

Capsule Network

Room 713 CT Hsieh

Reference

- Paper
 - [Transforming Auto-encoders](#)
 - [Dynamic Routing Between Capsules](#)
 - [Matrix Capsules with EM Routing](#)
- Video
 - [Geoffrey Hinton “Does the Brain do Inverse Graphics”](#)
 - [Geoffrey Hinton talk What is wrong with CNN](#)
 - [Capsule Networks Tutorial](#)
 - [How to implement CapsNets using TensorFlow](#)
 - [Capsule Networks: An Improvement to Convolutional Networks](#)
 - [<https://www.youtube.com/watch?v=wC0rhjvst8I>](#)
 - [<https://www.youtube.com/watch?v=akq6PNnkKY8>](#)

Reference

- Slide and Article
 - <https://www.slideshare.net/aureliengeron/introduction-to-capsule-networks-capsnets>
 - <https://www.slideshare.net/charlesmartin141/capsule-networks-84754653>
 - <https://www.slideshare.net/ssuser73ec8f/20171113-capsnet>
 - <https://medium.com/ai³-theory-practice-business/understanding-hintons-capsule-networks-part-i-intuition-b4b559d1159b>
 - http://helper.ipam.ucla.edu/publications/gss2012/gss2012_10754.pdf
 - <https://hep-ai.org/slides/2017-12-12.pdf>

Reference

- Github
 - <https://github.com/XifengGuo/CapsNet-Keras>
 - <https://github.com/bourdakos1/capsule-networks>
 - <https://github.com/JunYeopLee/capsule-networks>
 - https://github.com/lISourcell/capsule_networks
 - <https://github.com/naturomics/CapsNet-Tensorflow>
 - <https://github.com/Sarasra/models/tree/master/research/capsules>
 - https://github.com/jhui/machine_learning/tree/master/capsule_em
 - <https://github.com/www0wwwjs1/Matrix-Capsules-EM-Tensorflow>
 - <https://github.com/gyang274/capsulesEM>

AI Need to Start Over

- Geoffrey Hinton Says AI Needs To Start Over



In an interview with Axios Hinton is credited with saying that he is

"deeply suspicious" of back-propagation"

and

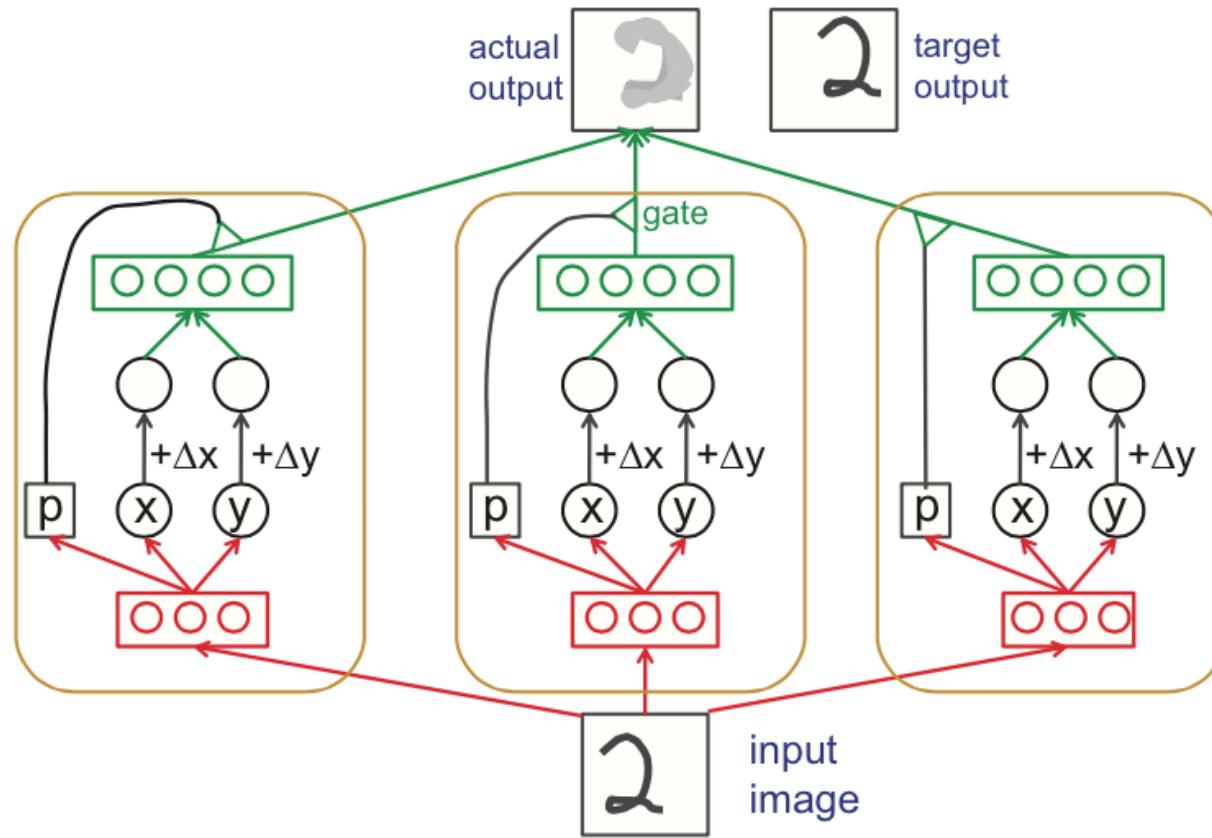
"My view is throw it all away and start again,"

The worry is that neural networks don't seem to learn like we do:

"I don't think it's how the brain works. We clearly don't need all the labeled data."

Transforming Auto-encoders

- Propose again in 2011 but not impressed



Outline

- Related Work
 - Geometric Transformation
- What's Wrong With CNN
 - Talking from Hinton
- Capsule Network
 - Idea and Implementation
 - MNIST
- Discuss
 - Problem

Geometric Transformation

- Non-Homogeneous VS Homogeneous
 - $[x, y, z, w]$ vs $[x, y, z, 1]$

X-Rotation in 3D

$$\begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos\phi & -\sin\phi & 0 \\ 0 & \sin\phi & \cos\phi & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

Z-Rotation in 3D

$$\begin{bmatrix} \cos\phi & -\sin\phi & 0 & 0 \\ \sin\phi & \cos\phi & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

Scale in 3D

$$\begin{bmatrix} S_x & 0 & 0 & 0 \\ 0 & S_y & 0 & 0 \\ 0 & 0 & S_z & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$(4 \times 4) * (4 \times 1) = (4 \times 1)$$

Y-Rotation in 3D

$$\begin{bmatrix} \cos\phi & 0 & \sin\phi & 0 \\ 0 & 1 & 0 & 0 \\ -\sin\phi & 0 & \cos\phi & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

Translation in 3D

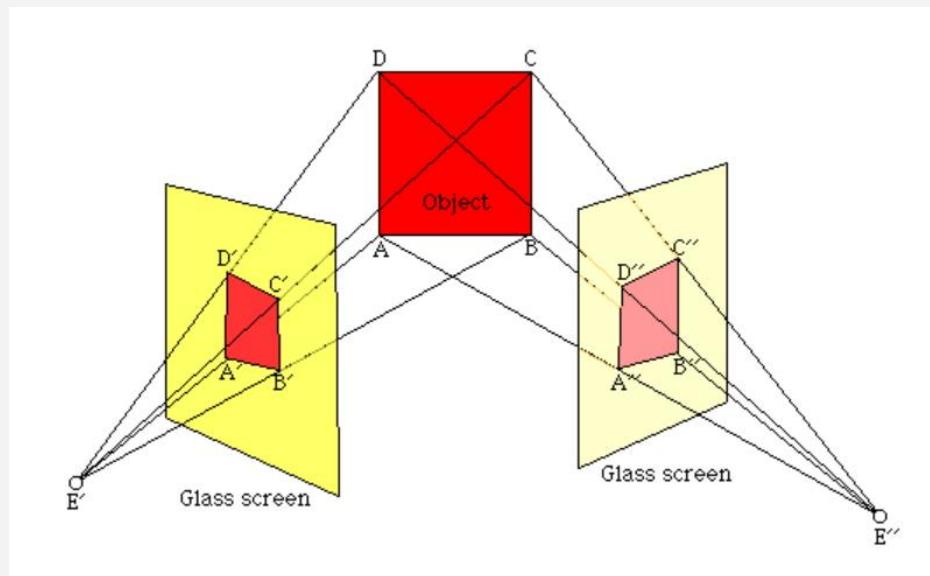
$$\begin{bmatrix} 1 & 0 & 0 & T_x \\ 0 & 1 & 0 & T_y \\ 0 & 0 & 1 & T_z \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

Matrix Multiplication

$$\begin{bmatrix} a & b & c & d \\ e & f & g & h \\ i & j & k & l \\ m & n & o & p \end{bmatrix} \begin{bmatrix} x \\ y \\ z \\ 1 \end{bmatrix} = \begin{bmatrix} x' \\ y' \\ z' \\ q \end{bmatrix}$$

Geometric Transformation

- Perspective Geometric



Transformation	Before	After
Projective		
Affine		
Similarity		
Euclidean		

Geometric Transformation

Group	Matrix	Distortion	Invariant properties	
Projective 8 dof	$\begin{bmatrix} h_{11} & h_{12} & h_{13} \\ h_{21} & h_{22} & h_{23} \\ h_{31} & h_{32} & h_{33} \end{bmatrix}$		Concurrency, collinearity, order of contact : intersection (1 pt contact); tangency (2 pt contact); inflections (3 pt contact with line); tangent discontinuities and cusps. cross ratio (ratio of ratio of lengths).	
Affine 6 dof	$\begin{bmatrix} a_{11} & a_{12} & t_x \\ a_{21} & a_{22} & t_y \\ 0 & 0 & 1 \end{bmatrix}$		Parallelism, ratio of areas, ratio of lengths on collinear or parallel lines (e.g. midpoints), linear combinations of vectors (e.g. centroids). The line at infinity, l_∞ .	
Similarity 4 dof	$\begin{bmatrix} sr_{11} & sr_{12} & t_x \\ sr_{21} & sr_{22} & t_y \\ 0 & 0 & 1 \end{bmatrix}$		Ratio of lengths, angle. The circular points, I, J (see section 2.7.3).	
Euclidean 3 dof	$\begin{bmatrix} r_{11} & r_{12} & t_x \\ r_{21} & r_{22} & t_y \\ 0 & 0 & 1 \end{bmatrix}$		Length, area	$\begin{bmatrix} x' \\ y' \end{bmatrix} = \begin{bmatrix} \cos \theta & \sin \theta \\ -\sin \theta & \cos \theta \end{bmatrix} \begin{bmatrix} x \\ y \end{bmatrix} + \begin{bmatrix} t_x \\ t_y \end{bmatrix}$

Expectation-Maximization EM Algorithm

Input:

$\Theta = \{\theta_1, \dots, \theta_p\}$ //Parameters to be Estimated
 $X_{obs} = \{x_1, \dots, x_k\}$ //Input Database Values Observed
 $X_{miss} = \{x_{k+1}, \dots, x_n\}$ //Input Database Values Missing

Output:

$\hat{\Theta}$ //Estimates for Θ

EM Algorithm:

i := 0;

Obtain initial parameter MLE estimate, $\hat{\Theta}^i$;

repeat

 Estimate missing data, \hat{X}_{miss}^i ;

 i++;

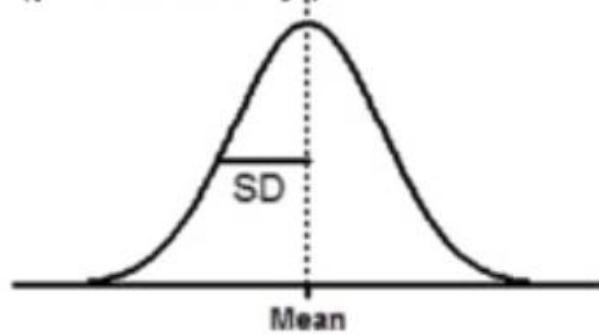
 Obtain next parameter estimate, $\hat{\theta}^i$ to maximize data;

until estimate converges;

Gaussian Mixture Model

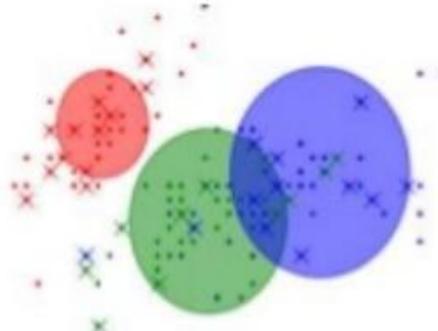
- Gaussian

“Gaussian is a characteristic symmetric "bell curve" shape that quickly falls off towards 0 (practically)”



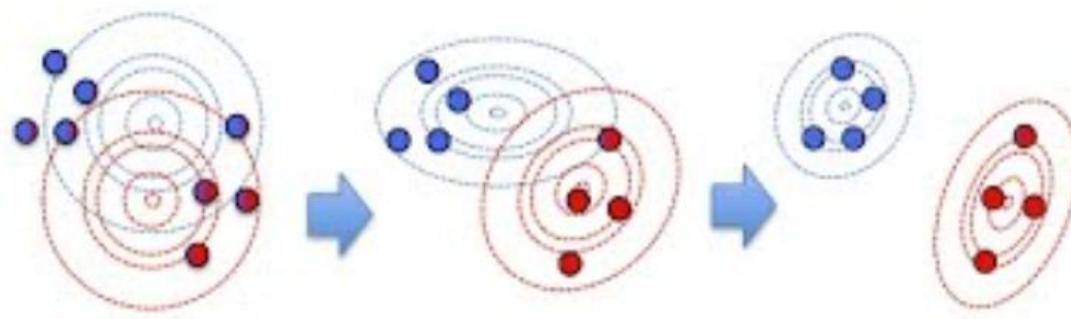
- Mixture Model

“mixture model is a probabilistic model which assumes the underlying data to belong to a mixture distribution”

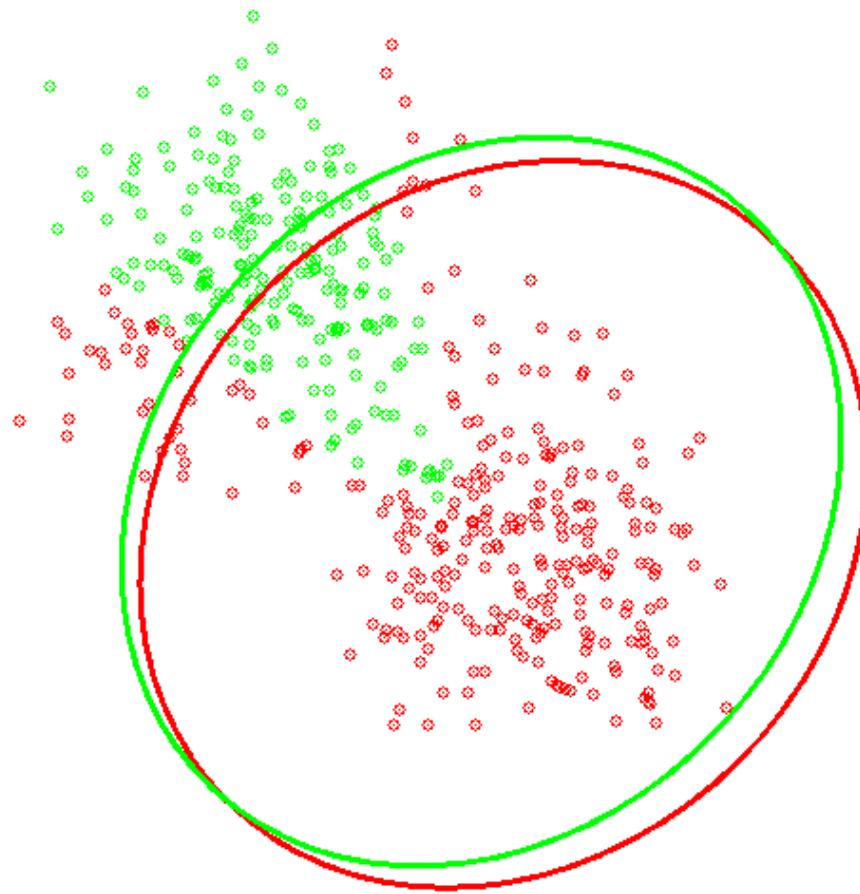


Gaussian Mixture Model

- Data with D attributes, from Gaussian sources $c_1 \dots c_k$
 - how typical is \vec{x}_i under source c
$$P(\vec{x}_i | c) = \frac{1}{\sqrt{2\pi|\Sigma_c|}} \exp\left\{-\frac{1}{2} \underbrace{(\vec{x}_i - \vec{\mu}_c)^T \Sigma_c^{-1} (\vec{x}_i - \vec{\mu}_c)}_{\sum_a \sum_b (x_{ia} - \mu_{ca}) [\Sigma_c^{-1}]_{ab} (x_{ib} - \mu_{cb})}\right\}$$
 - how likely that \vec{x}_i came from c
$$P(c | \vec{x}_i) = \frac{P(\vec{x}_i | c) P(c)}{\sum_{c=1}^k P(\vec{x}_i | c) P(c)}$$
 - how important is \vec{x}_i for source c : $w_{ic} = P(c | \vec{x}_i) / (P(c | \vec{x}_1) + \dots + P(c | \vec{x}_n))$
 - mean of attribute a in items assigned to c : $\mu_{ca} = w_{c1} x_{1a} + \dots + w_{cn} x_{na}$
 - covariance of a and b in items from c : $\Sigma_{cab} = \sum_{i=1}^n w_{ci} (x_{ia} - \mu_{ca})(x_{ib} - \mu_{cb})$
 - prior: how many items assigned to c : $P(c) = \frac{1}{n} (P(c | \vec{x}_1) + \dots + P(c | \vec{x}_n))$

