

SparseConvMIL: Sparse Convolutional Context-Aware Multiple Instance Learning for Whole Slide Image Classification

Marvin Lerousseau
CentraleSupélec

MARVIN.LEROUSSEAU@CENTRALESUPELEC.FR

Maria Vakalopoulou
CentraleSupélec

Eric Deutsch
Gustave Roussy

Nikos Paragios
CentraleSupélec

Editor: TBA

Abstract

Multiple instance learning (MIL) is the preferred approach for whole slide image classification. However, most MIL approaches do not exploit the interdependencies of tiles extracted from a whole slide image, which could provide valuable cues for classification. This paper presents a novel MIL approach that exploits the spatial relationship of tiles for classifying whole slide images. To do so, a sparse map is built from tiles embeddings, and is then classified by a sparse-input CNN. It obtained state-of-the-art performance over popular MIL approaches on the classification of cancer subtype involving 10,000 whole slide images. Our results suggest that the proposed approach might (i) improve the representation learning of instances and (ii) exploit the context of instance embeddings to enhance the classification performance. The code of this work is open-source at <https://github.com/MarvinLer/SparseConvMIL>.

Keywords: Multiple Instance Learning, Whole Slide Image Classification, Large-scale Histopathology

1. Introduction

An extremely large number of histological routine tasks involve the classification of whole slide images, including subtype diagnostic, tumor screening, tumor grading, or the choice of treatment. However, the extreme sizes of whole slide images impede their classification with conventional deep learning architectures which are the gold standard for classification in medical images (Litjens et al., 2017). Indeed, while traditional image weighs less than 1 megapixel — *e.g.* 0.09 megapixel for images of ImageNet (Deng et al., 2009) — whole slide images often contain several billions of pixels at full magnification. Unfortunately, classical deep learning architectures are not suited for such large images due to memory issues. For instance, ResNet200 (He et al., 2016) can only fit 32 images of width 224 for simultaneous forward and backward pass on popular graphic cards — equivalent to only around 1.6 megapixels.

WSI classification is a challenging problem. It cannot be tackled by downsampling WSI because many tasks rely on the phenotype of cells which is lost with downsampling. Classical approaches extract handwritten features from annotated elements of interest such as tumor tissue or lymphocytes and use traditional machine learning (Beck et al., 2011; Wang et al., 2014; Saltz et al., 2018). Apart from the limited power of manually designed features, this approach is impeded by the many difficulties of obtaining accurate annotations although recent approaches aim at automating the delineation of elements of interest (Saltz et al., 2018; Lerousseau et al., 2021). Meanwhile, classifying a (randomly) subsampled contiguous region from a WSI may result in a non-representativeness of a WSI, a phenomenon known as tumor heterogeneity (Heppner and Miller, 1983; Marusyk and Polyak, 2010). To circumvent tumor heterogeneity and the limitations of graphic cards memory, a solution consists in classifying a (pseudo-)uniformly sampled set of tiles using multiple instance learning (MIL) (Keeler et al., 1991; Dietterich et al., 1997). However, the majority of MIL approaches do not consider the relationship of tiles which undoubtedly yield valuable information. To the best of our knowledge, the only viable spatially-aware WSI classifying solution is Streaming CNN (Pinckaers et al., 2019). This approach leverages the divide and conquer paradigm by splitting a gigapixel image in subimages which are sequentially processed by graphic cards until the signal can fit wholly on video memory. While this approach can effectively entirely process gigapixel images, it suffers from additional processing time and memory usage due to the intermediate storage of temporary forward and backward maps.

