

Grad-CAM: Why did you say that?

Visual Explanations from Deep Networks via Gradient-based Localization

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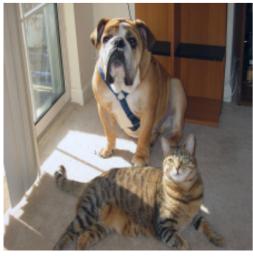
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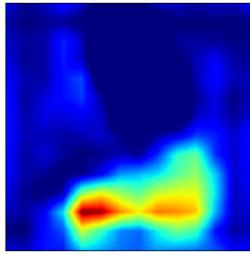
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(a) Original Image



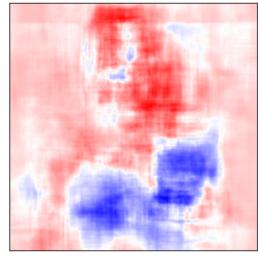
(b) Guided Backprop for ‘Cat’



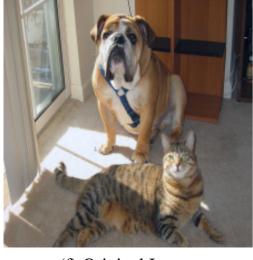
(c) Grad-CAM for ‘Cat’



(d) Guided Grad-CAM for ‘Cat’



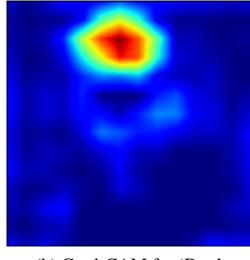
(e) Occlusion Map for ‘Cat’



(f) Original Image



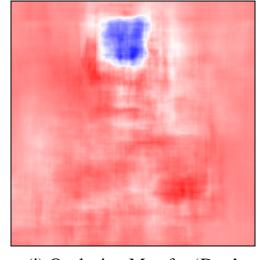
(g) Guided Backprop for ‘Dog’



(h) Grad-CAM for ‘Dog’



(i) Guided Grad-CAM for ‘Dog’



(j) Occlusion Map for ‘Dog’

Figure 1. (a) Original image with a cat and a dog. (b-e) Support for the cat category according to various visualizations. (b) Guided Backpropagation [38]: provides high-resolution visualization of contributing features, (c) Grad-CAM (Ours): localizes class-discriminative regions, (d) Combining (b) and (c) gives Guided Grad-CAM, which gives high-resolution visualizations that are class-discriminative. Interestingly, the localizations achieved by our Grad-CAM technique (c) are very similar to results from occlusion sensitivity (e), while being much cheaper to compute. Note that in (e), blue corresponds to evidence for the class while in (c) blue indicates regions with low score for the class. Figure best viewed in color.

Abstract

We propose a technique for making Convolutional Neural Network (CNN)-based models more transparent by visualizing the regions of input that are ‘important’ for predictions from these models – or visual explanations.

Our approach, called Gradient-weighted Class Activation Mapping (Grad-CAM), uses the class-specific gradient information flowing into the final convolutional layer of a CNN to produce a coarse localization map of the important regions in the image. Grad-CAM is a strict generalization of the Class Activation Mapping (CAM) [43]. While CAM is limited to a narrow class of CNN models, Grad-CAM is broadly applicable to any CNN-based architectures. We also show how Grad-CAM may be combined with existing pixel-space visualizations (such as Guided Backpropagation [38]) to create a high-resolution class-discriminative visualization

(Guided Grad-CAM).

We generate Grad-CAM and Guided Grad-CAM visual explanations to better understand image classification, image captioning, and visual question answering (VQA) models. In the context of image classification models, our visualizations (a) lend insight into failure modes of these models (showing that seemingly unreasonable predictions have reasonable explanations), and (b) outperform pixel-space gradient visualizations (Guided Backpropagation [38] and Deconvolution [41]) on the ILSVRC-15 weakly supervised localization task. For image captioning and VQA, our visualizations expose the somewhat surprising insight that common CNN + Long Short Term Memory (LSTM) models can often be good at localizing discriminative input image regions despite not being trained on grounded image-text pairs.

Finally, we design and conduct human studies to measure if

Guided Grad-CAM explanations help users establish trust in the predictions made by deep networks. Interestingly, we show that Guided Grad-CAM helps untrained users successfully discern a ‘stronger’ deep network from a ‘weaker’ one even when both networks make identical predictions, simply on the basis of their different explanations.

Our code is available at <https://github.com/ramprs/grad-cam/> and a demo is available on CloudCV [2]¹.

1. Introduction

Convolutional Neural Networks (CNNs) and other deep networks have enabled unprecedented breakthroughs in a variety of computer vision tasks, from image classification [22] to object detection [14], semantic segmentation [26], image captioning [6, 12, 19], and more recently, visual question answering [3, 13, 29, 33]. While these deep neural networks enable superior performance, their lack of decomposability into *intuitive and understandable* components makes them hard to interpret [25]. Consequently, when today’s intelligent systems fail, they fail spectacularly disgracefully, without warning or explanation, leaving a user staring at incoherent output, wondering why the system did what it did.

Interpretability Matters. In order to build trust in intelligent systems and move towards their meaningful integration into our everyday lives, it is clear that we must build ‘transparent’ models that explain *why they predict what they do*. Broadly speaking, this transparency is useful at three different stages of Artificial Intelligence (AI) evolution. First, when AI is significantly weaker than humans and not yet reliably ‘deployable’ (e.g. visual question answering [3]), the goal of transparency & explanations is to identify the failure modes [1, 15], thereby helping researchers focus their efforts on the most fruitful research directions. Second, when AI is on par with humans and reliably ‘deployable’ (e.g., image classification [20] on a set of categories with enough training data), the goal is to establish trust with users. Third, when AI is significantly stronger than humans (e.g. chess or Go playing bots [35]), the goal of transparency & explanations is machine teaching [18] – *i.e.*, a machine teaching a human on how to make accurate predictions.

There typically exists a trade-off between accuracy and simplicity/interpretability. Classical rule-based or expert systems [16] were highly interpretable but not very accurate (or robust). Decomposable pipelines where each stage is hand-designed are thought to be more interpretable as each individual component assumes a natural intuitive explanation. By using deep models, we sacrifice interpretable modules for uninterpretable ones that achieve greater performance through greater abstraction (more layers) and tighter integration (end-to-end training).

Deep models are beginning to explore the spectrum between interpretability and accuracy. Zhou *et al.* [43] recently proposed a technique called Class Activation Mapping (CAM) for identifying discriminative regions used by a particular class of image classification CNNs (not containing any fully-connected layers). In essence, this work trades off model complexity for more transparency into the working of the model. In contrast, we make existing state-of-the-art deep models interpretable without altering the architecture, thus avoiding a tradeoff between interpretability and accuracy. Our approach is a generalization of CAM [43] to any CNN-based architecture (CNNs with fully-connected layers, CNNs stacked with Recurrent Neural Networks (RNNs), *etc.*).

What makes a good visual explanation? Consider image classification [9] – a ‘good’ visual explanation from the model justifying a predicted class should be (a) class-discriminative (*i.e.* localize the category in the image) and (b) high-resolution (*i.e.* capture fine-grained detail).

Fig. 1 shows outputs from a number of visualizations for the ‘tiger cat’ class (top) and ‘boxer’ (dog) class (bottom). Pixel-space gradient visualizations such as Guided Back-propagation [38] and Deconvolution [41] are high-resolution and highlight fine-grained details in the image, but are not class-discriminative (for example, the visualization for both ‘cat’ and ‘dog’ in Figures 1b and 1g are very similar).

In contrast, our approach (Grad-CAM) shown in Figures 1c and 1h, is highly class-discriminative (*i.e.* the ‘cat’ explanation exclusively highlights the ‘cat’ regions, and not the ‘dog’ regions and *vice versa*). Note that these very closely match with the occlusion maps generated through multiple forward passes (Figures 1e and 1j). The spatial resolution of the most class-discriminative Grad-CAM maps is the size of the last convolution layer in the CNN, which is typically small (e.g. 14×14 in VGGNet [37]) and hence does not show fine-grained details.

In order to combine the best of both worlds, we show that it is possible to fuse existing pixel-space gradient visualizations with Grad-CAM to create Guided Grad-CAM visualizations that are both high-resolution and class-discriminative. As a result, important regions of the image which correspond to a class of interest are visualized in high-resolution detail even if the image contains multiple classes, as shown in Figures 1d and 1i. When visualized for ‘tiger cat’, Guided Grad-CAM not only highlights the cat regions, but also highlights the stripes on the cat which is important for predicting that particular variety of cat.

