

Lecture 9: Convolutional Neural Networks

Handling image data

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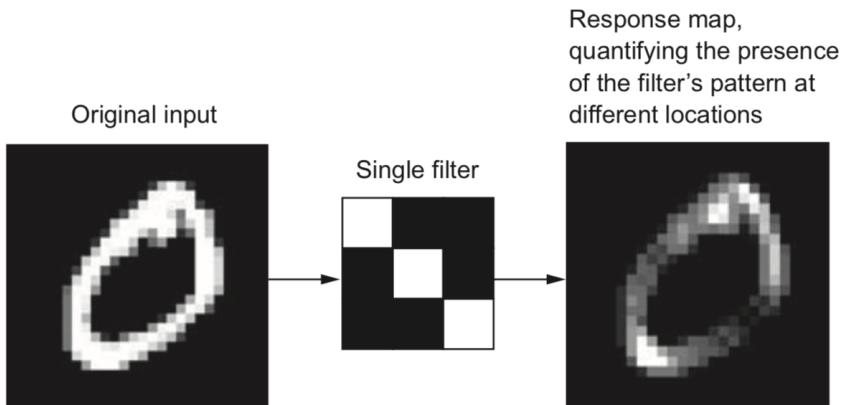
Overview

- Image convolution
- Convolutional neural networks
- Data augmentation
- Model interpretation
- Using pre-trained networks (transfer learning)

Convolution

- Operation that transforms an image by sliding a smaller image (called a *filter* or *kernel*) over the image and multiplying the pixel values
 - Slide an $n \times n$ filter over $n \times n$ patches of the original image
 - Every pixel is replaced by the *sum* of the *element-wise products* of the values of the image patch around that pixel and the kernel

```
# kernel and image_patch are n x n matrices  
pixel_out = np.sum(kernel * image_patch)
```

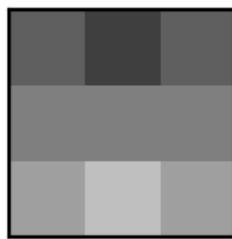


- Different kernels can detect different types of patterns in the image

Image and kernel



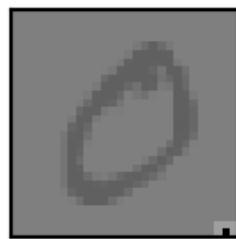
Hor. edge filter



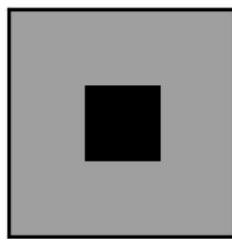
Filtered image



Image and kernel



Edge detect filter



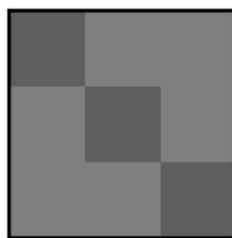
Filtered image



Image and kernel



Diag. edge filter



Filtered image

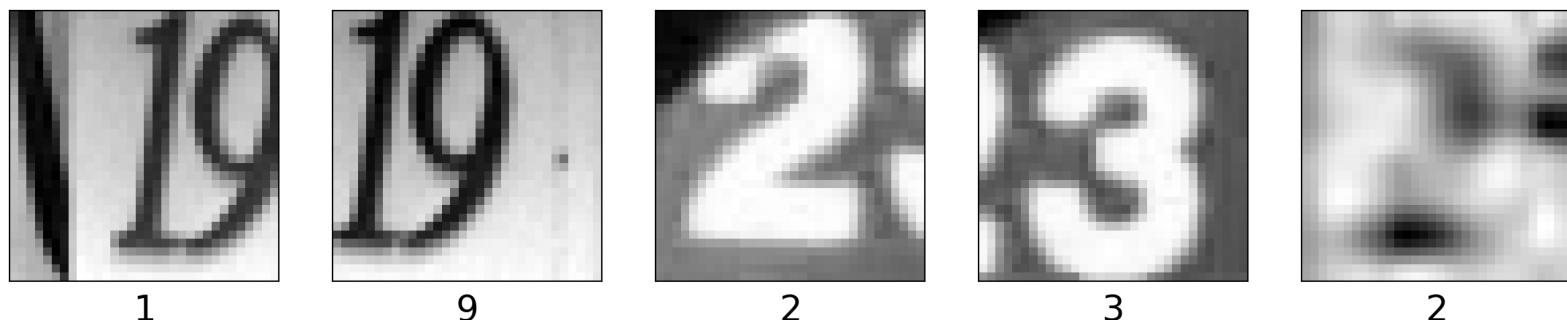


Demonstration on Google streetview data

House numbers photographed from Google streetview imagery, cropped and centered around digits, but with neighboring numbers or other edge artifacts.

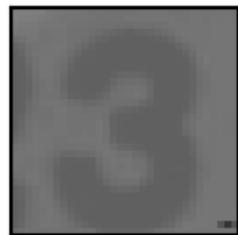


For recognizing digits, color is not important, so we grayscale the images

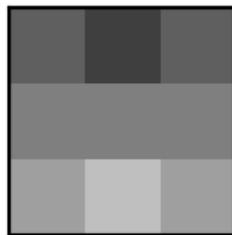


Demonstration

Image and kernel



Hor. edge filter



Filtered image

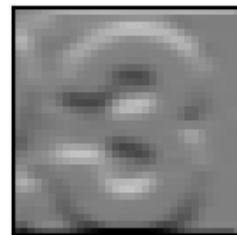
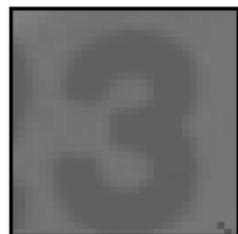
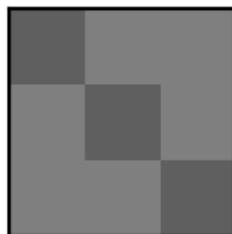


Image and kernel



Diag. edge filter



Filtered image

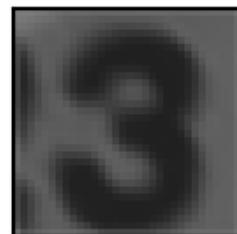
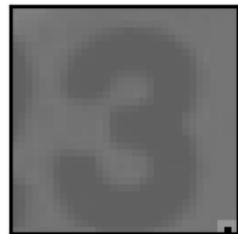
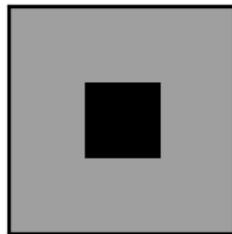


Image and kernel



Edge detect filter



Filtered image

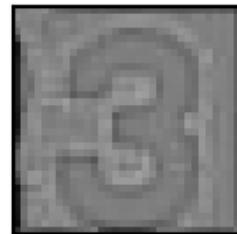
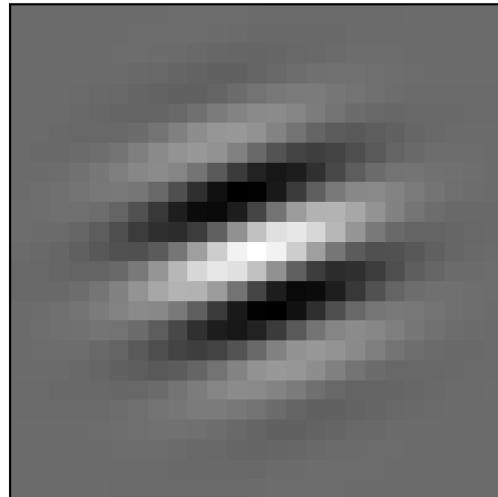


Image convolution in practice

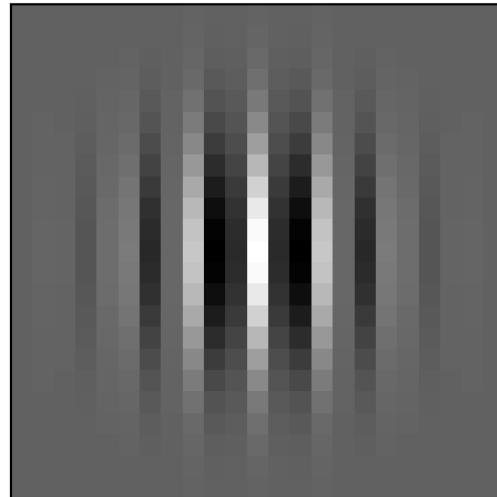
- How do we know which filters are best for a given image?
- *Families* of kernels (or *filter banks*) can be run on every image
 - Gabor, Sobel, Haar Wavelets,...
- Gabor filters: Wave patterns generated by changing:
 - Frequency: narrow or wide ondulations
 - Theta: angle (direction) of the wave
 - Sigma: resolution (size of the filter)