The objective of our work is to bridge the gap between traditional image classification and multiple instance learning for whole slide images. The purpose is to enhance WSI classification and tile representation learning with a scalable and modular tool. To this end, we propose a fully differentiable context-aware multiple instance learning paradigm that exploits the spatial relationship of tiles extracted from whole slide images. To do so, a sparse map is built by mapping the tiles embeddings to the locations of their associated tiles within the original WSI. Then, a sparse-input CNN computes a WSI embedding from the sparse map, which is further classified using a generic classifier. The potential of this approach is benchmarked on (i) a traditional histological MIL task, and (ii) an original large-scale experiment involving 10,000 whole slide images from The Cancer Genome Atlas for subtype classification among 32 classes. Our contributions are twofold:

- a modular and powerful multiple instance learning framework
- a very large scale experiment involving 10,000 slides on a task extremely pertinent to cancer clinical histopathological routine

2. Background

2.1 Multiple instance learning

MIL is a particular classification paradigm where the considered objects are called bags (here, WSI) and are made of other objects called instances (here, patches or tiles). Instances may or may not have labels, although in any case those are unavailable during training. The only available information is the label of bags. In the more general case, MIL models can be mathematically decomposed into 3 parts: (i) an instance embedder f_{θ_1} that converts each

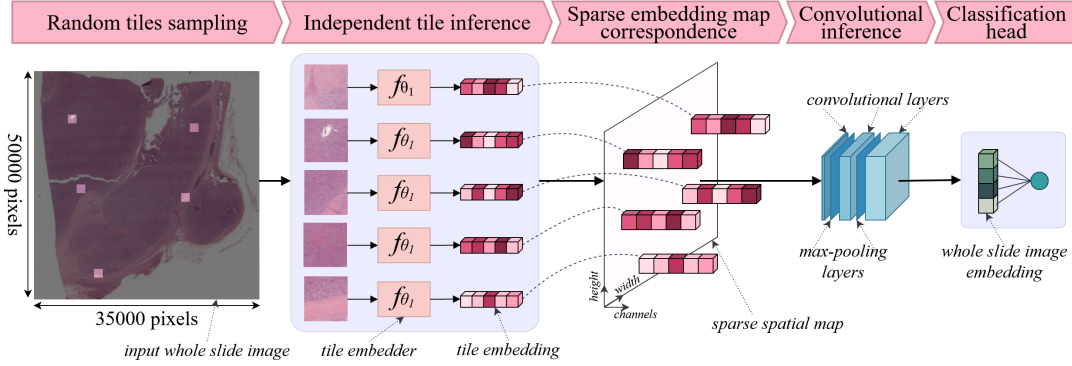


Figure 1: Visual representation of the proposed approach. First, a set of patches are randomly sampled throughout a WSI (here, 5 patches), and are then concurrently and independently forwarded into a shared patch embedder f_{θ_1} . Then, a sparse map is built by placing each resulting embedding at the location of its associated patch. This map is forwarded into a sparse-input CNN producing a bag embedding which is finally classified into scores or probabilities using a generic classifier h_{θ_3} .

instance into an embedding, (ii) a pooling operator g_{θ_2} that computes a bag embedding from the instance embeddings, and (iii) a generic classifier h_{θ_3} that converts the bag embedding into scores, such that a bag (x_1, \dots, x_K) is predicted with

$$h_{\theta_3}\left(g_{\theta_2}(f_{\theta_1}(x_1), \dots, f_{\theta_1}(x_K))\right) \quad (1)$$

f_{θ_1} can be any type of embedding function, with or without parameters, differentiable or not. In particular, instance-based MIL is a special case where f_{θ_1} outputs embeddings that lie in a unidimensional space, *i.e.* apparent to a probability space. The classifier h_{θ_3} can be any type of classifier, including a multi-layer perceptron. Actually, most of the MIL community efforts have revolved around pooling operators which can be grouped in two categories: permutation invariant operators, and others.

In some applications, such as the drug discovery problem (Dietterich et al., 1997), instances do not exhibit dependency, ordering, or spatial information among each other, *i.e.* they are independently and identically distributed (iid). For any permutation σ , the output of an iid pooling operator is the same for $x = (x_1, \dots, x_K)$ and $(\sigma(x_1), \dots, \sigma(x_K))$, *i.e.* they are permutation invariant. Examples of such pooling functions are max, mean, log-sum-exp (Ramon and De Raedt, 2000), attention-based (Ilse et al., 2018) — their mathematical formulations are provided in supplementary Appendix 1.