To summarize, our contributions are as follows:

(1) We propose a class-discriminative localization technique called Gradient-weighted Class Activation Mapping (Grad-CAM) that can be used to generate visual explanations from *any* CNN-based network without requiring architectural changes. We evaluate Grad-CAM for weakly-supervised image localization on ImageNet where it outperforms pixel-

¹<http://gradcam.cloudcv.org>

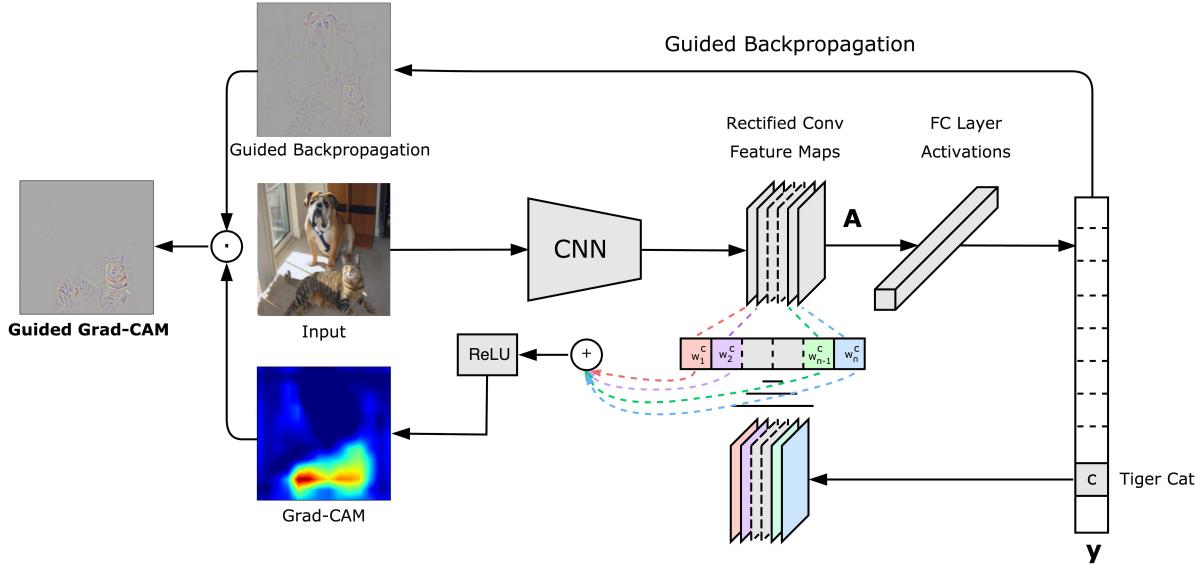


Figure 2: Grad-CAM overview: Given an image, and a category ('tiger cat') as input, we forward propagate the image through the model to obtain the raw class scores before softmax. The gradients are set to zero for all classes except the desired class (tiger cat), which is set to 1. This signal is then backpropagated to the rectified convolutional feature map of interest, where we can compute the coarse Grad-CAM localization (blue heatmap). Finally, we pointwise multiply the heatmap with guided backpropagation to get Guided Grad-CAM visualizations which are both high-resolution and class-discriminative.

space gradients.

(2) To illustrate the broad applicability of our technique across tasks, we apply Grad-CAM to state-of-the-art classification, image captioning and visual question answering models, effectively visualizing the image support for predictions from such networks. For image classification, our visualizations lend insight into failure modes of current generation CNNs, showing that seemingly unreasonable predictions have reasonable explanations. For image captioning and VQA, our visualizations expose the somewhat surprising insight that common CNN + Long Short Term Memory (LSTM) models can often be good at localizing discriminative input image regions despite not being trained on grounded image-text pairs.

(3) We design and conduct human studies to show that Guided Grad-CAM explanations are class-discriminative and help humans not only establish trust, but also helps untrained users successfully discern a ‘stronger’ deep network from a ‘weaker’ one *even when both networks make identical predictions, simply on the basis of their different explanations*.

2. Related Work

Our work draws on recent work in CNN visualizations, model trust assessment, and weakly-supervised localization.

Visualizing CNNs. A number of previous works [36, 38, 41] have visualized CNN predictions by highlighting ‘important’ pixels (*i.e.* change in intensities of these pixels have the most impact on the prediction’s score). Specifically, Simonyan *et al.* [36] visualize partial derivatives of predicted class scores w.r.t. pixel intensities, while Guided Backpropagation [38] and Deconvolution [41] make modifications to ‘raw’

gradients that result in qualitative improvements. Despite producing fine-grained visualizations, these methods are not class-discriminative. Visualizations with respect to different classes are nearly identical (see Figures 1b and 1g). Other visualization methods synthesize images to maximally activate a network unit [36, 11] or invert a latent representation [28, 10]. Although these can be high-resolution and class-discriminative, they visualize a model overall and not predictions for specific input images.

Assessing Model Trust. Motivated by notions of interpretability [25] and assessing trust in models [34], we evaluate Grad-CAM visualizations in a manner similar to Ribeiro *et al.* [34] via human studies to show that they can be important tools for users to evaluate and place trust in automated systems.

Weakly supervised localization. Another relevant line of work is weakly supervised localization in the context of CNNs, where the task is to localize objects in images using only whole image class labels [7, 30, 31, 43].

Most relevant to our approach is the Class Activation Mapping (CAM) approach to localization [43]. This approach modifies image classification CNN architectures replacing fully-connected layers with convolutional layers and global average pooling [23], thus achieving class-specific feature maps. Others have investigated similar methods using global max pooling [31] and log-sum-exp pooling [32].

A drawback of CAM is that it requires feature maps to directly precede softmax layers, so it is only applicable to a particular kind of CNN architectures performing global average pooling over convolutional maps immediately prior to prediction (*i.e.* conv feature maps → global average pooling → softmax layer). Such architectures may achieve inferior

accuracies compared to general networks on some tasks (*e.g.* image classification) or may simply be inapplicable to other tasks (*e.g.* image captioning or VQA). We introduce a new way of combining feature maps using the gradient signal that does not require *any* modification in the network architecture. This allows our approach to be applied to any CNN-based architecture, including those for image captioning and visual question answering. For a fully-convolutional architecture, Grad-CAM reduces to CAM (ignoring rectification/normalization for visualization purposes). Thus, Grad-CAM is a strict generalization to CAM.

Other methods approach localization by classifying perturbations of the input image. Zeiler and Fergus [41] perturb inputs by occluding small patches and classifying the occluded image, typically resulting in lower classification scores for relevant objects when those objects are occluded. This principle is applied for localization in [4]. Oquab *et al.* [30] classify many patches containing a pixel then average these patch class-wise scores to provide the pixel’s class-wise score. Unlike these methods, our approach achieves localization in one shot; it only requires a single forward and a partial backward pass per image and thus is typically an order of magnitude more efficient. In concurrent work Zhang *et al.* [42] introduce a probabilistic Winner-Take-All formulation for modelling the top-down attention for neural classification models.

3. Approach

We briefly recap the localization approach presented in CAM [43], and then describe our generalization, Grad-CAM. Then we describe how this class-discriminative but coarse localization technique can be combined with high-resolution visualizations obtained using Deconvolution and Guided Backpropagation to obtain both desirable properties (high-resolution and class-discrimination).

Class Activation Mapping (CAM). Recall that CAM [43] produces a localization map for an image classification CNN with a specific kind of architecture where global average pooled convolutional feature maps are fed directly into a softmax. Specifically, let the penultimate layer produce K feature maps $A^k \in \mathbb{R}^{u \times v}$ of width u and height v . These feature maps are then spatially pooled using Global Average Pooling (GAP) and linearly transformed to produce a score y^c for each class c

$$y^c = \sum_k w_k^c \underbrace{\frac{1}{Z} \sum_i \sum_j}_{\text{global average pooling}} A_{ij}^k \quad (1)$$

class feature weights feature map

To produce a localization map $L_{\text{CAM}}^c \in \mathbb{R}^{u \times v}$ for class c , CAM computes the linear combination of the final feature maps using the learned weights of the final layer:

$$L_{\text{CAM}}^c = \underbrace{\sum_k w_k^c A^k}_{\text{linear combination}}. \quad (2)$$

This is normalized to lie between 0 and 1 for visualization purposes. To apply CAM to a network which uses multiple fully-connected layers before the final layer, the fully connected layers are replaced with convolutional ones and the network is re-trained.

Gradient-weighted Class Activation Mapping. In order to obtain the class-discriminative localization map Grad-CAM $L_{\text{Grad-CAM}}^c \in \mathbb{R}^{u \times v}$ in general architectures, we first compute the gradient of y^c with respect to feature maps A of a convolutional layer, *i.e.* $\frac{\partial y^c}{\partial A_{ij}^k}$. These gradients flowing back are global-average-pooled to obtain weights α_k^c :

$$\alpha_k^c = \underbrace{\frac{1}{Z} \sum_i \sum_j}_{\text{global average pooling}} \underbrace{\frac{\partial y^c}{\partial A_{ij}^k}}_{\text{gradients via backprop}} \quad (3)$$

This weight α_k^c represents a *partial linearization* of the deep network downstream from A , and captures the ‘importance’ of feature map k for a target class c ². Empirically, using the averaged gradient through Global Average Pooling (GAP) is more robust to noise in the gradients and thus leads to better localizations than other choices like taking the Global Max Pooling, as shown in the supplementary. In general, y^c need not be the class score produced by an image classification CNN, and could be any differentiable activation.