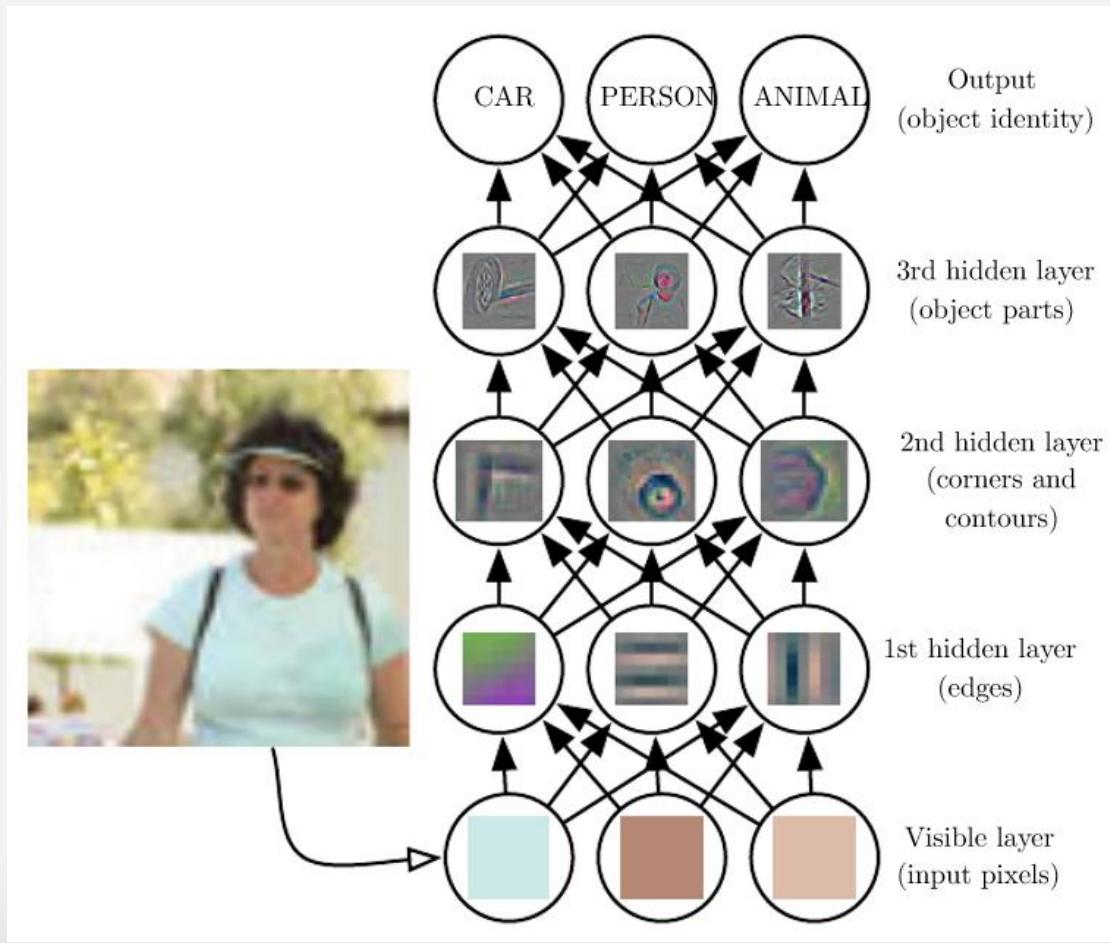


EM for GMM



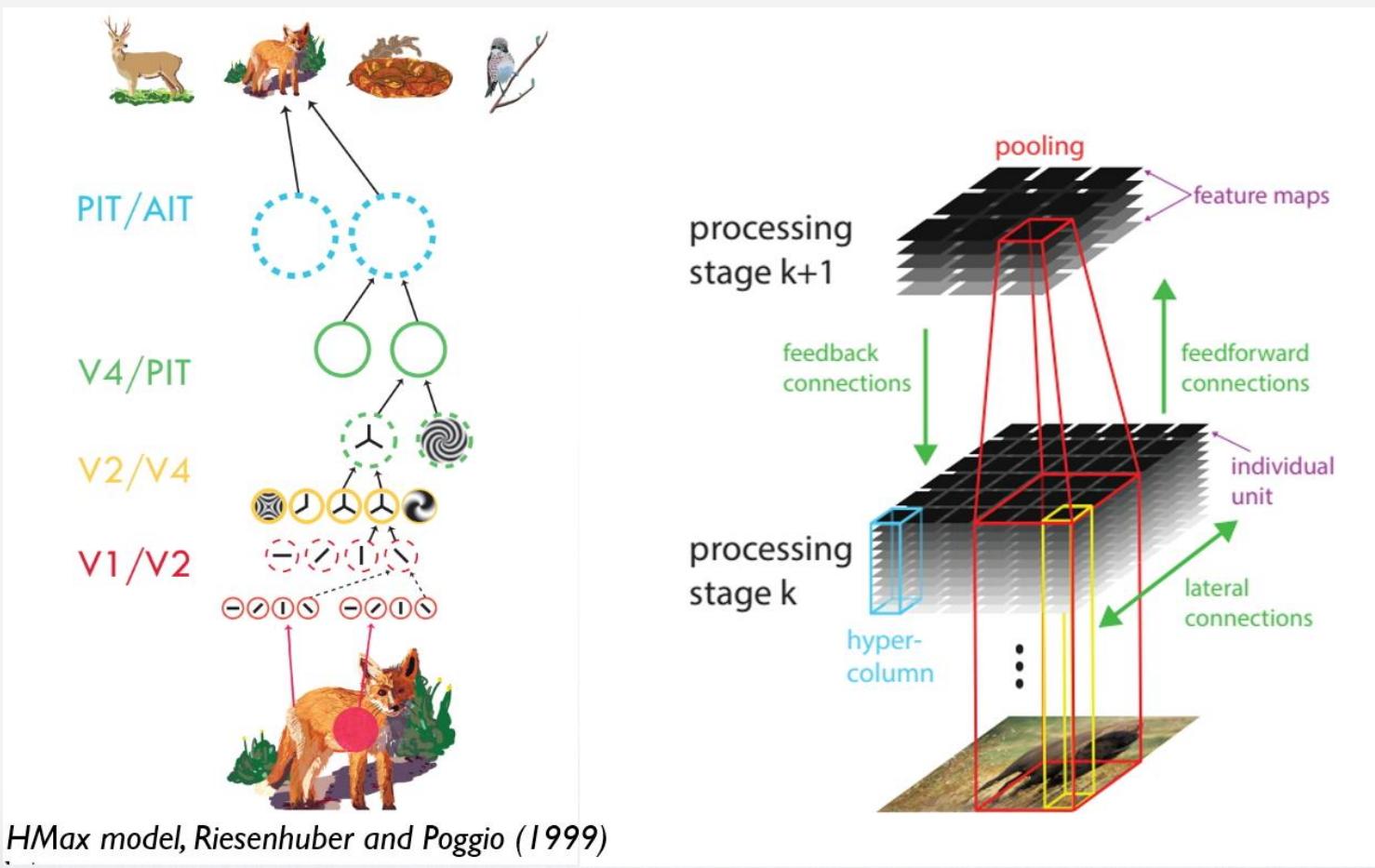
Review CNN

- Local Feature Based



CNN

- Hierarchical Model

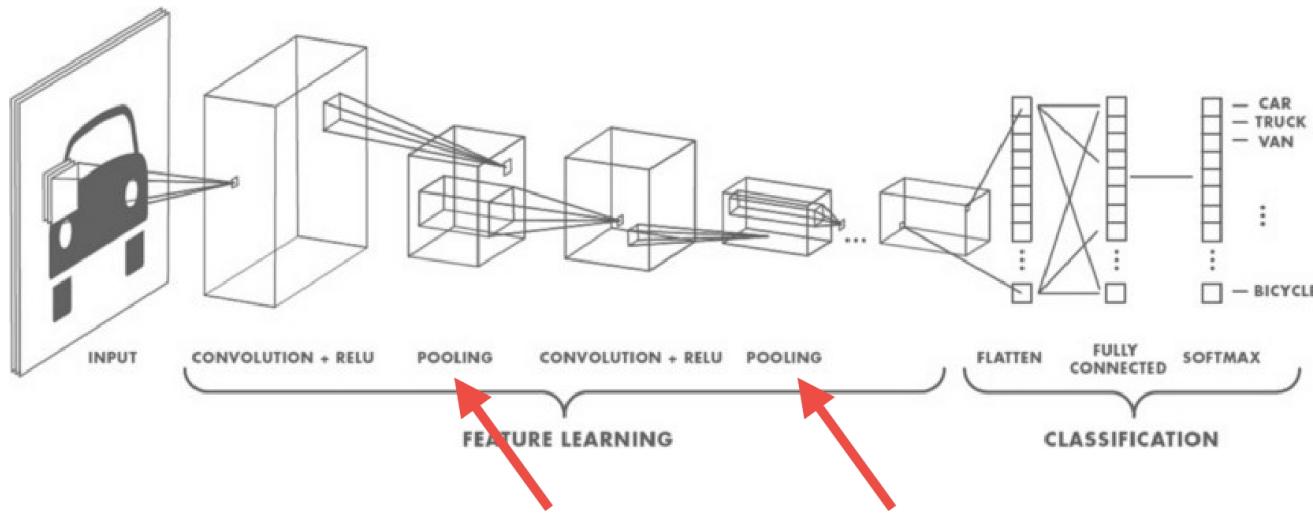


What's Wrong with CNN

- Everything is great but.....

PROBLEMS IS 'POOLING'

- ▶ ConvNet Architecture



Obtain translational, rotational invariance

What's Wrong with CNN

- Hinton's comment

- https://www.reddit.com/r/MachineLearning/comments/2lmo0l/ama_geoffrey_hinton/clyj4jv/

@REDDIT, MACHINE LEARNING

▶  [+] **geoffhinton** Google Brain [S] 29 점 3년 전에

You have many different questions. I shall number them and try to answer each one in a different reply.

1. What is your most controversial opinion in machine learning?

The pooling operation used in convolutional neural networks is a big mistake and the fact that it works so well is a disaster.

If the pools do not overlap, pooling loses valuable information about where things are. We need this information to detect precise relationships between the parts of an object. Its true that if the pools overlap enough, the positions of features will be accurately preserved by "coarse coding" (see my paper on "distributed representations" in 1986 for an explanation of this effect). But I no longer believe that coarse coding is the best way to represent the poses of objects relative to the viewer (by pose I mean position, orientation, and scale).

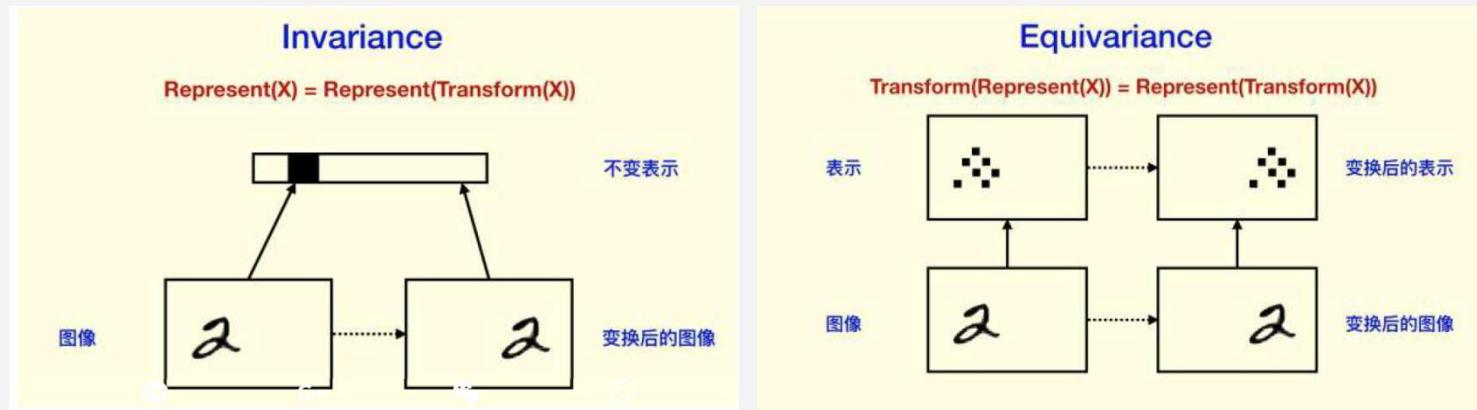
I think it makes much more sense to represent a pose as a small matrix that converts a vector of positional coordinates relative to the viewer into positional coordinates relative to the shape itself. This is what they do in computer graphics and it makes it easy to capture the effect of a change in viewpoint. It also explains why you cannot see a shape without imposing a rectangular coordinate frame on it, and if you impose a different frame, you cannot even recognize it as the same shape. Convolutional neural nets have no explanation for that, or at least none that I can think of.

Main Problem is....

- CNN is not learn like person
 - We don't need big data to learn
 - One shot learning / Zero shot learning is what people learn
- What's Problem of CNN
 - What and Where
 - Where objects are in space
 - What objects are

Equivariance VS Invariance

- CNN is Invariance but Hinton think we need Equivariance which is more like people do



Need Equivalence

- Example

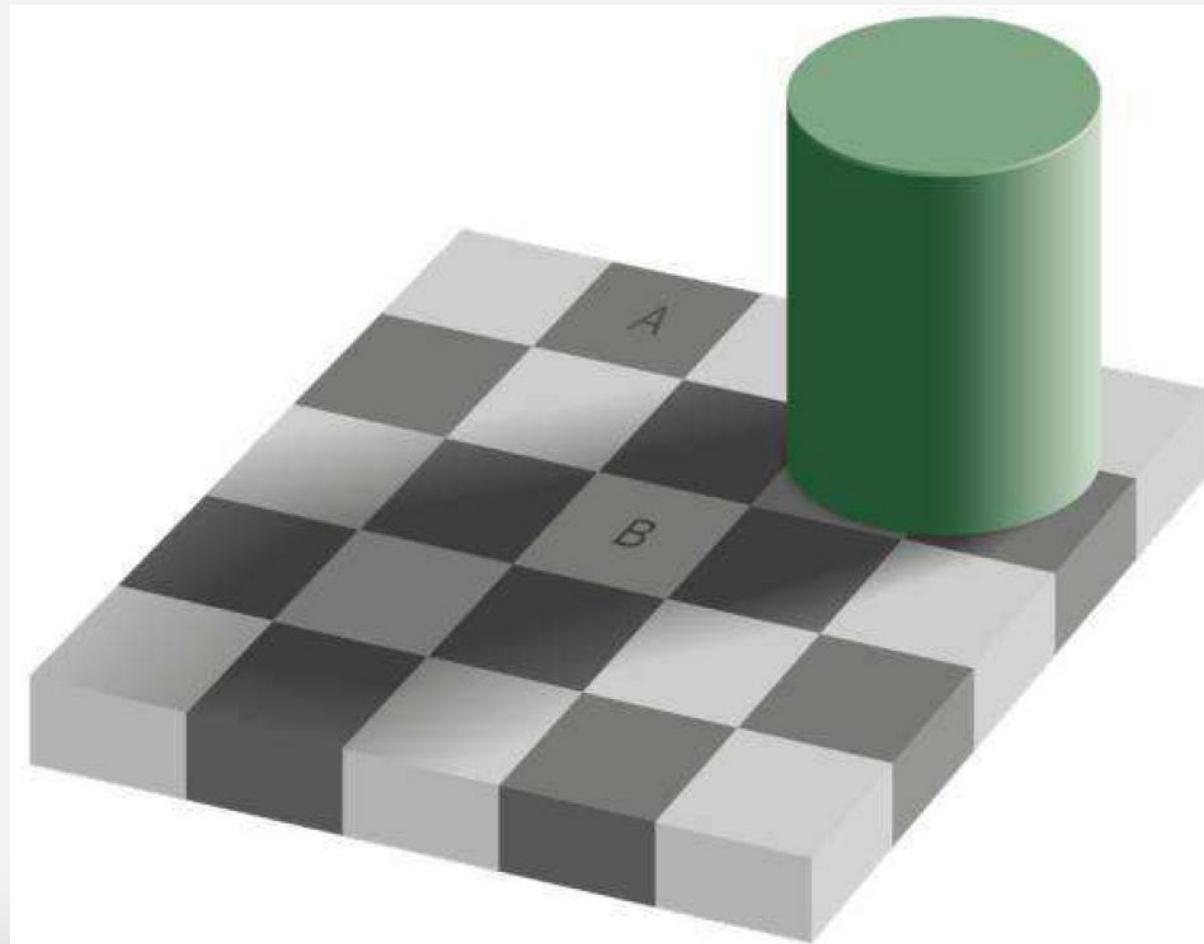
NEED EQUIVARIANCE, NOT INVARIANCE

The figure shows three images of Kim Kardashian with different makeup looks. The first image has her natural makeup. The second image has her eyes heavily lined. The third image has her eyes heavily shadowed. Below each image is a table of classification results.

Category	Score
person	0.88
reddish orange color	0.78
light brown color	0.78
starlet	0.66
entertainer	0.68
female	0.60
woman	0.59
young lady (heroine)	0.59
person	0.90
light brown color	0.84
starlet	0.77
entertainer	0.77
female	0.65
woman	0.64
young lady (heroine)	0.64
reddish orange color	0.64
newsreader	0.50
coal black color	0.79
hairpiece (hair)	0.71
dress	0.71
maroon color	0.71
person	0.58
toupee (hairpiece)	0.58
woman	0.56
Earrings	0.55
female	0.50

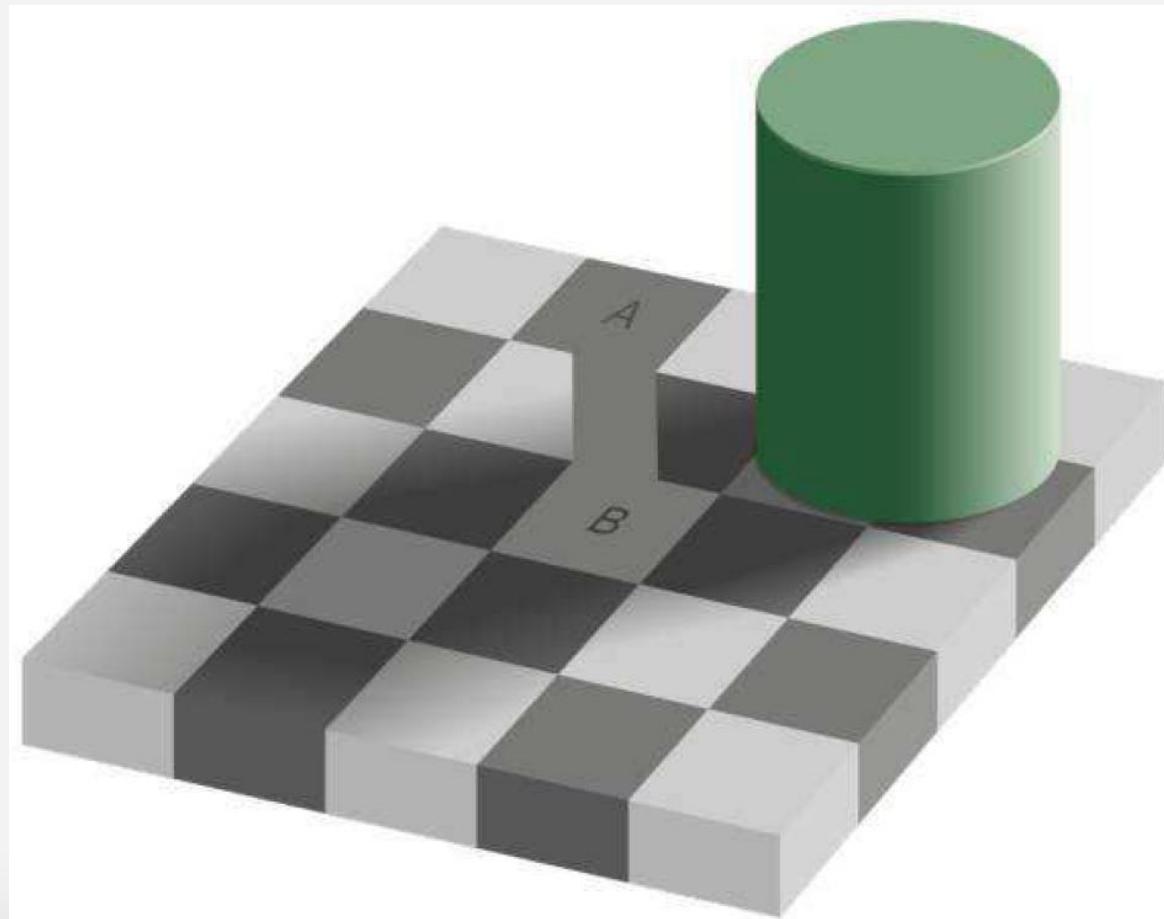
Visual Illusion

- Same Color ? A and B ?



Visual Illusion

- Same Color ! We know it's shadow then....