The iid assumption does not hold for applications where there is inherent structural information about instances, such as document classification from sentences (Angelidis and Lapata, 2018), or WSI classification from tiles. Zhou et al. (2009) have notably achieved state-of-the-art performance over iid MIL pooling operators by building a graph from instance embeddings, and then performing classification with kernel methods. With recent improvements of graph neural networks (Wu et al., 2020), further iterations have been proposed by the community (Tu et al., 2019; Yi and Lin, 2016; Zhao et al., 2020).

2.2 Sparse-input convolutional neural network

Sparse data involve the concept of *active* and *inactive* cells or pixels, where inactive cells contain no data — not even a value of 0 which uses memory. Truly sparse data have significantly less active cells than inactive cells. Examples of sparse data are point clouds from LiDAR, or tiles extracted from WSI. With their own structure, sparse data have decreased memory footprint over non-sparse (*i.e.* dense) data such as images. Several convolutional implementations designed for sparse input data have been proposed (Graham, 2015; Graham and van der Maaten, 2017; Riegler et al., 2017) revolving around the idea that convolutions should only be performed on active cells, which therefore decreases the number of computations by ignoring input regions with only inactive cells. In our work, we integrate sparse-input CNN within the MIL paradigm to shift the MIL paradigm towards a sparse convolutional one. From another point of view, we design a pooling layer that embed the MIL paradigm into a sparse fully convolutional classification architecture.

3. Methods

In this section, we present the processing of a WSI by SparseConvMIL, as illustrated in Figure 1 containing a first step of tile embeddings, followed by SparseConvMIL specific steps including (i) the sparse map construction, (ii) the sparse-input CNN processing of the sparse map, and (iii) specific data augmentation.

We consider a WSI $x \in \mathbb{R}^{3 \times w \times h}$ (3 channels, width w , height h) and a set of K patches (x_1, \dots, x_K) extracted from x . A generic tile embedder f_{θ_1} (*e.g.* a ResNet architecture (He et al., 2016)) concurrently and independently computes the tiles embeddings $(f_{\theta_1}(x_1), \dots, f_{\theta_1}(x_K))$.

Sparse map construction For each tile x_k , we also consider its location within the WSI denoted (i_k, j_k) , such as its center. A sparse embedding map S^x is built by assigning each tile embedding to their associated tile location, while other locations are set inactive. Alternatively, S^x can be formalized only by its active cells:

$$S^x = \left\{ [(i_k, j_k), f_{\theta_1}(x_{i_k, j_k})]; 1 \leq k \leq K \right\} \subset (\mathbb{N} \times \mathbb{N} \times \mathbb{H})^K \quad (2)$$

In theory, a sparse map thus built has the same size as the input WSI. However in practice, few tiles can be extracted from a WSI *i.e.* the sparse map is very sparse. This implies that most convolutional operations would involve at most one active cell — essentially not leveraging the locality of the filters of the CNN. To address this issue, we introduce an additional parameter called the *downsampling* factor, noted d . Rather than assigning a tile x_k at its associated location (i_k, j_k) within S^x , it is assigned to locations $\left(\left\lfloor \frac{i_k}{d} \right\rfloor, \left\lfloor \frac{j_k}{d} \right\rfloor \right)$. d sufficiently high would ensure that later neurons have at least two active cells in their receptive fields. We evaluate the impact of the downsampling factor in the experiments.

Because the sparse map construction only assigns vectors to locations, it is differentiable. In particular, an error signal from backpropagation can be assigned to vectors based on their locations — and subsequently to update the parameters of f_{θ_1} . Once S^x is built, it is forward into a sparse-input CNN.

Sparse-input convolutional neural network Sparse-input CNNs are essentially CNNs that operate specifically on sparse data, with reduced FLOPs and memory footprint. In particular with the formulation of Graham and van der Maaten (2017), a sparse-input convolution produces at most the number of input map active cells, by setting an inactive cell in the output for each input inactive cell. Mathematically, given a convolutional layer $U \in \mathbb{R}^{2f+1} \times \mathbb{R}^{2f+1} \times \mathbb{R}^o$ with a filter of half-size f , stride s , and o output channels, convolving U on a sparse map S^x produces the feature map $U \circledast S^x$ such that:

$$\forall i, j : (U \circledast S^x)_{i,j} = \begin{cases} \sum_{\substack{m=-f \\ n=-f}}^f U_{m+f,n+f} \cdot S_{si+m,sj+n}^x & \text{if } S_{si,sj}^x \neq \emptyset \\ \emptyset & \text{otherwise} \end{cases} \quad (3)$$

where \emptyset indicates inactive cells and an inactive cell has no impact on the sum.