Demonstration

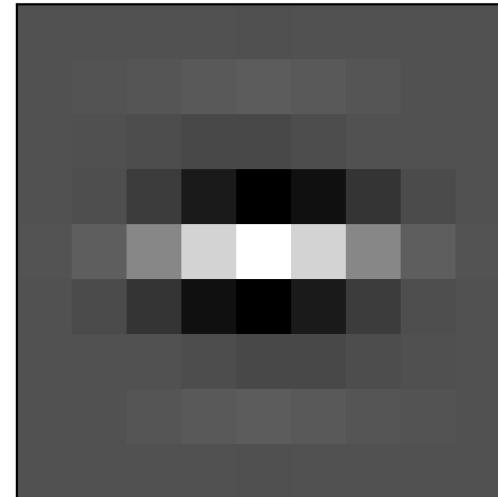
freq: 0.16, theta: 1.2, sigma: 4.0



freq: 0.31, theta: 0, sigma: 3.6

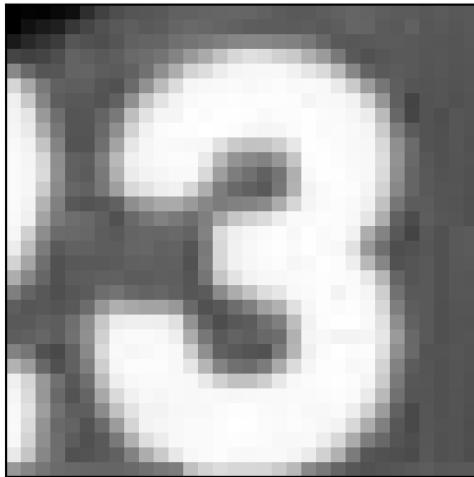


freq: 0.36, theta: 1.6, sigma: 1.3

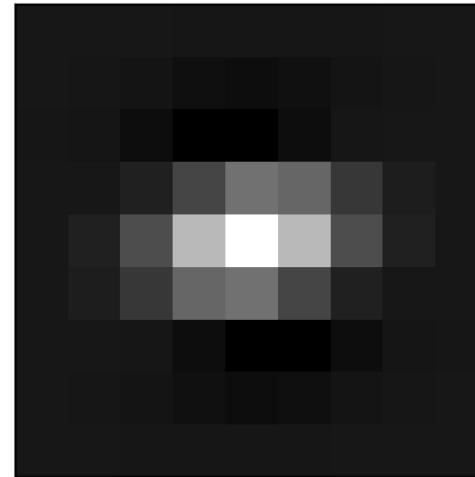


Demonstration on the streetview data

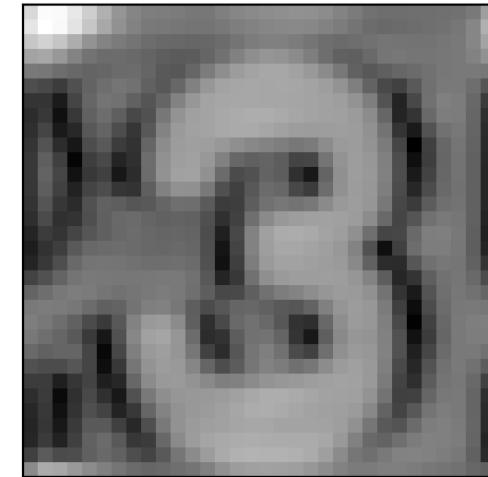
Original



Gabor kernel

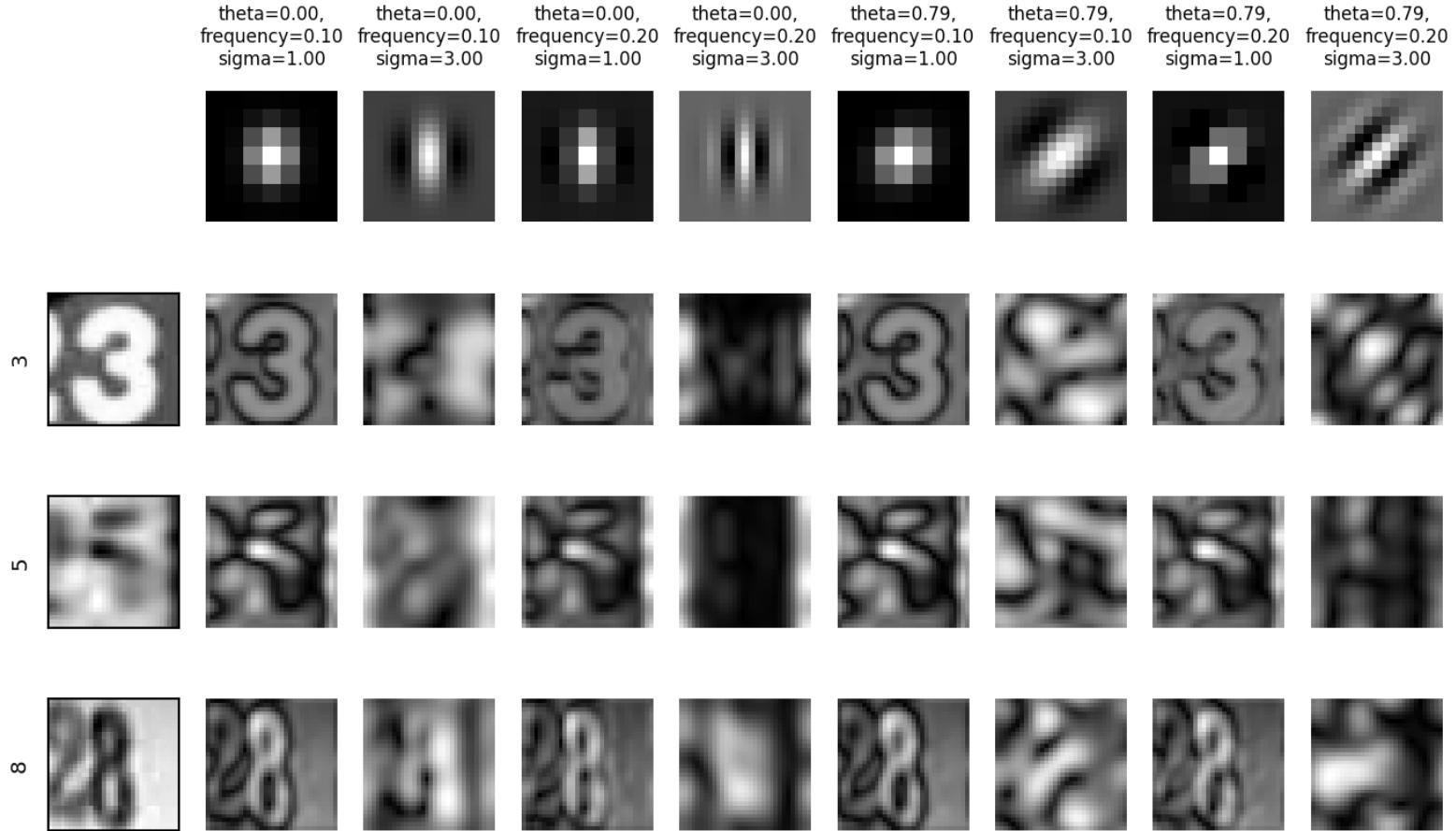


Response magnitude

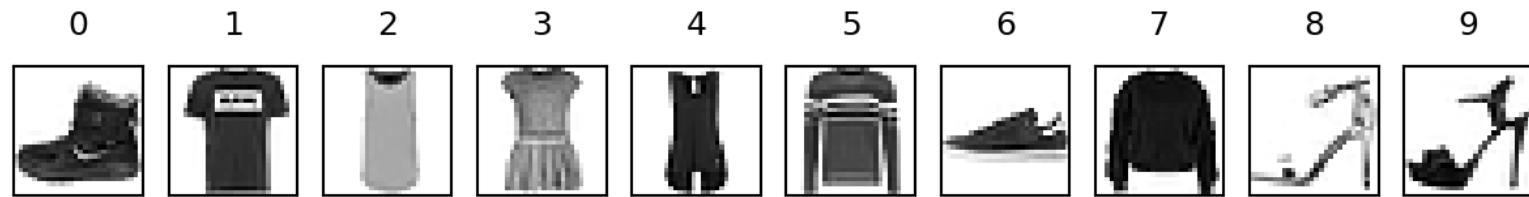


Filter banks

- Different filters detect different edges, shapes,...
- Not all seem useful

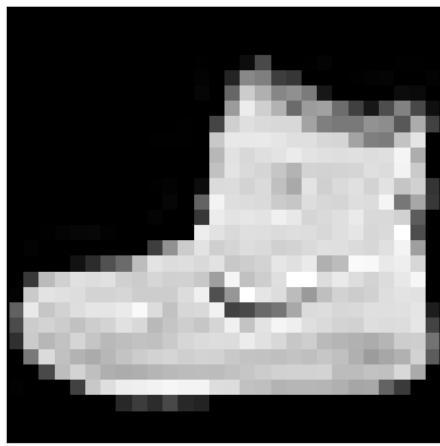


Another example: Fashion MNIST

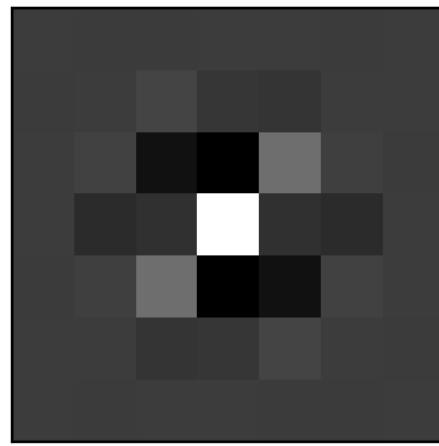


Demonstration

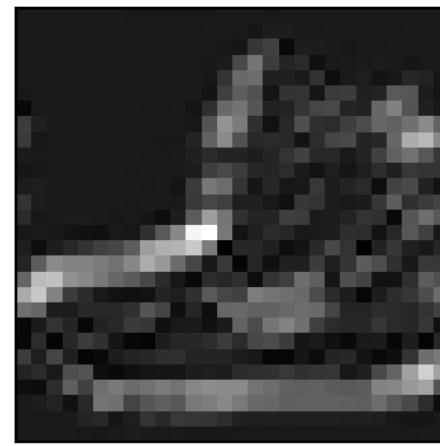
Original



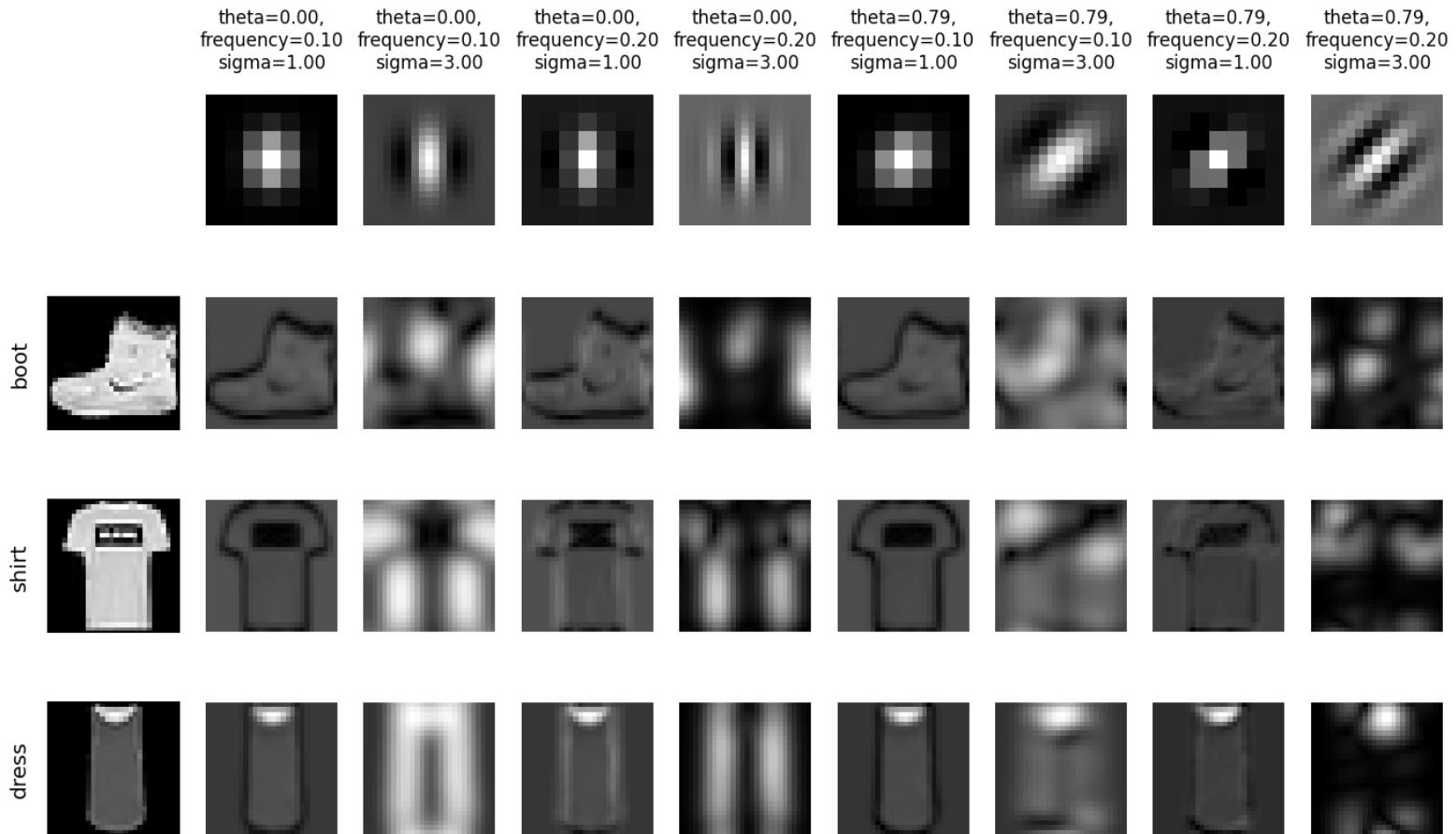
Gabor kernel



Response magnitude

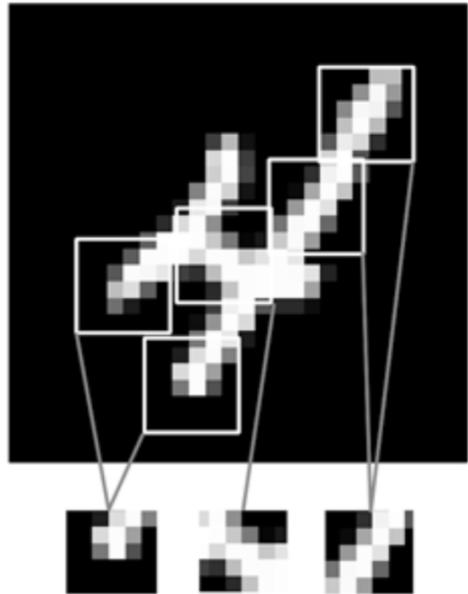


Fashion MNIST with multiple filters (filter bank)



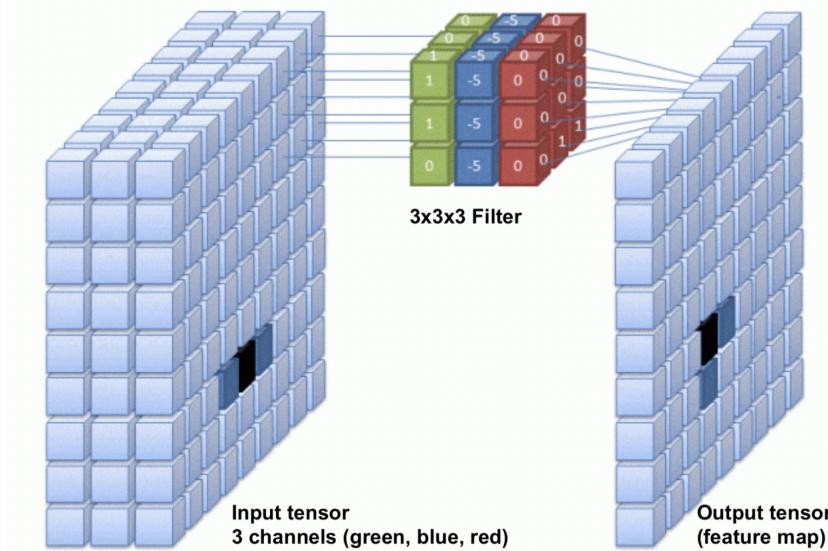
Convolutional neural nets

- Finding relationships between individual pixels and the correct class is hard
- We want to discover 'local' patterns (edges, lines, endpoints)
- Representing such local patterns as features makes it easier to learn from them
- We could use convolutions, but how to choose the filters?



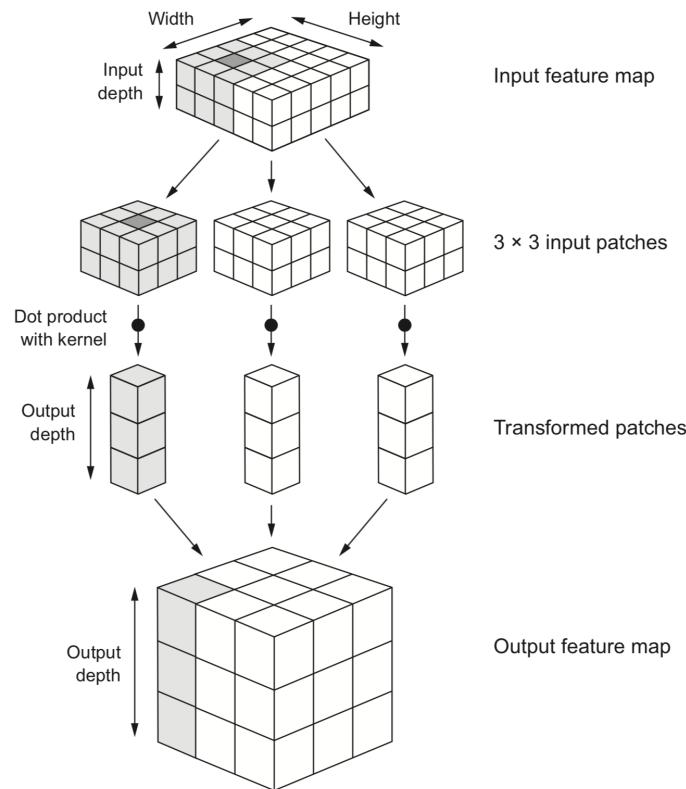
Convolutional Neural Networks (ConvNets)

- Instead of manually designing the filters, we can also *learn* them based on data
 - Choose filter sizes (manually), initialize with small random weights
- Forward pass: Convolutional layer slides the filter over the input, generates the output
- Backward pass: Update the filter weights according to the loss gradient
- Illustration for 1 filter:



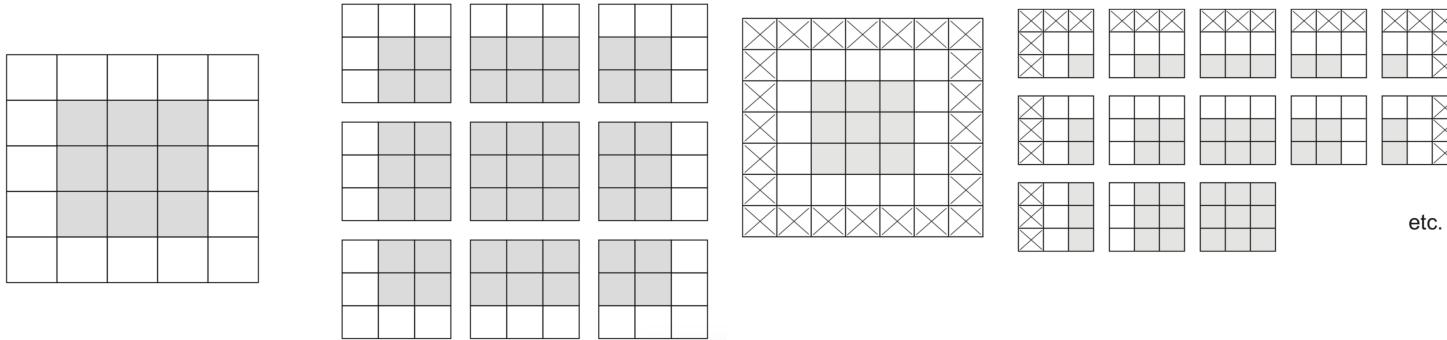
Convolutional layers: Feature maps

- One filter is not sufficient to detect all relevant patterns in an image
- A convolutional layer applies and learns d filters in parallel
- Slide d filters across the input image (in parallel) -> a $(1 \times 1 \times d)$ output per patch
- Reassemble into a *feature map* with d 'channels', a $(\text{width} \times \text{height} \times d)$ tensor.



Border effects (zero padding)

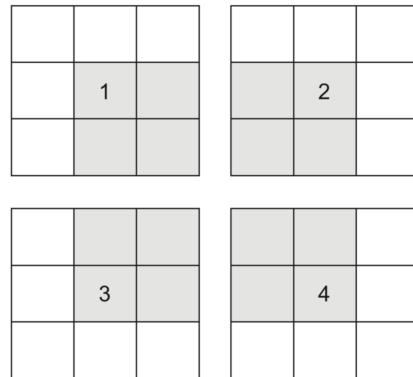
- Consider a 5×5 image and a 3×3 filter: there are only 9 possible locations, hence the output is a 3×3 feature map
- If we want to maintain the image size, we use *zero-padding*, adding 0's all around the input tensor.