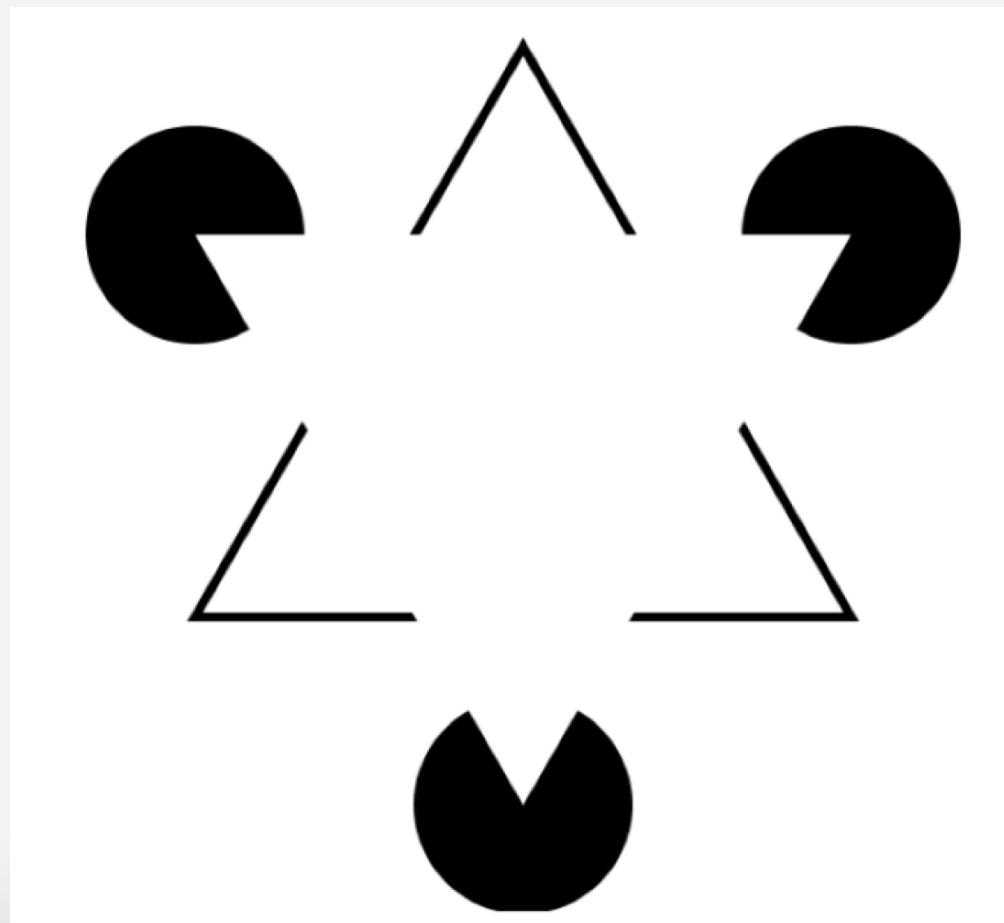
Visual Illusion

- Same Color – Contrast Sensitive



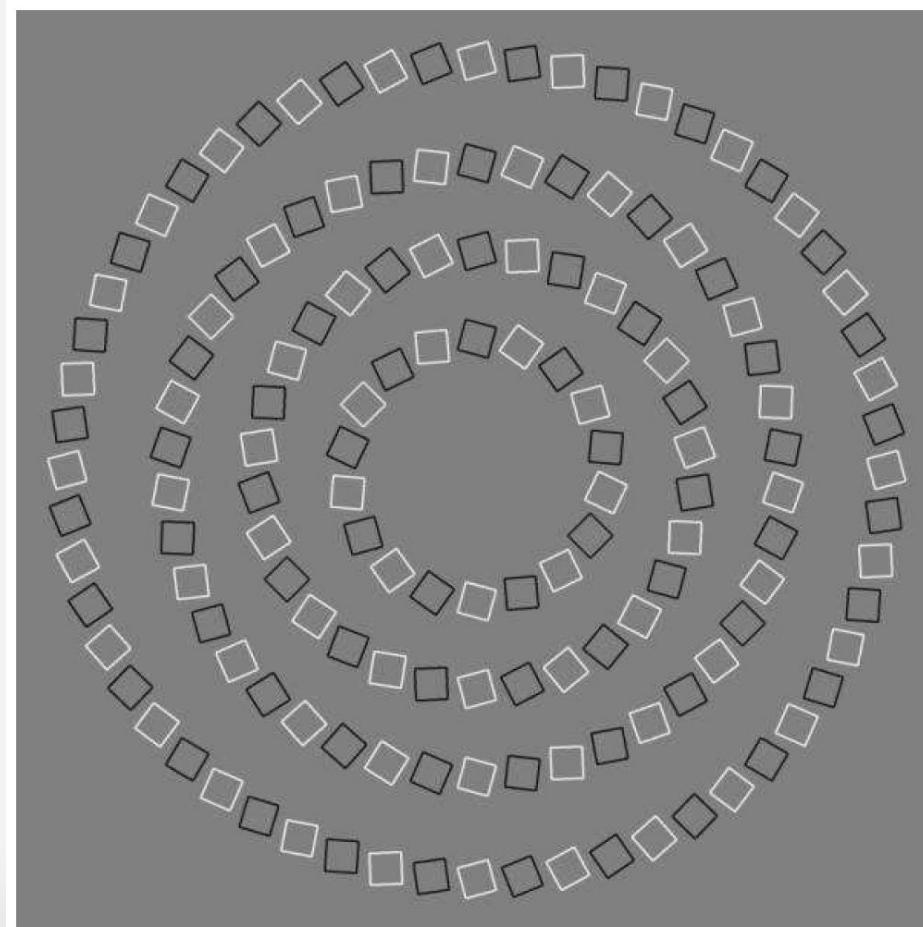
Visual Illusion

- Triangle – Space Sensitive



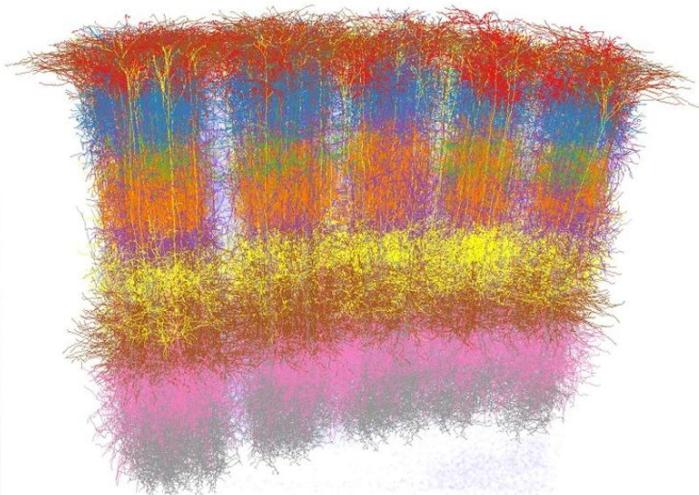
Visual Illusion

- Circle or Spiral Screw ?



Cortical Microcolumns

- AI need to learn computer graphs ?



Column through cortical layers of the brain
80-120 neurons (2X long in V1)
share the same receptive field

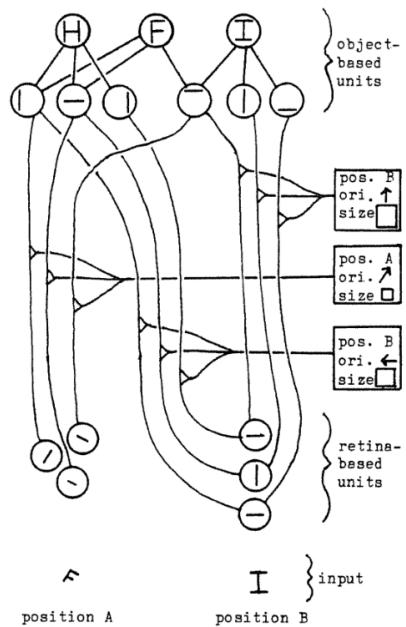
Capsules may encode
orientation scale
velocity color ...

part of Hubel and Wiesel, Nobel Prize 1981

Cortical Microcolumns

- A kind of inverse computer graphs

Canonical object based frames of reference:
Hinton 1981



In: Proceedings of the Seventh International Joint Conference
on Artificial Intelligence, Vancouver, B.C. Canada, 1981

A PARALLEL COMPUTATION THAT ASSIGNS CANONICAL OBJECT-BASED
FRAMES OF REFERENCE

Geoffrey F. Hinton

MRC Applied Psychology Unit
Cambridge, England

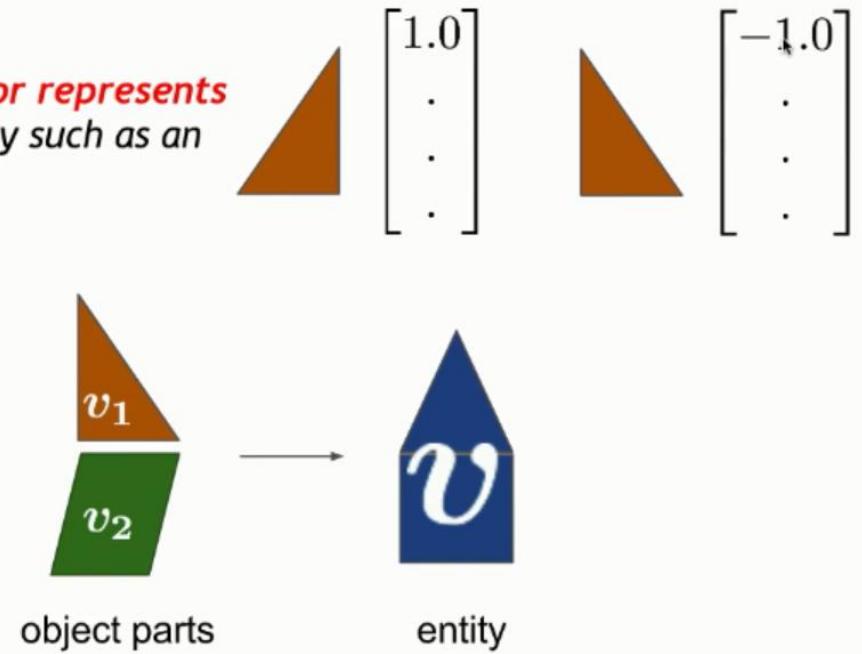
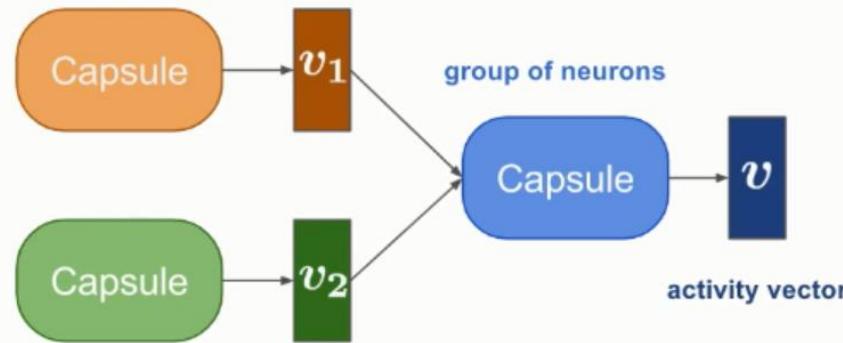
A kind of inverse computer graphics

Hinton has been thinking about this a long time

What is a Capsule?

- Definition from Dynamic Routing

“A **capsule** is a group of neurons whose **activity vector** represents the instantiation parameters of a specific type of entity such as an object or an object part.”



General ideas:

- Each dimension of v represents the characteristic of pattern;
- The norm of v represents the existence (confidence). !!!

Dynamic Routing Between Capsules

		capsule	vs.	traditional neuron
Input from low-level neuron/capsule		vector(u_i)		scalar(x_i)
Operation	Affine Transformation	$\hat{u}_{j i} = W_{ij} u_i$ (Eq. 2)		—
	Weighting	$s_j = \sum_i c_{ij} \hat{u}_{j i}$ (Eq. 2)		$a_j = \sum_{i=1}^3 W_i x_i + b$
	Sum			
	Non-linearity activation fun	$v_j = \frac{\ s_j\ ^2}{1 + \ s_j\ ^2} \frac{s_j}{\ s_j\ }$ (Eq. 1)		$h_{w,b}(x) = f(a_j)$
output		vector(v_i)		scalar(h)
		$u_1 \xrightarrow{w_{1j}} \hat{u}_1$ $u_2 \xrightarrow{w_{2j}} \hat{u}_2$ $u_3 \xrightarrow{w_{3j}} \hat{u}_3$ $+1 \xrightarrow{b}$	Σ squash(\cdot)	u_j
		$x_1 \xrightarrow{w_1}$ $x_2 \xrightarrow{w_2}$ $x_3 \xrightarrow{w_3}$ $+1 \xrightarrow{b}$	Σ $f(\cdot)$	$h_{w,b}(x)$ <small>$f(\cdot)$: sigmoid, tanh, ReLU, etc.</small>

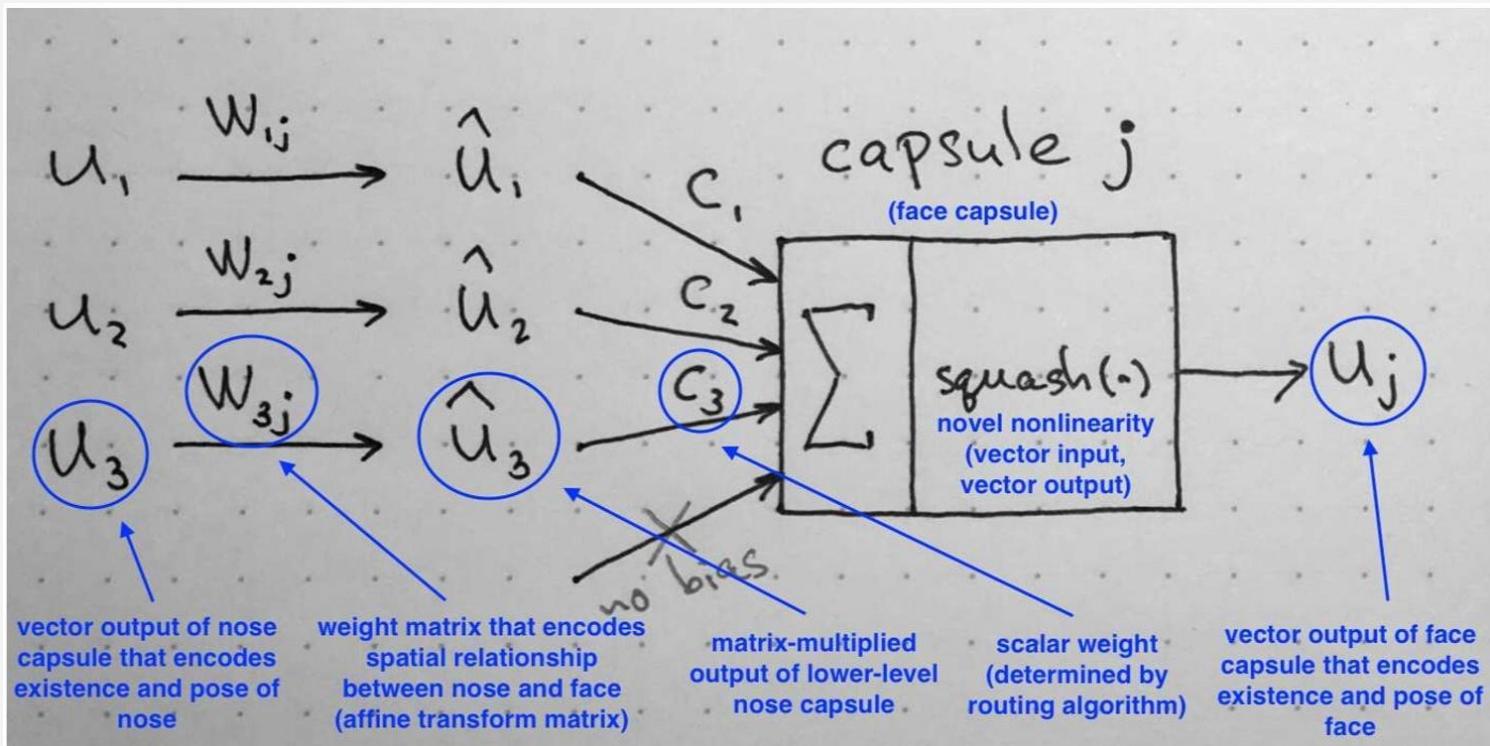
Capsule = New Version Neuron!
 vector in, vector out VS. scalar in, scalar out

Capsule Network

- Dynamic Routing

$$\mathbf{v}_j = \frac{\|\mathbf{s}_j\|^2}{1 + \|\mathbf{s}_j\|^2} \frac{\mathbf{s}_j}{\|\mathbf{s}_j\|}$$

additional “squashing” unit scaling



How do capsule networks work?

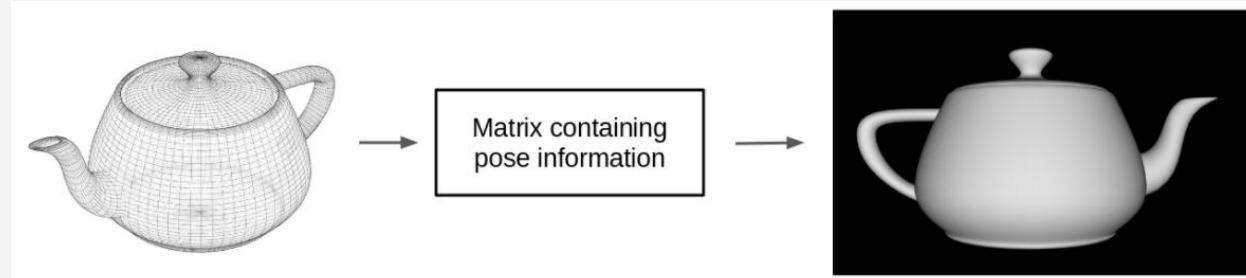
- A capsule network is composed of **many** capsules.
- A capsule is a function that tries to predict the **presence** and instantiation parameters of any particular object primitive at a particular **location**.
- The output of a capsule is a **vector**.
- The length of the **vector** is the **estimated probability of a particular object at a location**.
- The instantiation parameters of the object such orientation, thickness are all **encoded along** the multiple dimensions of the vectors it outputs.

How do capsule networks work?

- A capsule function **is implemented by applying convolution layers** which generate as output **feature maps** - these maps are then used to get the vectors for each location.
- Capsule networks may perform **better** than convolutional neural networks for **image segmentation/object detection** because of a key feature - they preserve details information of the object - such as its location and pose, unlike convolutional neural networks where pooling layers can cause loss of some of this information (precise location and pose of object).
- While it looks promising it has **not** been tested on larger images. Also **slower** to train etc.

What is routing do?

- Using an **iterative routing process**, each **active** capsule will choose a capsule in the layer above to be its parent in the tree.
- For the higher levels of a visual system, this iterative process will be **solving the problem of assigning parts to whole**.

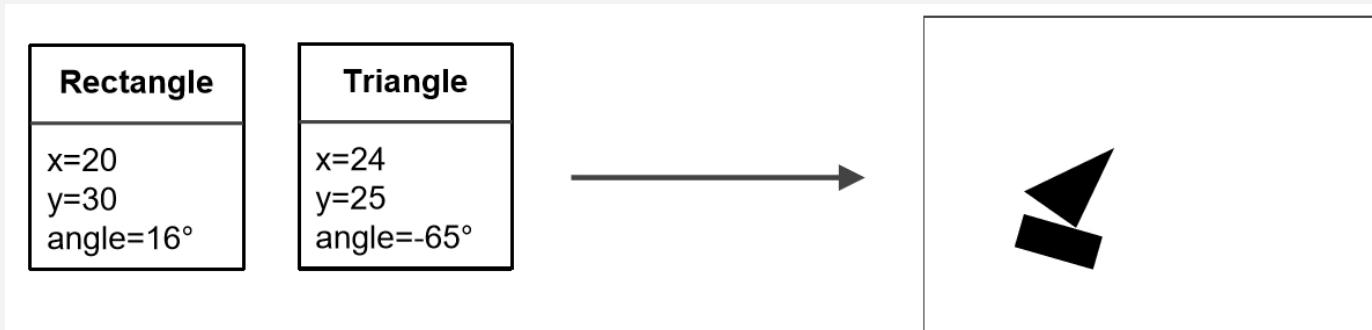


Inverse Graphics

You can think of (computer) vision as “Inverse Graphics” - Geoffrey Hinton

Dynamic Routing Between Capsules

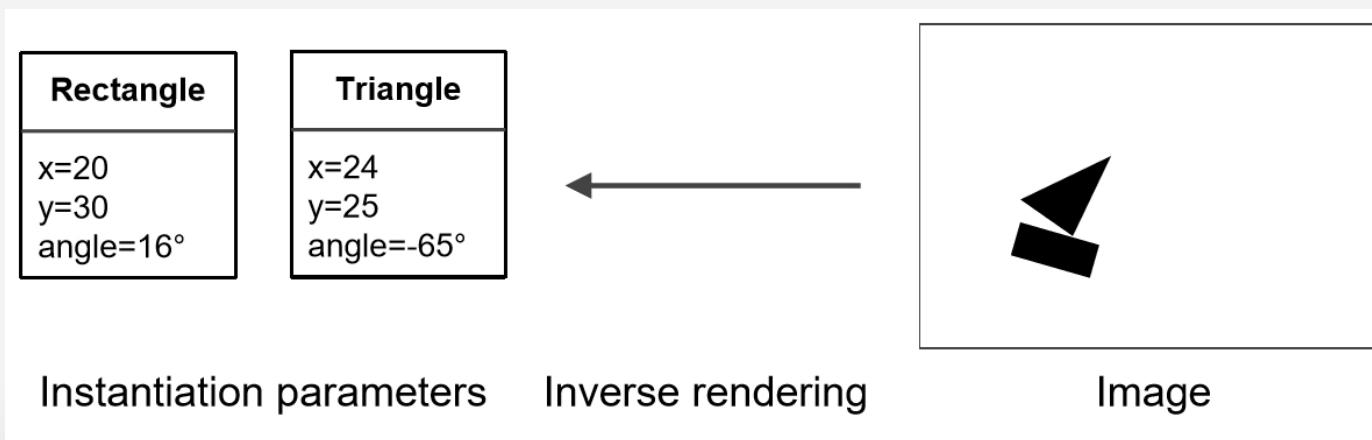
- Computer Graphics and Inverse Graphics