Similarly, for a pooling function p such as max or average, the output of a p -pooling layer with filter size f and stride s on S^x produces $p(S^x)$ such that:

$$\forall i, j : p(S^x)_{i,j} = \begin{cases} p(\{S_{si+m,sj+n}^x; 0 \leq m, n < f, S_{si+m,sj+n}^x \neq \emptyset\}) & \text{if } S_{si,sj}^x \neq \emptyset \\ \emptyset & \text{otherwise} \end{cases} \quad (4)$$

In particular, sparse-input adaptive global pooling layers with output size o are defined as sparse-input pooling layers of both stride and filter size $\lfloor \frac{w}{o} \rfloor$ for the width and $\lfloor \frac{h}{o} \rfloor$ for the height. Activation functions are processed in the same fashion with stride 1, filter size 1 (therefore only on active cells) and with functions such as ReLU, tanh, or sigmoid.

Eventually a bag embedding is obtained after a succession of sparse-input (strided) convolutions and activations. To ensure that the spatial dimension of the bag embedding does not depend on the size of the input whole slide image, a (sparse-)adaptive global pooling layer is used at the end of the sparse-input CNN MIL operator — effectively transforming the output sparse feature map into a dense one. Bag scores can then be computed with any type of classifier, including multi-layer perceptrons.

Context-aware specific data augmentation The proposed approach benefits from additional data augmentation strategies over permutation non-invariant pooling strategies, precisely because it treats instances as non i.i.d. Spatial augmentations (*e.g.* flipping, rotations, local shuffling or elastic deformations) performed on tiles locations, or equivalently on the sparse map, can help reduce the burden of overfitting by artificially increasing the input data to the pooling CNN. Besides, these augmentations can be performed after tile embedding inference, implying that multiple sparse map spatial augmentations can be done with a low additional memory footprint. Examples of data augmented sparse maps are shown in supplementary Figure 1.

4. Experimental validation

We have used two data examples to demonstrate the extreme potentials of our method: CRCHISTOPHENOTYPE (subsection 4.1) and THE CANCER GENOME ATLAS (TCGA) (subsection 4.2).

4.1 Classical MIL dataset

Dataset The CRCHISTOPHENOTYPE (Sirinukunwattana et al., 2016) dataset consists of 100 haematoxylin and eosin-stained (H&E) 500×500 pixels histology images of colorectal adenocarcinomas. A total of 22,444 nuclei are annotated with (i) the position of their center and (ii) their class type *i.e.* one of epithelial, inflammatory, fibroblast, or miscellaneous. We considered the binary task of classifying power fields as having epithelial cells or not: accurately detecting epithelial cells is a valuable clinical task since most cancers arise from the epithelium (Thiery et al., 2009). To do so, 27×27 pixels-wide images were extracted from all annotated cell centers. Although each 27×27 image has a binary annotation (epithelial or not), those were hidden during training, and only the power field-level labels were made available, which were set to 1 if at least one 27×27 image is epithelial. This resulted in 51 positive and 49 negative bags.

Implementation details SparseConvMIL was benchmarked along attention-based MIL approaches (Ilse et al., 2018), as well as instance and embedding-based max and mean pooling. All of these approaches shared the same training parameters which are detailed in supplementary Appendix B. This included (i) architectures of the tile embedding network f_{θ_1} and classifier h_{θ_3} , (ii) hyper-parameters such as learning rate, optimizer, and batch size, and (iii) data augmentation. We now detail the specificities of each approach. Attention-based approaches used a two-layer neural network for attention with 128 hidden neurons as used in Ilse et al. (2018), resulting in 66,304 pooling parameters and 131,968 for the gated version. The proposed SparseConvMIL was implemented with two 12-channels convolutional filters with filter size 3 and stride 1, and ReLU activation, resulting in a module with 56,628 parameters. For SparseConvMIL, the position of the center of each tile was used to build the sparse maps with a downsampling factor of 5, resulting in sparse maps of size 50×50 .