Undersampling (striding)

- Sometimes, we want to *downsample* a high-resolution image
 - Faster processing, less noisy (hence less overfitting)
- One approach is to *skip* values during the convolution
 - Distance between 2 windows: *stride length*
- Example with stride length 2 (without padding):

1			2	
3			4	



Max-pooling

- Another approach to shrink the input tensors is *max-pooling* :
 - Run a filter with a fixed stride length over the image
 - Usually 2x2 filters and stride lenght 2
 - The filter simply returns the *max* (or *avg*) of all values
- Agressively reduces the number of weights (less overfitting)
- Information from every input node spreads more quickly to output nodes
 - In `pure` convnets, one input value spreads to 3x3 nodes of the first layer, 5x5 nodes of the second, etc.
 - Without maxpooling, you need much deeper networks, harder to train
- Increases *translation invariance* : patterns can affect the predictions no matter where they occur in the image

Convolutional nets in practice

- ConvNets usually use multiple convolutional layers to learn patterns at different levels of abstraction
 - Find local patterns first (e.g. edges), then patterns across those patterns
- Use MaxPooling layers to reduce resolution, increase translation invariance
- Use sufficient filters in the first layer (otherwise information gets lost)
- In deeper layers, use increasingly more filters
 - Preserve information about the input as resolution decreases
 - Avoid decreasing the number of activations (resolution x nr of filters)

Example with Keras:

- `Conv2D` for 2D convolutional layers
 - 32 filters (default), randomly initialized (from uniform distribution)
 - Deeper layers use 64 filters
 - Filter size is 3x3
 - ReLU activation to simplify training of deeper networks
- `MaxPooling2D` for max-pooling
 - 2x2 pooling reduces the number of inputs by a factor 4

```
model = models.Sequential()
model.add(layers.Conv2D(32, (3, 3), activation='relu',
                      input_shape=(28, 28, 1)))
model.add(layers.MaxPooling2D((2, 2)))
model.add(layers.Conv2D(64, (3, 3), activation='relu'))
model.add(layers.MaxPooling2D((2, 2)))
model.add(layers.Conv2D(64, (3, 3), activation='relu'))
```

Observe how the input image on 28x28x1 is transformed to a 3x3x64 feature map

- Convolutional layer:
 - No zero-padding: every output 2 pixels less in every dimension
 - 320 weights: (3x3 filter weights + 1 bias) * 32 filters
- After every MaxPooling, resolution halved in every dimension

```
Model: "sequential"
```

Layer (type)	Output Shape	Param #
<hr/>		
conv2d (Conv2D)	(None, 26, 26, 32)	320
max_pooling2d (MaxPooling2D)	(None, 13, 13, 32)	0
conv2d_1 (Conv2D)	(None, 11, 11, 64)	18496
max_pooling2d_1 (MaxPooling 2D)	(None, 5, 5, 64)	0
conv2d_2 (Conv2D)	(None, 3, 3, 64)	36928
<hr/>		
Total params: 55,744		
Trainable params: 55,744		
Non-trainable params: 0		

Completing the network

- To classify the images, we still need a Dense and Softmax layer.
- We need to flatten the 3x3x64 feature map to a vector of size 576

```
model.add(layers.Flatten())
model.add(layers.Dense(64, activation='relu'))
model.add(layers.Dense(10, activation='softmax'))
```

Complete network

```
Model: "sequential"
-----

| Layer (type)                   | Output Shape       | Param # |
|--------------------------------|--------------------|---------|
| conv2d (Conv2D)                | (None, 26, 26, 32) | 320     |
| max_pooling2d (MaxPooling2D )  | (None, 13, 13, 32) | 0       |
| conv2d_1 (Conv2D)              | (None, 11, 11, 64) | 18496   |
| max_pooling2d_1 (MaxPooling2D) | (None, 5, 5, 64)   | 0       |
| conv2d_2 (Conv2D)              | (None, 3, 3, 64)   | 36928   |
| flatten (Flatten)              | (None, 576)        | 0       |
| dense (Dense)                  | (None, 64)         | 36928   |
| dense_1 (Dense)                | (None, 10)         | 650     |

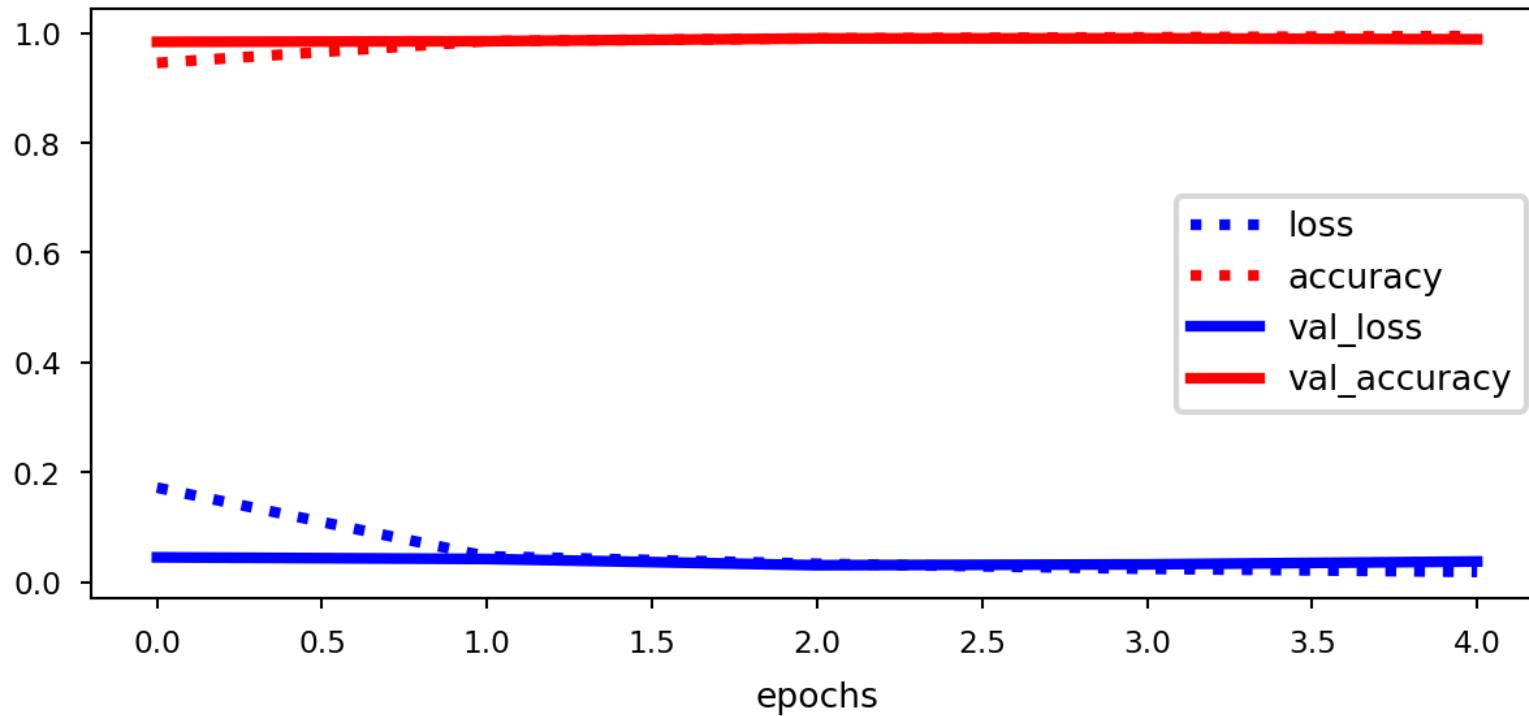

=====
```

Total params: 93,322
Trainable params: 93,322
Non-trainable params: 0

Run the model on MNIST dataset

- Train and test as usual: 99% accuracy
 - Compared to 97,8% accuracy with the dense architecture

Accuracy: 0.988800048828125



Tip:

- Training ConvNets can take a lot of time
- Save the trained model (and history) to disk so that you can reload it later

```
model.save(os.path.join(model_dir, 'mnist.h5'))
with open(os.path.join(model_dir, 'mnist_history.p'), 'wb') as
file_pi:
    pickle.dump(history.history, file_pi)
```

Cats vs Dogs

- A more realistic dataset: [Cats vs Dogs](#)
 - Colored JPEG images, different sizes
 - Not nicely centered, translation invariance is important
- Preprocessing
 - Create balanced subsample of 4000 colored images
 - 3000 for training, 1000 validation
 - Decode JPEG images to floating-point tensors
 - Rescale pixel values to [0,1]
 - Resize images to 150x150 pixels

Data generators

- `ImageDataGenerator` : allows to encode, resize, and rescale JPEG images
- Returns a Python *generator* we can endlessly query for batches of images
- Separately for training, validation, and test set

```
train_generator =  
    ImageDataGenerator(rescale=1./255).flow_from_directory(  
        train_dir,                      # Directory with images  
        target_size=(150, 150),          # Resize images  
        batch_size=20,                  # Return 20 images at a time  
        class_mode='binary')           # Binary labels
```



Since the images are larger and more complex, we add another convolutional layer and increase the number of filters to 128.

```
model = models.Sequential()
model.add(layers.Conv2D(32, (3, 3), activation='relu',
                      input_shape=(150, 150, 3)))
model.add(layers.MaxPooling2D((2, 2)))
model.add(layers.Conv2D(64, (3, 3), activation='relu'))
model.add(layers.MaxPooling2D((2, 2)))
model.add(layers.Conv2D(128, (3, 3), activation='relu'))
model.add(layers.MaxPooling2D((2, 2)))
model.add(layers.Conv2D(128, (3, 3), activation='relu'))
model.add(layers.MaxPooling2D((2, 2)))
model.add(layers.Flatten())
model.add(layers.Dense(512, activation='relu'))
model.add(layers.Dense(1, activation='sigmoid'))
```

Model: "sequential_1"

Layer (type)	Output Shape	Param #
<hr/>		
conv2d_3 (Conv2D)	(None, 148, 148, 32)	896
max_pooling2d_2 (MaxPooling 2D)	(None, 74, 74, 32)	0
conv2d_4 (Conv2D)	(None, 72, 72, 64)	18496
max_pooling2d_3 (MaxPooling 2D)	(None, 36, 36, 64)	0
conv2d_5 (Conv2D)	(None, 34, 34, 128)	73856
max_pooling2d_4 (MaxPooling 2D)	(None, 17, 17, 128)	0
conv2d_6 (Conv2D)	(None, 15, 15, 128)	147584
max_pooling2d_5 (MaxPooling 2D)	(None, 7, 7, 128)	0
flatten_1 (Flatten)	(None, 6272)	0
dense_2 (Dense)	(None, 512)	3211776
dense_3 (Dense)	(None, 1)	513
<hr/>		
Total params: 3,453,121		
Trainable params: 3,453,121		
Non-trainable params: 0		

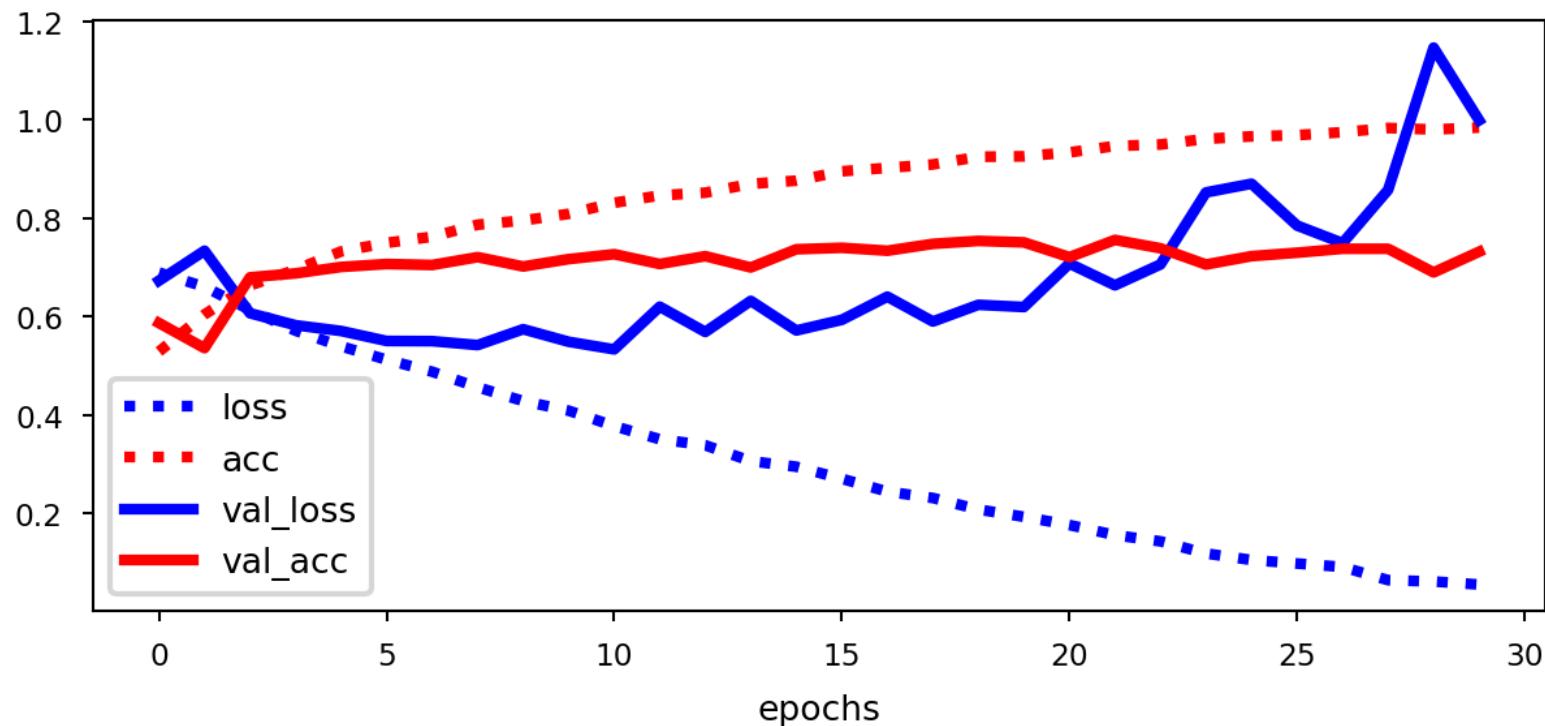
Training

- The `fit` function also supports generators
 - 100 steps per epoch (batch size: 20 images per step), for 30 epochs
 - Provide a separate generator for the validation data

```
model.compile(loss='binary_crossentropy',
              optimizer=optimizers.RMSprop(lr=1e-4),
              metrics=['acc'])
history = model.fit(
    train_generator, steps_per_epoch=100,
    epochs=30, verbose=0,
    validation_data=validation_generator,
    validation_steps=50)
```

Results

- The network seems to be overfitting. Validation accuracy is stuck at 75% while the training accuracy reaches 100%
- There are many things we can do:
 - Regularization (e.g. Dropout, L1/L2, Batch Normalization,...)
 - Generating more training data
 - Meta-learning: Use pretrained rather than randomly initialized filters



Data augmentation

- Generate new images via image transformations
 - Images will be randomly transformed every epoch
- We can again use a data generator to do this

```
datagen = ImageDataGenerator(  
    rotation_range=40,      # Rotate image up to 40 degrees  
    width_shift_range=0.2,  # Shift image left-right up to 20% of  
    image width  
    height_shift_range=0.2, # Shift image up-down up to 20% of  
    image height  
    shear_range=0.2,        # Shear (slant) the image up to 0.2  
    degrees  
    zoom_range=0.2,         # Zoom in up to 20%  
    horizontal_flip=True,   # Horizontally flip the image  
    fill_mode='nearest')
```