Instantiation parameters

Rendering

Image

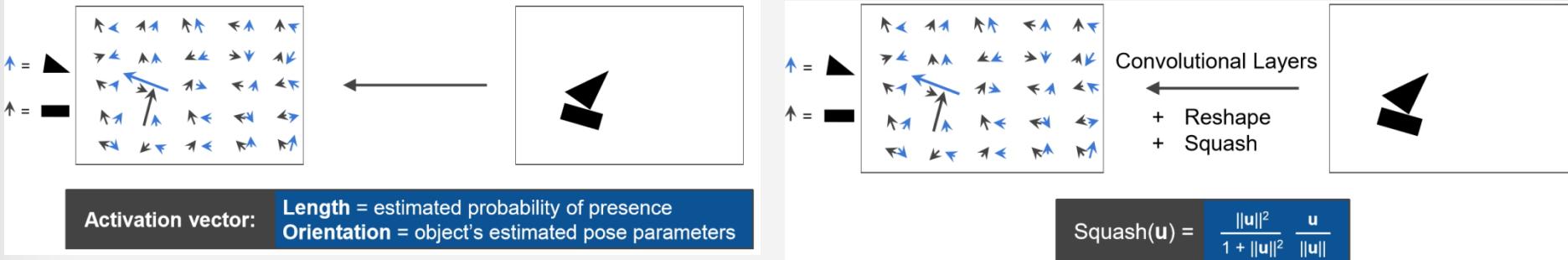
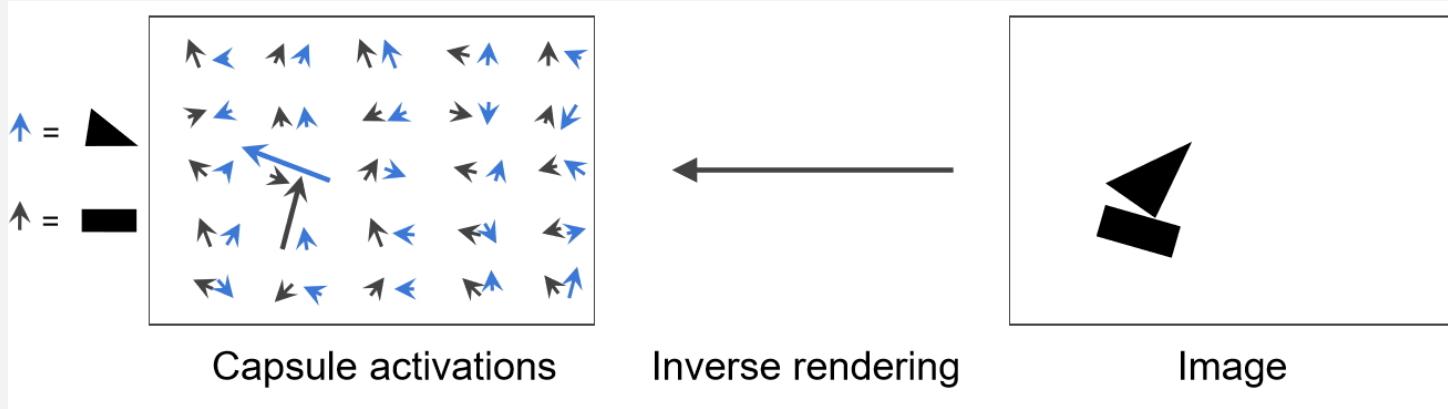


Instantiation parameters

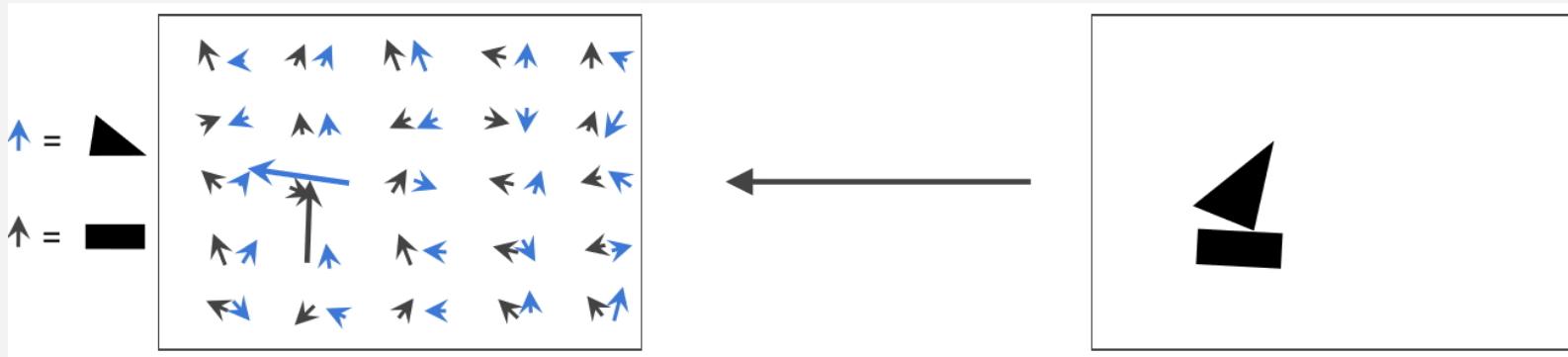
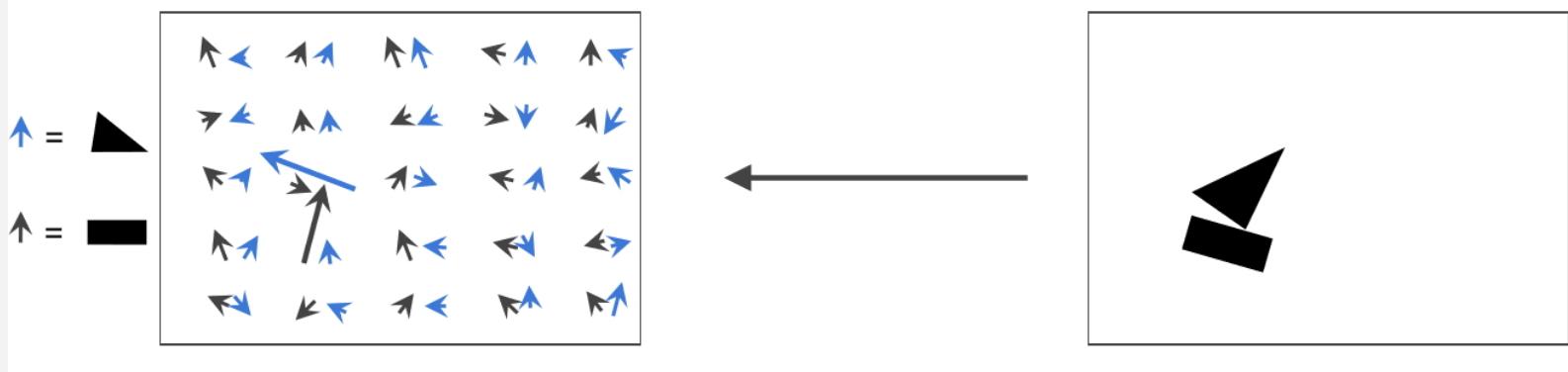
Inverse rendering

Image

Learning Vector and Squash



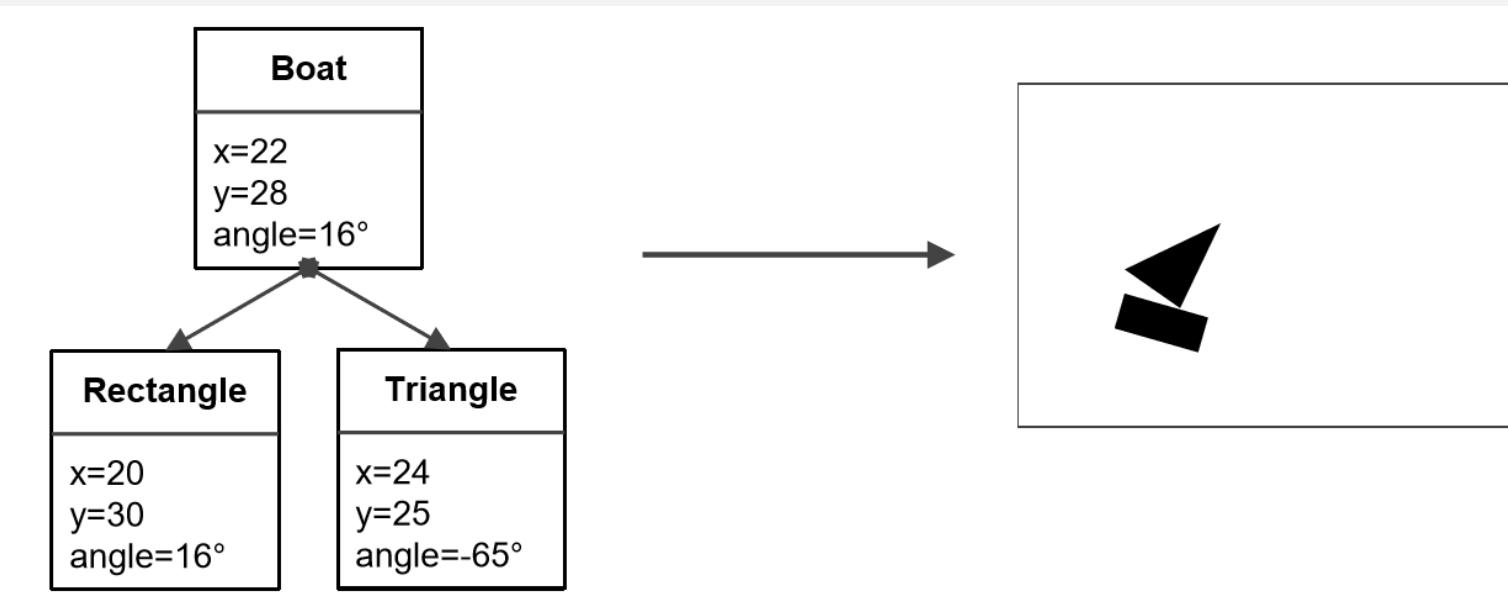
Parameters Fine Tuning



Boat Learned

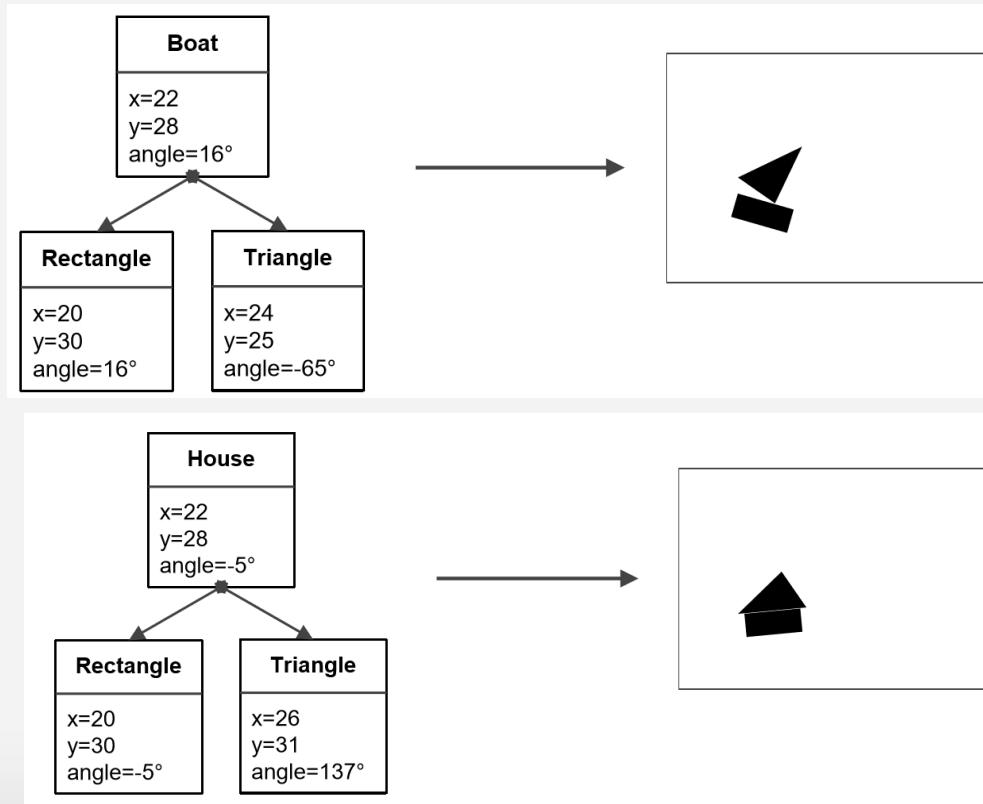
- Composed by two part

Boat
x=22
y=28
angle=16°

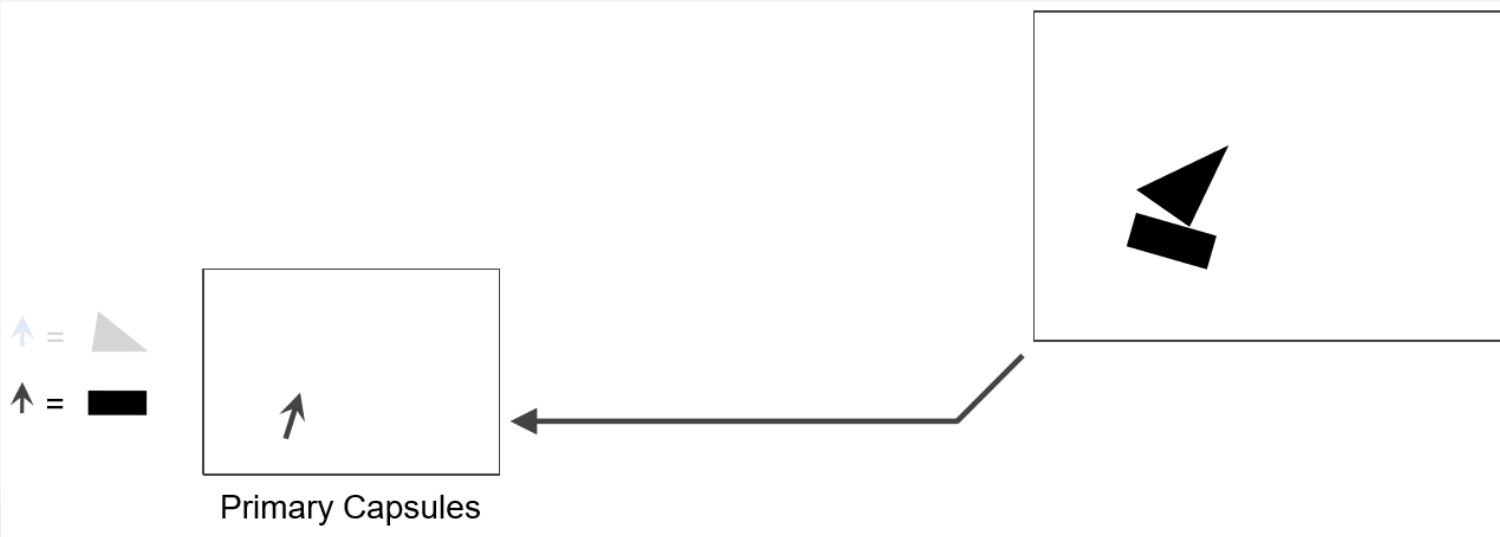
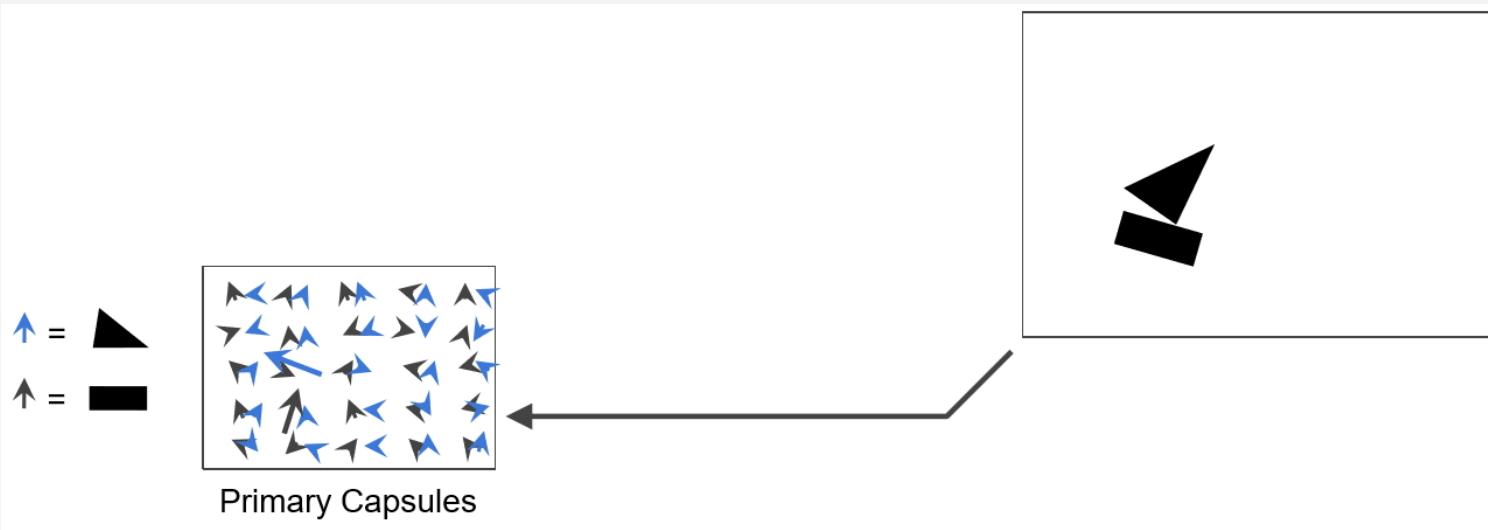


How to Predict ?

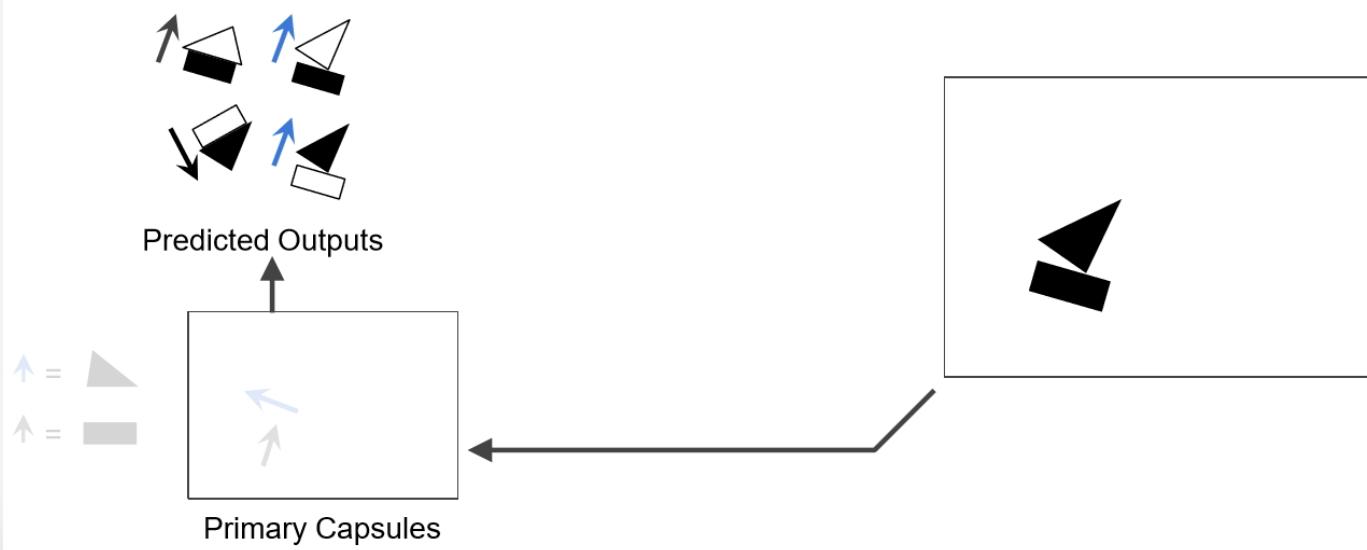
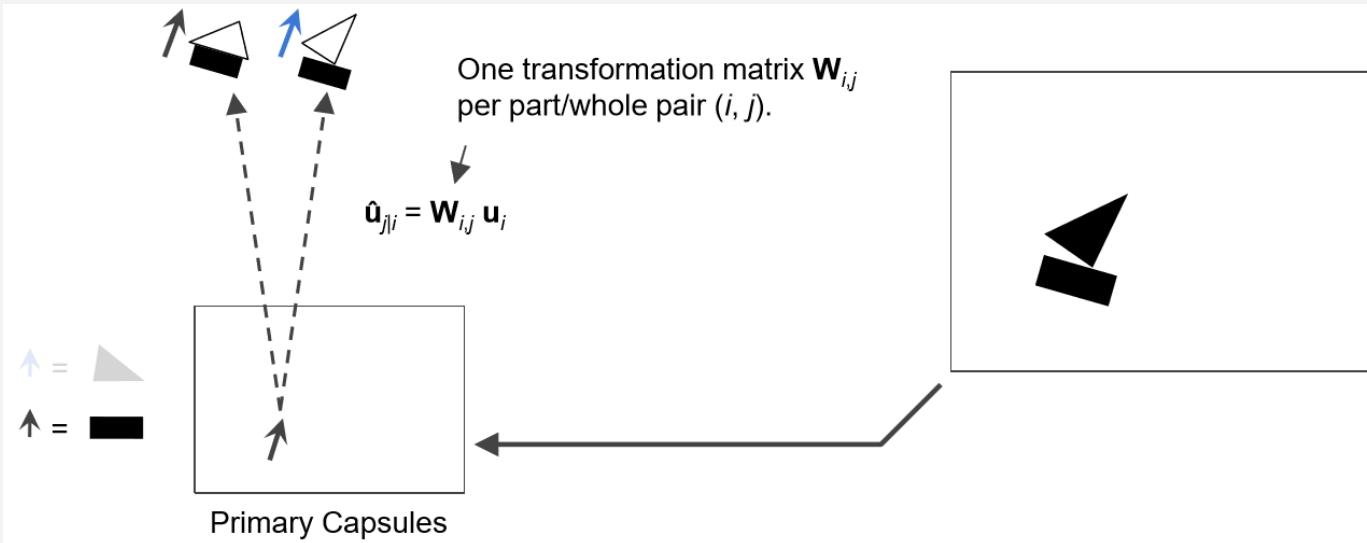
- A boat or a house? Hierarchy of parts
 - Predict a boat for example