As in CAM, our Grad-CAM heat-map is a weighted combination of feature maps, but we follow this by a ReLU:

$$L_{\text{Grad-CAM}}^c = \text{ReLU} \left(\underbrace{\sum_k \alpha_k^c A^k}_{\text{linear combination}} \right) \quad (4)$$

Notice that this results in a coarse heat-map of the same size as the convolutional feature maps (14×14 in the case of last convolutional layers of VGG [37] and AlexNet [22] networks). For visualization as in Figure 1c, 1h, and others, $L_{\text{Grad-CAM}}^c$ is normalized so the values lie between 0 and 1. For architectures where CAM is applicable – *i.e.*, fully-convolutional CNNs with A being the output of the final conv layer, followed by global average pooling and softmax – the weights used in CAM w_k^c are precisely α_k^c . Other than the ReLU in (4), *this makes Grad-CAM a generalization of CAM*. The motivation for the ReLU is the following – we are only interested in the features that have a *positive* influence on the class of interest, *i.e.* pixels whose intensity should be

² We performed some initial experiments using variants of gradients used in the computation of α_k^c . The “gradients” computed using Deconvolution led to non-discriminative localizations while Guided Backpropagation led to somewhat discriminative localizations, though much less so than normal unmodified gradients.

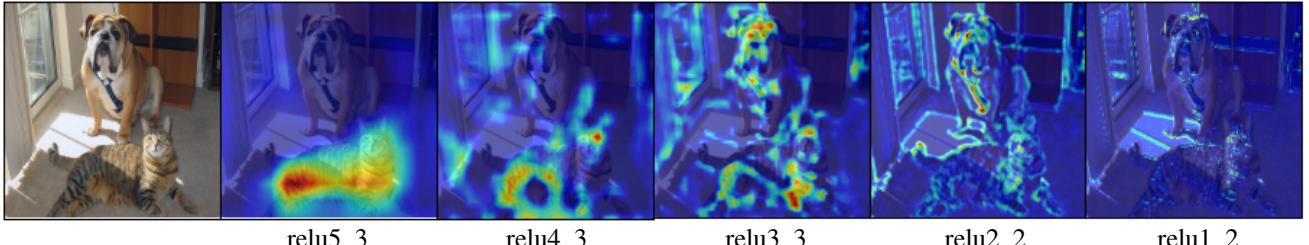


Figure 3: Grad-CAM at different convolutional layers for the ‘tiger cat’ class. This figure analyzes how localizations change qualitatively as we perform Grad-CAM with respect to different feature maps in a CNN (VGG16 [37]). We find that the best looking visualizations are often obtained after the deepest convolutional layer in the network, and localizations get progressively worse at shallower layers. This is consistent with our intuition described in Section 3.

increased in order to increase y^c . Since the feature maps A are already non-negative, we rectify the heat-map obtained in (4) to highlight such pixels. And as expected, without this ReLU, localization maps sometimes highlight more than just the desired class and achieve lower localization performance (see supplementary). Intuitively, negative values indicate pixels that are likely to belong to other categories in the image, and the application of ReLU excludes them. Figures 1c and 1h show Grad-CAM visualizations for ‘tiger cat’ and ‘boxer (dog)’ respectively. More Grad-CAM visual explanations can be found in the supplementary.

Note that the above generalization also allows us to generate visual explanations from CNN-based models that cascade convolutional layers with more complex interactions. Indeed, we apply Grad-CAM to “beyond classification” tasks and models that utilize CNNs for image captioning and Visual Question Answering (VQA) (Sec. 7).

Guided Grad-CAM. While Grad-CAM visualizations are class-discriminative and localize relevant image regions well, they lack the ability to show fine-grained importance like pixel-space gradient visualization methods (Guided Backpropagation and Deconvolution). For example in Figure 1c, Grad-CAM can easily localize the cat region; however, it is unclear from the low-resolutions of the heat-map why the network predicts this particular instance is ‘tiger cat’. In order to combine the best aspects of both, we fuse Guided Backpropagation and Grad-CAM visualizations via point-wise multiplication (L_{CAM}^c is first up-sampled to the input image resolution using bi-linear interpolation). Fig. 2 bottom-left illustrates this fusion. This visualization is both high-resolution (when the class of interest is ‘tiger cat’, it identifies important ‘tiger cat’ features like stripes, pointy ears and eyes) and class-discriminative (it shows the ‘tiger cat’ but not the ‘boxer (dog)’). Replacing Guided Backpropagation with Deconvolution in the above gives similar results, but we found Deconvolution to have artifacts (and Guided Backpropagation visualizations were generally noise-free), so we chose Guided Backpropagation over Deconvolution.

A number of works have asserted that as the depth of a CNN increases, higher-level visual constructs are captured [5, 28]. Furthermore, convolutional layers naturally retain spatial information which is lost in fully-connected layers, so we

expect the last convolutional layers to have the best compromise between high-level semantics and detailed spatial information. We provide Grad-CAM visualizations in Fig. 3 computed at various convolutional layers by replacing A with feature maps of indicated layer to demonstrate this effect.

4. Weakly-supervised Localization

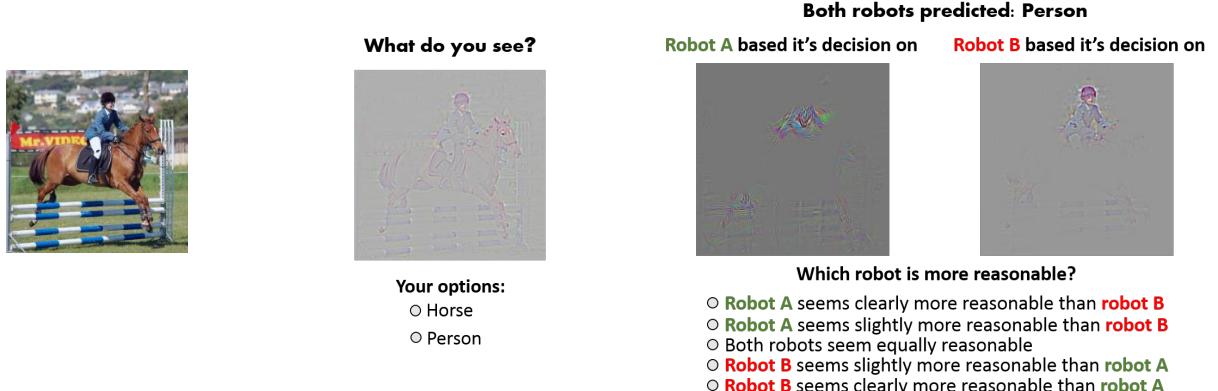
In this section, we evaluate the localization capability of Grad-CAM in the context of image classification. The ImageNet localization challenge [9] requires competing approaches to provide bounding boxes in addition to classification labels. Similar to classification, evaluation is performed for both the top-1 and top-5 predicted categories. Similar to Zhou *et al.* [43], given an image, we first obtain class predictions from our network. Next, we generate Grad-CAM localization maps for each of the predicted classes and binarize with threshold of 15% of the max intensity. This results in connected segments of pixels and we draw our bounding box around the single largest segment. We evaluate the pretrained off-the-shelf VGG-16 [37] model from the Caffe [17] Model Zoo. Following ILSVRC evaluation, we report both top-1 and top-5 localization error on ILSVRC-15 validation set in Table 1. Grad-CAM localization errors are lower than those achieved by Simonyan *et al.* [36] for the VGG-16 model, which uses grabcut to post-process image space gradients into heat maps. We also see that CAM achieves a slightly better localization, but requires a change in the VGG architecture, necessitates re-training, and achieves worse top-1 val classification error (2.76% increase) [43], whereas our model makes no compromise on classification accuracy.

Method	Top-1 loc error	Top-5 loc error	Top-1 cls error	Top-5 cls error
Backprop on VGG-16 [36]	61.12	51.46	30.64	11.03
Grad-CAM on VGG-16	57.80	48.03	30.64	11.03
VGG-16-GAP [43]	57.20	45.14	33.40	12.20

Table 1: Classification and Localization results on ILSVRC-15 val. Grad-CAM outperforms [36] which uses backpropagation to pixel-space for localization. [43] achieves slightly better localization via a modified architecture which results in higher classification error. Note that these networks are off-the-shelf classification CNNs, trained only with class labels and not bounding box annotations.

5. Evaluating Visualizations

Our first human study evaluates the main premise of our approach: are Grad-CAM visualizations more class-



(a) Raw input image. Note that this is not a part of the tasks (b) and (c)

(b) AMT interface for evaluating the class-discriminative property

(c) AMT interface for evaluating if our visualizations instill trust in an end user

Figure 4: We evaluate visualizations extracted from image (a) for class discrimination (b) and trust worthiness (c). The class discrimination study measures if people can tell from the visualization which class is being visualized. Trust evaluations check if a visualization helps humans place trust in a more accurate classifier. Our results show that our Grad-CAM approach outperforms baseline approaches (Guided Backpropagation and Deconvolution) on both tasks.

discriminative than previous techniques? Moreover, we want to understand if our class-discriminative interpretations can lead an end user to trust the visualized models.

For these experiments, we use VGG and AlexNet CNNs finetuned on PASCAL VOC 2007 train set, and the validation set is used to generate visualizations.

5.1. Evaluating Class Discrimination

We select images from PASCAL VOC 2007 val set that contain exactly two annotated categories, and create visualizations for one of the classes. For both VGG-16 and AlexNet CNNs, we obtain visualizations using four techniques: Deconvolution, Guided Backpropagation, and Grad-CAM versions of each these methods (Deconvolution Grad-CAM and Guided Grad-CAM). We show visualizations to workers on Amazon Mechanical Turk (AMT) and ask them “Which of the two object categories is depicted in the image?”, as shown in Fig. 4a. The two PASCAL categories present in the original image are shown as options. This task measures if people can tell from the visualization which class is being visualized.