Results Results are reported in Table 1. The proposed approach achieved the best performance in terms of balanced accuracy and f1-score. Although its precision was slightly lower than the attention-based methods, it achieved a significantly higher recall, which is desirable for clinical considerations in order not to miss potentially arising tumor tissue.

METHOD	ACCURACY	PRECISION	RECALL	F1-SCORE	AUC
Instance+max	0.842±0.021	0.866±0.017	0.816±0.031	0.839±0.023	0.914±0.010
Instance+mean	0.772±0.012	0.821±0.011	0.710±0.031	0.759±0.017	0.866±0.008
max	0.824±0.015	0.884±0.014	0.753±0.020	0.813±0.017	0.918±0.010
mean	0.860±0.014	0.911±0.011	0.804±0.027	0.853±0.016	0.940±0.010
Attention	0.904±0.011	0.953 ±0.014	0.855±0.017	0.901±0.011	0.968 ±0.009
Gated-Attention	0.898±0.020	0.944±0.016	0.851±0.035	0.893±0.022	0.968 ±0.010
Proposed	0.944 ±0.019	0.929±0.021	0.944 ±0.019	0.932 ±0.024	0.958±0.008

Table 1: Results on CRCHISTOPHENOTYPE in mean \pm standard deviation of 5 runs. Attention and Gated-Attention are from Ilse et al. (2018).

4.2 Large-scale whole slide image dataset

Dataset 10,000 whole slide images were downloaded from THE CANCER GENOME ATLAS from 32 cancer subtypes as detailed in supplementary Table 3, for a total of 5.57 TB of data. The only inclusive criteria was that WSI must display tumor material since the downstream task was cancer subtype classification which cannot be accurately done on benign samples. All WSI were tiled into 512 pixel-wide tiles with 128 pixels overlap on both sides at $10\times$ magnification using the repository from Lerousseau et al. (2020). The cohort was split on a patient-basis in 4397, 2001 and 3602 slides for respectively the training, validation and testing sets.

Implementation details 14 MIL approaches were benchmarked: (i) embedding and instance-based max, mean, and log-sum-exp, (ii) several flavors of attention-based approaches, (iii) a graph-CNN approach (Tu et al., 2019), and (iv) several flavors of SparseConvMIL. Similar to the previous experiment, all approaches share the same training context detailed in supplementary Appendix B which includes hyper-parameters, data augmentation, architectures of both tile embedder and classifier from WSI embeddings. For specific details of the benchmarked approaches, SparseConvMIL used a downsampling of 128. We experimented with only 2 convolutional layers with 32, or 128 channels. The attention module of attention MIL approaches were made of a 1 hidden layer perceptron with 128, 512 or 2048 neurons. Graph-based MIL was implemented with the same parameters as in Tu et al. (2019).

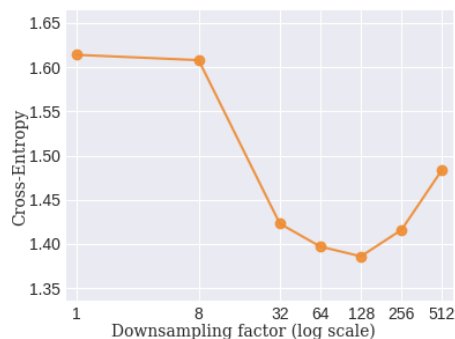
METHOD	#PARAMS	ACCURACY	PRECISION	F1-SCORE	AUC	CE↓
Random performance	N/A	0.031	0.031	0.031	0.500	3.506
Instance+max [†]	0	0.417	0.365	0.360	0.879	2.027
Instance+mean [†]	0	0.463	0.417	0.414	0.905	1.783
Instance+LSE [†]	0	0.451	0.406	0.403	0.898	1.819
max [†]	0	0.441	0.434	0.403	0.913	1.821
mean [†]	0	0.488	0.463	0.456	0.917	1.604
Attention-128	12k	0.481	0.448	0.449	0.913	1.619
Attention-512	219k	0.487	0.451	0.453	0.912	1.616
Attention-2048	985k	0.472	0.452	0.452	0.909	1.621
Gated-Attention-128	24k	0.492	0.452	0.456	0.916	1.613
Gated-Attention-512	261k	0.487	0.447	0.450	0.911	1.629
Gated-Attention-2048	1986k	0.483	0.457	0.459	0.911	1.604
Graph-CNN	719k	0.464	0.439	0.436	0.907	1.673
Proposed-c32,c32	87k	0.523	0.508	0.504	0.935	1.386
Proposed-c128,c128	672k	0.568	0.568	0.553	0.944	1.267
Random performance	N/A	0.031	0.031	0.031	0.500	3.506