Find Primary Capsules First

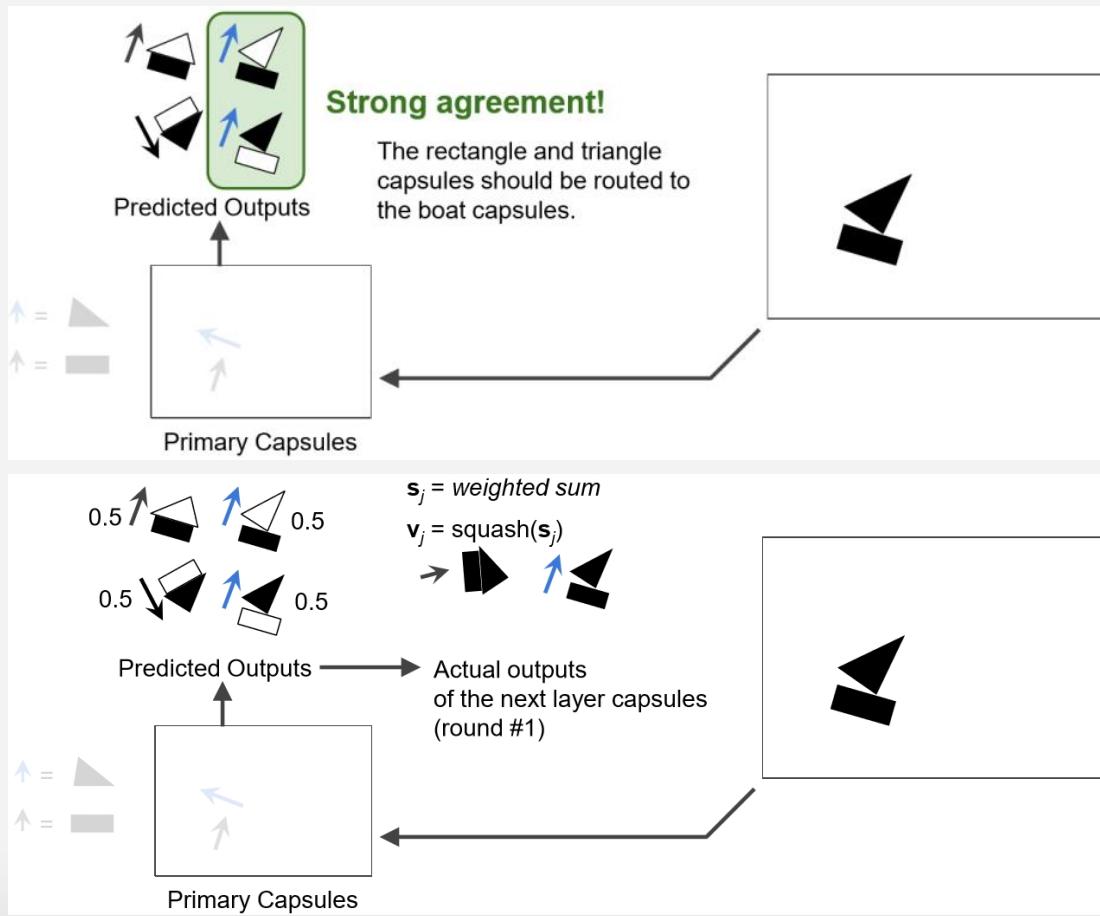


Predict Next Layer's Output

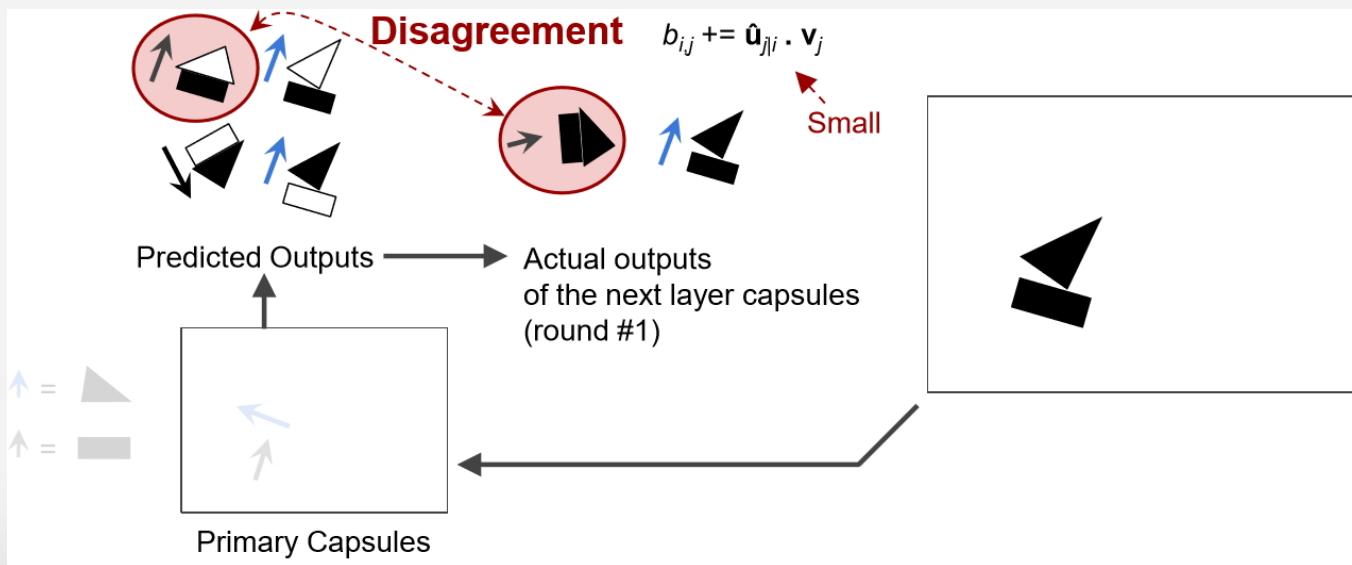
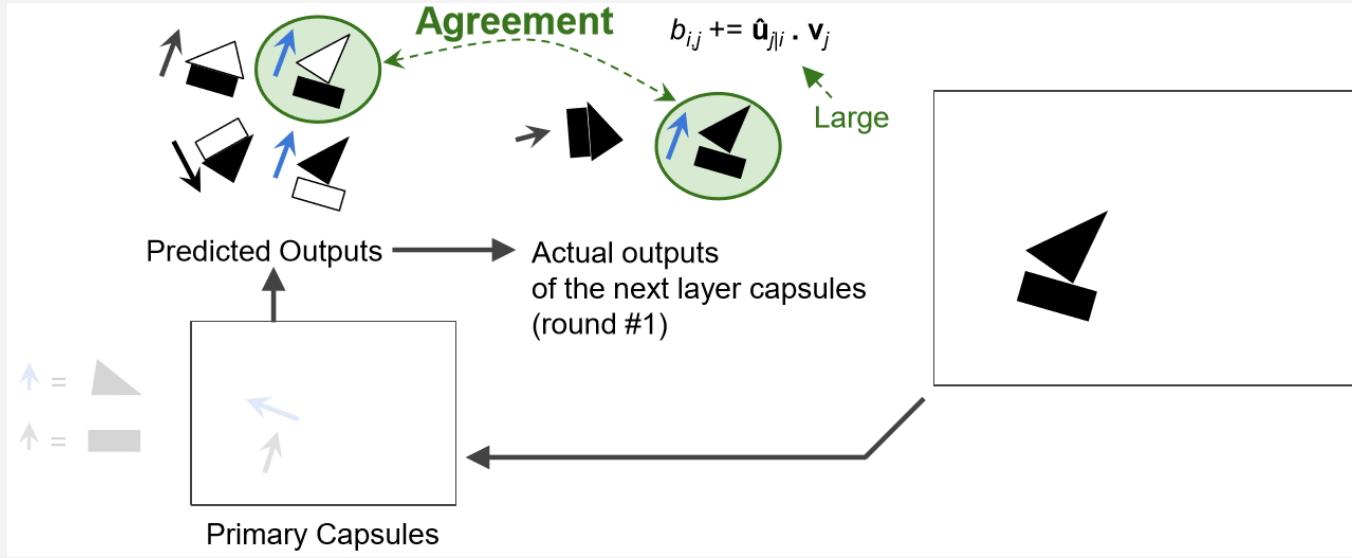


Routing By Agreement

- Strong Agreement

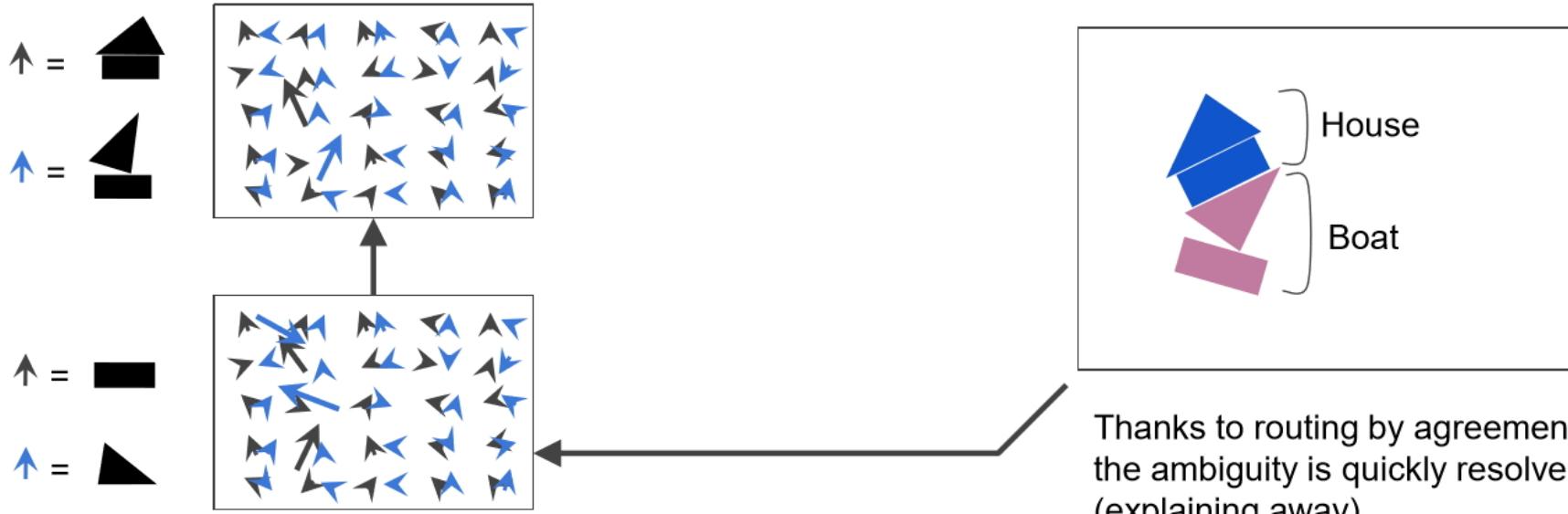


Strong Agreement



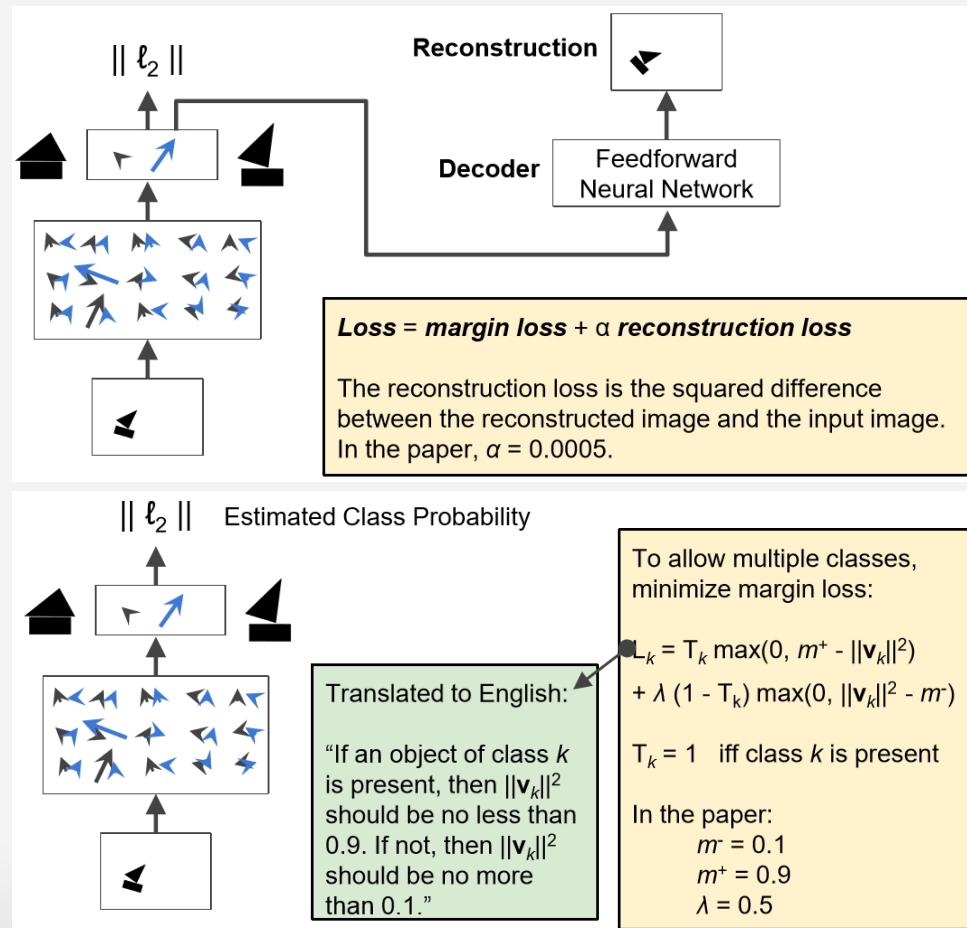
Handling Crowded Scenes

- Easy for Capsule Network



Regularization

- Recognize by Reconstruction



Dynamic VS EM Routing

- Dynamic Routing
 - Vectors as Pose (usually 8), Squash as Activation
 - Calculate Inner Product for Routing

Procedure 1 Routing algorithm.

```
1: procedure ROUTING( $\hat{\mathbf{u}}_{j|i}$ ,  $r$ ,  $l$ )
2:   for all capsule  $i$  in layer  $l$  and capsule  $j$  in layer  $(l + 1)$ :  $b_{ij} \leftarrow 0$ .
3:   for  $r$  iterations do
4:     for all capsule  $i$  in layer  $l$ :  $\mathbf{c}_i \leftarrow \text{softmax}(\mathbf{b}_i)$ 
5:     for all capsule  $j$  in layer  $(l + 1)$ :  $\mathbf{s}_j \leftarrow \sum_i c_{ij} \hat{\mathbf{u}}_{j|i}$ 
6:     for all capsule  $j$  in layer  $(l + 1)$ :  $\mathbf{v}_j \leftarrow \text{squash}(\mathbf{s}_j)$ 
7:     for all capsule  $i$  in layer  $l$  and capsule  $j$  in layer  $(l + 1)$ :  $b_{ij} \leftarrow b_{ij} + \hat{\mathbf{u}}_{j|i} \cdot \mathbf{v}_j$ 
return  $\mathbf{v}_j$ 
```

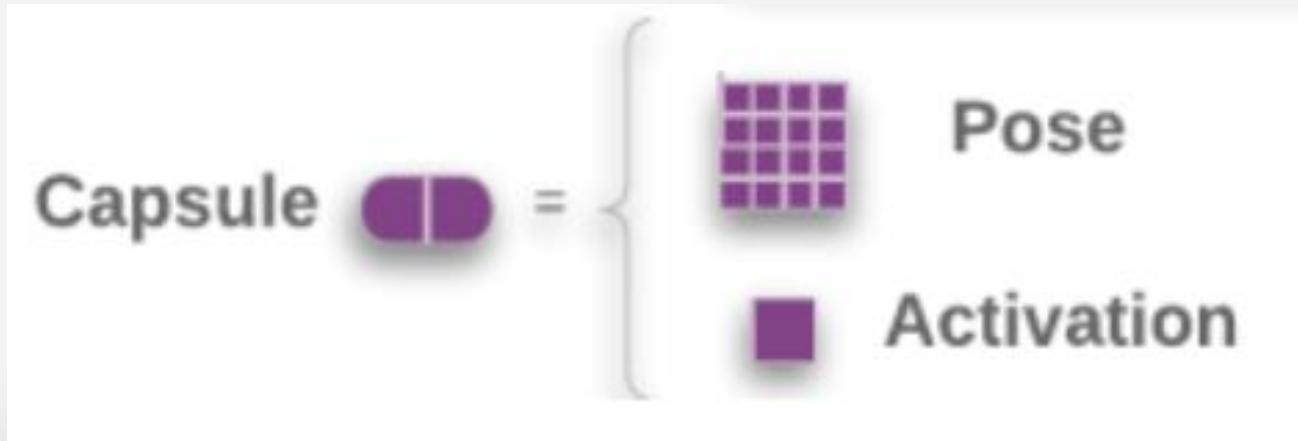
$$\vec{a} \cdot \vec{b} = \|\vec{a}\| \|\vec{b}\| \cos\theta$$
$$\cos\theta = \frac{\vec{a} \cdot \vec{b}}{\|\vec{a}\| \|\vec{b}\|}$$

$$\theta = \cos^{-1} \left(\frac{\vec{a} \cdot \vec{b}}{\|\vec{a}\| \|\vec{b}\|} \right)$$

- EM Routing
 - Pose Matrix (4X4 in paper), A Probability of Activation
 - EM Approach Routing

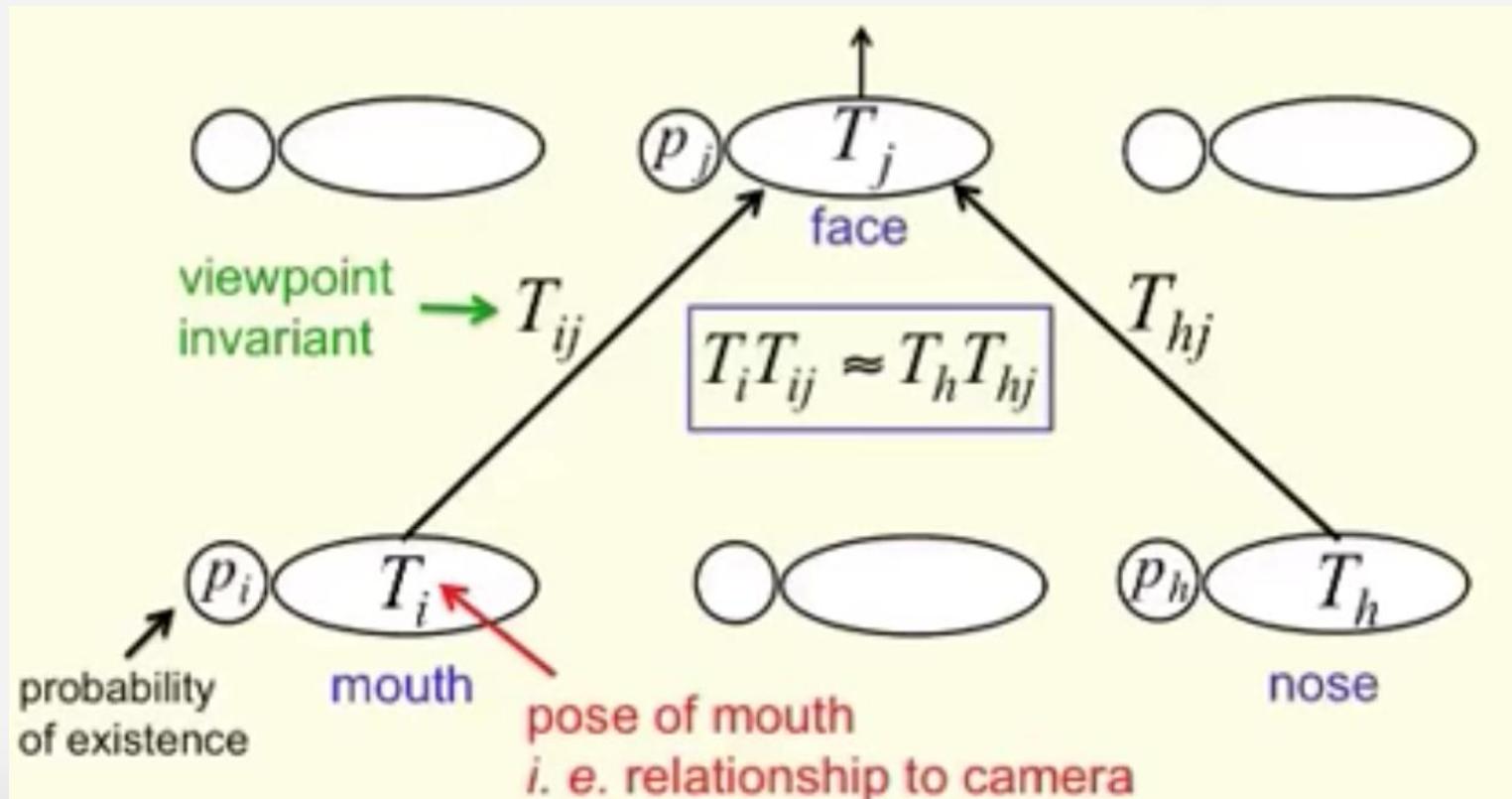
Dynamic VS EM Routing

- Dynamic Routing
 - Vectors as Pose (usually 8), Squash as Activation
 - Calculate Inner Product for Routing
- EM Routing
 - Pose Matrix (4X4 in paper), A Probability of Activation
 - EM Approach Routing