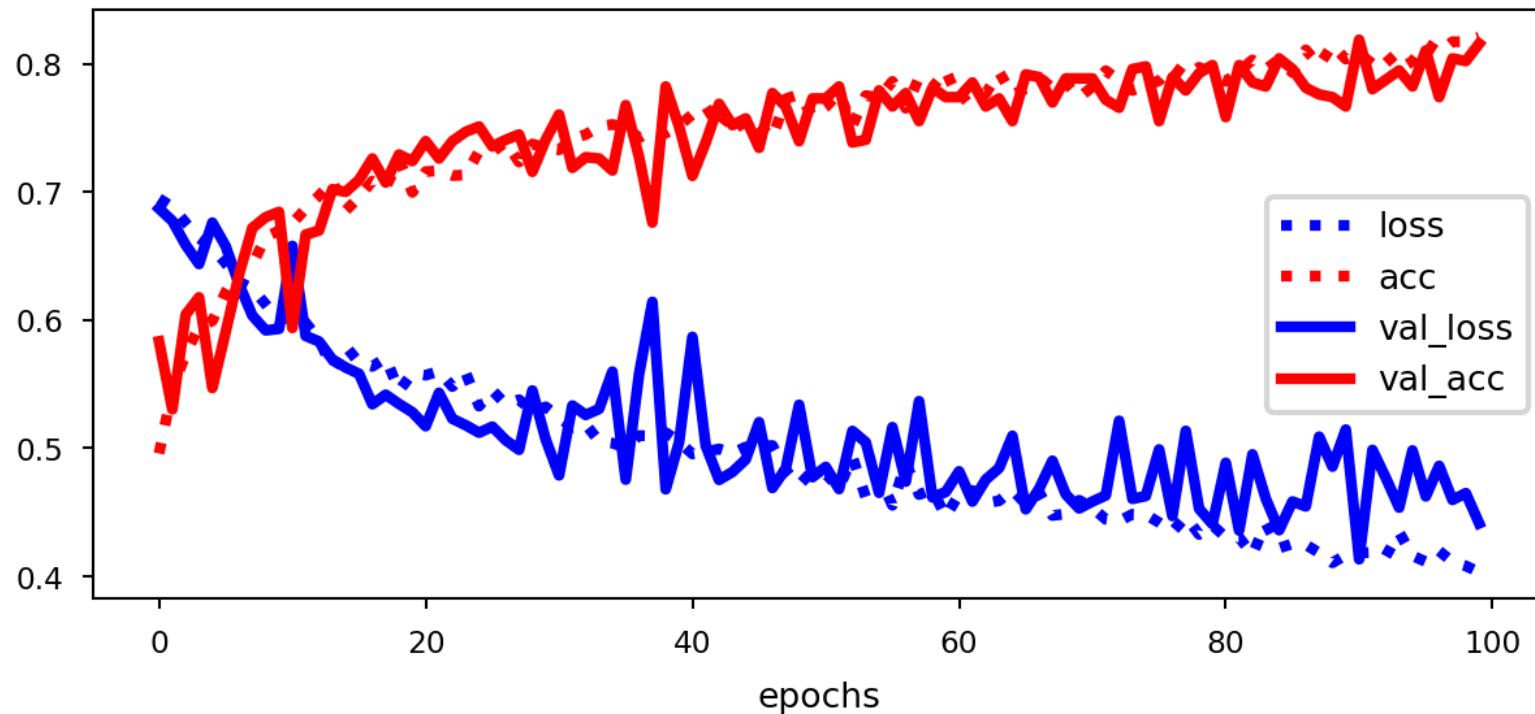
Example



We also add Dropout before the Dense layer

```
model = models.Sequential()
model.add(layers.Conv2D(32, (3, 3), activation='relu',
                      input_shape=(150, 150, 3)))
model.add(layers.MaxPooling2D((2, 2)))
model.add(layers.Conv2D(64, (3, 3), activation='relu'))
model.add(layers.MaxPooling2D((2, 2)))
model.add(layers.Conv2D(128, (3, 3), activation='relu'))
model.add(layers.MaxPooling2D((2, 2)))
model.add(layers.Conv2D(128, (3, 3), activation='relu'))
model.add(layers.MaxPooling2D((2, 2)))
model.add(layers.Flatten())
model.add(layers.Dropout(0.5))
model.add(layers.Dense(512, activation='relu'))
model.add(layers.Dense(1, activation='sigmoid'))
```

(Almost) no more overfitting!



Interpreting the model

- Let's see what the convnet is learning exactly by observing the intermediate feature maps
 - A layer's output is also called its *activation*
- We can choose a specific test image, and observe the outputs
- We can retrieve and visualize the activation for every filter for every layer

- Layer 0: has activations of resolution 148x148 for each of its 32 filters
- Layer 2: has activations of resolution 72x72 for each of its 64 filters
- Layer 4: has activations of resolution 34x34 for each of its 128 filters
- Layer 6: has activations of resolution 15x15 for each of its 128 filters

Model: "sequential_3"

Layer (type)	Output Shape	Param #
<hr/>		
conv2d_10 (Conv2D)	(None, 148, 148, 32)	896
max_pooling2d_8 (MaxPooling 2D)	(None, 74, 74, 32)	0
conv2d_11 (Conv2D)	(None, 72, 72, 64)	18496
max_pooling2d_9 (MaxPooling 2D)	(None, 36, 36, 64)	0
conv2d_12 (Conv2D)	(None, 34, 34, 128)	73856
max_pooling2d_10 (MaxPooling2D)	(None, 17, 17, 128)	0
conv2d_13 (Conv2D)	(None, 15, 15, 128)	147584
max_pooling2d_11 (MaxPooling2D)	(None, 7, 7, 128)	0
flatten_2 (Flatten)	(None, 6272)	0
dropout (Dropout)	(None, 6272)	0
dense_4 (Dense)	(None, 512)	3211776
dense_5 (Dense)	(None, 1)	513
<hr/>		
Total params: 3,453,121		
Trainable params: 3,453,121		
Non-trainable params: 0		

- To extract the activations, we create a new model that outputs the trained layers
 - 8 output layers in total (only the convolutional part)
- We input a test image for prediction and then read the relevant outputs

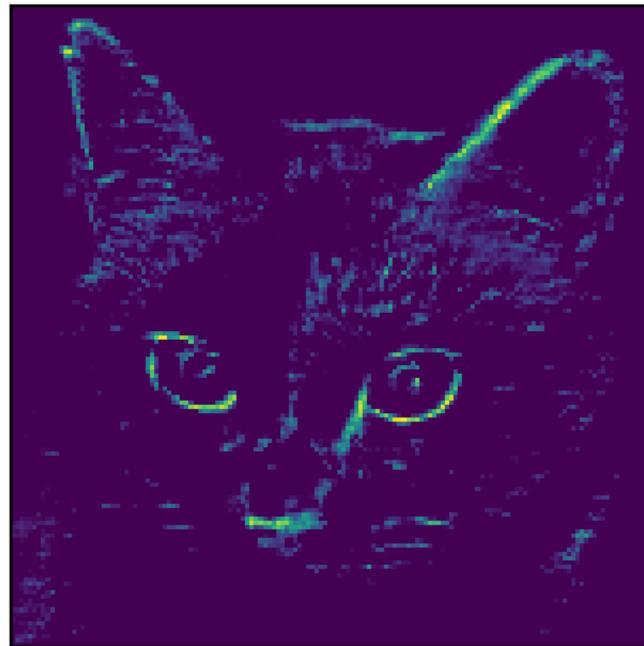
```
layer_outputs = [layer.output for layer in model.layers[:8]]
activation_model = models.Model(inputs=model.input,
outputs=layer_outputs)
activations = activation_model.predict(img_tensor)
```

Output of the first Conv2D layer, 3rd channel (filter):

- Similar to a diagonal edge detector
- Your own channels may look different



Input image



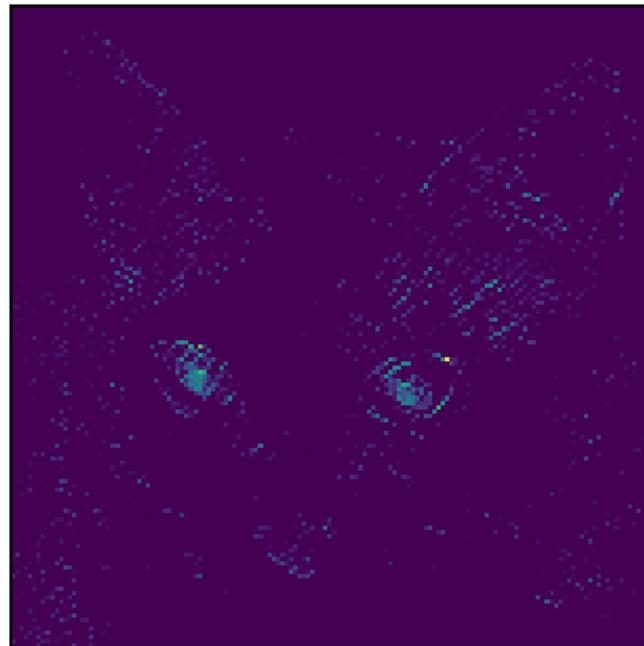
Activation of filter 6

Output of filter 16:

- Cat eye detector?



Input image

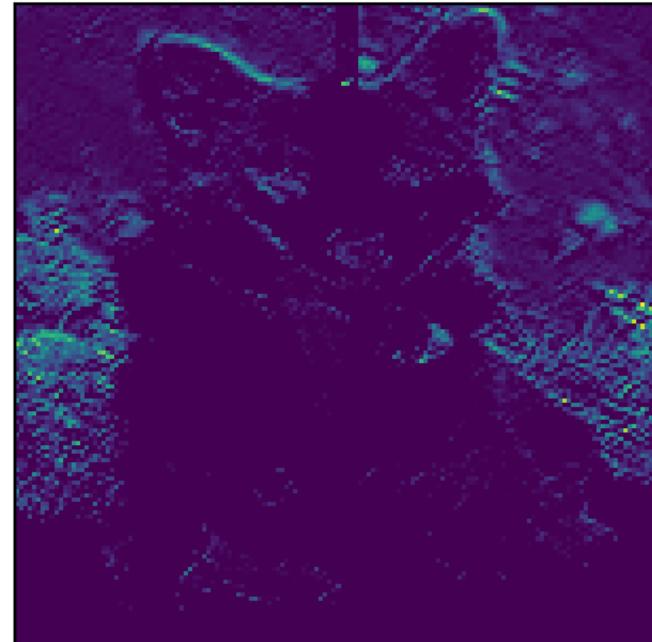


Activation of filter 25

The same filter responds quite differently for other inputs (green detector?).



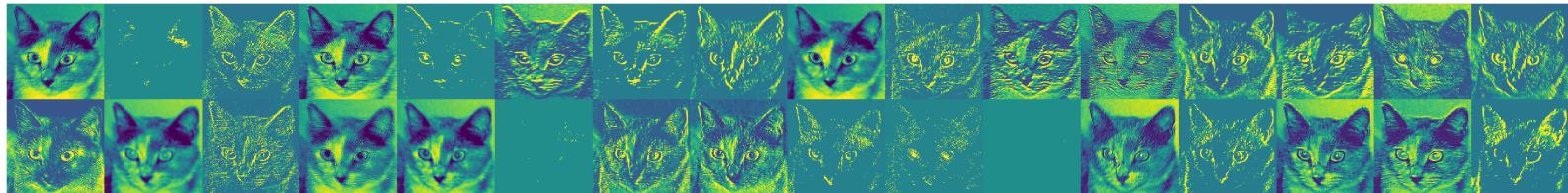
Input image



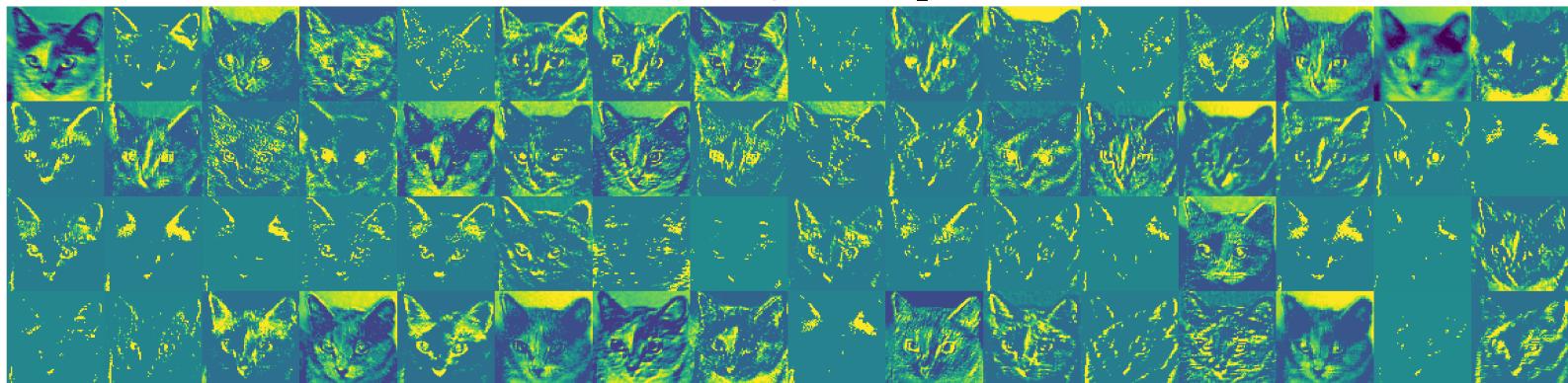
Activation of filter 25

- First 2 convolutional layers: various edge detectors

Activation of layer 1 (conv2d_10)

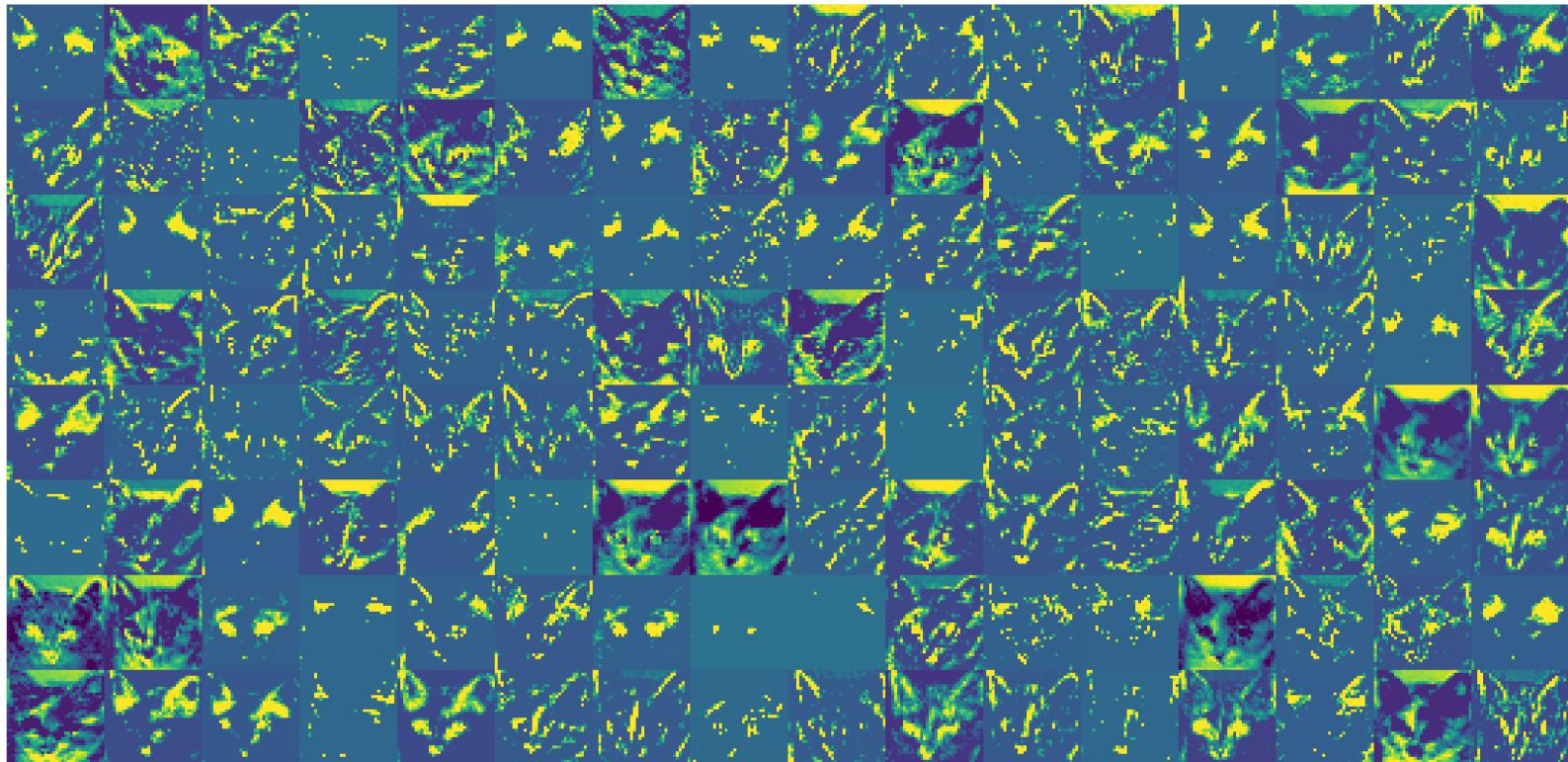


Activation of layer 3 (conv2d_11)