Approach	Accuracy
Deconvolution	53.33%
Deconvolution Grad-CAM (ours)	60.37%
Guided Backpropagation	44.44%
Guided Grad-CAM (ours)	61.23%

Table 2: Human accuracy on classifying class-specific visualizations. Best performing methods are shown in **bold**. We can see that combining Grad-CAM with Guided Backpropagation and Deconvolution makes them more class-discriminative (human-identifiable).

Intuitively, a good prediction explanation is one that produces discriminative visualizations for the class of interest. The experiment was conducted using all 4 visualizations for 90 image-category pairs; 9 ratings were collected for each image, evaluated against the ground truth and averaged to obtain the accuracy in Table. 2. When viewing Guided Grad-CAM, human subjects can correctly identify

the category being visualized in 61.23% of cases (compared to 44.44% for Guided Backpropagation; thus, Grad-CAM improves human performance by 16.79%). Similarly, we find that Grad-CAM helps make both Deconvolution and Guided Backpropagation more class-discriminative. Guided Grad-CAM performs the best among all the methods. Interestingly, our results seem to indicate that Deconvolution is more class discriminative than Guided Backpropagation, although Guided Backpropagation is more aesthetically pleasing than Deconvolution. To the best of our knowledge, our evaluations are the first to quantify these subtle differences.

5.2. Evaluating Trust

Given two prediction explanations, we want to evaluate which of them seems more trustworthy. We use AlexNet and VGG-16 to compare Guided Backpropagation and Guided Grad-CAM visualizations, noting that VGG-16 is known to be more reliable than AlexNet with an accuracy of 79.09 mAP vs. 69.20 mAP for AlexNet. In order to tease apart the efficacy of the visualization from the accuracy of the model being visualized, we consider only those instances where *both* models made the same prediction as ground truth. Given a visualization from AlexNet and one from VGG-16, and the name of object predicted by both the networks, workers are instructed to rate the reliability of the models relative to each other on a scale of clearly more reliable (+/-2), slightly more reliable (+/-1), and equally reliable (0). This interface is shown in Fig. 4c. To eliminate any biases in the study, VGG and AlexNet were assigned to be *model1* with approximately equal probability. Remarkably, we find that human subjects are able to identify the more accurate classifier (VGG over AlexNet) *despite viewing identical predictions from the two, simply from the different explanations* generated from the two. With Guided Backpropagation, humans assign VGG an average score of 1.00 which means that it is slightly more reliable than AlexNet, while Guided Grad-CAM achieves

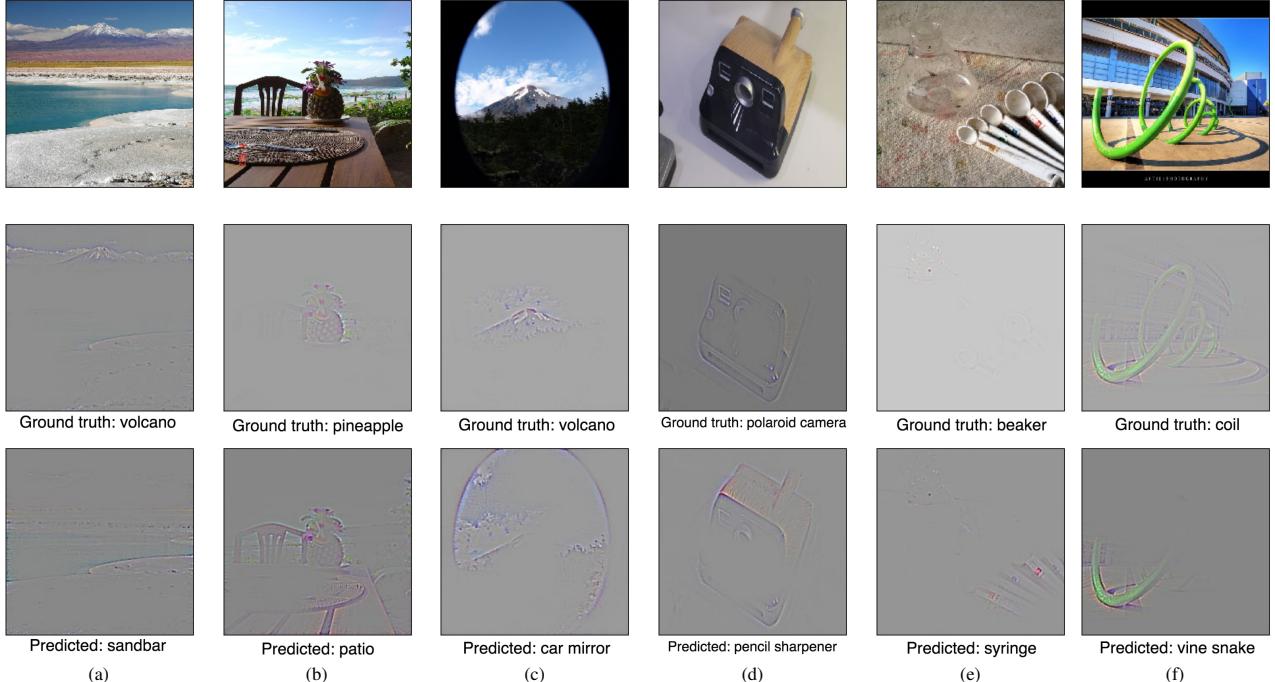


Figure 5: In these cases the model (VGG-16) failed to predict the correct class as its top 1 prediction, but it even failed to predict the correct class in its top 5 for figures b, c, and e. All of these errors are due in part to class ambiguity. (a-b) For example, the network predicts ‘sandbar’ based on the foreground of (a), but it also knows where the correct label ‘volcano’ is located. (c-f) In other cases, these errors are still reasonable but not immediately apparent. For example, humans would find it hard to explain the predicted ‘syringes’ in (e) without looking at the visualization for the predicted class.

a higher score of 1.27 which is closer to the option saying that VGG is clearly more reliable. Thus our Guided Grad-CAM visualization can help users place trust in a model that can generalize better, based on individual prediction explanations.

5.3. Faithfulness vs. Interpretability

Faithfulness of a visualization to a model is its ability to accurately explain the function learned by the model. Naturally, there exists a tradeoff between the interpretability and faithfulness of a visualization: a more faithful visualization is typically less interpretable and *vice versa*. In fact, one could argue that a fully faithful explanation is the entire description of the model, which in the case of deep models is not interpretable/easy to visualize. We have verified in previous sections that our visualizations are reasonably interpretable. We now evaluate how faithful they are to the underlying model. One expectation is that our explanations should be locally accurate or faithful. That is, in the vicinity of the input data point, our explanation should be faithful to the model [34].

For comparison, we need a reference explanation with high local-faithfulness. One obvious choice for such a visualization is image occlusion [41], where we mask out different regions of the input image, and perform multiple CNN evaluations to observe how the resulting score for the class of interest changes. If masking out a region causes the score for the particular category of interest to decrease, that region

is considered to be important for predicting that class. We compare Guided Backpropagation *vs.* Guided Grad-CAM on their correlation with occluded scores.

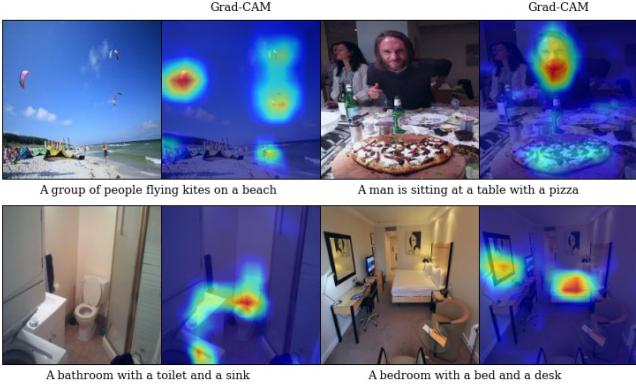
We divide the input image into an 8×8 grid, occlude each region, and perform a forward pass through the VGG-16 CNN. At each location on the grid we store the rectified value of the difference in scores between the masked version and the original score for the class of interest. The regions with highest rectified difference in scores are the most discriminative for a given class. Next, we compute the energy of a test visualization method (Guided Backpropagation and Guided Grad-CAM) in each region of the grid by taking the L-1 norm of the intensities.

We concatenate values from every grid to compute the rank-correlation between the visualization method and the occlusion map, averaged over the 2510 images from PASCAL VOC 2007 validation set. We find that Guided Grad-CAM has a higher mean rank-correlation with occlusion maps than Guided Backpropagation (0.261 vs. 0.168). This shows that Guided Grad-CAM is more faithful to the original model than Guided Backpropagation.

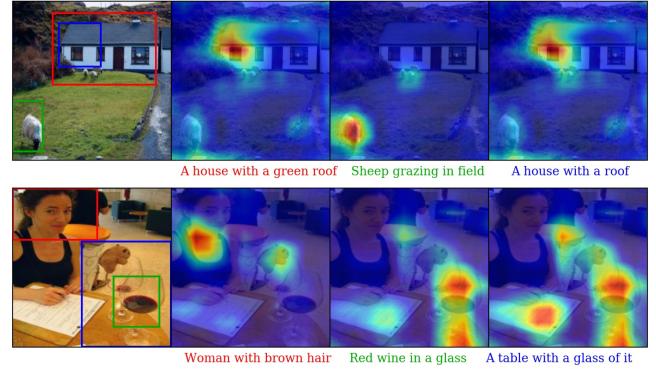
6. Analyzing Failure Modes for Image Classification

We use Guided Grad-CAM to analyze failure modes of the VGG-16 CNN on ImageNet classification [9].