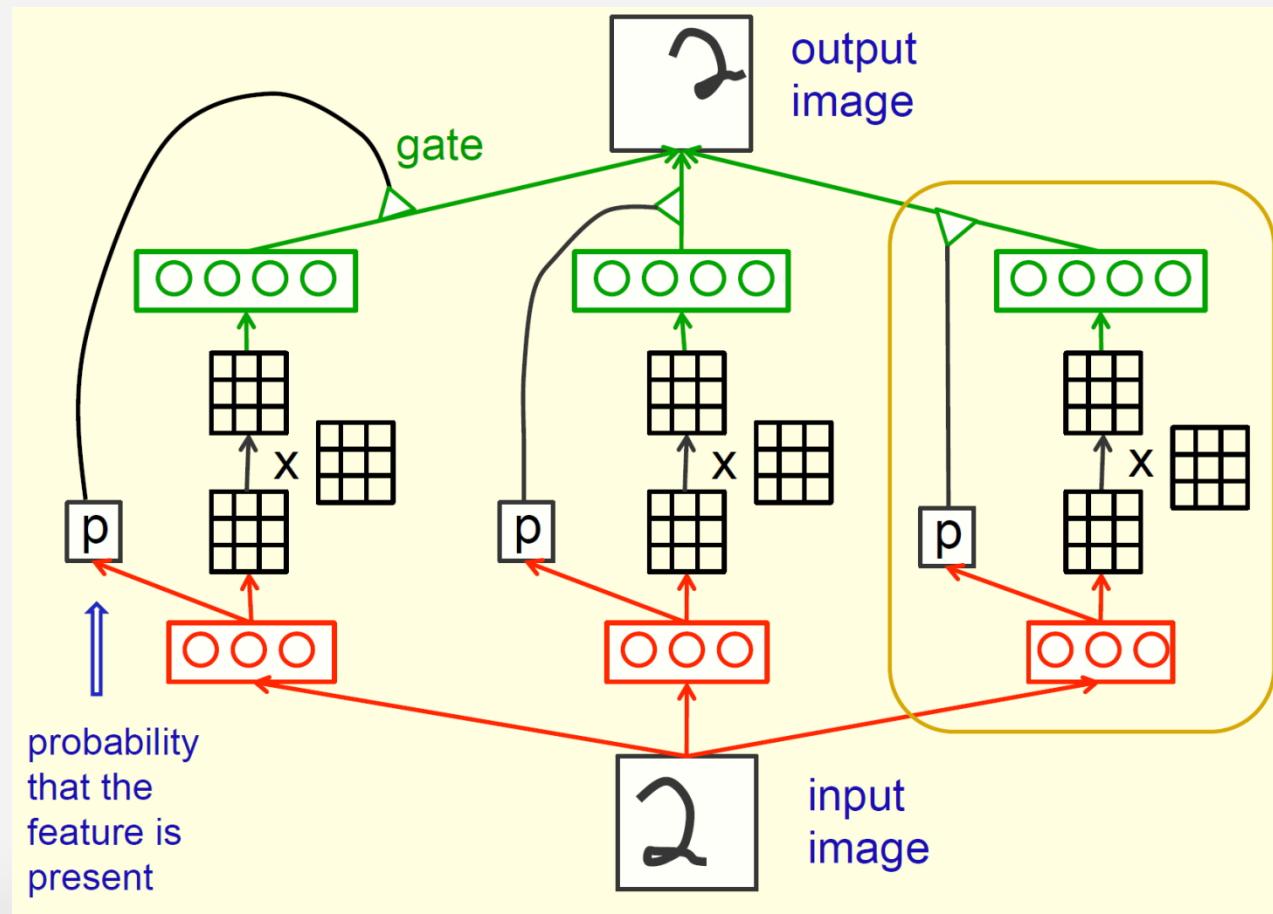
EM Routing Method

- Computer Graphics Transformation
 - Learn to represent part-whole relationships



EM Routing Method

- Picture from Transforming Auto-Encoder



EM Routing Algorithm

Procedure 1 Routing algorithm returns **activation** and **pose** of the capsules in layer $L + 1$ given the **activations** and **votes** of capsules in layer L . V_{ij}^h is the h^{th} dimension of the vote from capsule i with activation a_i in layer L to capsule j in layer $L + 1$. β_a , β_v are learned discriminatively and the inverse temperature λ increases at each iteration with a fixed schedule.

```

1: procedure EM ROUTING( $\mathbf{a}, V$ )
2:    $\forall i \in \Omega_L, j \in \Omega_{L+1}: R_{ij} \leftarrow 1/|\Omega_{L+1}|$ 
3:   for  $t$  iterations do
4:      $\forall j \in \Omega_{L+1}: M\text{-STEP}(\mathbf{a}, R, V, j)$ 
5:      $\forall i \in \Omega_L: E\text{-STEP}(\mu, \sigma, \mathbf{a}, V, i)$ 
return  $\mathbf{a}, \bar{M}$ 

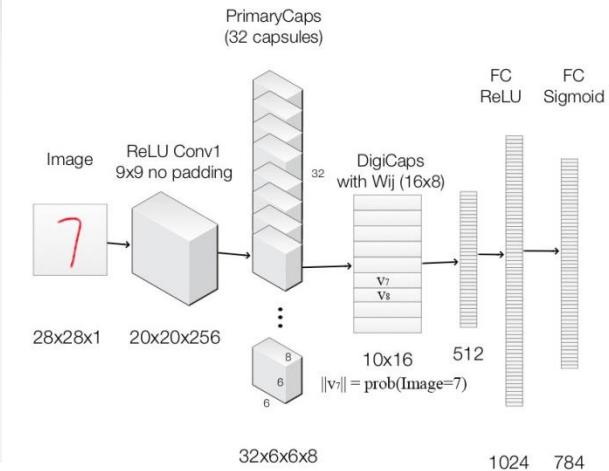
1: procedure M-STEP( $\mathbf{a}, R, V, j$ ) ▷ for one higher-level capsule
2:    $\forall i \in \Omega_L: R_{ij} \leftarrow R_{ij} * a_i$ 
3:    $\forall h: \mu_j^h \leftarrow \frac{\sum_i R_{ij} V_{ij}^h}{\sum_i R_{ij}}$ 
4:    $\forall h: (\sigma_j^h)^2 \leftarrow \frac{\sum_i R_{ij} (V_{ij}^h - \mu_j^h)^2}{\sum_i R_{ij}}$ 
5:    $cost^h \leftarrow (\beta_v + \log(\sigma_j^h)) \sum_i R_{ij}$ 
6:    $a_j \leftarrow \text{sigmoid}(\lambda(\beta_a - \sum_h cost^h))$ 

1: procedure E-STEP( $\mu, \sigma, \mathbf{a}, V, i$ ) ▷ for one lower-level capsule
2:    $\forall j \in \Omega_{L+1}: p_j \leftarrow \frac{1}{\sqrt{\prod_h^H 2\pi(\sigma_j^h)^2}} e^{-\sum_h^H \frac{(V_{ij}^h - \mu_j^h)^2}{2(\sigma_j^h)^2}}$ 
3:    $\forall j \in \Omega_{L+1}: R_{ij} \leftarrow \frac{a_j p_j}{\sum_{u \in \Omega_{L+1}} a_u p_u}$ 

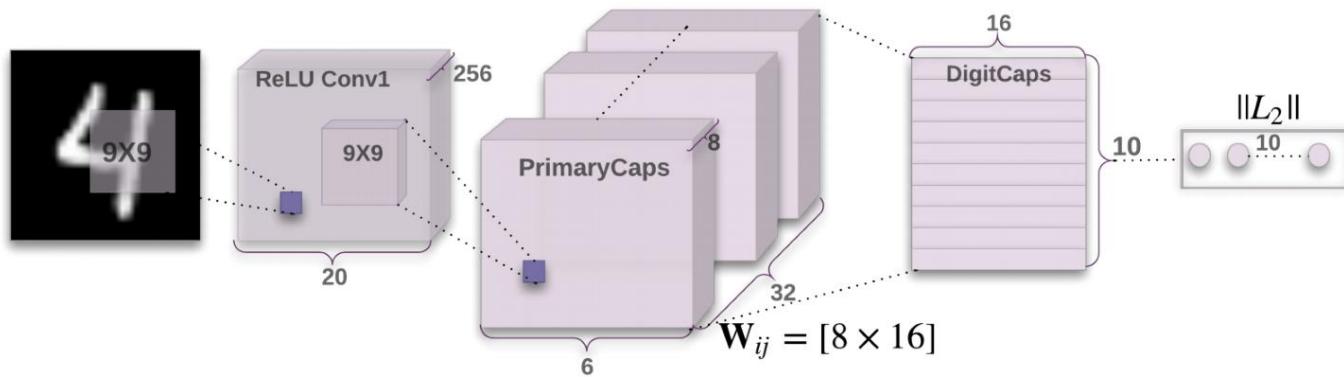
```

Architecture

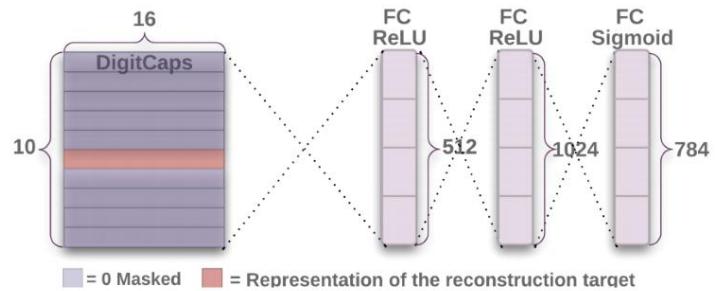
- Dynamic Routing on MNIST



supervised | max norm loss



+ unsupervised | reconstruction loss



Architecture

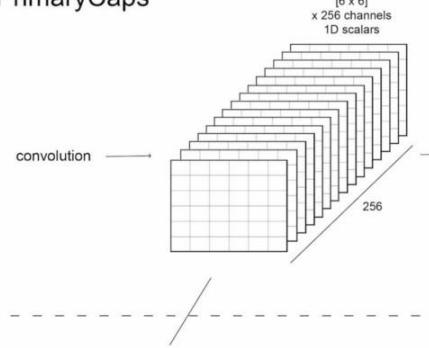
- Dynamic Routing on MNIST
 - <https://jhui.github.io/2017/11/03/Dynamic-Routing-Between-Capsules/>

Layer Name	Apply	Output shape
Image	Raw image array	28x28x1
ReLU Conv1	Convolution layer with 9x9 kernels output 256 channels, stride 1, no padding with ReLU	20x20x256
PrimaryCapsules	Convolution capsule layer with 9x9 kernel output 32x6x6 8-D capsule, stride 2, no padding	6x6x32x8
DigiCaps	Capsule output computed from a W_{ij} (16x8 matrix) between u_i and v_j (i from 1 to 32x6x6 and j from 1 to 10).	10x16
FC1	Fully connected with ReLU	512
FC2	Fully connected with ReLU	1024
Output image	Fully connected with sigmoid	784 (28x28)

Dynamic Routing

A Visual Representation of Capsule Connections in
Dynamic Routing Between Capsules

PrimaryCaps



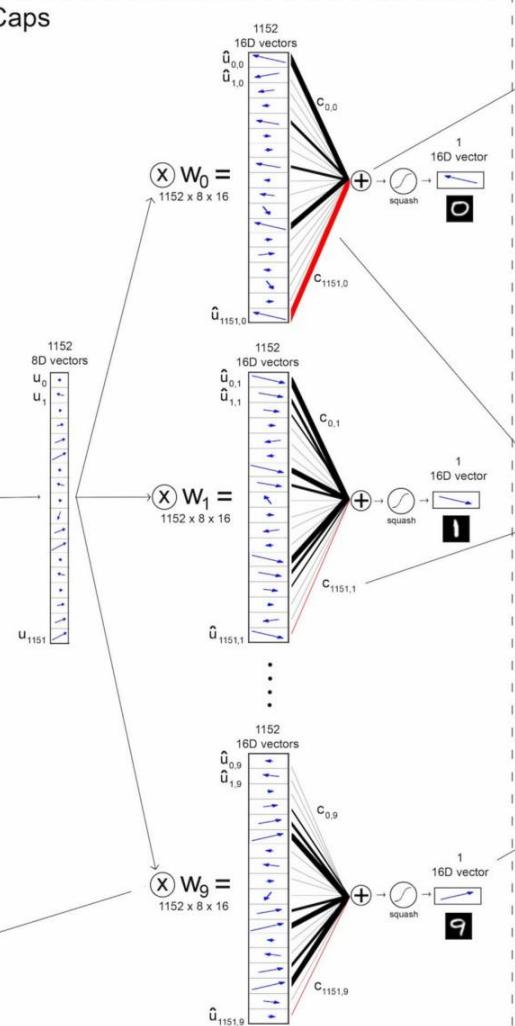
Standard convolution outputs 256 channels of scalars in 6x6 arrays.

The 256 channels may be grouped by 8, and reinterpreted as 32 channels of 8D vectors in 6x6 arrays.

The squash non-linearity function is a vector analogue of the sigmoid. Just as sigmoid remaps scalars onto (0, 1), squash scales vector lengths onto (0, 1), without changing their orientation.

Each of the 1152 8D vectors (\mathbf{u} in the paper) is transformed into a 16D vector via matrix multiplication with \mathbf{W} . The result is $\hat{\mathbf{u}}$, consisting of 1152 16D vectors for each output class capsule (11520 in total).

DigitCaps



Each capsule computes a weighted average of the transformed input vectors in $\hat{\mathbf{u}}$. The "coupling" weights, \mathbf{c} , are determined on each forward pass via an iterative routing algorithm that acts as a sort of orientation-popularity filter. If multiple large vectors point in the same direction, they will get a large weight. Shorter vectors pointing in scattered directions will get a small weight.

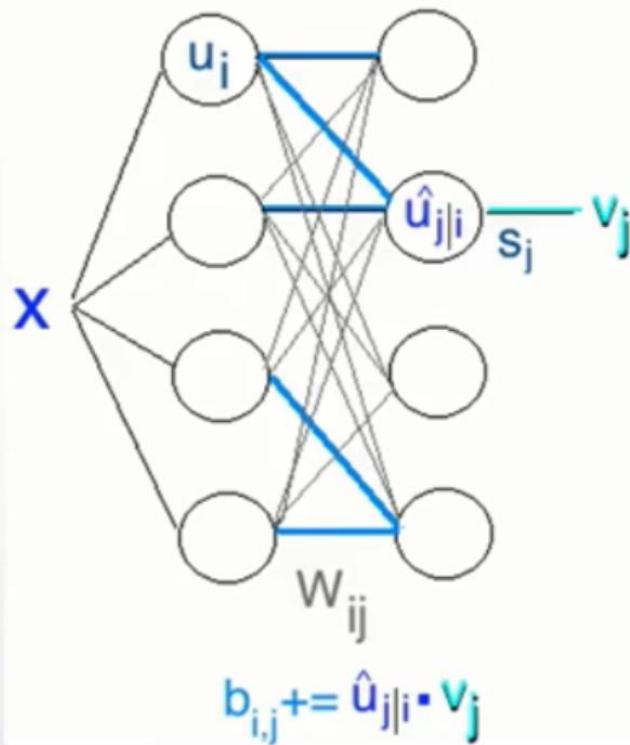
The routing algorithm also uses softmax so that each of the 1152 input vectors in \mathbf{u} , sends most of its activity to just one of the ten outputs.

The routing for \mathbf{u}_{1151} is shown in red. Although both $\hat{\mathbf{u}}_{1151,0}$ and $\hat{\mathbf{u}}_{1151,1}$ have popular orientations in their respective digit capsules, only one has a large weight, $\mathbf{c}_{1151,0}$, so most of the activity flows to the digit 0 output.

The output vector is squashed so that its length can model the probability that the capsule's digit is present.

Routing Method

Data-specific dynamic routes



squash

$$\mathbf{v}_j = \frac{\|\mathbf{s}_j\|^2}{1 + \|\mathbf{s}_j\|^2} \frac{\mathbf{s}_j}{\|\mathbf{s}_j\|}$$

weighted sum

$$\mathbf{s}_j = \sum_i c_{ij} \hat{\mathbf{u}}_{j|i},$$

weighted mean prediction

$$\hat{\mathbf{u}}_{j|i} = \mathbf{W}_{ij} \mathbf{u}_i$$

softmax

$$c_{ij} = \frac{\exp(b_{ij})}{\sum_k \exp(b_{ik})}$$

“ c_{ij} are determined by an iterative dynamic routing process”

Routing Method

- Dynamic Routing

Dynamic *Routing* (by Agreement)

Initialize $b_{11}, b_{21} = 0$ Routing Algorithm

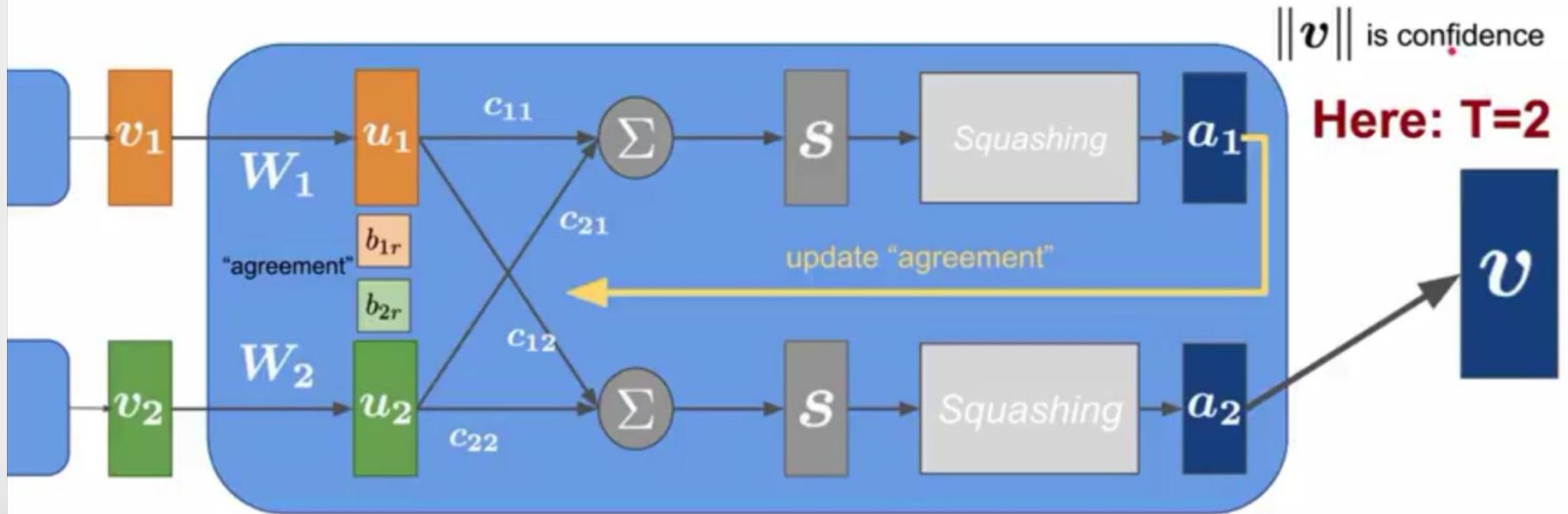
for r in range(1... T)

