A LEARNABLE SCATTERNET: LOCALLY INVARIANT CONVOLUTIONAL LAYERS

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ABSTRACT

In this paper we explore tying together the ideas from Scattering Transforms and Convolutional Neural Networks (CNN) for Image Analysis by proposing a learnable ScatterNet. Previous attempts at tying them together in hybrid networks have tended to keep the two parts separate, with the ScatterNet forming a fixed front end and a CNN forming a learned backend. We instead look at adding learning between scattering orders, as well as adding learned layers before the ScatterNet. We do this by breaking down the scattering orders into single convolutional-like layers we call 'locally invariant' layers, and adding a learned mixing term to this layer. Our experiments show that these locally invariant layers can improve accuracy when added to either a CNN or a ScatterNet. We also discover some surprising results in that the ScatterNet may be best positioned after one or more layers of learning rather than at the front of a neural network.

Index Terms— CNN, ScatterNet, invariant, wavelet, DTCWT

1. INTRODUCTION

In image understanding tasks such as classification, recognition and segmentation, Convolutional Neural Networks (CNNs) have now become the *de facto* and the state of the art model. Since they proved their worth in 2012 by winning the ImageNet Large Scale Visual Recognition Competition (ILSVRC) [20] with the AlexNetwork [12], they have been fine tuned and developed into very powerful and flexible models. Most of this development has been in changing the architecture, such as the Residual Network[8], the Inception Network [27] and the DenseNet [10]. However one of the key building blocks of CNNs, the convolutional filter bank, has seen less development and in today's models they are not too dissimilar to what they were in 2012. We believe there is still much to explore in the way convolutional filters are built and learned.

Current layers are randomly initialized and learned through back-propagation by minimizing a custom loss function. The properties and purpose of learned filters past the first layer of a CNN are not well understood, a deeply unsatisfying situation, particularly when we start to see problems in modern solutions such as significant redundancy [7] and weakness to adversarial attacks [2].

The Scattering Transform by Mallat et. al. [15, 1] attempts to address the problems of poorly understood filtering layers by using predefined wavelet bases whose properties are well known. Using this knowledge, Mallat derives bounds on the effect of noise and deformations to the input. This work inspires us, but the fixed nature of ScatterNets has proved a limiting factor for them so far. To combat this, [17, 16, 23] use ScatterNets as a front end for deep learning tasks, calling them Hybrid ScatterNets; these have had some initial success.

In [6] we visualized what features a ScatterNet extracted and showed that they were ripple-like and very dissimilar from an equivalent CNN. This stems from the fact that the higher orders of scattering do not permit filtering across the channel dimension. We believe it could prove beneficial for the Hybrid ScatterNet design if we expand it to allow for this cross-channel mixing.

To do this, we take inspiration from works like [18, 11, 28, 5], which decompose convolutional filters as a learned mixing of fixed harmonic functions. Instead, we learn to mix locally invariant scattering terms.

In section 2 we briefly review convolutional layers and scattering layers before introducing our learnable scattering layers in section 3. In section 4 we describe how we implement our proposed layer, and present some experiments we have run in section 5, showing the proposed layer does indeed improve the Hybrid ScatterNet design.

2. RELATED WORK

2.1. Convolutional Layers

Let the output of a CNN at layer l be:

$$x^{(l)}(c, \mathbf{u}), \quad c \in \{0, \dots C_l - 1\}, \mathbf{u} \in \mathbb{R}^2$$

where c indexes the channel dimension , and $\mathbf{u}$ is a vector of coordinates for the spatial position. Of course, $\mathbf{u}$ is typically sampled on a grid, but following the style of [18], we keep it continuous to more easily differentiate between the spatial and channel dimensions. A typical convolutional layer in a standard CNN (ignoring the bias term) is:

$$y^{(l+1)}(f, \mathbf{u}) = \sum_{c=0}^{C_l - 1} x^{(l)}(c, \mathbf{u}) * h_f^{(l)}(c, \mathbf{u}) \tag{1}$$