Table 2: Results of the 32 classes classification on the TCGA dataset. PARAMS are the number of pooling parameters (in thousand) *i.e.* without considering tile embedder and classifier. ACCURACY is balanced. CE stands for cross-entropy. Random is the random performance. [†] denotes pooling methods that are non-parametric *i.e.* that cannot have parameters in their pooling operator.

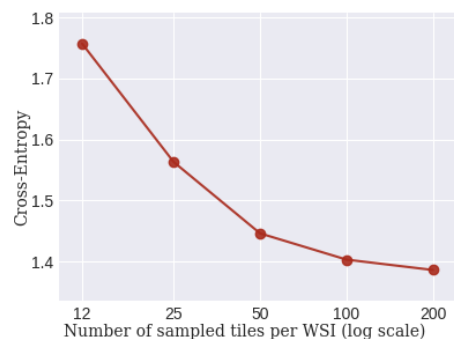
Results Table 2 reports results for several metrics computed by averaging one-vs-all metrics for each class. In particular, the random performance is 0.031 for both accuracy, precision and f1-score, 0.5 AUC, and 3.506 cross-entropy. Although the number of pooling parameters differed for some methods, the comparisons are otherwise fair since both tile embedder and final classifier were the same.

The proposed approach achieved superior results in all metrics and for all configurations. Even the smaller SparseConvMIL configuration outcompeted other benchmarked approaches with 0.568 of precision and balanced accuracy, f1-score of 0.553, and AUC of 0.944. This is extremely encouraging given that the task has 32 classes and that many classes are under-represented: for instance, 14 classes have less than 100 training samples as detailed in supplementary Table 4. Furthermore, SparseConvMIL seemed to scale better with parameters than attention-based MIL. Indeed, increasing the parameters of SparseConvMIL significantly improved its performance whereas attention-based MIL stagnated with additional parameters. The graph-based approach notoriously underperformed, which may be due to the difficulty in choosing appropriate parameters for the many modules involved in this approach.

We aimed at understanding the limitations of the proposed approach. Figure 2a plots the performance of SparseConvMIL-c32,c32 on the same task but with various downsampling factors. In particular, the method performed significantly worse for low downsampling, which we conjecture is due to the fact that tiles are too far apart to exploit spatial context with convolutions. Furthermore, the performance of SparseConvMIL decreased for high downsampling, *e.g.* 256 or 512, which is probably due to uncoalesced sparse maps, where there may be duplicate coordinates for several tiles provoking a loss of input tiles. Meanwhile, Figure 2b plots the performance of SparseConvMIL by varying the number of tiles sampled per WSI for a downsampling of 128. Its performance increased with respect to the number of sampled tiles, which is not surprising since increasing the number of sampled tiles provides additional information about the underlying whole slide images.



(a) varying the downsampling factor



(b) varying the number of sampled tiles

Figure 2: Performance of SparseConvMIL-c32,c32 by varying the input sparsity on the TCGA experiment.

5. Conclusion

In this paper, we proposed a flexible and powerful sparse-input convolutional multiple instance learning approach for classifying whole slide images. SparseConvMIL demonstrated significantly better performance for the pan-cancer subtype classification of whole slide image, an extremely pertinent task for clinical purposes. Although some limitations of our approach have been highlighted, we believe that SparseConvMIL has the potential to become a gold standard for WSI classification and tile representation learning.