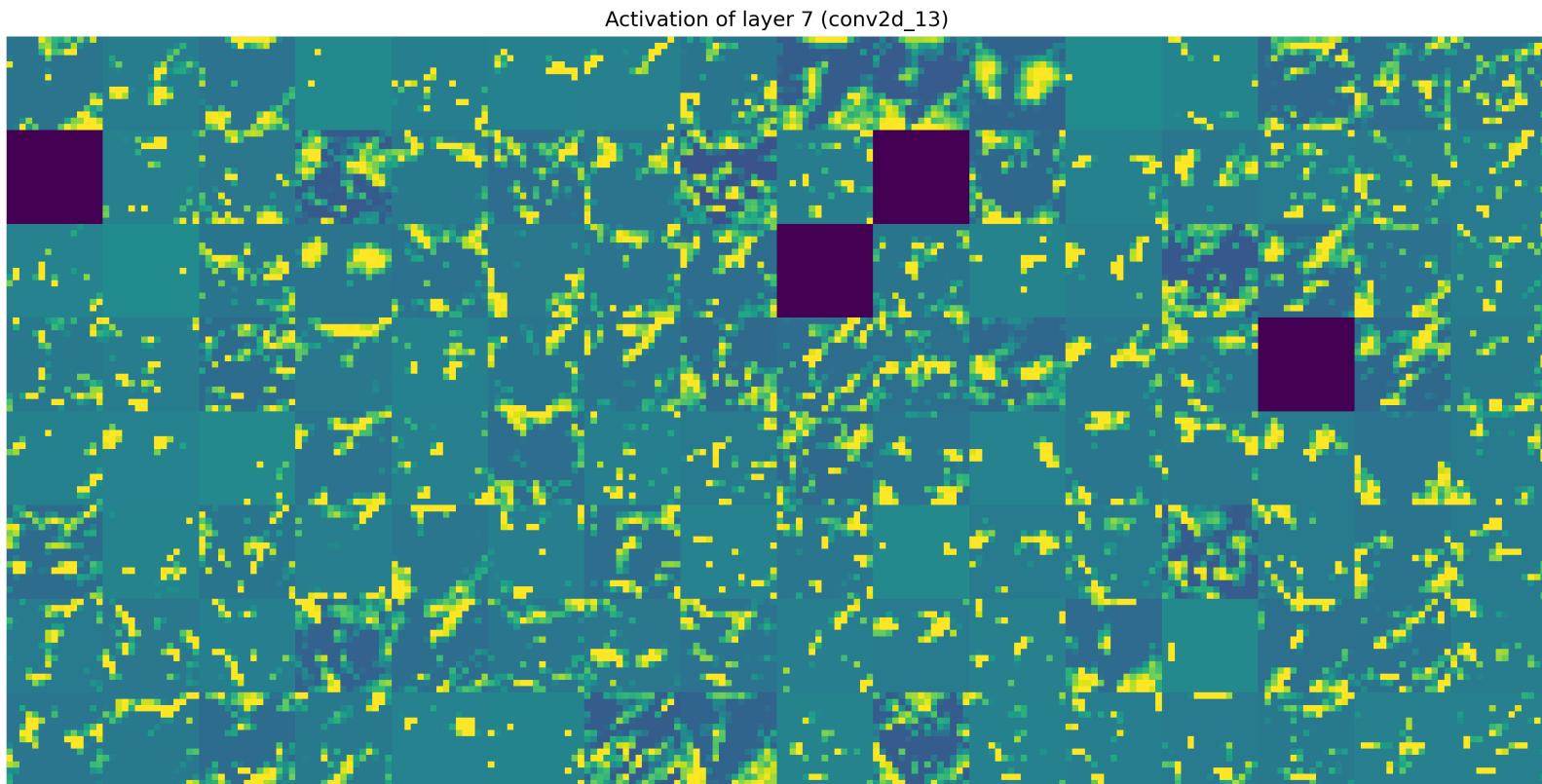


- 3rd convolutional layer: increasingly abstract: ears, eyes

Activation of layer 5 (conv2d_12)

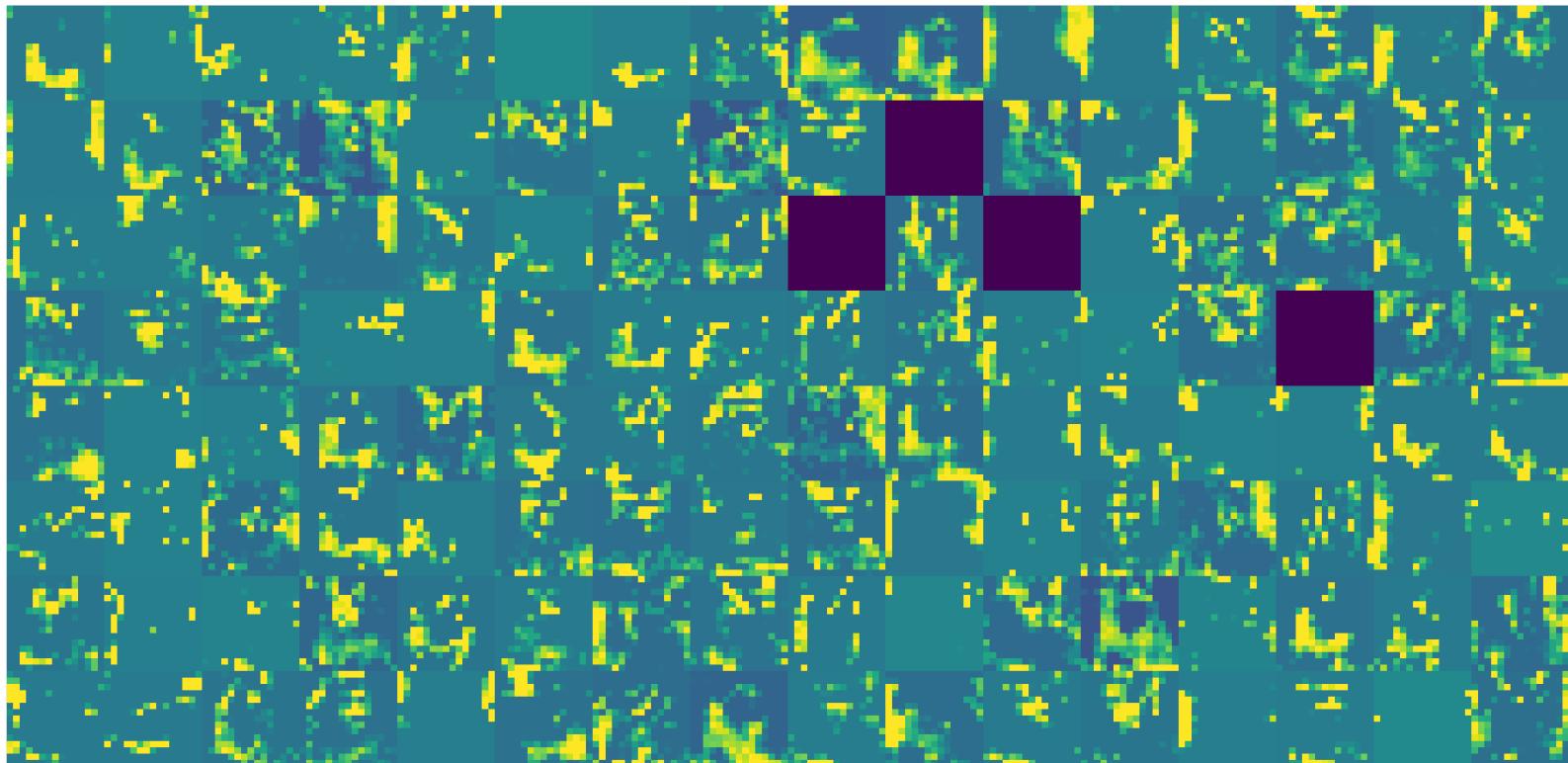


- Last convolutional layer: more abstract patterns
- Empty filter activations: input image does not have the information that the filter was interested in



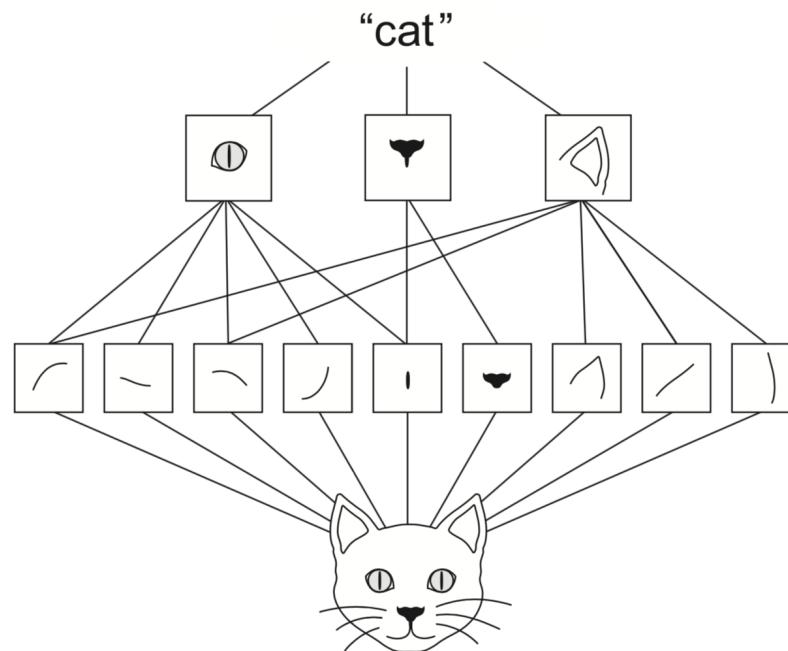
- Same layer, with dog image input
 - Very different activations

Activation of layer 7 (conv2d_13)



Spatial hierarchies

- Deep convnets can learn *spatial hierarchies* of patterns
 - First layer can learn very local patterns (e.g. edges)
 - Second layer can learn specific combinations of patterns
 - Every layer can learn increasingly complex *abstractions*



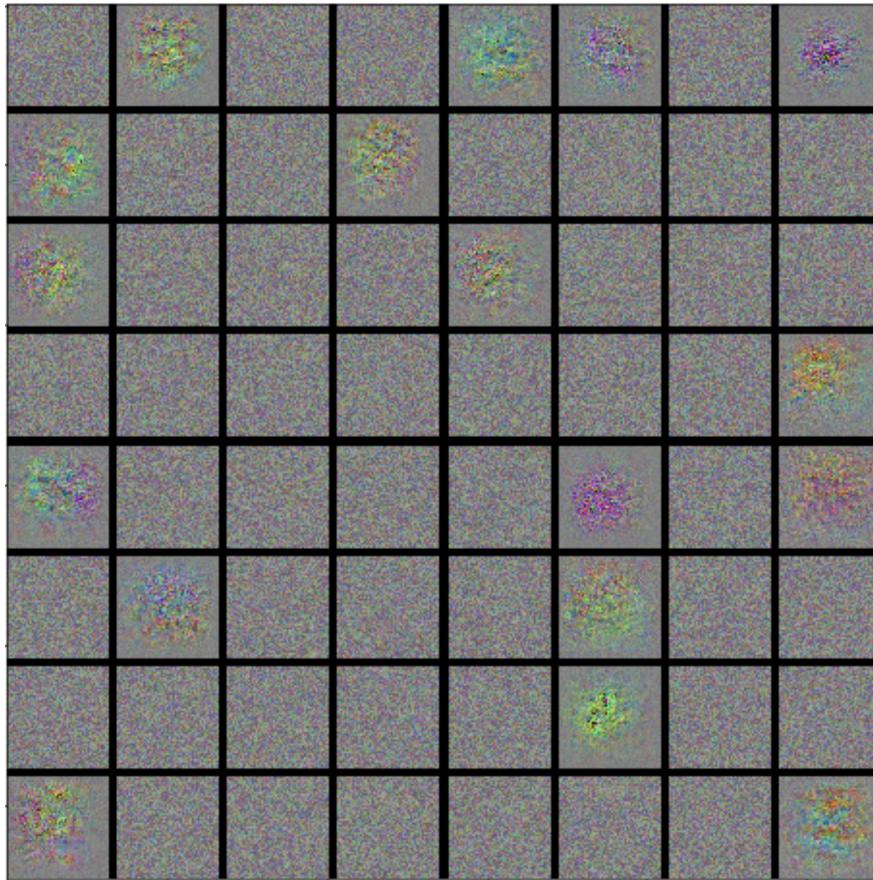
Visualizing the learned filters

- The filters themselves can be visualized by finding the input image that they are maximally responsive to
- *gradient ascent in input space* : start from a random image, use loss to update the pixel values to values that the filter responds to more strongly

```
from keras import backend as K
input_img = np.random.random((1, size, size, 3)) * 20 + 128.
loss = K.mean(layer_output[:, :, :, filter_index])
grads = K.gradients(loss, model.input)[0] # Compute gradient
for i in range(40): # Run gradient ascent for 40 steps
    loss_v, grads_v = K.function([input_img], [loss, grads])
    input_img_data += grads_v * step
```

- Learned filters of second convolutional layer
- Mostly general, some respond to specific shapes/colors

- Learned filters of last convolutional layer
- More focused on center, some vague cat/dog head shapes



Let's do this again for the `VGG16` network pretrained on `ImageNet` (much larger)

```
model = VGG16(weights='imagenet', include_top=False)
```

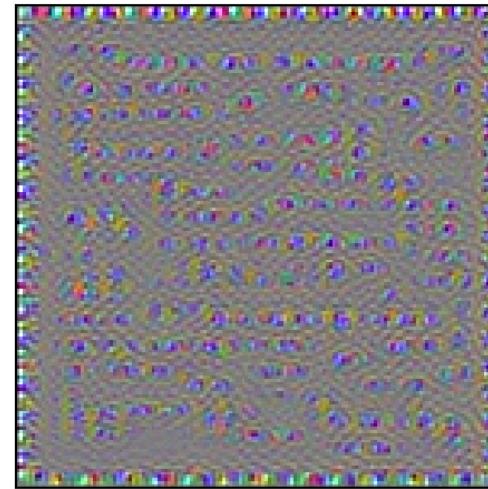
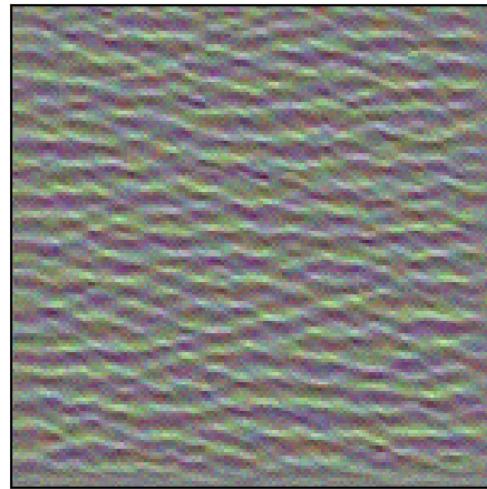
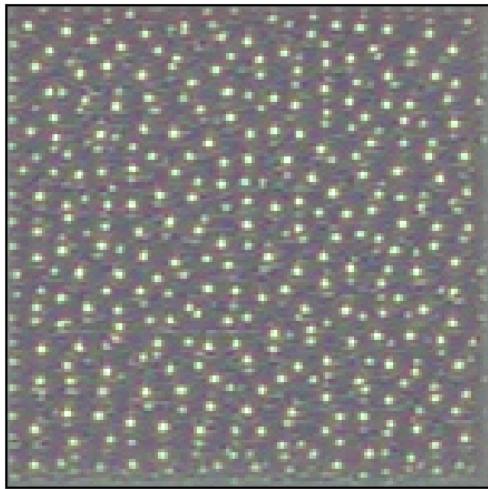
Model: "vgg16"