$$x^{(l+1)}(f, \mathbf{u}) = \sigma\left(y^{(l+1)}(f, \mathbf{u})\right) \tag{2}$$

where $h_f^{(l)}(c, \mathbf{u})$ is the fth filter of the lth layer (i.e. $f \in \{0, \dots, C_{l+1} - 1\}$) with C_l different point spread functions. σ is a non-linearity possibly combined with scaling such as batch normalization. The convolution is done independently for each c in the C_l channels and the resulting outputs are summed together to give one activation map. This is repeated C_{l+1} times to give $\left\{x^{(l+1)}(f, \mathbf{u})\right\}_{f \in \{0, \dots, C_{l+1}-1\}, \mathbf{u} \in \mathbb{R}^2}$

2.2. Wavelets and Scattering Transforms

The 2-D wavelet transform is done by convolving the input with a mother wavelet dilated by 2^j and rotated by θ:

$$\psi_{j,\theta}(\mathbf{u}) = 2^{-j}\psi\left(2^{-j}R_{-\theta}\mathbf{u}\right) \tag{3}$$

where R is the rotation matrix, $1 \leq j \leq J$ indexes the scale, and $1 \leq k \leq K$ indexes θ to give K angles between 0 and π. We copy notation from [1] and define $\lambda = (j, k)$ and the set of all possible λs is Λ whose size is $|\Lambda| = JK$. The wavelet transform, including lowpass, is then:

$$Wx(c, \mathbf{u}) = \{x(c, \mathbf{u}) * \phi_J(\mathbf{u}),\ x(c, \mathbf{u}) * \psi_\lambda(\mathbf{u})\}_{\lambda \in \Lambda} \quad (4)$$

Taking the modulus of the wavelet coefficients removes the high frequency oscillations of the output signal while preserving the energy of the coefficients over the frequency band covered by ψ_λ. This is crucial to ensure that the scattering energy is concentrated towards zero-frequency as the scattering order increases, allowing sub-sampling. We define the wavelet modulus propagator to be:

$$\tilde{W}x(c, \mathbf{u}) = \{x(c, \mathbf{u}) * \phi_J(\mathbf{u}),\ |x(c, \mathbf{u}) * \psi_\lambda(\mathbf{u})|\}_{\lambda \in \Lambda} \quad (5)$$

Let us call these modulus terms $U[\lambda]x = |x * \psi_\lambda|$. We define a path as a sequence of λs given by $p = (\lambda_1, \lambda_2, \ldots \lambda_m)$ and define the modulus propagator acting on a path p by:

$$\begin{aligned} U[p]x &= U[\lambda_m] \cdots U[\lambda_2]U[\lambda_1]x & (6) \\ &= ||\cdots|x * \psi_{\lambda_1}| * \psi_{\lambda_2}| \cdots * \psi_{\lambda_m}| & (7) \end{aligned}$$

These descriptors are then averaged over a window 2^J by a scaled lowpass filter $\phi_J = 2^{-J}\phi(2^{-J}\mathbf{u})$ giving the 'invariant' scattering coefficient

$$S[p]x(\mathbf{u}) = U[p]x * \phi_J(\mathbf{u}) \quad (8)$$

If we define $p + \lambda = (\lambda_1, \ldots, \lambda_m, \lambda)$ then we can combine eq. (5) and eq. (6) to give:

$$\tilde{W}U[p]x = \{S[p]x, U[p+\lambda]x\}_\lambda \quad (9)$$

Hence we iteratively apply $\tilde{W}$ to all of the propagated U terms of the previous layer to get the next order $U[p+\lambda]$ terms and the desired scattering coefficients $S[p]$.