$c_{1r}, c_{2r} = \text{softmax}(b_{1r}, b_{2r})$

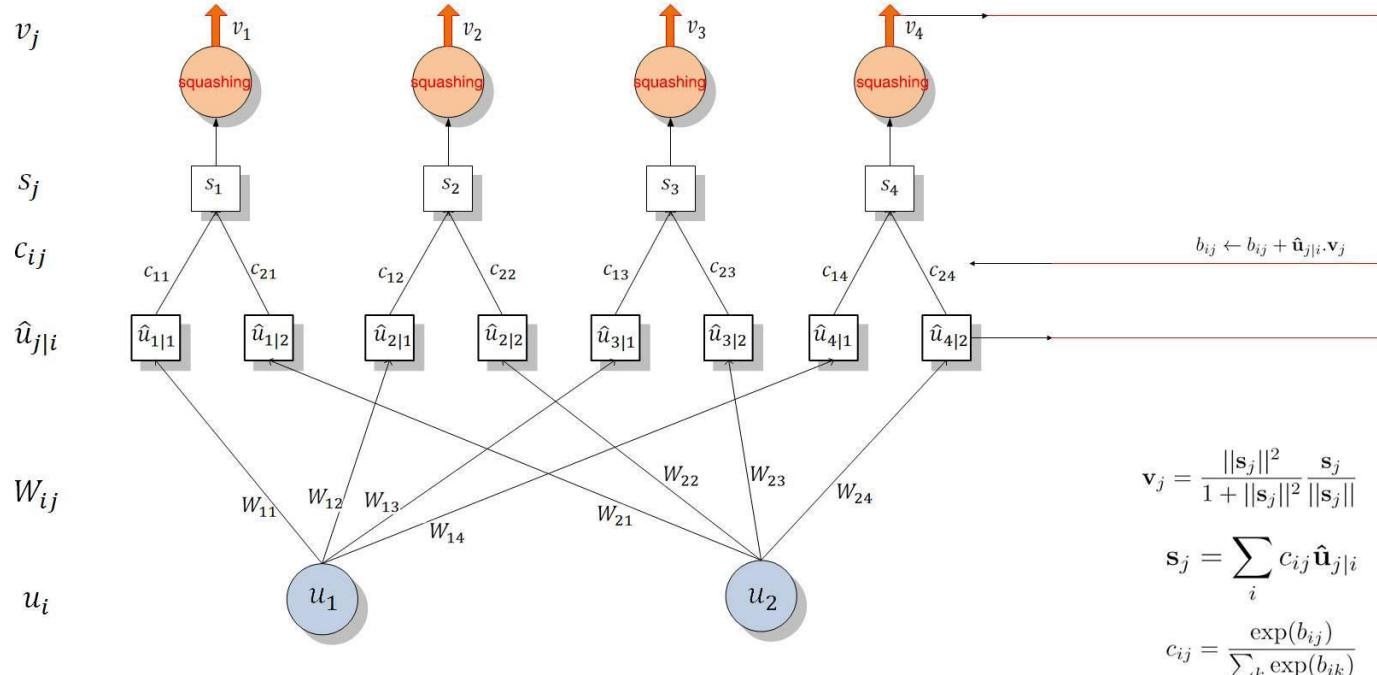
$a_r = \text{squashing}(c_{1r}u_1 + c_{2r}u_2)$

$b_{1(r+1)} = b_{1r} + a_r \cdot u_1$

$b_{2(r+1)} = b_{2r} + a_r \cdot u_2$



Dynamic Routing



Procedure 1 Routing algorithm.

```

1: procedure ROUTING( $\hat{u}_{j|i}, r, l$ )
2:   for all capsule  $i$  in layer  $l$  and capsule  $j$  in layer  $(l+1)$ :  $b_{ij} \leftarrow 0$ .
3:   for  $r$  iterations do
4:     for all capsule  $i$  in layer  $l$ :  $\mathbf{c}_i \leftarrow \text{softmax}(\mathbf{b}_i)$ 
5:     for all capsule  $j$  in layer  $(l+1)$ :  $\mathbf{s}_j \leftarrow \sum_i c_{ij} \hat{u}_{j|i}$ 
6:     for all capsule  $j$  in layer  $(l+1)$ :  $\mathbf{v}_j \leftarrow \text{squash}(\mathbf{s}_j)$ 
7:     for all capsule  $i$  in layer  $l$  and capsule  $j$  in layer  $(l+1)$ :  $b_{ij} \leftarrow b_{ij} + \hat{u}_{j|i} \cdot \mathbf{v}_j$ 
return  $\mathbf{v}_j$ 

```

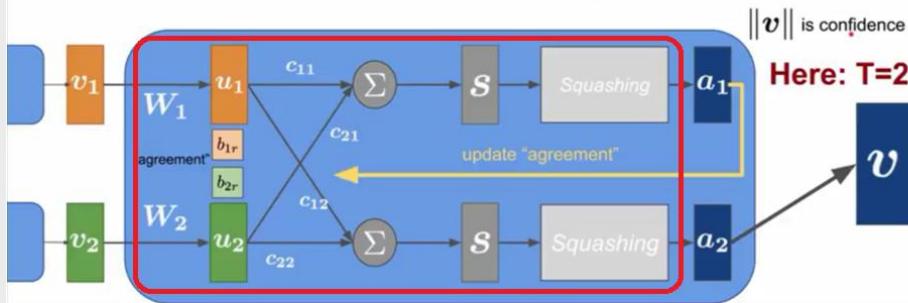
Dynamic Routing

Dynamic Routing (by Agreement)

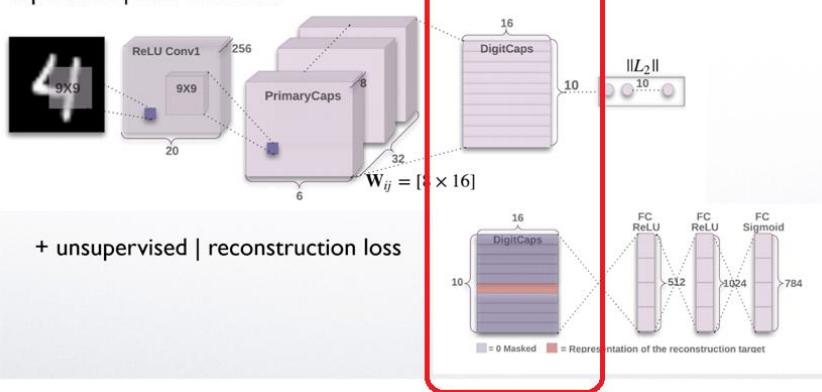
```

Initialize  $b_{11}, b_{21} = 0$ 
for r in range(1...T)
     $c_{1r}, c_{2r} = \text{softmax}(b_{1r}, b_{2r})$ 
     $a_r = \text{squashing}(c_{1r}u_1 + c_{2r}u_2)$ 
     $b_{1(r+1)} = b_{1r} + a_r \cdot u_1$ 
     $b_{2(r+1)} = b_{2r} + a_r \cdot u_2$ 

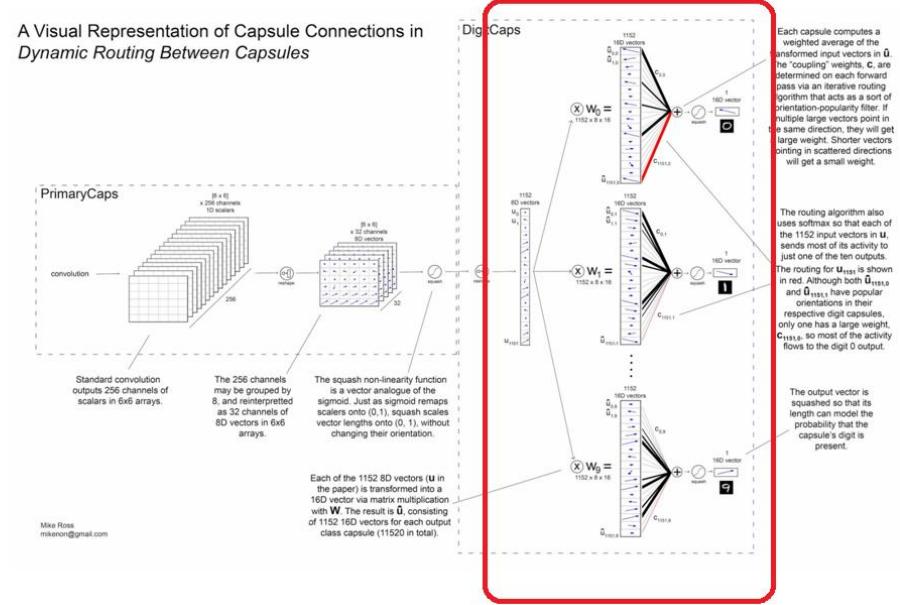
```



supervised | max norm loss

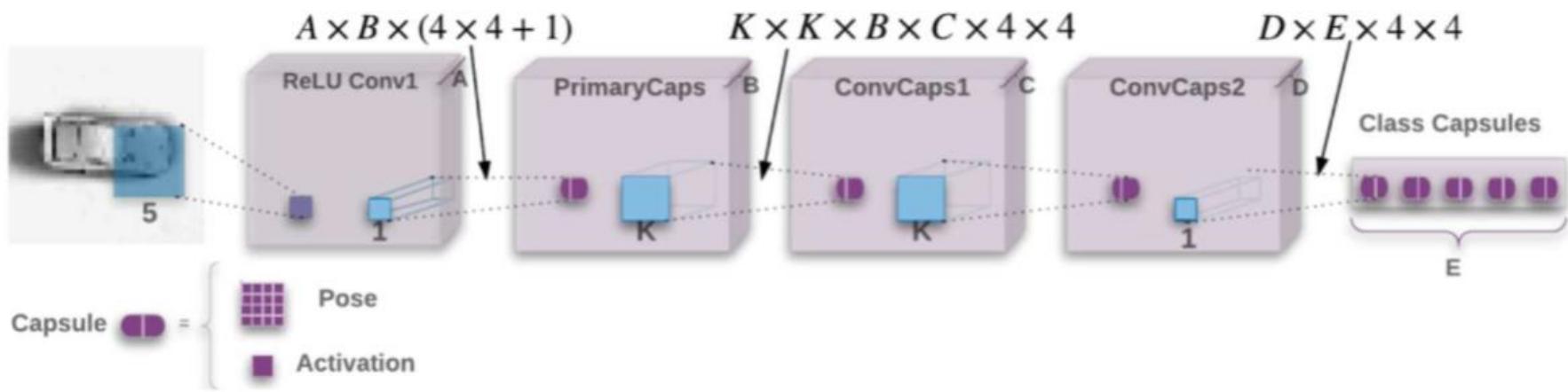


A Visual Representation of Capsule Connections in Dynamic Routing Between Capsules

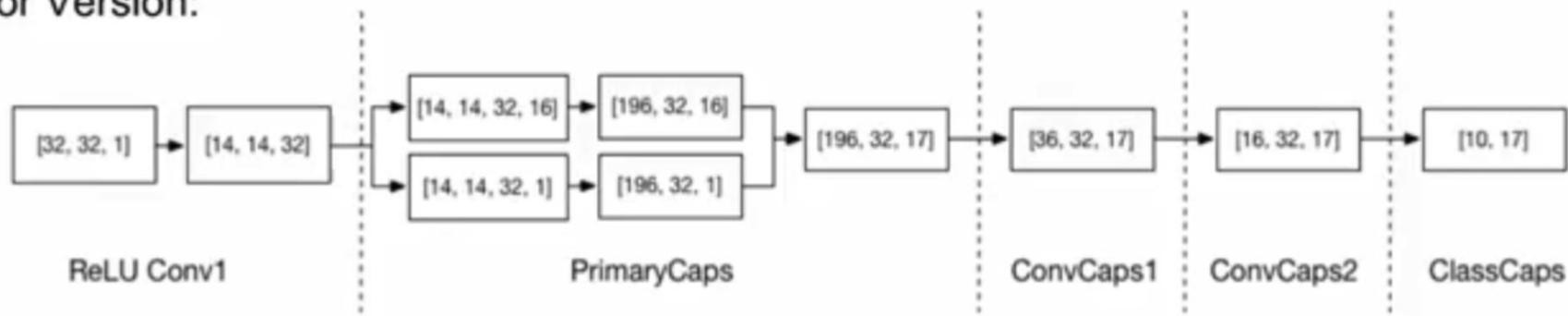


Architecture

- EM Routing on MNIST



Tensor Version:



Architecture

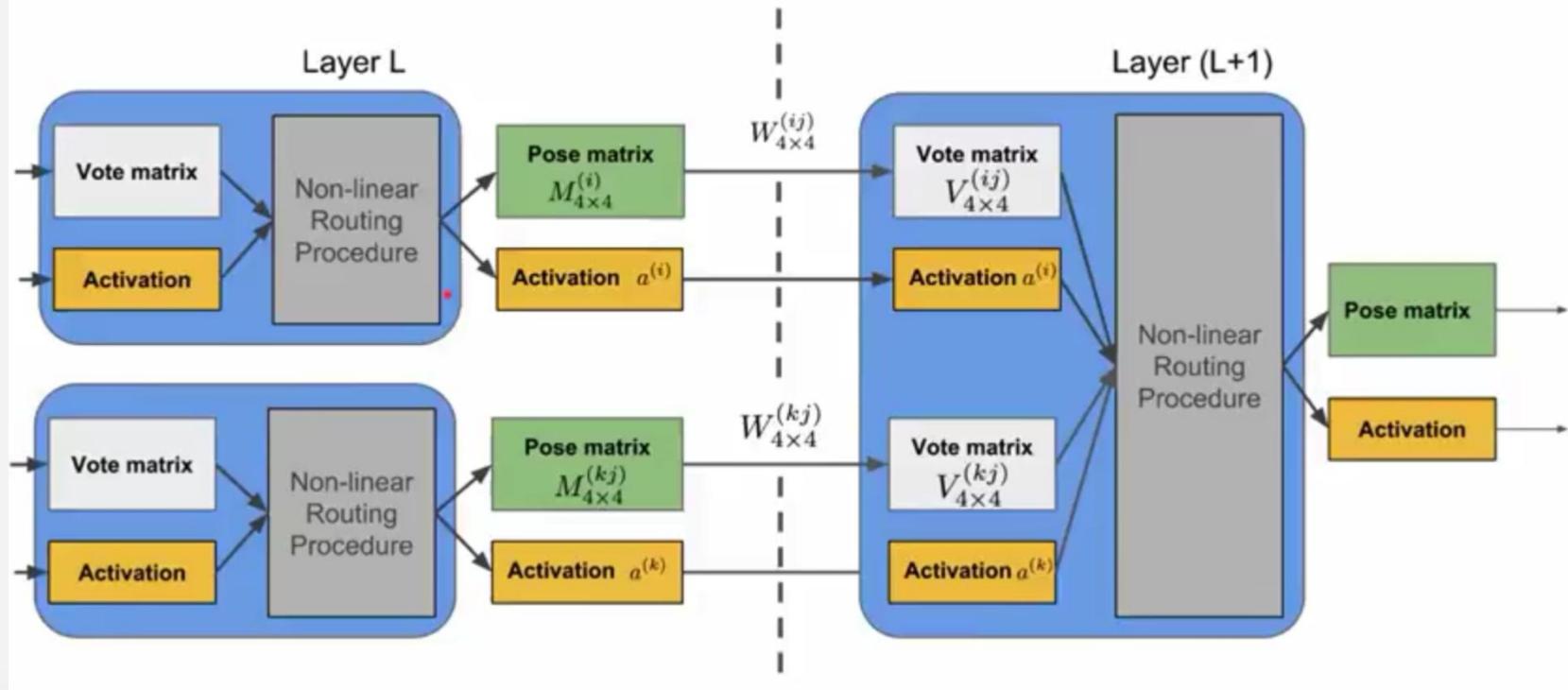
- EM Routing on MNIST
 - <https://jhui.github.io/2017/11/14/Matrix-Capsules-with-EM-routing-Capsule-Network/>

Layer Name	Apply	Output shape
MNist image		28, 28, 1
ReLU Conv1	Regular Convolution (CNN) layer using 5x5 kernels with 32 output channels, stride 2 and padding	14, 14, 32
PrimaryCaps	Modified convolution layer with 1x1 kernels, strides 1 with padding and outputting 32 capsules. Requiring 32x32x(4x4+1) parameters.	pose (14, 14, 32, 4, 4), activations (14, 14, 32)
ConvCaps1	Capsule convolution with 3x3 kernels, strides 2 and no padding. Requiring 3x3x32x32x4x4 parameters.	poses (6, 6, 32, 4, 4), activations (6, 6, 32)
ConvCaps2	Capsule convolution with 3x3 kernels, strides 1 and no padding	poses (4, 4, 32, 4, 4), activations (4, 4, 32)
Class Capsules	Capsule with 1x1 kernel. Requiring 32x10x4x4 parameters.	poses (10, 4, 4), activations (10)