In order to see what mistakes a network is making we first get a list of examples that the network (VGG-16) fails to



(a) Image captioning explanations



(b) Comparison to DenseCap

Figure 6: Interpreting image captioning models: We use our class-discriminative localization technique, Grad-CAM to find spatial support regions for captions in images. Fig. 6a Visual explanations from image captioning model [21] highlighting image regions considered to be important for producing the captions. Fig. 6b Grad-CAM localizations of a global or holistic captioning model for captions generated by a dense captioning model [19] for the three bounding box proposals marked on the left. We can see that we get back Grad-CAM localizations (right) that agree with those bounding boxes – even though the captioning model and Grad-CAM techniques do not use any bounding box annotations.

classify correctly. For the misclassified examples, we use Guided Grad-CAM to visualize both the correct class and the predicted class. A major advantage of Guided Grad-CAM over other methods is its ability to more usefully investigate and explain classification mistakes, since our visualizations are high-resolution and more class-discriminative. As seen in Fig. 5, some failures are due to ambiguities inherent in ImageNet classification. We can also see that seemingly unreasonable predictions have reasonable explanations, which is a similar observation to HOGgles [40].

7. Image Captioning and VQA

In this subsection we apply our Grad-CAM technique to the image captioning [6, 19, 39] and Visual Question Answering (VQA) [3, 13, 29, 33] tasks. We find that Grad-CAM leads to interpretable visual explanations for these tasks as compared to baseline visualizations which do not change noticeably across different predictions.

7.1. Image Captioning

In this section, we visualize spatial support for a simple image captioning model (without attention) using Grad-CAM visualizations. More specifically, we build on top of the publicly available ‘neuraltalk2’³ implementation [21] that makes use of a finetuned VGG-16 CNN for images and an LSTM-based language model. Given a caption, we compute the gradient of its log probability w.r.t. units in the last convolutional layer of the CNN (*conv5_3* for VGG-16) and generate Grad-CAM visualizations as described in Section 3. Results are shown in Fig. 6a. For first example, the Grad-CAM maps for the generated caption localize every occurrence of both the kites and people inspite of their relatively small size. In the top right example, see how Grad-CAM correctly highlights the pizza and the man, but ignores the woman nearby, since ‘woman’ is not mentioned in the caption. More

qualitative examples can be found in the supplementary.

Comparison to dense captioning. Johnson *et al.* [19] recently introduced the Dense Captioning (DenseCap) task that requires a system to jointly localize and caption salient regions in a given image. The model proposed in [19] consists of a Fully Convolutional Localization Network (FCLN) and an LSTM-based language model that produces both bounding boxes for regions of interest and associated captions in a single forward pass. Using the DenseCap model, we generate region-specific captions. Next, we visualize Grad-CAM localizations for these region-specific captions using the simple captioning model described earlier (neuraltalk2). Interestingly, we observe that Grad-CAM localizations correspond to regions in the image that the DenseCap model described, even though the holistic captioning model was not trained with any region or bounding-box level annotations. Results are shown in Fig. 6b.

7.2. Visual Question Answering

Typical VQA pipelines [3, 13, 29, 33] consist of a CNN to model images and an RNN language model for questions. The image and the question representations are fused to predict the answer (typically a distribution of the top-1000 frequent answers in the VQA-train set). Since this is a classification problem, the visualization is similar to the image classification case: given an image and a question, pick an answer and use Grad-CAM to show image evidence that supports the answer.

Qualitative Examples. We explain the answers of a VQA model [27] that combines a CNN and an LSTM representation through a pointwise multiplication. Despite the complexity of the task, involving both visual and language components, the evidence found by Grad-CAM is surprisingly intuitive and informative. For instance, consider the image in Fig. 7, paired with the question “What color is the firehydrant”. Creating Grad-CAM visualizations w.r.t. the predicted answer “red” shows the lower red regions of the

³<https://github.com/karpathy/neuraltalk2>

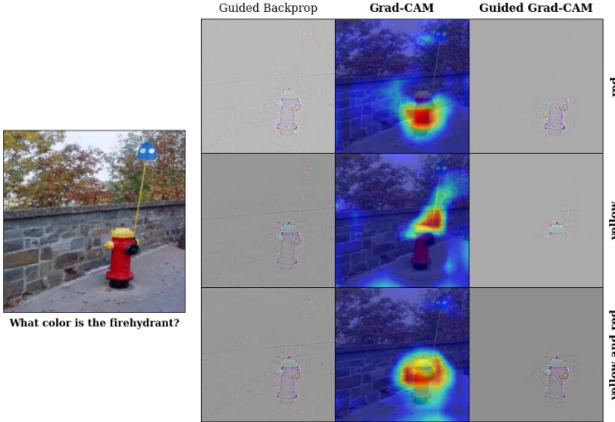


Figure 7: Qualitative Results for our VQA experiments: Given the image on the left and the question “What color is the firehydrant?”, we visualize Grad-CAMs and Guided Grad-CAMs for the answers “red”, “yellow” and “yellow and red”. Grad-CAM localizations are highly interpretable and help explain the model’s predictions – for “red”, the model focuses on the bottom red part of the firehydrant; when forced to answer “yellow”, the model concentrates on its top yellow cap, and when forced to answer “yellow and red”, it looks at the whole firehydrant!.

firehydrant. When asked to provide support for “yellow” (or “yellow and red”), just the top (or the entirety) of the hydrant is highlighted. Additional qualitative results including Grad-CAM and Guided Grad-CAM visualizations for VQA models with different CNNs can be found in the supplementary material.

Comparison to Human Attention. Das *et al.* [8] collected human attention maps for a subset of the VQA dataset [3]. These maps have high intensity where humans looked in order to answer a visual question. Human attention maps are compared to Grad-CAM visualizations of the simple VQA model introduced above [27] on 1374 question-image (QI) pairs from the validation set of the VQA dataset [3]. We use the rank correlation evaluation protocol developed in [8]. Grad-CAM and human attention maps have a correlation of 0.136, which is statistically higher than chance or random attention maps (zero correlation). This shows that despite not being trained on grounded image-text pairs, CNN+LSTM based VQA models are surprisingly good at localizing discriminative regions required to output a particular answer.

8. Conclusion

In this work, we proposed a novel class-discriminative localization technique – Gradient-weighted Class Activation Mapping (Grad-CAM) – for making CNN-based models more transparent by producing visual explanations. Our technique achieved better localization accuracy on ILSVRC val than Simonyan *et al.* [36]. Further, we combined our Grad-CAM localizations with existing high-resolution visualizations having poor localization ability to obtain high-resolution class-discriminative visualizations, Guided Grad-CAM. Extensive human studies with visualizations reveal that our localization-augmented visualizations can discriminate between classes more accurately and better reveal the

trustworthiness of a classifier. Finally, we provide some quantitative and qualitative results on interpreting predictions from image classification, visual question answering and image captioning. We believe that a true AI system should not only be intelligent, but also be able to reason about its beliefs and actions for humans to trust it. Future work includes explaining the decisions made by deep networks in domains such as reinforcement learning and natural language processing. Our code is publicly available at <https://github.com/rampers/grad-cam/> and an online demo is available on CloudCV [2]⁴.

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⁴<http://gradcam.cloudcv.org>

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Appendix

A. Introduction

We provide more qualitative examples of our class-discriminative localization technique Grad-CAM and high-resolution visualization technique Guided Grad-CAM on image classification, image captioning and Visual Question Answering (VQA) tasks. We compare our visualizations with those obtained via other approaches such as Guided Backpropagation. Finally, we describe various ablation studies we performed.

B. Experimental Results

In this section we provide more qualitative results for Grad-CAM and Guided Grad-CAM applied to the task of image classification, image captioning and VQA.