The resulting scattering coefficients have many nice properties, one of which is stability to diffeomorphisms (such as shifts and warping). From [15], if $\mathcal{L}_\tau x = x(\mathbf{u} - \tau(\mathbf{u}))$ is a diffeomorphism which is bounded with $\|\nabla\tau\|_\infty \leq 1/2$, then there exists a $K_L > 0$ such that:

$$\|S\mathcal{L}_\tau x - Sx\| \leq K_L P H(\tau)\|x\| \quad (10)$$

where $P = \text{length}(p)$ is the scattering order, and $H(\tau)$ is a function of the size of the displacement, derivative and Hessian of τ.

Note that an inherent property of the scattering transform is that the number of output channels grows exponentially with the scattering order m. E.g. for the favored second order scattering transform with $J = 2$, the output has $(K+1)^2$ as many channels as the input. A typical value for K is 6 or 8, giving a 49 or 81 fold increase in the number of channels.

3. LOCALLY INVARIANT LAYER

The U terms in subsection 2.2 are often called 'covariant' terms but in this paper we will call them locally invariant, as they tend to be invariant up to a scale 2^j. We propose to mix the locally invariant terms U and the lowpass terms S with learned weights $a_{f,\lambda}$ and b_f. For example, consider a first order ScatterNet, and let the input to it be $x^{(l)}$. Our proposed output $y^{(l+1)}$ is then:

$$\begin{aligned} y^{(l+1)}(f, \mathbf{u}) &= \sum_{\lambda \in \Lambda} \sum_{c=0}^{C-1} |x^{(l)}(c, \mathbf{u}) * \psi_\lambda(\mathbf{u})|\ a_{f,\lambda}(c) \\ &+ \left(\sum_{c=0}^{C-1} x^{(l)}(c, \mathbf{u}) * \phi_J(\mathbf{u}) \right) b_f(c) \quad (11) \end{aligned}$$

Returning to eq. (5), we define a new index variable γ such that $\tilde{W}[\gamma]x = x * \phi_J$ for $\gamma = 1$ and $\tilde{W}[\gamma]x = |x * \psi_\lambda|$ for $2 \leq \gamma \leq JK + 1$. We do the same for the weights a, b by defining $\tilde{a}_f = \{b_f, a_{f,\lambda}\}_\lambda$ and $\tilde{a}_f[\gamma] = b_f$ if $\gamma = 1$ and $\tilde{a}_f[\gamma] = a_{f,\lambda}$ if $2 \leq \gamma \leq JK + 1$. We further define $q = (c, \gamma) \in Q$ to combine the channel and index terms. This simplifies eq. (11) to be:

$$\begin{aligned} z^{(l+1)}(q, \mathbf{u}) &= \tilde{W}x^{(l)}[q] = \tilde{W}[\gamma]x^{(l)}(c, \mathbf{u}) & (12) \\ y^{(l+1)}(f, \mathbf{u}) &= \sum_{q \in Q} z^{(l+1)}(q, \mathbf{u})\tilde{a}_f(q) & (13) \end{aligned}$$

or in matrix form with $A_{f,q} = \tilde{a}_f(q)$

$$Y^{(l+1)}(\mathbf{u}) = AZ^{(l+1)}(\mathbf{u}) \quad (14)$$

This is very similar to the standard convolutional layer from eq. (1), except we have replaced the previous layer's x with intermediate coefficients z (with $|Q| = (JK+1)C$ channels), and the convolutions of eq. (1) have been replaced by a matrix multiply (which can also be seen as a 1×1 convolutional layer). We can then apply eq. (2) to eq. (13) to get the next layer's output.

3.1. Properties

With careful choice of A and σ, we can recover the original translation invariant ScatterNet [1, 17], making the invariant layer a superset of the scattering layer.