Layer (type)	Output Shape	Param #
<hr/>		
input_1 (InputLayer)	[(None, None, None, 3)]	0
block1_conv1 (Conv2D)	(None, None, None, 64)	1792
block1_conv2 (Conv2D)	(None, None, None, 64)	36928
block1_pool (MaxPooling2D)	(None, None, None, 64)	0
block2_conv1 (Conv2D)	(None, None, None, 128)	73856
block2_conv2 (Conv2D)	(None, None, None, 128)	147584
block2_pool (MaxPooling2D)	(None, None, None, 128)	0
block3_conv1 (Conv2D)	(None, None, None, 256)	295168
block3_conv2 (Conv2D)	(None, None, None, 256)	590080
block3_conv3 (Conv2D)	(None, None, None, 256)	590080
block3_pool (MaxPooling2D)	(None, None, None, 256)	0
block4_conv1 (Conv2D)	(None, None, None, 512)	1180160
block4_conv2 (Conv2D)	(None, None, None, 512)	2359808
block4_conv3 (Conv2D)	(None, None, None, 512)	2359808
block4_pool (MaxPooling2D)	(None, None, None, 512)	0
block5_conv1 (Conv2D)	(None, None, None, 512)	2359808
block5_conv2 (Conv2D)	(None, None, None, 512)	2359808
block5_conv3 (Conv2D)	(None, None, None, 512)	2359808

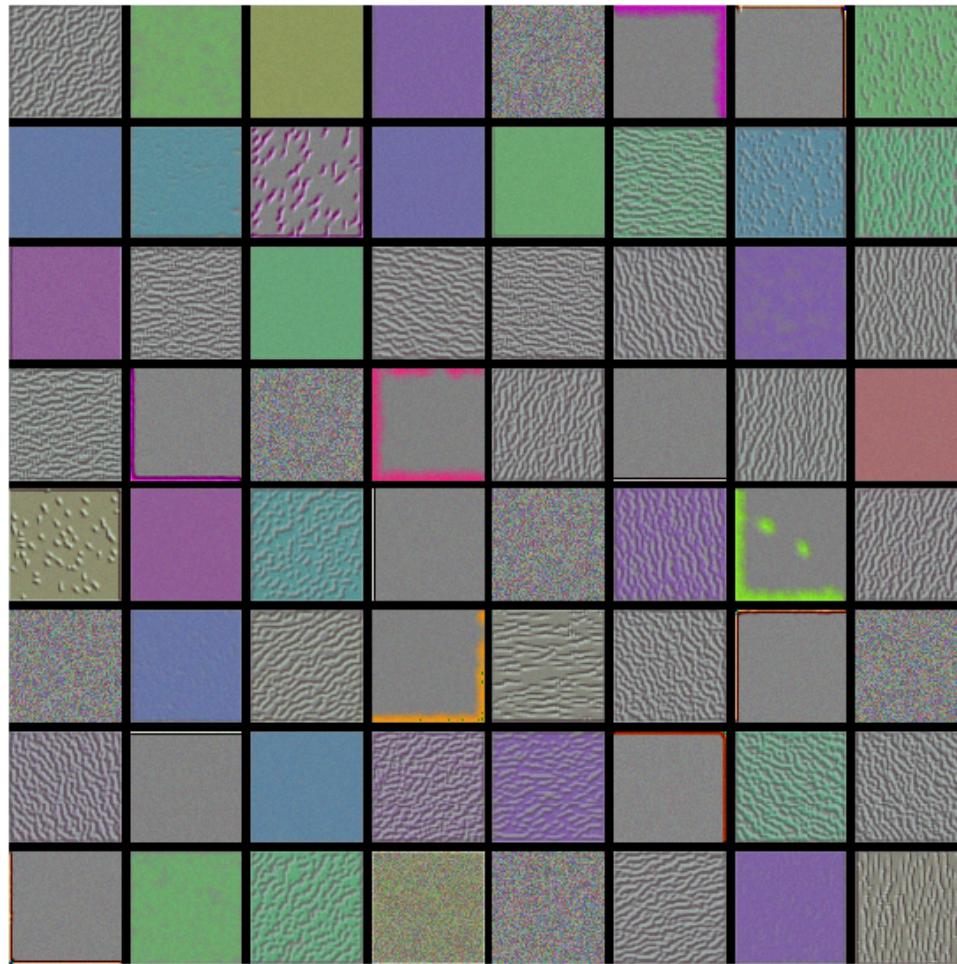
```
block5_pool (MaxPooling2D)  (None, None, None, 512)    0
```

```
=====
Total params: 14,714,688
Trainable params: 14,714,688
Non-trainable params: 0
```

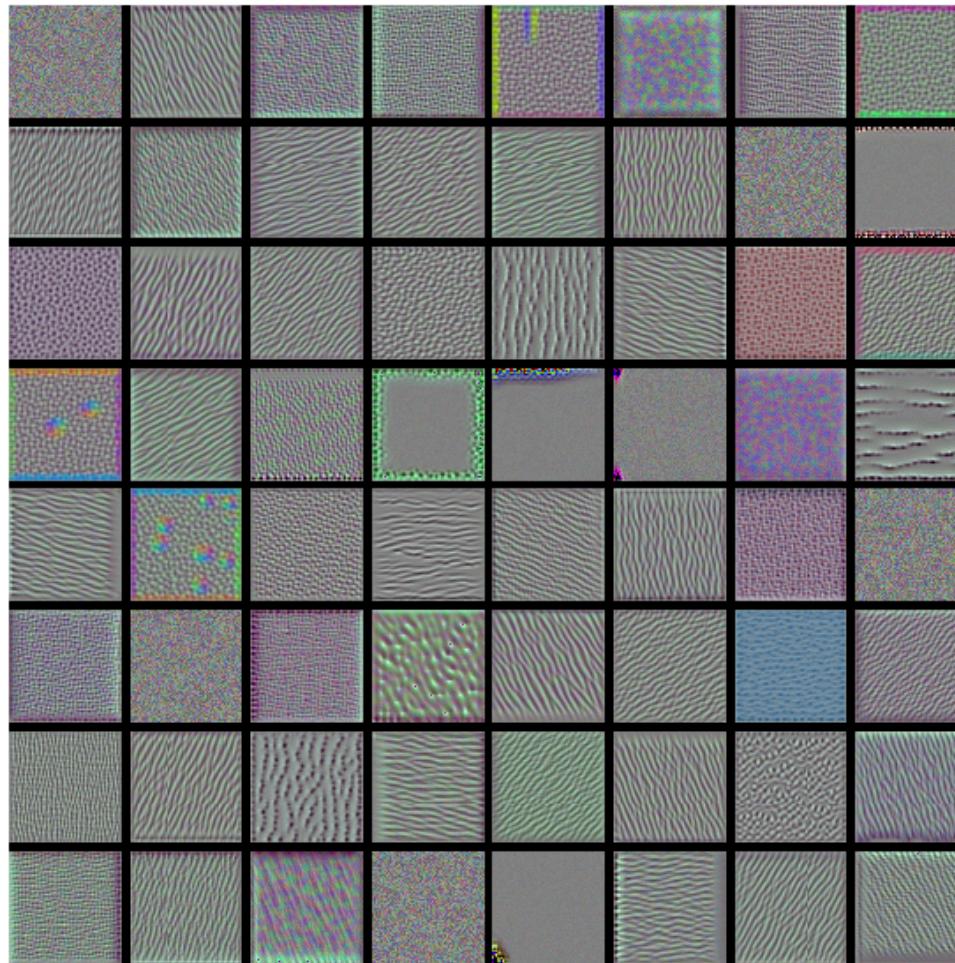
- Visualize convolution filters 0-2 from layer 5 of the VGG network trained on ImageNet
- Some respond to dots or waves in the image



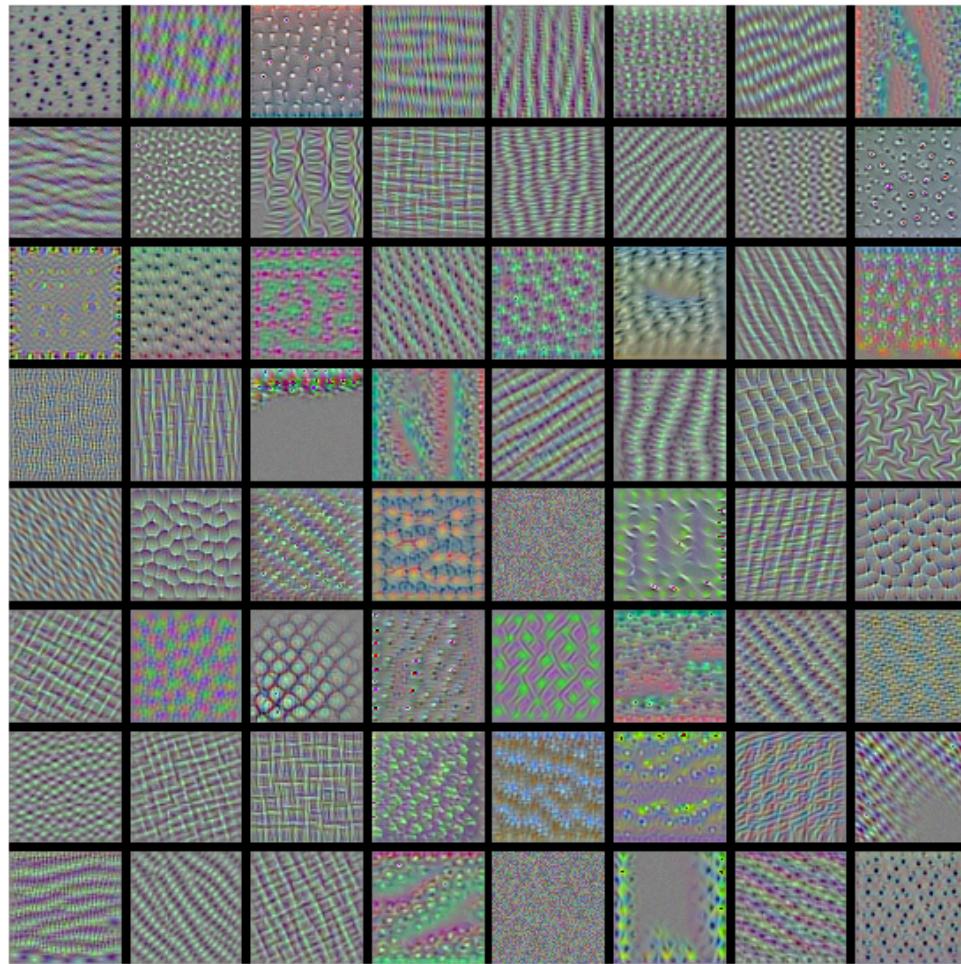
First 64 filters for 1st convolutional layer in block 1: simple edges and colors



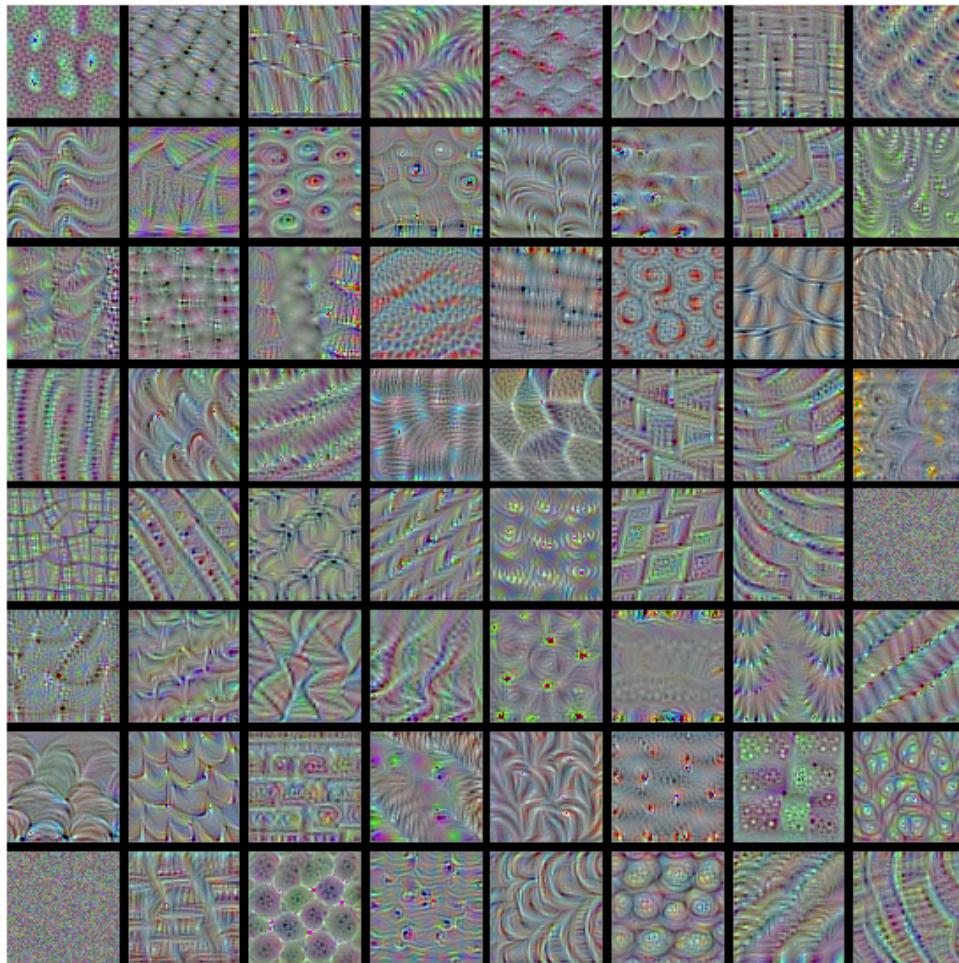
Filters in 2nd block of convolution layers: simple textures (combined edges and colors)



Filters in 3rd block of convolution layers: more natural textures



Filters in 4th block of convolution layers: feathers, eyes, leaves,...



Visualizing class activation

- We can also visualize which part of the input image had the greatest influence on the final classification
 - Helpful for interpreting what the model is paying attention to
- *Class activation maps* : produce heatmap over the input image
 - Take the output feature map of a convolution layer (e.g. the last one)
 - Weigh every filter by the gradient of the class with respect to the filter