B.1. Image Classification

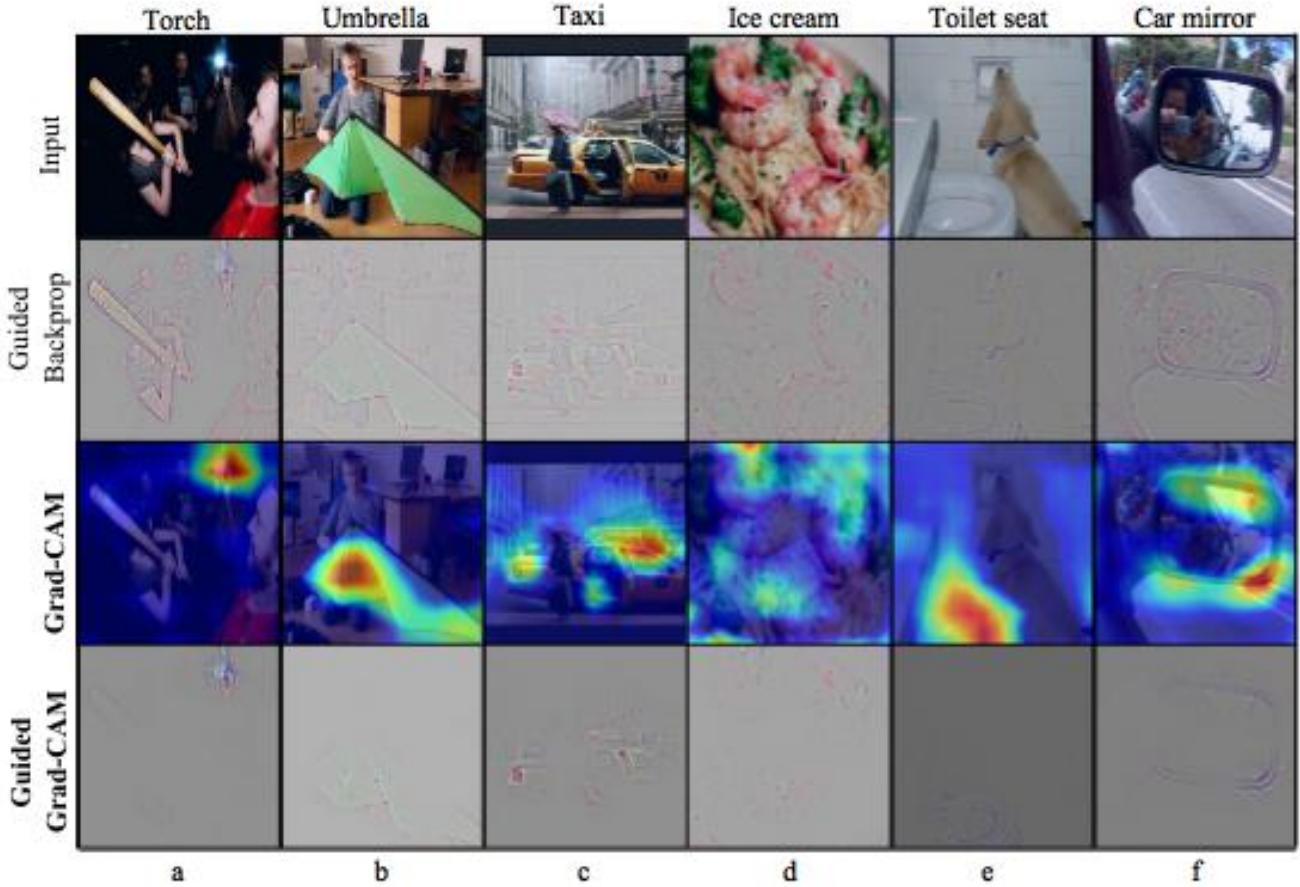


Figure A1: Visualizations for randomly sampled images from the COCO validation dataset. Predicted classes are mentioned at the top of each column.

We use Grad-CAM and Guided Grad-CAM to visualize the regions of the image that provide support for a particular prediction. The results reported below correspond to the VGG-16 [37] network trained on ImageNet.

Fig. A1 shows randomly sampled examples from COCO [24] validation set. COCO images typically have multiple objects per image and Grad-CAM visualizations show precise localization to support the model’s prediction.

Guided Grad-CAM can even localize tiny objects. For example our approach correctly localizes the predicted class “torch” (Fig. A1.a) inspite of its size and odd location in the image. Our method is also class-discriminative – it places attention *only* on the “toilet seat” even when a popular ImageNet category “dog” exists in the image (Fig. A1.e).

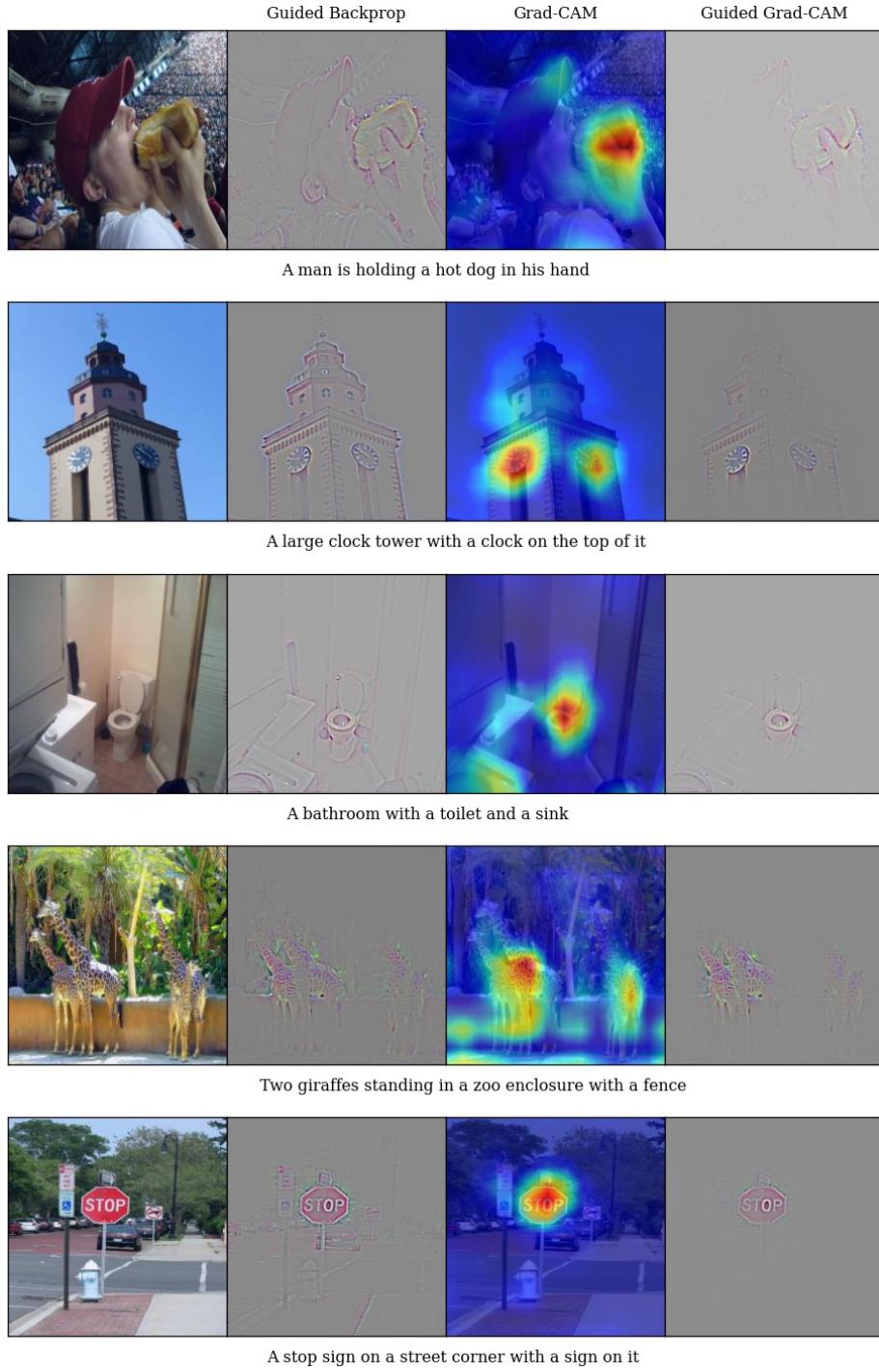


Figure A2: Guided Backpropagation, Grad-CAM and Guided Grad-CAM visualizations for the captions produced by the Neuraltalk2 image captioning model.

We also visualized Grad-CAM, Guided Backpropagation (GB), Deconvolution (DC), GB + Grad-CAM (Guided Grad-CAM), DC + Grad-CAM (Deconvolution Grad-CAM) for images from the ILSVRC-15 detection val set that have at least 2 unique object categories each. The visualizations for the mentioned class can be found in the following links.