Proof. If $C_{l+1} = (JK+1)C_l$ and A is the identity matrix $I_{C_{l+1}}$, we remove the mixing and then $y^{(l+1)} = \tilde{W}x$. Further, if $\sigma = \text{ReLU}$ as is commonly the case in training CNNs, it has no effect on the positive locally invariant terms U. It will affect the averaging terms if the signal is not positive, but this can be dealt with by adding a channel dependent bias term α_c to $x^{(l)}$ to ensure it is positive. This bias term will not affect the propagated signals as $\int \alpha_c \psi_\lambda(\mathbf{u}) d\mathbf{u} = 0$. The bias can then be corrected by subtracting $\alpha_c \|\phi_J\|_2$ from the averaging terms after taking the ReLU, then $x^{(l+1)} = \tilde{W}x$. □

This means we can recover a first order scattering transform with one invariant layer, giving S_0 and U_1 (invariant to input shifts of 2^1). Repeating the same process for the higher orders, as we saw in eq. (6), we can recover S_{m-1} and U_m, invariant to shifts of 2^m. After m layers, we can recover S_m by average pooling the output U_m terms.

Additionally, the proposed mixing does not impact the stability to diffeomorphisms (eq. (10)).

Proof. Let us define the action of our layer on the scattering coefficients to be Vx. We would like to find a bound on $\|V\mathcal{L}_\tau x - Vx\|$. To do this, note that the mixing is a linear operator and hence is Lipschitz continuous. Constraint (A2) from [18] sets simple conditions on the mixing weights to make them non-expansive (i.e. Lipschitz constant 1). Further, the ReLU is non-expansive meaning the combination of the two is also non-expansive, so $\|V\mathcal{L}_\tau x - Vx\| \leq \|S\mathcal{L}_\tau x - Sx\|$, and eq. (10) holds. □

4. IMPLEMENTATION

Like [25, 24] we use the DTℂWT [21] for our wavelet filters $\psi_{j,\theta}$ due to their fast implementation with separable convolutions which we will discuss more in subsection 4.2. A side effect of this choice is that the number of orientations of wavelets is restricted to $K = 6$.

The output of the DTℂWT is decimated by a factor of 2^j in each direction for each scale j. In all our experiments we set $J = 1$ for each invariant layer, meaning we can mix the lowpass and bandpass coefficients at the same resolution. Figure 1 shows how this is done.