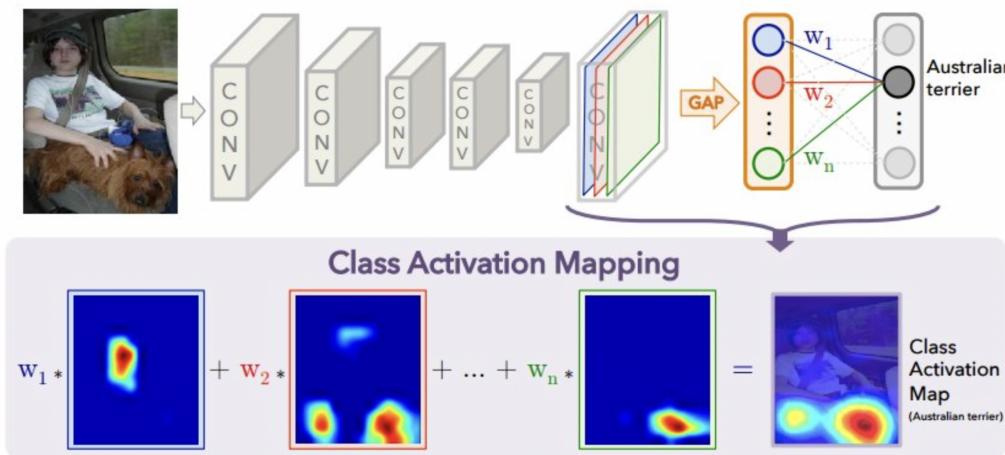
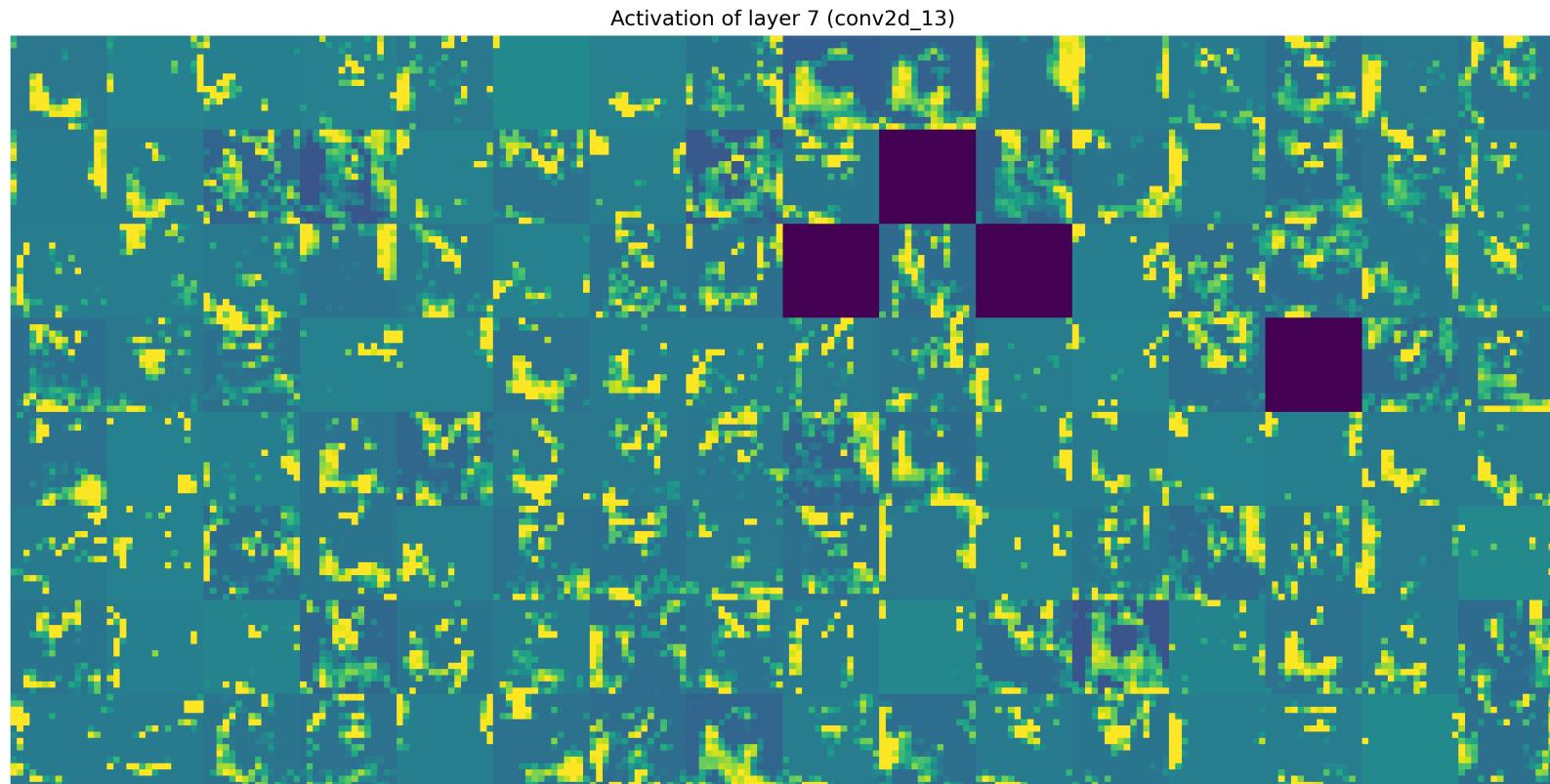


Illustration (cats vs dogs)

- These were the output feature maps of the last convolutional layer
 - These are flattened and fed to the dense layer
- Compute gradient of the 'cat' node output wrt. every filter output (pixel) here
 - Average the gradients per filter, use that as the filter weight
- Take the weighted sum of all filter maps to get the class activation map



More realistic example:

- Try VGG (including the dense layers) and an image from ImageNet

```
model = VGG16(weights='imagenet')
```



Preprocessing

- Load image
 - Resize to 224 x 224 (what VGG was trained on)
 - Do the same preprocessing (Keras VGG utility)

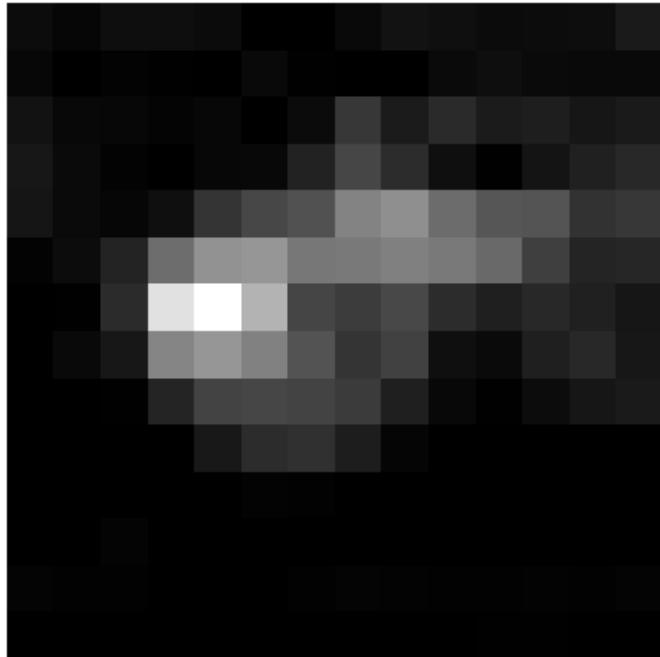
```
from keras.applications.vgg16 import preprocess_input
img_path = '../images/10_elephants.jpg'
img = image.load_img(img_path, target_size=(224, 224))
x = image.img_to_array(img)
x = np.expand_dims(x, axis=0) # Transform to batch of size (1, 224,
224, 3)
x = preprocess_input(x)
```

- Sanity test: do we get the right prediction?

```
preds = model.predict(x)
```

```
Predicted: [('n02504458', 'African_elephant', 0.90988594), ('n01871265', 'tusker', 0.085724816), ('n02504013', 'Indian_elephant', 0.0043471307)]
```

Visualize the class activation map



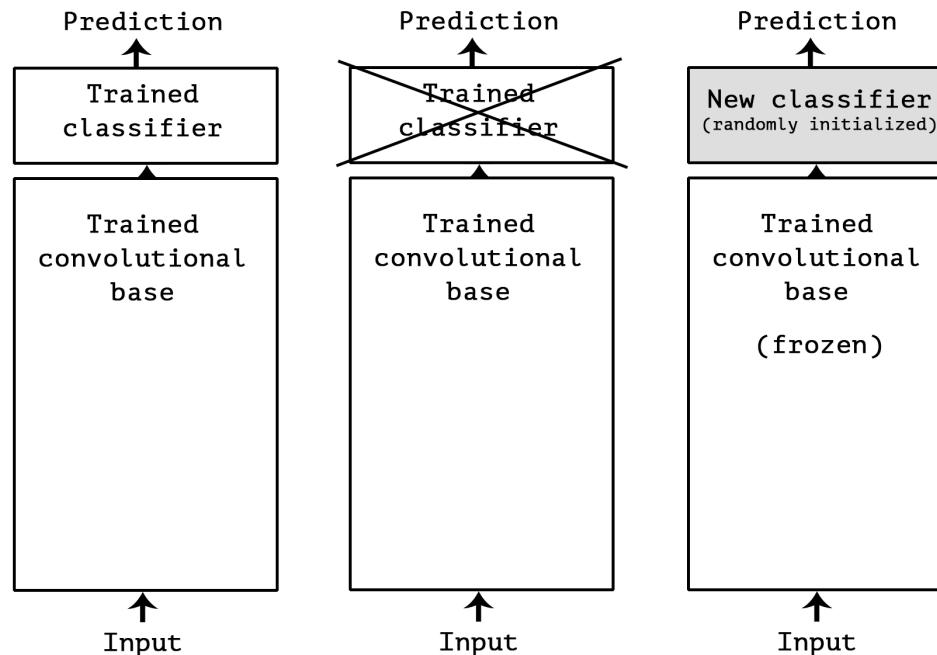
Superimposed on the original image

Class activation map



Using pretrained networks

- We can re-use pretrained networks instead of training from scratch
- Learned features can be a generic model of the visual world
- Use *convolutional base* to construct features, then train any classifier on new data
- Also called *transfer learning*, which is a kind of *meta-learning*



- Let's instantiate the VGG16 model (without the dense layers)
- Final feature map has shape (4, 4, 512)

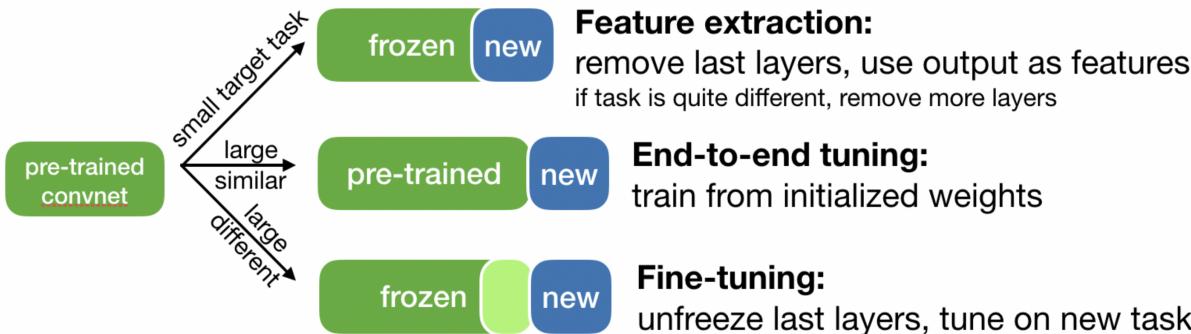
```
conv_base = VGG16(weights='imagenet', include_top=False,
                   input_shape=(150, 150, 3))
```

Layer (type)	Output Shape	Param #
<hr/>		
input_2 (InputLayer)	[None, 150, 150, 3]	0
block1_conv1 (Conv2D)	(None, 150, 150, 64)	1792
block1_conv2 (Conv2D)	(None, 150, 150, 64)	36928
block1_pool (MaxPooling2D)	(None, 75, 75, 64)	0
block2_conv1 (Conv2D)	(None, 75, 75, 128)	73856
block2_conv2 (Conv2D)	(None, 75, 75, 128)	147584
block2_pool (MaxPooling2D)	(None, 37, 37, 128)	0
block3_conv1 (Conv2D)	(None, 37, 37, 256)	295168
block3_conv2 (Conv2D)	(None, 37, 37, 256)	590080
block3_conv3 (Conv2D)	(None, 37, 37, 256)	590080
block3_pool (MaxPooling2D)	(None, 18, 18, 256)	0
block4_conv1 (Conv2D)	(None, 18, 18, 512)	1180160
block4_conv2 (Conv2D)	(None, 18, 18, 512)	2359808
block4_conv3 (Conv2D)	(None, 18, 18, 512)	2359808
block4_pool (MaxPooling2D)	(None, 9, 9, 512)	0
block5_conv1 (Conv2D)	(None, 9, 9, 512)	2359808

```
block5_conv2 (Conv2D)      (None, 9, 9, 512)      2359808
block5_conv3 (Conv2D)      (None, 9, 9, 512)      2359808
block5_pool (MaxPooling2D) (None, 4, 4, 512)       0
=====
Total params: 14,714,688
Trainable params: 14,714,688
Non-trainable params: 0
```

Using pre-trained networks: 3 ways

- Fast feature extraction (similar task, little data)
 - Call `predict` from the convolutional base to build new features
 - Use outputs as input to a new neural net (or other algorithm)
- End-to-end tuning (similar task, lots of data + data augmentation)
 - Extend the convolutional base model with a new dense layer
 - Train it end to end on the new data (expensive!)
- Fine-tuning (somewhat different task)
 - Unfreeze a few of the top convolutional layers, and retrain
 - Update only the more abstract representations



Fast feature extraction (without data augmentation)

- Run every batch through the pre-trained convolutional base

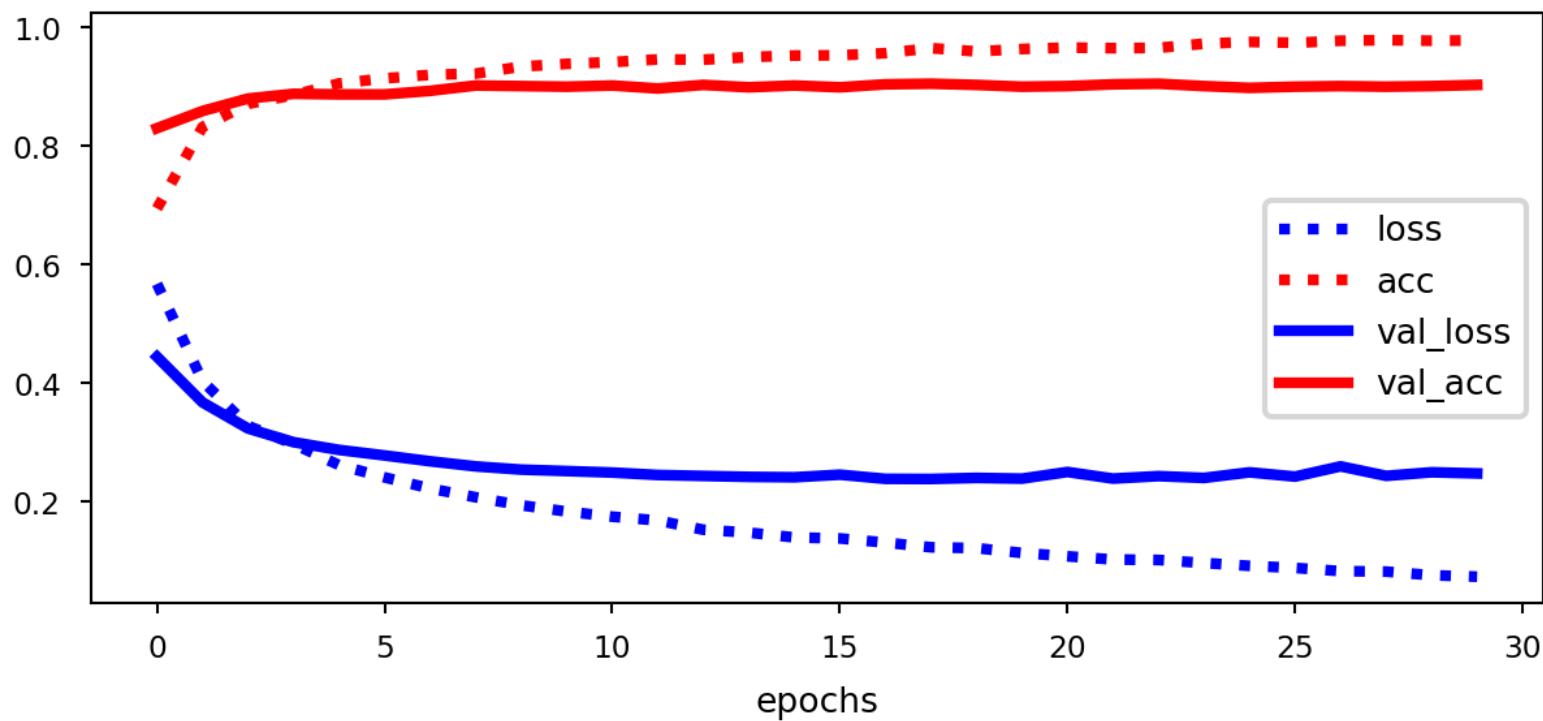
```
generator = datagen.flow_from_directory(dir, target_size=(150, 150),
                                         batch_size=batch_size, class_mode='binary')
for inputs_batch, labels_batch in generator:
    features_batch = conv_base.predict(inputs_batch)
```

- Build Dense neural net (with Dropout)
- Train and evaluate with the transformed examples

```
model = models.Sequential()
model.add(layers.Dense(256, activation='relu', input_dim=4 * 4 *
512))
model.add(layers.Dropout(0.5))
model.add(layers.Dense(1, activation='sigmoid'))
```

- Validation accuracy around 90%, much better!
- Still overfitting, despite the Dropout: not enough training data

```
Max val_acc 0.90500003
```



