domain TL (2D)

Our proposed transfer learning strategy shows excellent results across 2D datasets. We outperform the baseline without pretraining and self-supervised pretraining on all datasets across all object detection and graph similarity metrics; see Tab. 1. As the domain shift increases, we significantly outperform naive pretraining.

Roads in diverse locations. First, we show that we can learn to extract road graphs in topographically diverse locations with vastly variant land cover via TL. On both datasets (see Tab. 1 A), we tripled the performance across almost all metrics compared to our baseline. Our results show that edge detection fails without any form of transfer learning. Although the self-supervised method improves the baseline across all metrics, the performance does not reach the level of supervised pretraining. While our approach yields the best performance, the difference to the baseline with naive pretraining is small. We attribute this small difference to the small domain shift between the source (U.S. roads) and the

target domains, which eases knowledge transfer.

Retinal blood vessels. In the next experiment, we introduce a larger domain shift in our TL. Our target sets are two retinal blood vessel datasets (see Tab. 1 B and C). Our method doubles the node and edge detection performance on the OCTA-500 dataset [26] compared to "no pretraining." Furthermore, we significantly increase object detection and graph similarity metrics across both datasets compared to all baselines. The qualitative examples (Fig. 3) indicate that this improvement is associated with identifying more correct nodes and edges. We observe that the self-supervised method does not improve performance on the synthetic dataset but still achieves minor improvements for OCTA-500. We attribute this to the differences between the target sets: in the OCTA-500, only the arterioles and venules are annotated, leading to an easy topological structure. The main difficulty here lies in differentiating foreground from background, a task in which contrastive self-supervised training shows excellent performance. While this differentiation is easy in the synthetic OCTA dataset, the main difficulty is learning the topological structure with many (often overlapping) edges (see Fig. 3 and the Supplement). Learning this complex structure requires label information, as visible in the superior performance of the supervised pretraining methods. Naive pretraining still improves performance, but we observe a large (compared to A) performance difference between naive pretraining and our method. We attribute this to the larger domain shift, which is better addressed by our proposed methodology.

4.2. Results on Cross-dimension TL (2D to 3D)

Finally, we explore dimensional shifts in addition to a stark domain shift. Leveraging our new proposed loss (Sec. 3.1), our DA framework (Sec. 3.2), and our 2D-3D projection function (Sec. 3.4), we pretrain models on raw satellite images for the challenging task of 3D vessel graph extraction on a synthetic and a real dataset. Our experiments on the VesSAP dataset [47] show strong improvements in all graph similarity and object detection scores (see Tab. 1 E). The self-supervised method also displays improvements, which, however, do not reach our method's performance. Similarly, our method roughly doubles the object detection metrics on the 3D MRI dataset compared to the baselines (see Tab. 1 D).

We do not report results for naive pretraining because, in contrast to our method, it simply does not allow for 2D-to-3D TL. Our ablation in Sec. 4.3 shows results for applying our projection function only, without any use of our other proposed contributions. When studying the lower-performing baselines, we observe that self-supervised pretraining with MoCo v3 leads to higher improvements in the real microscopic vessel data compared to the synthetic

Table 2. Ablation study on our proposed Loss ($\mathcal{L}_{\text{Reslt}}$) and DA framework in a transfer learning setting (experiments congruent to Tab. 1). Performance improvements are associated with both our loss and DA. Both components combined lead to the best results.

Experiment	$\mathcal{L}_{\text{Reslt}}$	DA	Node mAP	Node mAR	Edge mAP	Edge mAR
C	✗	✗	0.389	0.475	0.294	0.383
	✗	✓	0.456	0.538	0.351	0.464
	✓	✓	0.491	0.571	0.366	0.489
D	✗	✗	0.190	0.285	0.122	0.210
	✗	✓	0.349	0.443	0.219	0.320
	✓	✓	0.356	0.450	0.221	0.322

Table 3. Ablation study on our proposed Loss ($\mathcal{L}_{\text{Reslt}}$) with and without pretraining (experiments congruent to Tab. 1). We find that our loss improves performance in an arbitrary image-to-graph learning setting. Here, the DA is employed in all experiments.

Experiment	Pre-training	$\mathcal{L}_{\text{Reslt}}$	Node mAP	Node mAR	Edge mAP	Edge mAR
E	✗	✗	0.231	0.308	0.249	0.329
	✗	✓	0.410	0.464	0.468	0.512
	✓	✗	0.424	0.488	0.449	0.510
	✓	✓	0.483	0.535	0.523	0.566

MRI dataset. Both datasets have complex topologies that require supervised training (see Sec. 4.1), but only the real dataset has high-intensity variations, which can be efficiently learned in a self-supervised setting. The qualitative results in Fig. 3 and the Supplement indicate that the 3D tasks were often unsolvable without our contributions.

4.3. Ablations on our Methods

In Tab. 2 and 3, we present ablations on the regularized edge sampling loss (3.1) and DA framework (3.2) for the 2D OCTA-500 [26] (Tab. 2 C), the 3D MRI [40] (Tab. 2 D), and the 3D brain vessel dataset [47] (Tab. 3 E). Expectedly, we observe that our DA alone leads to compelling performance gains for the 3D setting (almost double the performance) and 2D setting across all metrics; see Tab. 2. This is expected since the domain shift between the source dataset of satellite images and our medical images is large. Note that our projection function is always employed for the 3D dataset since pretraining is otherwise impossible. We further observe that employing the projection function alone diminishes the performance because of the domain gap, which is only alleviated by our other contributions.

Next, we ablate on our loss. When applying the DA, adding our $\mathcal{L}_{\text{Reslt}}$ loss further improves the performance (Tab. 2), indicating its strength in stabilizing and improving the loss landscape to train better networks. Additionally, we ablate our proposed $\mathcal{L}_{\text{Reslt}}$ in an experiment with and without TL. Importantly, our experiments show that $\mathcal{L}_{\text{Reslt}}$ is

a general contribution that improves image-to-graph transformation for TL as well as for general network training (Tab. 3). In a TL setting, $\mathcal{L}_{\text{Reslt}}$ is particularly useful as it reduces the data-specific hyperparameter search. Interestingly, our loss improves not only edge detection but also node detection metrics across our ablations. These improvements can be attributed to the transformer’s cross-attention modules, which treat node and edge detection as joint prediction tasks instead of separate problems. Consequently, both metrics improve jointly. For further ablation studies, e.g., experiments without the domain adversarial networks or an alternative over-sampling of the parameter r , please refer to the Supplement. In conclusion, we note that each individual contribution enhances the overall performance of the graph prediction task.

5. Discussion and Conclusion

In this work, we propose a framework for cross-domain and cross-dimension transfer learning for image-to-graph transformers. At the core of this work are our strong empirical results, which show that our proposed inductive transfer learning method outperforms competing approaches across six benchmark datasets that contain 2D and 3D images by a margin. We achieve these results through our three methodological contributions, which we ablate individually. We conclude that transfer learning has the potential to substantially reduce data requirements for highly complex geometric deep learning tasks, such as transformer-based image-to-graph inference, see Supplement. Our work shows that this holds especially when the targeted graph representations are defined by a similar physical principle or physical network. In the presented work, this shared principle is the transport of physical units (cars and blood) in a physical network.

Limitations and future work. Our problem setting is specific to image-to-graph tasks and our learning scenario in which we have some labeled data in both domains. Future work should investigate how our solution translates to different settings. Furthermore, we use a dimensionality-dependent feature extractor, which might limit generalizability to other dimensions. Future work should explore the development of strong dimension-invariant graph extractors to allow further generalization.

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