Our most important future work is to integrate interpretability through visualization, and notably by automatically extracting key instances. We obtained encouraging early results by using several common CNN visualization techniques such as Class Activation Mapping (Zhou et al., 2016), GradCAM (Selvaraju et al., 2017), and DeepLIFT (Shrikumar et al., 2017). Meanwhile, there are endless possibilities on the choice of architectures for the sparse-input CNN part of our approach which can be investigated.

References

- Stefanos Angelidis and Mirella Lapata. Multiple instance learning networks for fine-grained sentiment analysis. *Transactions of the Association for Computational Linguistics*, 6: 17–31, 2018.
- Andrew H Beck, Ankur R Sangoi, Samuel Leung, Robert J Marinelli, Torsten O Nielsen, Marc J Van De Vijver, Robert B West, Matt Van De Rijn, and Daphne Koller. Systematic analysis of breast cancer morphology uncovers stromal features associated with survival. *Science translational medicine*, 3(108):108ra113–108ra113, 2011.
- Jia Deng, Wei Dong, Richard Socher, Li-Jia Li, Kai Li, and Li Fei-Fei. Imagenet: A large-scale hierarchical image database. In *2009 IEEE conference on computer vision and pattern recognition*, pages 248–255. Ieee, 2009.
- Thomas G Dietterich, Richard H Lathrop, and Tomás Lozano-Pérez. Solving the multiple instance problem with axis-parallel rectangles. *Artificial intelligence*, 89(1-2):31–71, 1997.
- Ben Graham. Sparse 3d convolutional neural networks. *arXiv preprint arXiv:1505.02890*, 2015.
- Benjamin Graham and Laurens van der Maaten. Submanifold sparse convolutional networks. *arXiv preprint arXiv:1706.01307*, 2017.
- Kaiming He, Xiangyu Zhang, Shaoqing Ren, and Jian Sun. Identity mappings in deep residual networks. In *European conference on computer vision*, pages 630–645. Springer, 2016.
- Gloria H Heppner and Bonnie E Miller. Tumor heterogeneity: biological implications and therapeutic consequences. *Cancer and Metastasis Reviews*, 2(1):5–23, 1983.
- Maximilian Ilse, Jakub Tomczak, and Max Welling. Attention-based deep multiple instance learning. In *International conference on machine learning*, pages 2127–2136. PMLR, 2018.

- James D Keeler, David E Rumelhart, and Wee-Kheng Leow. *Integrated segmentation and recognition of hand-printed numerals*. Microelectronics and Computer Technology Corporation, 1991.
- Diederik P Kingma and Jimmy Ba. Adam: A method for stochastic optimization. *arXiv preprint arXiv:1412.6980*, 2014.
- Marvin Lrousseau, Maria Vakalopoulou, Marion Classe, Julien Adam, Enzo Battistella, Alexandre Carré, Théo Estienne, Théophraste Henry, Eric Deutsch, and Nikos Paragios. Weakly supervised multiple instance learning histopathological tumor segmentation. In *International Conference on Medical Image Computing and Computer-Assisted Intervention*, pages 470–479. Springer, 2020.
- Marvin Lrousseau, Marion Classe, Enzo Battistella, Théo Estienne, Théophraste Henry, Amaury Leroy, Roger Sun, Maria Vakalopoulou, Jean-Yves Scoazec, Eric Deutsch, et al. Weakly supervised pan-cancer segmentation tool. *arXiv preprint arXiv:2105.04269*, 2021.
- Geert Litjens, Thijs Kooi, Babak Ehteshami Bejnordi, Arnaud Arindra Adiyoso Setio, Francesco Ciompi, Mohsen Ghafoorian, Jeroen Awm Van Der Laak, Bram Van Ginneken, and Clara I Sánchez. A survey on deep learning in medical image analysis. *Medical image analysis*, 42:60–88, 2017.
- Andriy Marusyk and Kornelia Polyak. Tumor heterogeneity: causes and consequences. *Biochimica et Biophysica Acta (BBA)-Reviews on Cancer*, 1805(1):105–117, 2010.
- Fabian Pedregosa, Gaël Varoquaux, Alexandre Gramfort, Vincent Michel, Bertrand Thirion, Olivier Grisel, Mathieu Blondel, Peter Prettenhofer, Ron Weiss, Vincent Dubourg, et al. Scikit-learn: Machine learning in python. *the Journal of machine Learning research*, 12:2825–2830, 2011.
- Hans Pinckaers, Bram van Ginneken, and Geert Litjens. Streaming convolutional neural networks for end-to-end learning with multi-megapixel images. *arXiv preprint arXiv:1911.04432*, 2019.
- Jan Ramon and Luc De Raedt. Multi instance neural networks. In *Proceedings of the ICML-2000 workshop on attribute-value and relational learning*, pages 53–60, 2000.
- Gernot Riegler, Ali Osman Ulusoy, and Andreas Geiger. Octnet: Learning deep 3d representations at high resolutions. In *Proceedings of the IEEE conference on computer vision and pattern recognition*, pages 3577–3586, 2017.
- Arnout C Ruifrok, Dennis A Johnston, et al. Quantification of histochemical staining by color deconvolution. *Analytical and quantitative cytology and histology*, 23(4):291–299, 2001.
- Joel Saltz, Rajarsi Gupta, Le Hou, Tahsin Kurc, Pankaj Singh, Vu Nguyen, Dimitris Samaras, Kenneth R Shroyer, Tianhao Zhao, Rebecca Batiste, et al. Spatial organization and molecular correlation of tumor-infiltrating lymphocytes using deep learning on pathology images. *Cell reports*, 23(1):181–193, 2018.