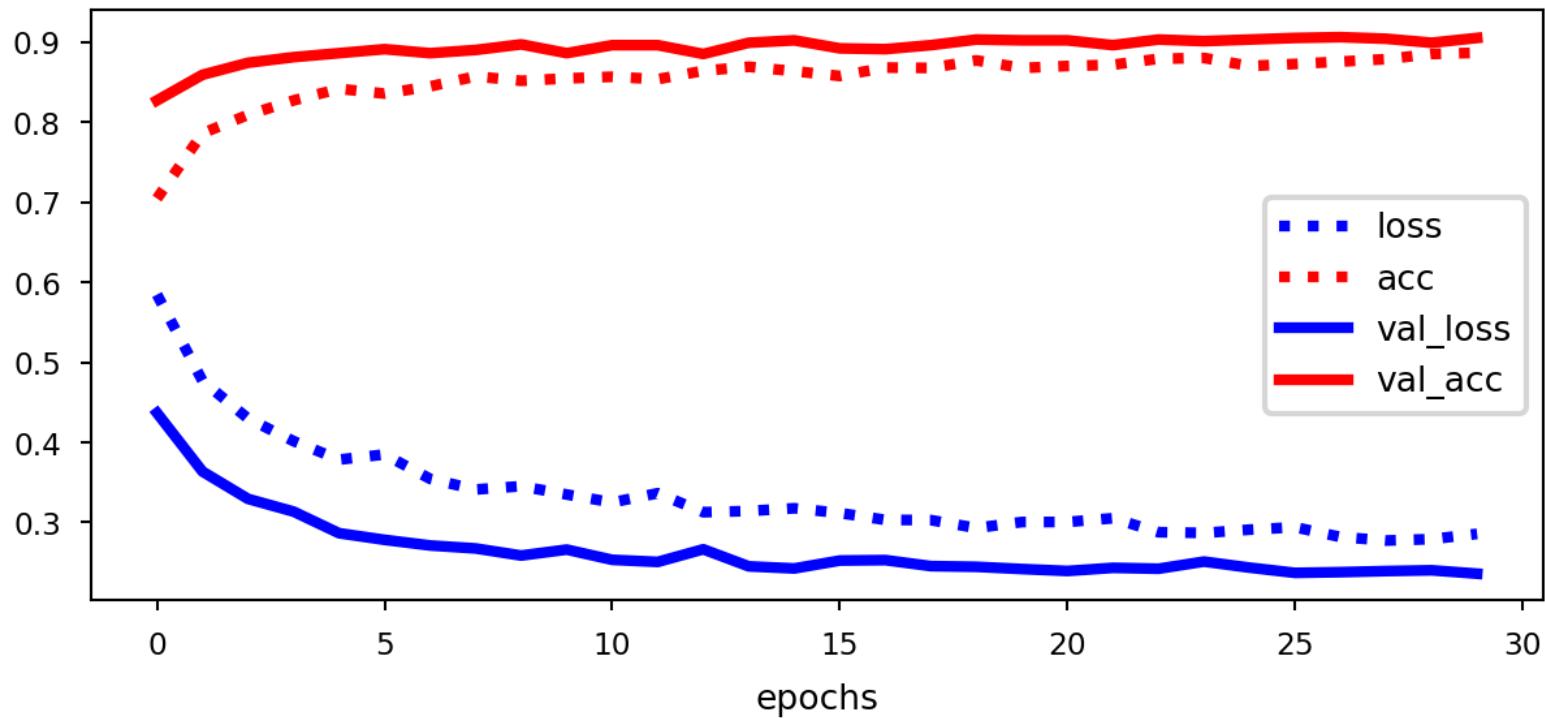
Fast feature extraction (with data augmentation)

- Simply add the Dense layers to the convolutional base
- *Freeze* the convolutional base (before you compile)
 - Without freezing, you train it end-to-end (expensive)

```
model = models.Sequential()
model.add(conv_base)
model.add(layers.Flatten())
model.add(layers.Dense(256, activation='relu'))
model.add(layers.Dense(1, activation='sigmoid'))
conv_base.trainable = False
```

We now get about 90% accuracy again, and very little overfitting

Max val_acc 0.906

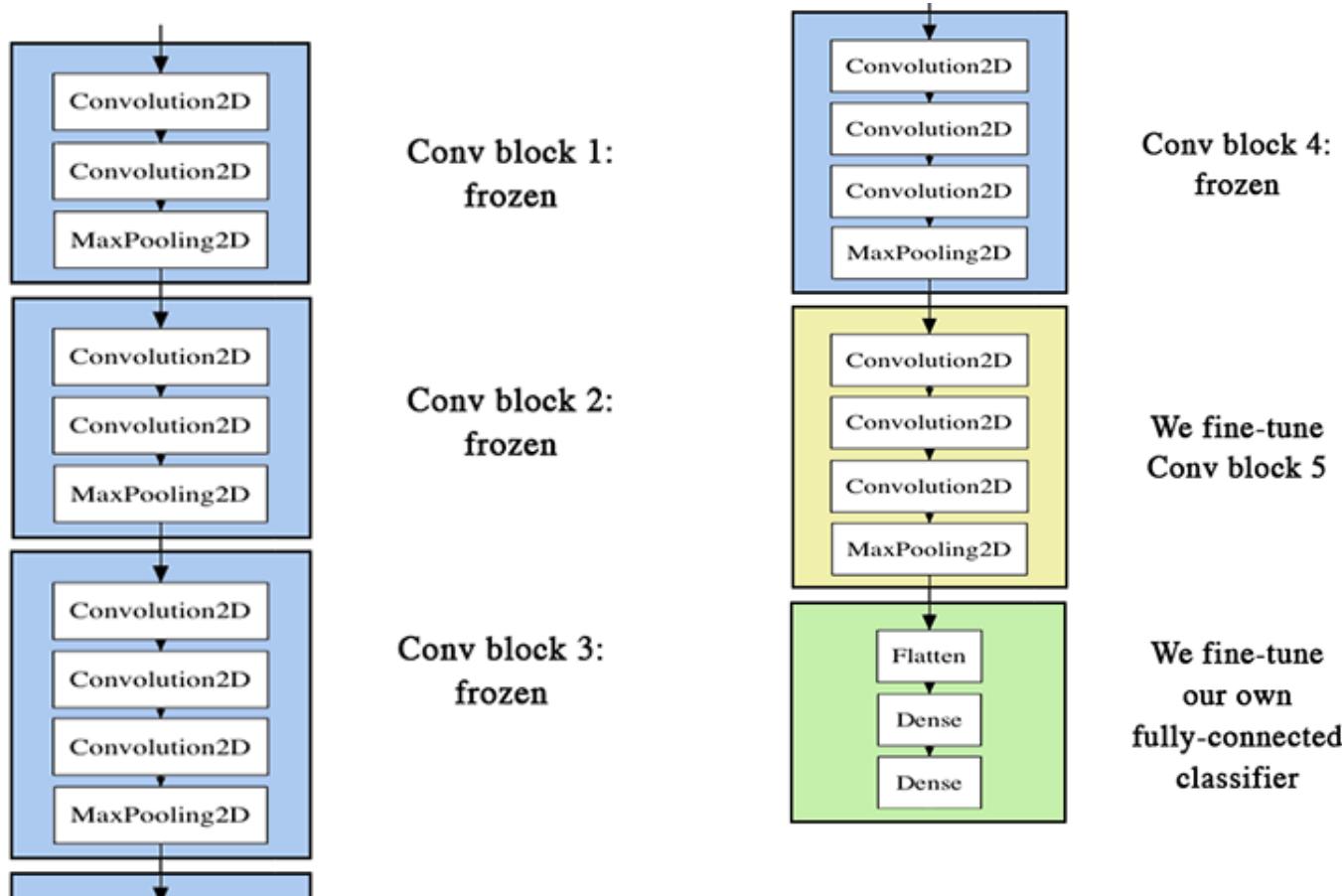


Fine-tuning

- Add your custom network on top of an already trained base network.
- Freeze the base network, but unfreeze the last block of conv layers.

```
for layer in conv_base.layers:  
    if layer.name == 'block5_conv1':  
        layer.trainable = True  
    else:  
        layer.trainable = False
```

Visualized

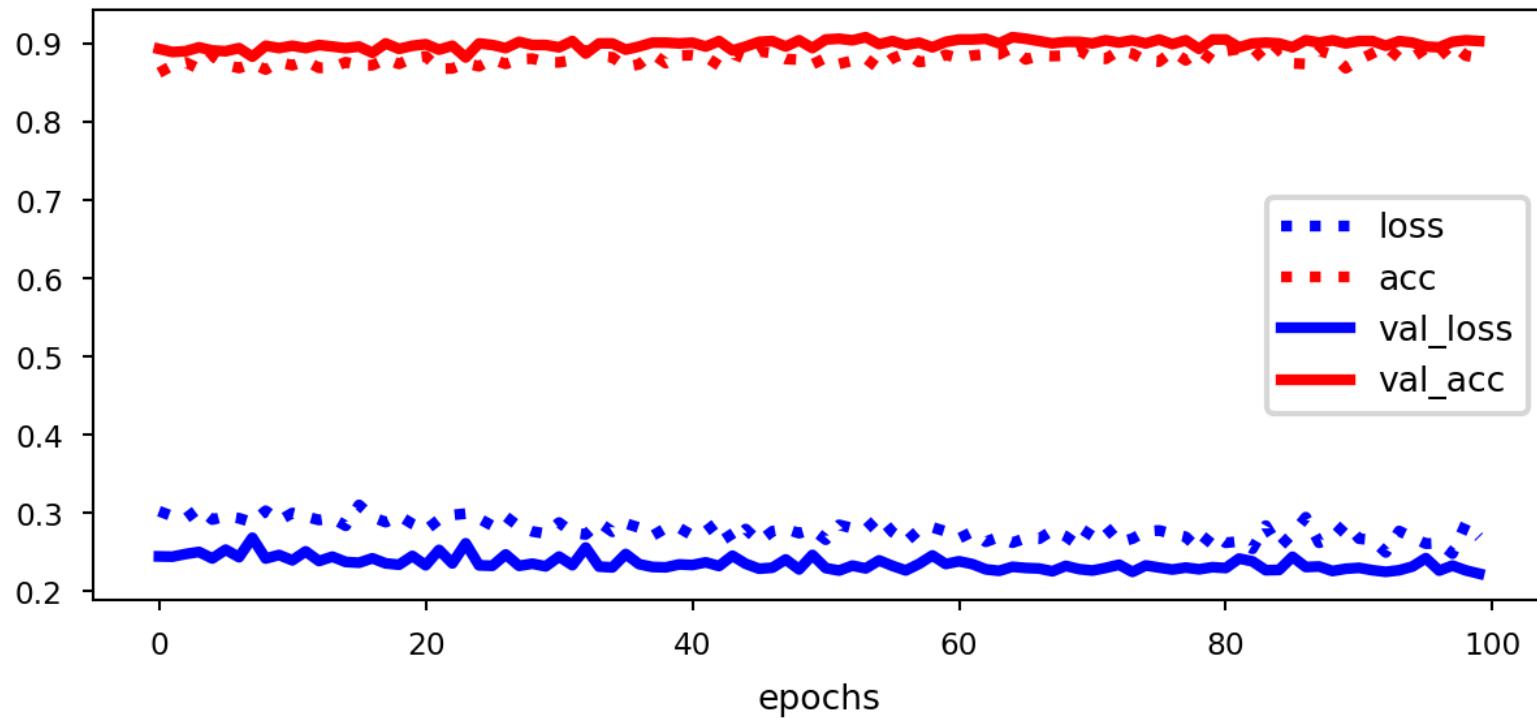


- Load trained network, finetune
 - Use a small learning rate, large number of epochs
 - You don't want to unlearn too much: *catastrophic forgetting*

```
model = load_model(os.path.join(model_dir,
 'cats_and_dogs_small_3b.h5'))
model.compile(loss='binary_crossentropy',
               optimizer=optimizers.RMSprop(lr=1e-5),
               metrics=['acc'])
history = model.fit(
    train_generator, steps_per_epoch=100, epochs=100,
    validation_data=validation_generator,
    validation_steps=50)
```

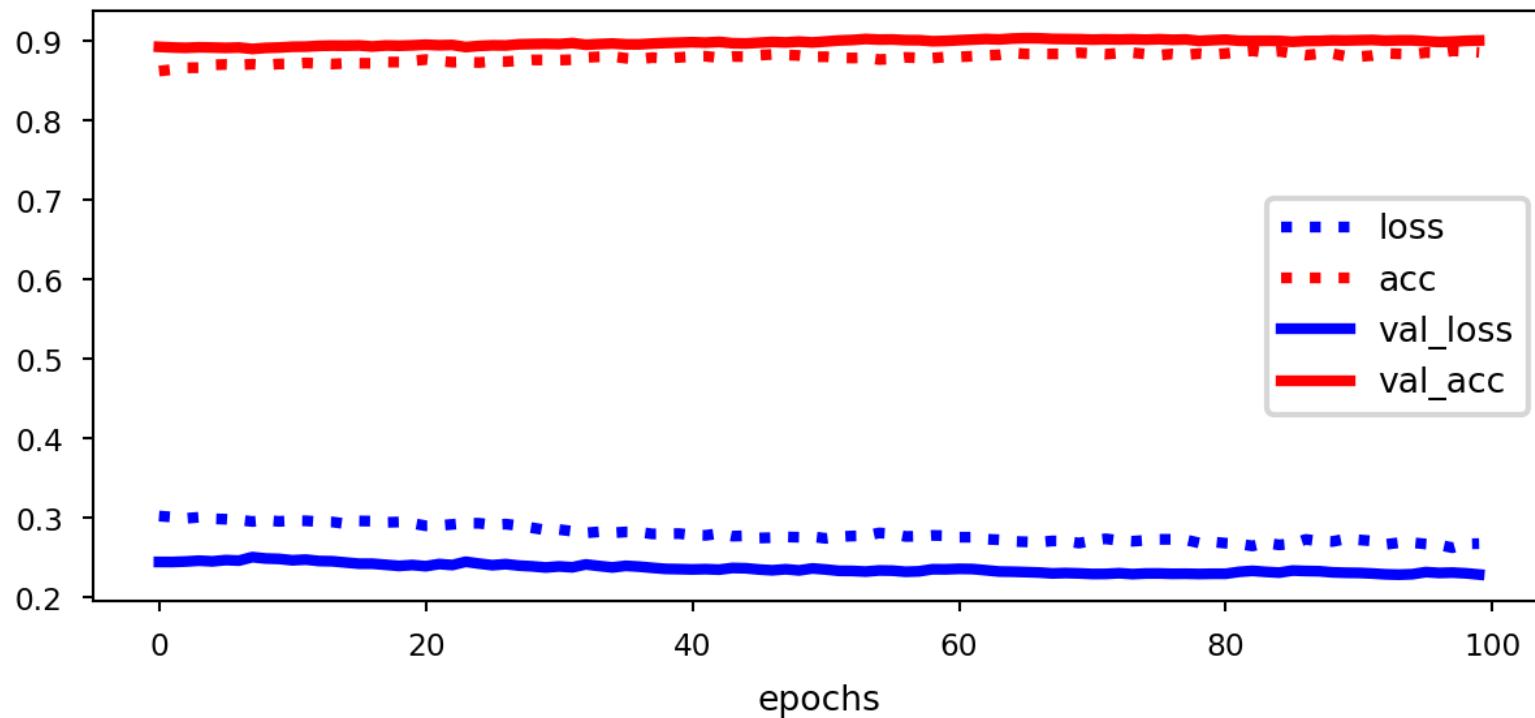
Almost 95% accuracy. The curves are quite noisy, though.

Max val_acc 0.90800005



- We can smooth the learning curves using a running average

```
Max val_acc 0.9039536851123335
```



Take-aways

- Convnets are ideal for attacking visual-classification problems.
- They learn a hierarchy of modular patterns and concepts to represent the visual world.
- Representations are easy to inspect
- Data augmentation helps fight overfitting
- You can use a pretrained convnet to build better models via transfer learning