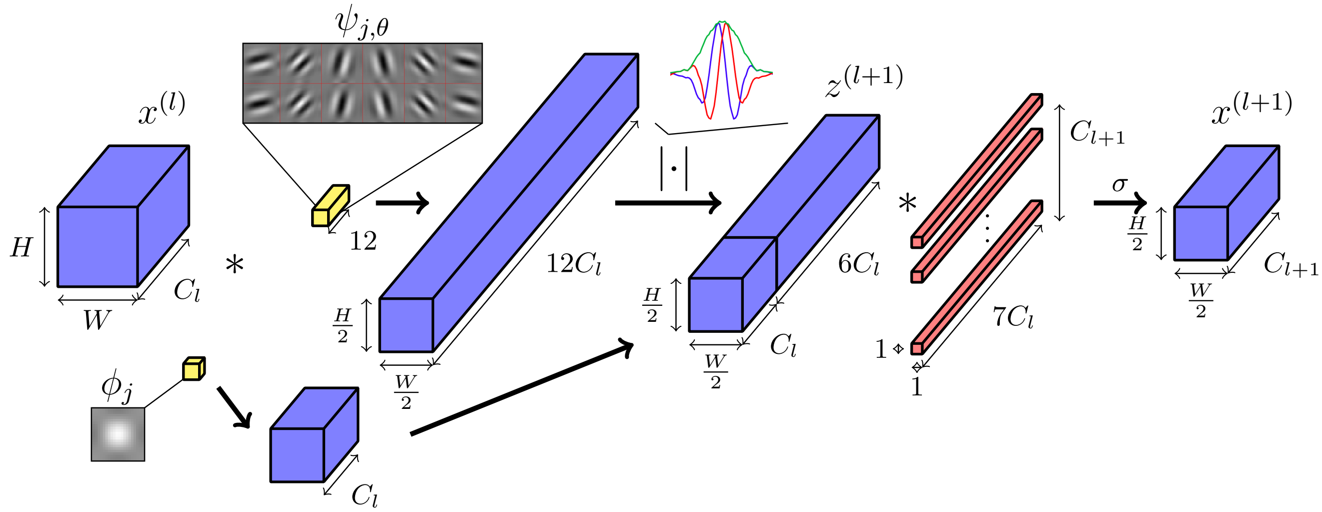

Fig. 1: Block Diagram of Proposed Invariant Layer for $J = 1$. Activations are shaded blue, fixed parameters yellow and learned parameters red. Input $x^{(l)} \in \mathbb{R}^{C_l \times H \times W}$ is filtered by $K = 6$ real and imaginary oriented wavelets and a lowpass filter and is downsampled. The real and imaginary parts are combined by taking their magnitude. An example of what this looks like in 1D is shown above the magnitude operator - the components oscillating in quadrature are combined to give the smoother/more invariant $z^{(l+1)}$. The resulting activations are concatenated with the lowpass filtered activations, mixed across the channel dimension, and then passed through a nonlinearity σ to give $x^{(l+1)}$. If the desired output spatial size is $H \times W$, $x^{(l+1)}$ can be bilinearly upsampled paying only a few multiplies per pixel.

Note that setting $J = 1$ for a single layer does not restrict us from having $J > 1$ for the entire system, as if we have a second layer with $J = 1$ after the first, including downsampling ($\downarrow$), we would have:

$$(((x * \phi_1) \downarrow 2) * \psi_{1,\theta}) \downarrow 2 = (x * \psi_{2,\theta}) \downarrow 4 \tag{15}$$

4.1. Memory Cost

A standard convolutional layer with C_l input channels, C_{l+1} output channels and kernel size L has $L^2 C_l C_{l+1}$ parameters.

The number of learnable parameters in each of our proposed invariant layers with $J = 1$ and $K = 6$ orientations is:

$$\#\text{params} = (JK + 1)C_l C_{l+1} = 7 C_l C_{l+1} \tag{16}$$

The spatial support of the wavelet filters is typically 5×5 pixels or more, and we have reduced #params to less than 3×3 per filter, while producing filters that are significantly larger than this.

4.2. Computational Cost

A standard convolutional layer with kernel size L needs $L^2 C_{l+1}$ multiplies per input pixel (of which there are $C_l \times H \times W$).

As mentioned in subsection 4.1, we use the $\mathrm{DT}\mathbb{C}\mathrm{WT}$ for our complex, shift invariant wavelet decomposition. We use the open source Pytorch implementation of the $\mathrm{DT}\mathbb{C}\mathrm{WT}$ [3] as it can run on GPUs and has support for backpropagating gradients.

There is an overhead in doing the wavelet decomposition for each input channel. A regular discrete wavelet transform (DWT) with filters of length L will have $2L\left(1 - 2^{-2J}\right)$ multiplies for a J scale decomposition. A $\mathrm{DT}\mathbb{C}\mathrm{WT}$ has 4 DWTs for a 2-D input, so its cost is $8L\left(1 - 2^{-2J}\right)$, with $L = 6$ a common size for the filters. It is important to note that unlike the filtering operation, this does not scale with C_{l+1}, the end result being that as C_{l+1} grows, the cost of C_l forward transforms is outweighed by that of the mixing process.

As part of the scatternet design, the sample rate decreases after each wavelet layer. The benefit of this is that the mixing process then only works on one quarter the spatial size after one first scale and one sixteenth the spatial after the second scale. Restricting ourselves to $J = 1$ as we mentioned in section 4, the computational cost is then:

$$\underbrace{\frac{7}{4} C_{l+1}}_{\text{mixing}} + \underbrace{36}_{\mathrm{DT}\mathbb{C}\mathrm{WT}} \quad \text{multiplies per input pixel} \tag{17}$$

In most CNNs, C_{l+1} is several dozen if not several hundred, which makes eq. (17) significantly smaller than $L^2 C_{l+1} = 9C_{l+1}$ multiplies for 3×3 convolutions.