- Ramprasaath R Selvaraju, Michael Cogswell, Abhishek Das, Ramakrishna Vedantam, Devi Parikh, and Dhruv Batra. Grad-cam: Visual explanations from deep networks via gradient-based localization. In *Proceedings of the IEEE international conference on computer vision*, pages 618–626, 2017.
- Avanti Shrikumar, Peyton Greenside, and Anshul Kundaje. Learning important features through propagating activation differences. In *International Conference on Machine Learning*, pages 3145–3153. PMLR, 2017.
- Korsuk Sirinukunwattana, Shan E Ahmed Raza, Yee-Wah Tsang, David RJ Snead, Ian A Cree, and Nasir M Rajpoot. Locality sensitive deep learning for detection and classification of nuclei in routine colon cancer histology images. *IEEE transactions on medical imaging*, 35(5):1196–1206, 2016.
- Jean Paul Thiery, Hervé Acloque, Ruby YJ Huang, and M Angela Nieto. Epithelial-mesenchymal transitions in development and disease. *cell*, 139(5):871–890, 2009.
- Ming Tu, Jing Huang, Xiaodong He, and Bowen Zhou. Multiple instance learning with graph neural networks. *arXiv preprint arXiv:1906.04881*, 2019.
- Hongyuan Wang, Fuyong Xing, Hai Su, Arnold Stromberg, and Lin Yang. Novel image markers for non-small cell lung cancer classification and survival prediction. *BMC bioinformatics*, 15(1):1–12, 2014.
- Zonghan Wu, Shirui Pan, Fengwen Chen, Guodong Long, Chengqi Zhang, and S Yu Philip. A comprehensive survey on graph neural networks. *IEEE transactions on neural networks and learning systems*, 2020.
- Yang Yi and Maoqing Lin. Human action recognition with graph-based multiple-instance learning. *Pattern Recognition*, 53:148–162, 2016.
- Yu Zhao, Fan Yang, Yuqi Fang, Hailing Liu, Niyun Zhou, Jun Zhang, Jiarui Sun, Sen Yang, Bjoern Menze, Xinjuan Fan, et al. Predicting lymph node metastasis using histopathological images based on multiple instance learning with deep graph convolution. In *Proceedings of the IEEE/CVF Conference on Computer Vision and Pattern Recognition*, pages 4837–4846, 2020.
- Bolei Zhou, Aditya Khosla, Agata Lapedriza, Aude Oliva, and Antonio Torralba. Learning deep features for discriminative localization. In *Proceedings of the IEEE conference on computer vision and pattern recognition*, pages 2921–2929, 2016.
- Zhi-Hua Zhou, Yu-Yin Sun, and Yu-Feng Li. Multi-instance learning by treating instances as non-iid samples. In *Proceedings of the 26th annual international conference on machine learning*, pages 1249–1256, 2009.