“computer keyboard, keypad” class: <http://i.imgur.com/QMhsRzf.jpg>

“sunglasses, dark glasses, shades” class: <http://i.imgur.com/a1C7DGh.jpg>

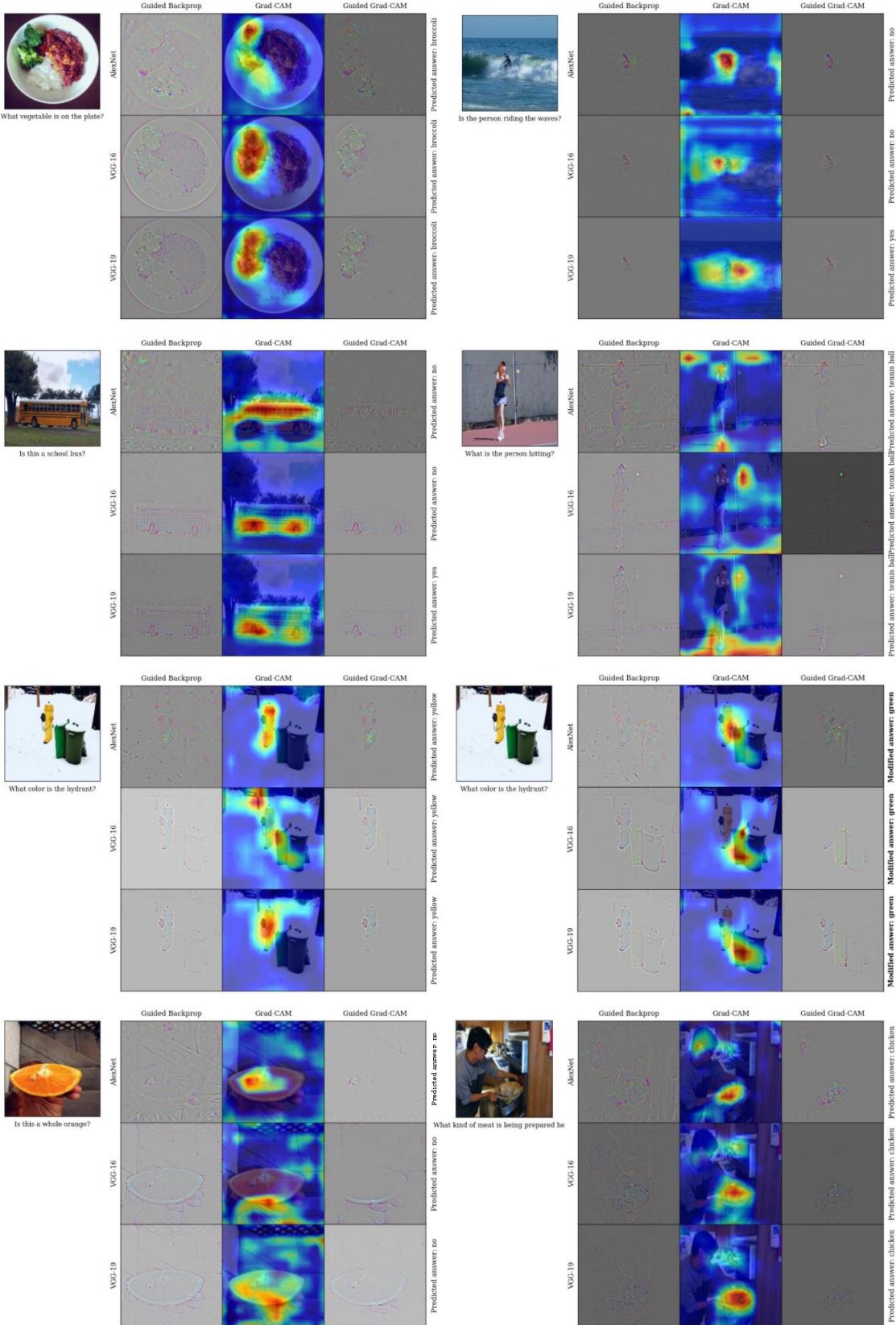


Figure A3: Guided Backpropagation, Grad-CAM and Guided Grad-CAM visualizations for the answers from a VQA model. For each image-question pair, we show visualizations for AlexNet, VGG-16 and VGG-19. Notice how the attention changes in row 3, as we change the answer from *Yellow* to *Green*.

B.2. Image Captioning

We use the publicly available Neuraltalk2 code and model⁵ for our image captioning experiments. The model uses VGG-16 to encode the image. The image representation is passed as input at the first time step to an LSTM that generates a caption for the image. The model is trained end-to-end along with CNN finetuning using the COCO [24] Captioning dataset. We feedforward the image to the image captioning model to obtain a caption. We use Grad-CAM to get a coarse localization and combine it with Guided Backpropagation to get a high-resolution visualization that highlights regions in the image that provide support for the generated caption.

B.3. Visual Question Answering (VQA)

We use Grad-CAM and Guided Grad-CAM to explain why a publicly available VQA model [27] answered what it answered. The VQA model by Lu *et al.* uses a standard CNN followed by a fully connected layer to transform the image to 1024-dim to match the LSTM embeddings of the question. Then the transformed image and LSTM embeddings are pointwise multiplied to get a combined representation of the image and question and a multi-layer perceptron is trained on top to predict one among 1000 answers. We show visualizations for the VQA model trained with 3 different CNNs - AlexNet [22], VGG-16 and VGG-19 [37]. Even though the CNNs were not finetuned for the task of VQA, it is interesting to see how our approach can serve as a tool to understand these networks better by providing a localized high-resolution visualization of the regions the model is looking at. Note that these networks were trained with no explicit attention mechanism enforced.

Notice in the first row of Fig. A3, for the question, “*Is the person riding the waves?*”, the VQA model with AlexNet and VGG-16 answered “No”, as they concentrated on the person mainly, and not the waves. On the other hand, VGG-19 correctly answered “Yes”, and it looked at the regions around the man in order to answer the question. In the second row, for the question, “*What is the person hitting?*”, the VQA model trained with AlexNet answered “Tennis ball” just based on context without looking at the ball. Such a model might be risky when employed in real-life scenarios. It is difficult to determine the trustworthiness of a model just based on the predicted answer. Our visualizations provide an accurate way to explain the model’s predictions and help in determining which model to trust, without making any architectural changes or sacrificing accuracy. Notice in the last row of Fig. A3, for the question, “*Is this a whole orange?*”, the model looks for regions around the orange to answer “No”.

C. Ablation studies

In this section we provide details of the ablation studies we performed.

C.1. Varying mask size for occlusion

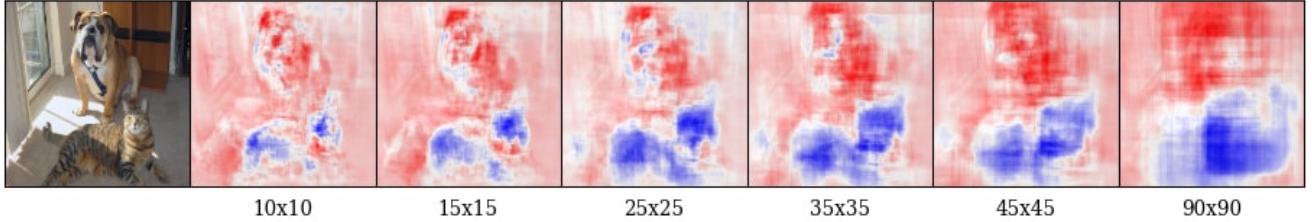


Figure A4: Occlusion maps with different mask sizes for the “tiger cat” category.

Fig. 1 (e,j) of main paper show the results of occlusion sensitivity for the “cat” and “dog” class. We compute this occlusion map by repeatedly masking regions of the image and forward propagate each masked image. At each location of the occlusion map we store the difference in the original score for the particular class and the score obtained after forward propagating the masked image. Our choices for mask sizes include (10×10 , 15×15 , 25×25 , 35×35 , 45×45 , and 90×90). We zero-pad the images so that the resultant occlusion map is of the same size as the original image. The resultant occlusion maps can be found in Fig. A4. Note that blue regions correspond to a decrease in score for a particular class (“tiger cat” in the case of Fig. A4) when the region around that pixel is occluded. Hence it serves as an evidence for the class. Whereas the red regions correspond to an increase in score as the region around that pixel is occluded. Hence these regions might indicate existence of other confusing classes. We observe that 35×35 is a good trade-off between sharp results and a smooth appearance.

⁵<https://github.com/karpathy/neuraltalk2>

C.2. Grad-CAM on different layers

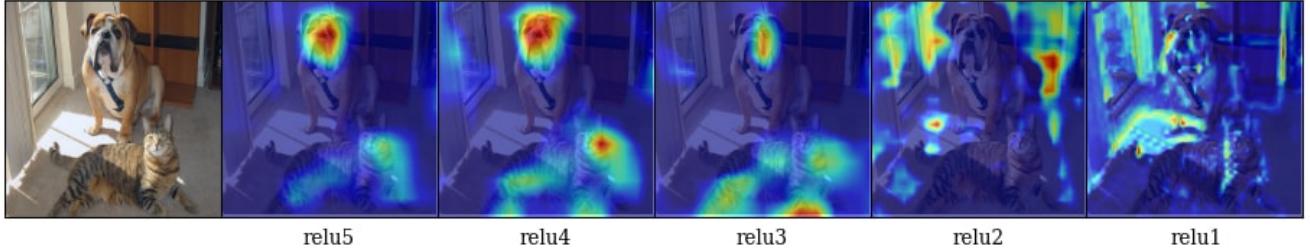


Figure A5: Grad-CAM localizations for “tiger cat” category for different rectified convolutional layer feature maps for AlexNet.

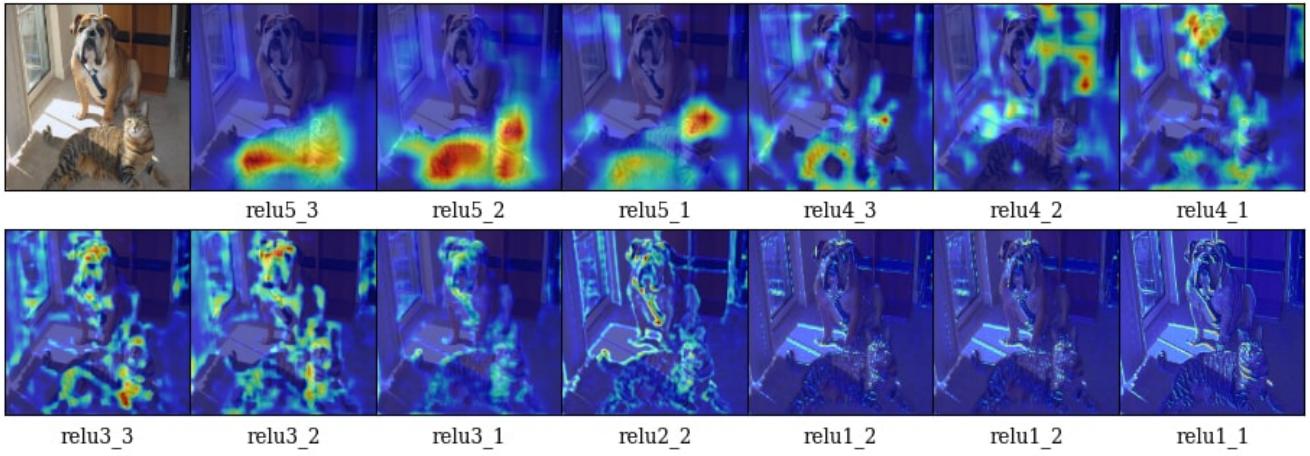


Figure A6: Grad-CAM localizations for “tiger cat” category for different rectified convolutional layer feature maps for VGG-16.