5. EXPERIMENTS

In this section we examine the effectiveness of our invariant layer by testing its performance on the well known datasets CIFAR-10 (10 classes, 5000 images per class at 32×32 pixels per image), CIFAR-100 (100 classes, 500 images per class at 32×32 pixels per image) and Tiny ImageNet[13] (a dataset like ImageNet with 200 classes and 500 training images per class, each image at 64×64 pixels).

Our networks are optimized with stochastic gradient descent with momentum. We found that a learning rate of 0.5 with momentum 0.85, batch size $N = 128$ and weight decay 10^{-4} achieved near optimal results for all experiments. For CIFAR-10/CIFAR-100 we scale the learning rate by a factor of 0.2 after 60, 80 and 100 epochs, training for 120 epochs in total. For Tiny ImageNet, the rate change is at 18, 30 and 40 epochs (training for 45 in total).

Our experiment code is available at [4].

5.1. Reference

To compare our proposed locally invariant layer (inv) to a regular convolutional layer (conv), we build from a simple yet powerful VGG-like architecture. This reference architecture (hereby called 'ref') has 6 convolutional layers for CIFAR and 8 layers for Tiny ImageNet. The network quarters the spatial area every second layer with max pooling, resulting in an 8×8 output after all convolutions.

Table 1: Results for testing VGG like architecture with convolutional and invariant layers on several datasets. An architecture with 'invX' means the equivalent convolutional layer 'convX' was swapped for our proposed layer.

	CIFAR-10		CIFAR-100		Tiny ImgNet	
Trainset Size	10k	50k	10k	50k	20k	100k
ref	84.4	91.9	53.2	70.3	37.4	59.1
invA	82.8	91.3	48.4	69.5	33.2	57.7
invB	84.8	91.8	54.8	70.7	36.9	59.5
invC	85.3	92.3	54.2	71.2	37.1	59.8
invD	83.8	91.2	51.2	70.1	37.6	59.3
invE	83.3	91.6	50.3	70.0	37.8	59.4
invF	82.1	90.5	47.6	68.9	34.0	57.8
invA, invB	83.1	90.5	49.8	68.4	35.0	57.9
invB, invC	83.8	91.2	50.6	69.1	34.6	57.5
invC, invD	85.1	92.1	54.3	70.1	**37.9**	59.0
invD, invE	80.2	89.1	49.0	67.3	33.9	57.5
invA, invC	82.8	90.7	49.5	69.6	34.0	56.9
invB, invD	**85.4**	**92.7**	**54.6**	**71.3**	**37.9**	59.8
invC, invE	84.8	91.8	53.5	70.9	37.6	**60.2**

This 8×8 activation is average-pooled and passed through a single fully connected layer.

The initial number of channels we use is 64. This doubles after every pooling layer as is common practice [9, 22]. We label each layer 'conv' (or 'inv') followed by a letter enumerating its depth. E.g. 'convA' is the first convolutional layer, and 'convF' is the sixth. See [4] for a table and a more detailed description of this architecture.

This reference network is chosen for its simple design. Despite this, it achieves competitive performance for the three datasets.

5.2. Layer Level Comparison

We perform an ablation study where we progressively swap out convolutional layers for invariant layers keeping the input and output activation sizes the same. As there are 6 layers (or 8 for Tiny ImgNet), there are too many permutations to list the results for swapping out all layers for our locally invariant layer, so we restrict our results to swapping 1 or 2 layers. Table 1 reports the top-1 classification accuracies for CIFAR-10, CIFAR-100 and Tiny ImageNet. In addition to testing on the full datasets we report results for a reduced training set size.

Interestingly, we see improvements when one or two invariant layers are used near the start of a system, but not for the first layer.

5.3. Network Comparison

In the previous section, we examined how the locally invariant layer performs when directly swapped in for a convolutional layer in a regular convolutional network. This requires us to compress the number of channels in the scattering outputs, which naturally grow by $K + 1$ for each layer. In this section, we use a square A matrix, keeping this channel growth. This also allows us to directly compare to the original hybrid scatternet design [16, 17] by setting $A = I$.