We show results of applying Grad-CAM for the “Tiger-cat” category on different convolutional layers in AlexNet and VGG-16 CNN. As expected, the results from Fig. A6 show that localization becomes progressively worse as we move to shallower convolutional layers. This is because the later convolutional layers capture high-level semantic information and at the same time retain spatial information, while the shallower layers have smaller receptive fields and only concentrate on local features that are important for the next layers.

C.3. Design choices

Method	Top-1 error
Grad-CAM	59.65
Grad-CAM without ReLU in (4)	74.98
Grad-CAM with Absolute gradients	58.19
Grad-CAM with GMP gradients	59.96
Grad-CAM with Deconv ReLU	83.95
Grad-CAM with Guided ReLU	59.14

Table A1: Localization results on ILSVRC-15 val for the ablation studies.

We evaluate design choices via top-1 localization error on the ILSVRC-15 val set [9], with each image resized to 224×224 .

C.3.1 Importance of ReLU in (4) in main paper

Removing ReLU ((4) in main paper) increases error by 15.3%. See Table. A1. Negative values in Grad-CAM indicate confusion between multiple occurring classes. Thus, localization improves when we suppress them (see Fig. A7).

C.3.2 Absolute value of each derivative in (3) in main paper

Taking the absolute value of each derivative in (3) in main paper decreases the error by 1.5% (see Table. A1). But qualitatively maps look a bit worse (see Fig. A7), and this evaluation does not capture class discriminability (most ImageNet images have only 1 class).

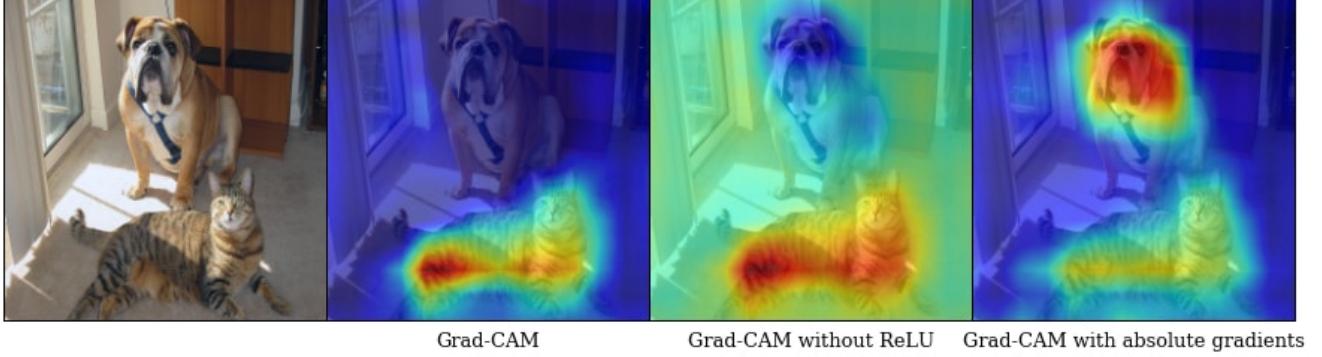


Figure A7: Grad-CAM visualizations for “tiger cat” category stating the importance of ReLU and effect of using absolute gradients in (4) of main paper.

C.3.3 Global Average Pooling vs. Global Max Pooling

Instead of Global Average Pooling (GAP) the incoming gradients to the convolutional layer, we tried Global Max Pooling (GMP) the gradients. We observe that using GMP lowers the localization ability of our Grad-CAM technique. An example can be found in Fig. A8 below. This observation is also summarized in Table. A1. This may be due to the fact *max* is statistically less robust to noise compared to the *averaged* gradient.

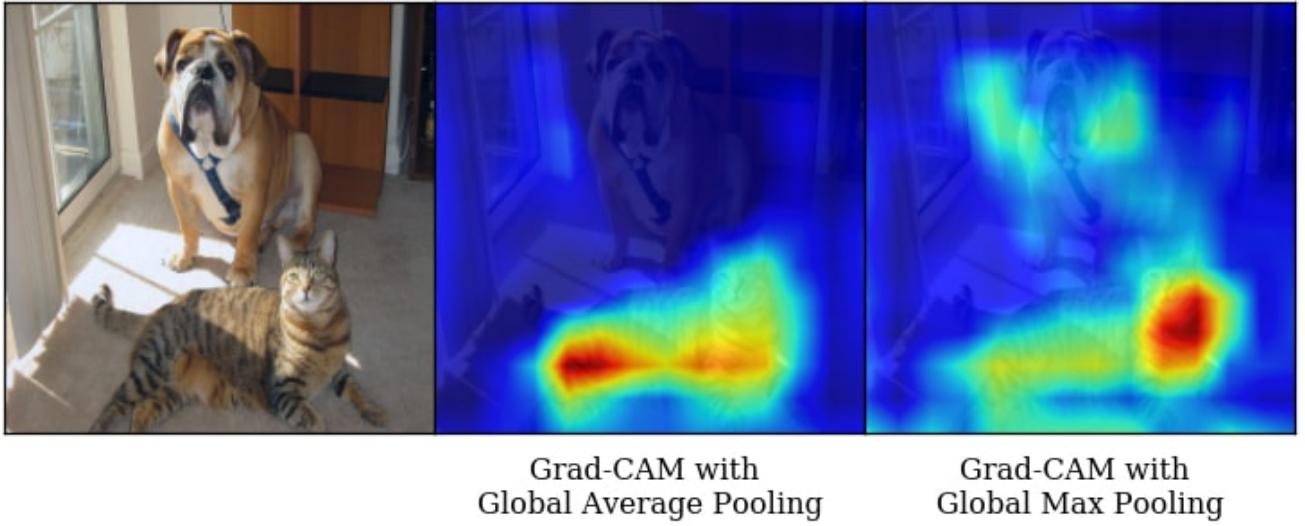


Figure A8: Grad-CAM visualizations for “tiger cat” category with Global Average Pooling and Global Max Pooling.

C.3.4 Effect of different ReLU on Grad-CAM

We experiment with different modifications to the backward pass of ReLU, namely, using Guided-ReLU [38] and Deconv-ReLU [41].

Effect of Guided-ReLU:

Springenberg *et al.* [38] introduced Guided Backprop, where they modified the backward pass of ReLU to pass only positive gradients to regions with positive activations. Applying this change to the computation of our Grad-CAM maps introduces a drop in the class-discriminative ability of Grad-CAM as can be seen in Fig. A9, but it gives a slight improvement in the localization ability on ILSVRC-15 localization challenge (see Table. A1).

Effect of Deconv-ReLU:

Zeiler and Fergus [41] in their Deconvolution work introduced a slight modification to the backward pass of ReLU, to pass only the positive gradients from higher layers. Applying this modification to the computation of our Grad-CAM gives worse qualitative results as shown in Fig. A9 and Table. A1.

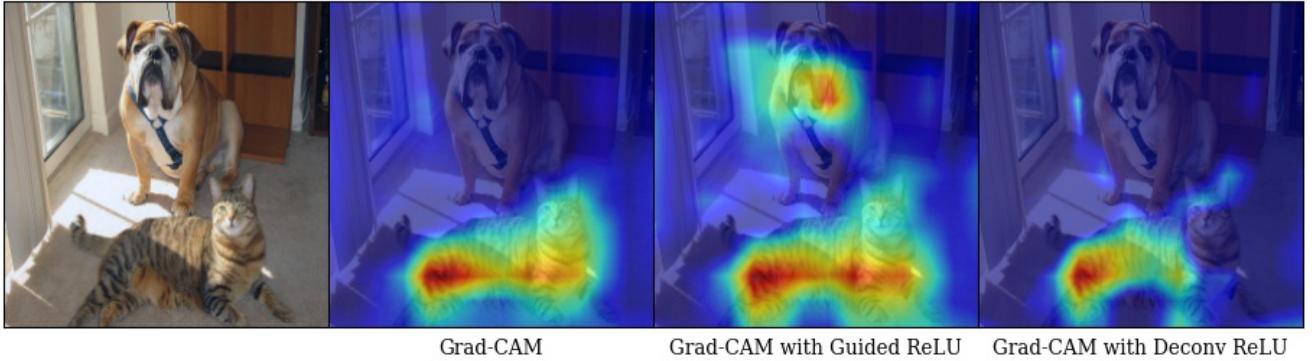


Figure A9: Grad-CAM visualizations for “tiger cat” category for different modifications to the ReLU backward pass. The best results are obtained when we use the actual gradients during the computation of Grad-CAM.