The networks tested have a scattering front end followed by the last 4 convolutional layers from 'ref' (last 6 for Tiny ImgNet). We test 4 different frontends: (i) ScatNet A is a standard second order scatternet (ii) ScatNet B uses the proposed invariant layers instead of scattering layers (iii) ScatNet C tests the hypothesis from subsection 5.2 that scattering may work well after a learned convolutional layer by putting a small layer before ScatNet A, and (iv) ScatNet D does the same for ScatNet B. The outputs of ScatNet A and B have $C(K + 1)^2 = 147$ channels whereas ScatNet C and D have $16/3 \times 147 = 784$ channels, all at $1/16$ the spatial input size.

Table 2: Hybrid ScatterNet top-1 classification accuracies on CIFAR-10 and CIFAR-100. N_l is the number of learned convolutional layers, #param is the number of parameters, and #mults is the number of multiplies per $32 \times 32 \times 3$ image. An asterisk indicates that the value was estimated from the architecture description.

	N_l	#param	#mults	CIFAR-10	CIFAR-100
ScatNet A	4	2.6M	165M	89.4	67.0
ScatNet B	6	2.7M	167M	91.1	70.7
ScatNet C	5	3.7M	251M	91.6	70.8
ScatNet D	7	4.3M	294M	93.0	73.5
All Conv[26]	8	1.4M	281M*	92.8	66.3
VGG16[14]	16	138M*	313M*	91.6	-
FitNet[19]	19	2.5M	382M	91.6	65.0
ResNet-1001[9]	1000	10.2M	4453M*	95.1	77.3
WRN-28-10[29]	28	36.5M	5900M*	96.1	81.2

Table 2 shows the results from these experiments. It is clear from the improvements from ScatNet A to B and ScatNet C to D that the mixing significantly helps the Scattering front end with little parameter cost. Further, ScatNet C and D are big improvements on the A and B versions (albeit with a larger parameter and multiply cost than the mixing operation). This reaffirms that there may be benefit to add learning before as well as inside the ScatterNet.

For comparison, we have also listed the performance of other architectures as reported by their authors in order of increasing complexity. Our proposed ScatNet D achieves comparable performance with the the All Conv, VGG16 and FitNet architectures. The Deep[9] and Wide[29] ResNets perform best, but with very many more multiplies, parameters and layers.

We do not include the Tiny ImgNet results in the table, as not many other architectures report scores on this dataset. Our experiments with ScatNets A to D with 6 convolutional layers achieved $58.1, 59.6, 60.8$ and 62.1% top-1 accuracy.

6. CONCLUSION

In this work we have proposed a new learnable scattering layer, dubbed the locally invariant convolutional layer, tying together ScatterNets and CNNs. We do this by adding a mixing between the layers of ScatterNet allowing the learning of more complex shapes than the ripples seen in [6]. This invariant layer can easily be shaped to allow it to drop in the place of a convolutional layer, theoretically saving on parameters and computation. However, care must be taken when doing this, as our ablation study showed that the layer only improves upon regular convolution at certain depths. Typically, it seems wise to interleave convolutional layers and invariant layers.

We have developed a system that allows us to pass gradients through the Scattering Transform, something that previous work has not yet researched. Because of this, we were able to train end-to-end a system that has a ScatterNet surrounded by convolutional layers and with our proposed mixing. We were surprised to see that even a small convolutional layer before Scattering helps the network, and a very shallow and simple Hybrid-like ScatterNet was able to achieve good performance on CIFAR-10 and CIFAR-100.

There is still much research to do - why does the proposed layer work best near, but not at the beginning of deeper networks? Why is it beneficial to precede an invariant layer with a convolutional layer? Can we combine invariant layers in Residual style architectures? The work presented here is still nascent but we hope that it will stimulate further interest and research into both ScatterNets and the design of convolutional layers in CNNs.

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