Routing Method

- EM Routing

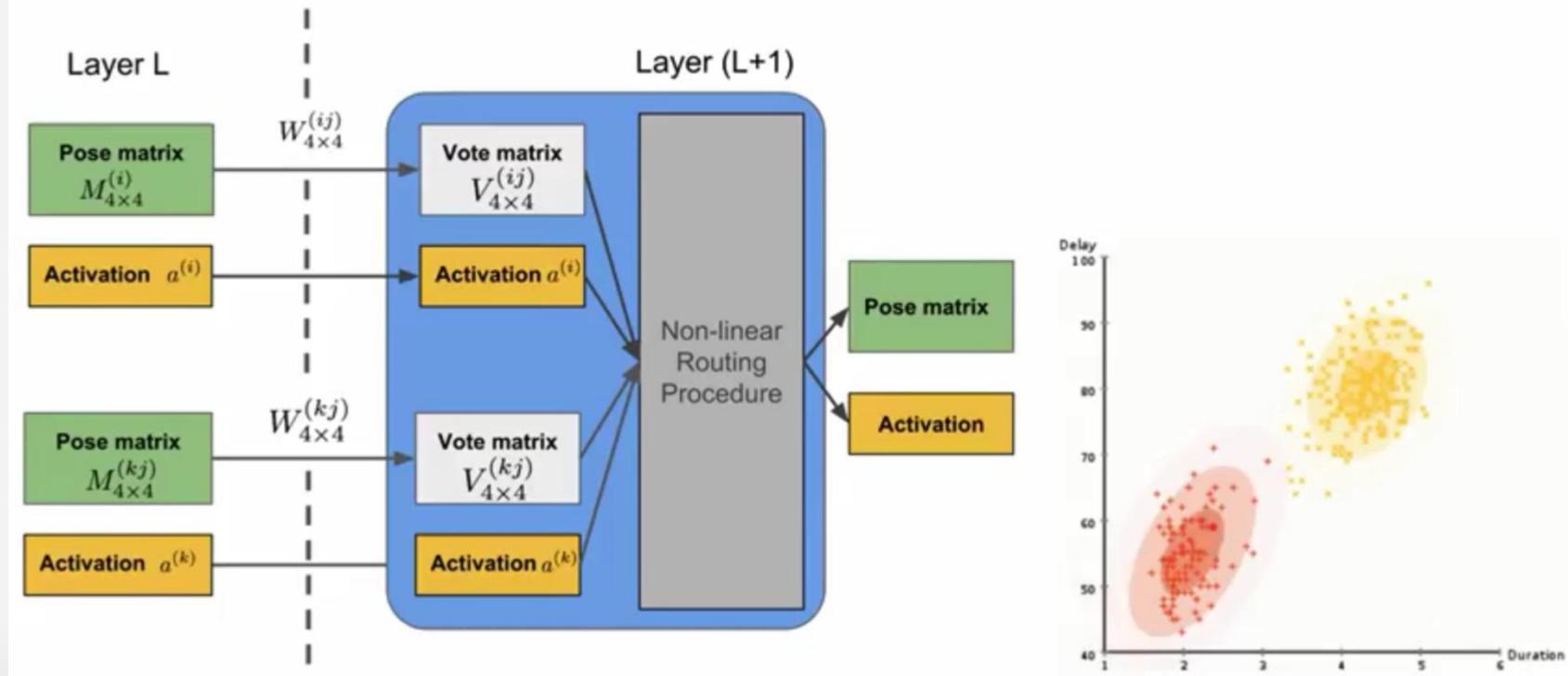
(Matrix) Capsule Network Blueprint



Routing Method

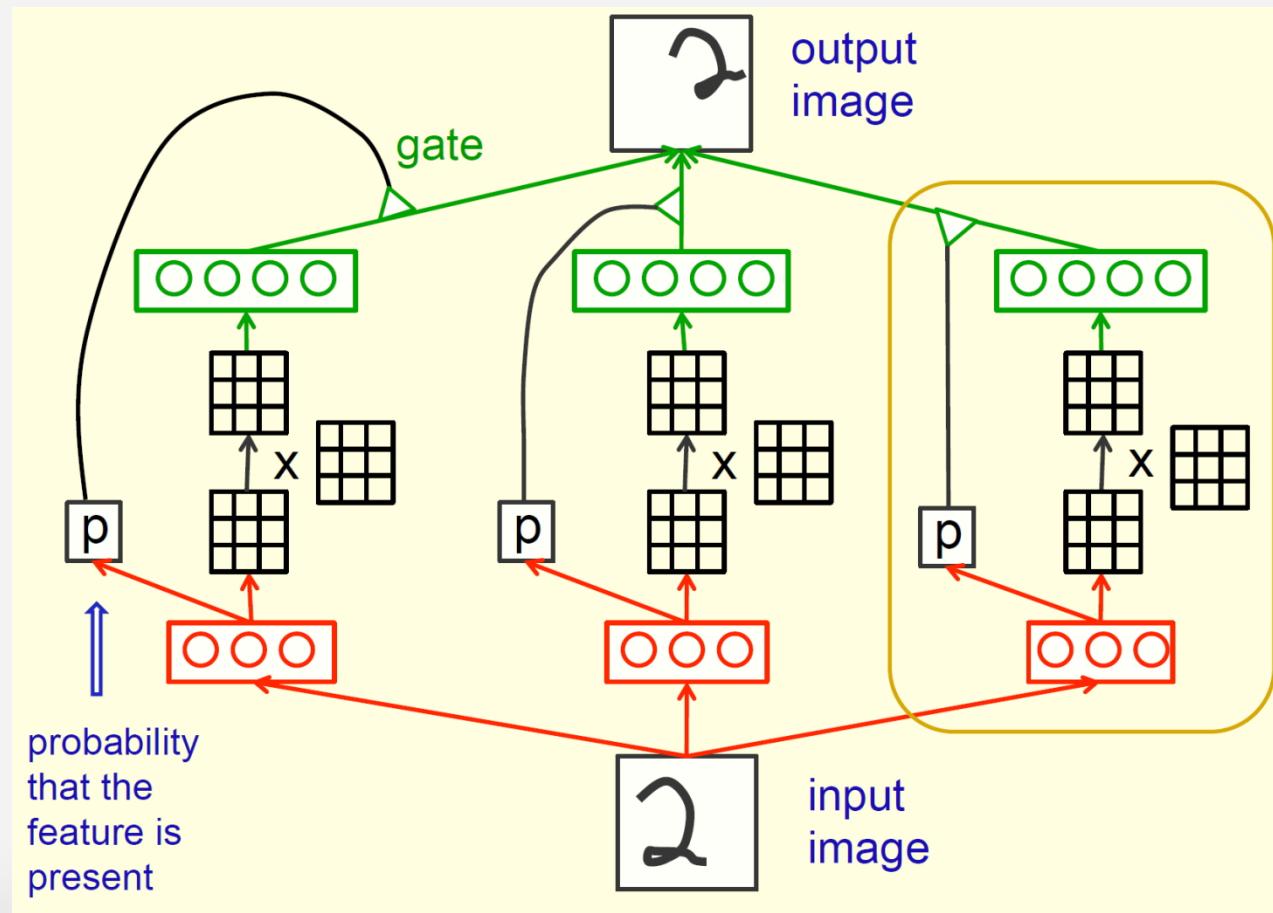
- EM Routing

Routing by EM Clustering (GMM)



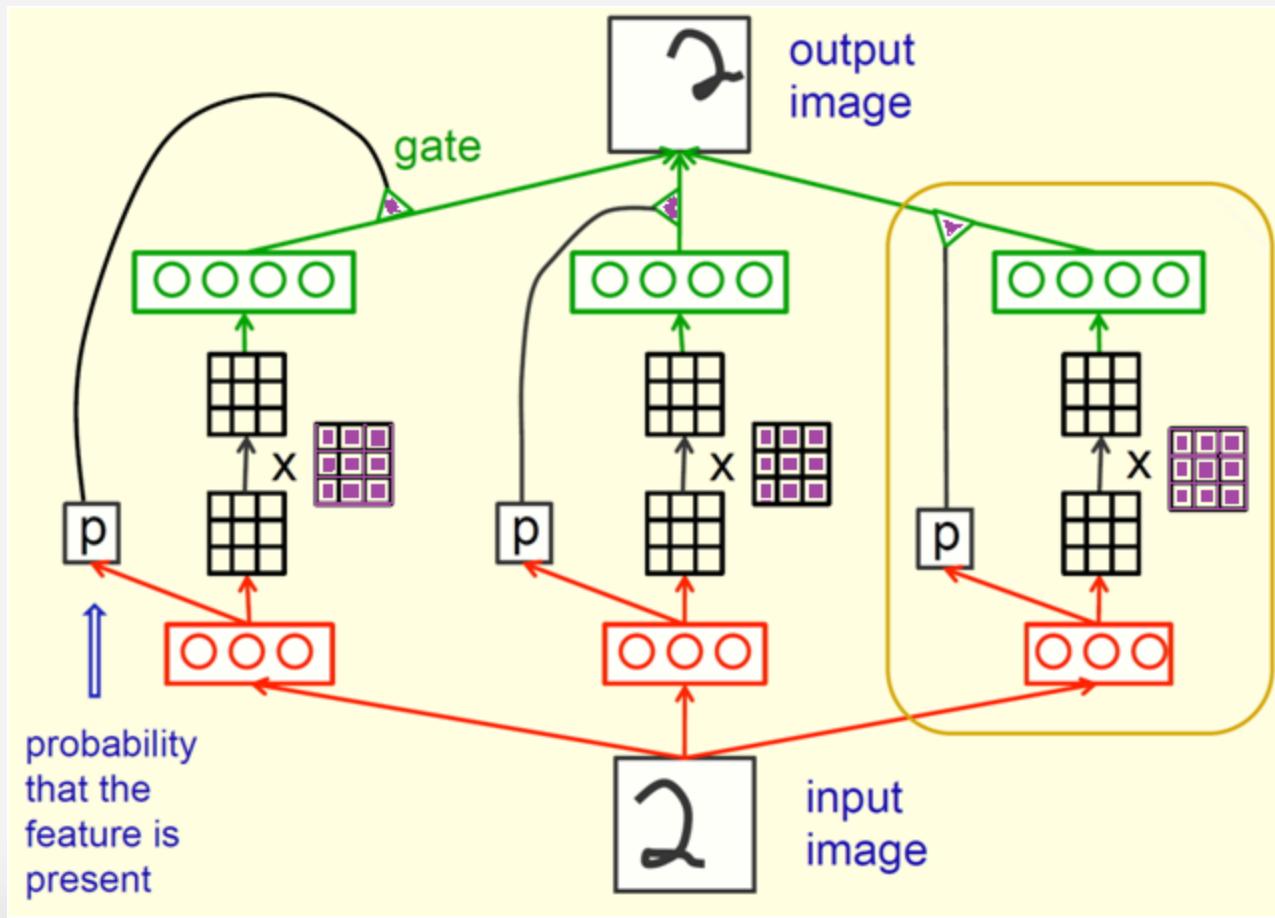
EM Routing Method

- Picture from Transforming Auto-Encoder



EM Routing Method

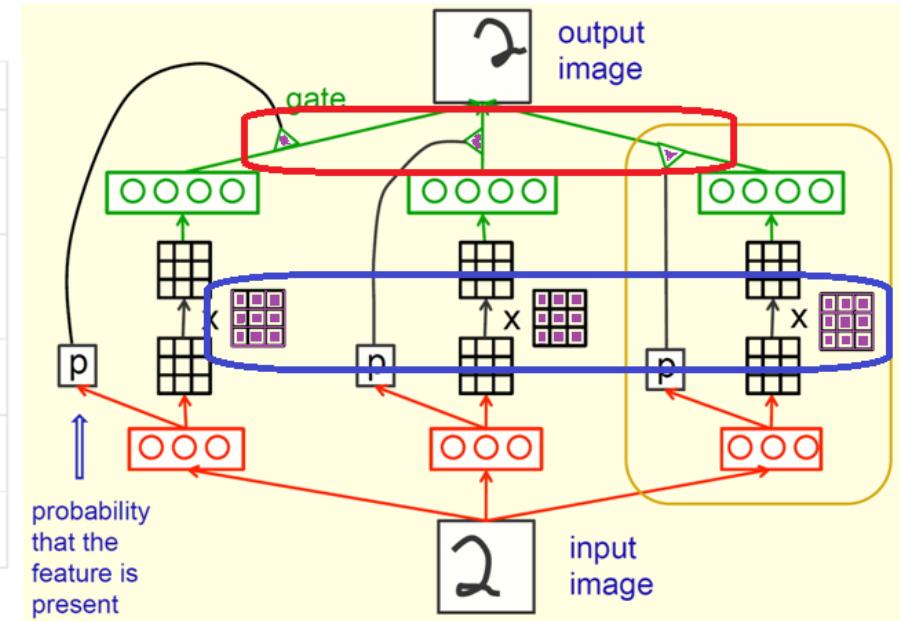
- Picture from Transforming Auto-Encoder



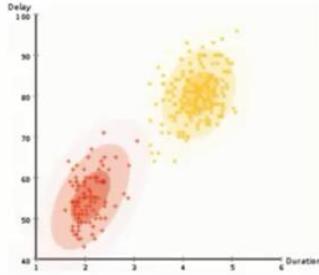
EM Routing Method

- Picture from Transforming Auto-Encoder

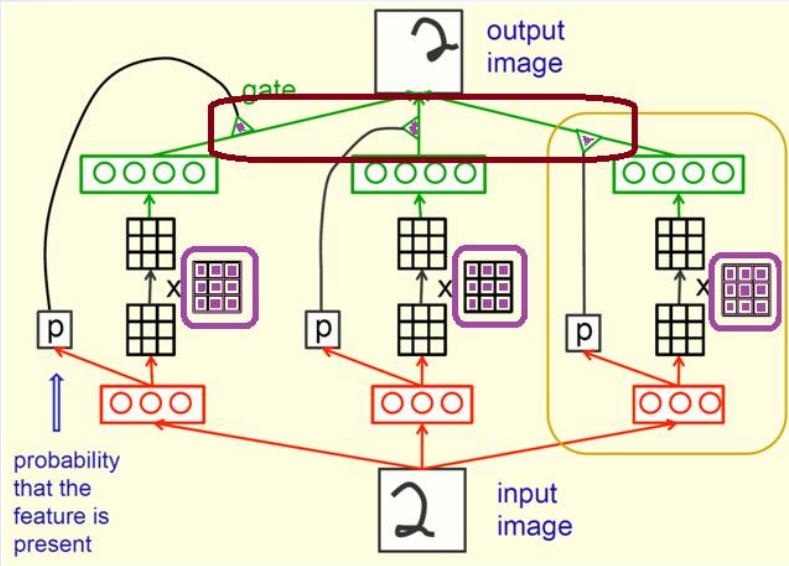
Layer Name	Apply	Output shape
MNist image		28, 28, 1
ReLU Conv1	Regular Convolution (CNN) layer using 5x5 kernels with 32 output channels, stride 2 and padding	14, 14, 32
PrimaryCaps	Modified convolution layer with 1x1 kernels, strides 1 with padding and outputting 32 capsules. Requiring $32 \times 32 \times (4 \times 4 + 1)$ parameters.	poses (14, 14, 32, 4, 4), activations (14, 14, 32)
ConvCaps1	Capsule convolution with 3x3 kernels, strides 2 and no padding. Requiring $3 \times 3 \times 32 \times 32 \times 4 \times 4$ parameters.	poses (6, 6, 32, 4, 4), activations (6, 6, 32)
ConvCaps2	Capsule convolution with 3x3 kernels, strides 1 and no padding	poses (4, 4, 32, 4, 4), activations (4, 4, 32)
Class Capsules	Capsule with 1x1 kernel. Requiring $32 \times 10 \times 4 \times 4$ parameters.	poses (10, 4, 4), activations (10)



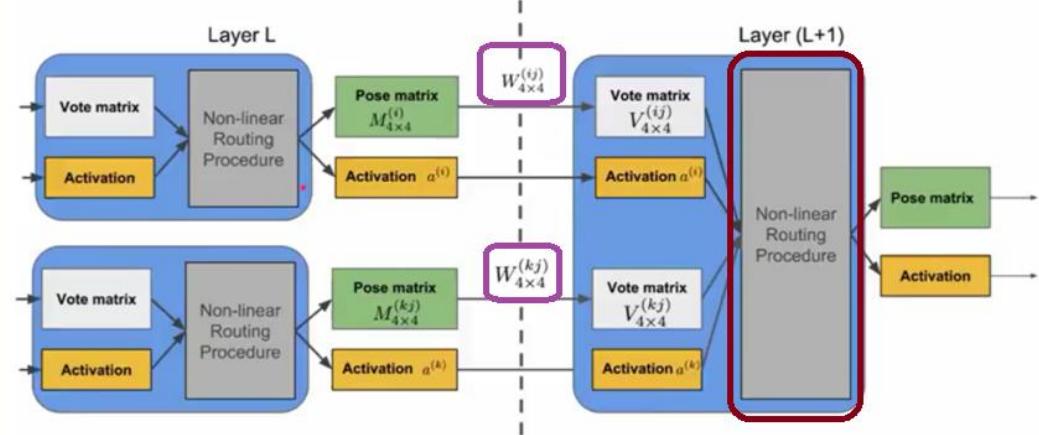
EM Routing Method



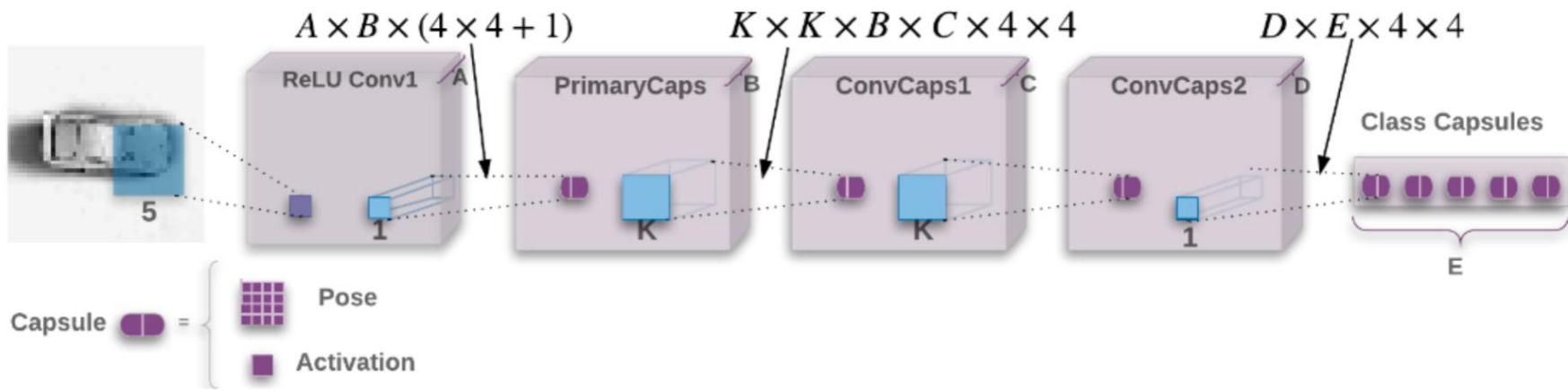
- Picture from Transforming Auto-Encoder



(Matrix) Capsule Network Blueprint



EM Routing



- Organize pose as 4×4 matrix + activation logit instead of vector. Transformation weights are a 4×4 matrix.
- Primary capsules' poses are learned linear transform of local features. Activation is sigmoid of learned weighted sum of local features.
- Convolutional capsules share transformation weights and see poses from a local kernel.

EM Routing

- Model higher layer as mixture of Gaussians that explains lower layer's poses.
- Start with uniform routing priors c_{ij} , weight by the activations of the lower capsules a_i :

$$r_{ij} = c_{ij} a_i$$

- Determine mean and variance:

$$\mu_{jh} = \frac{\sum_i r_{ij} \hat{u}_{ijh}}{\sum_i r_{ij}} \quad \sigma_{jh}^2 = \frac{\sum_i r_{ij} (\hat{u}_{ijh} - \mu_{jh})^2}{\sum_i r_{ij}} \quad \text{per pose component } h$$

- Activate upper capsule as:

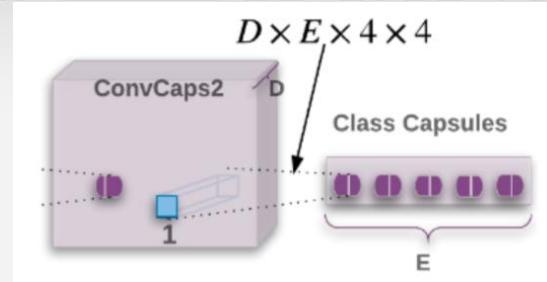
$$a_j = \text{sigmoid} \left[\lambda \left(\beta_a - \sum_h (\beta_v + \log(\sigma_{jh})) \sum_i r_{ij} \right) \right] \quad \begin{matrix} \beta_a, \beta_v \text{ learned by backprop.} \\ \lambda \text{ fixed schedule.} \end{matrix}$$

- Calculate new routing coefficients:

$$p_{ij} = \frac{1}{\sqrt{2\pi \sum_h \sigma_{ijh}^2}} e^{\frac{-\sum_h (\hat{u}_{ijh} - \mu_{jh})^2}{2\sigma_{ijh}^2}} \quad c_{ij} = \frac{a_j p_{ij}}{\sum_j a_j p_{ij}}$$

- Iterate 3 times.

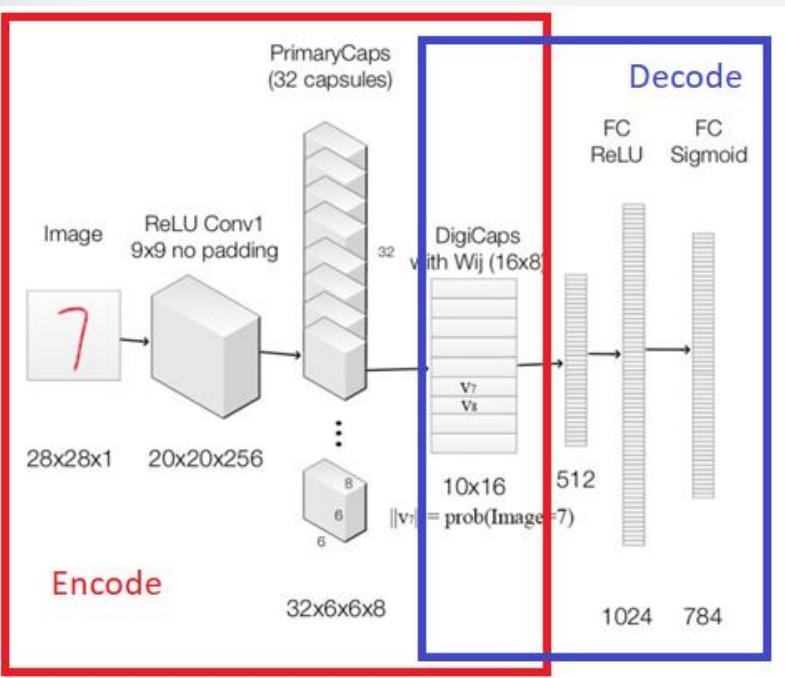
LOSS



- Connection to class capsules uses coordinate addition scheme
 - Weights shared across locations, like convolutional layer.
 - Explicit (x,y) offset of kernel added to first two elements of pose passed to class capsules.
- Spread loss:
$$L_i = \max(0, m - (a_t - a_i))^2, \quad L = \sum_{i \neq t} L_i$$
- Margin increases linearly from 0.2 to 0.9 during training.

Code Study Dynamic Routing

- <https://github.com/XifengGuo/CapsNet-Keras>



```
def CapsNet(input_shape, n_class, routings):
    """
    A Capsule Network on MNIST.
    :param input_shape: data shape, 3d, [width, height, channels]
    :param n_class: number of classes
    :param routings: number of routing iterations
    :return: Two Keras Models, the first one used for training, and the second one for evaluation.
            `eval_model` can also be used for training.
    """
    x = layers.Input(shape=input_shape)

    # Layer 1: Just a conventional Conv2D layer
    conv1 = layers.Conv2D(filters=256, kernel_size=9, strides=1, padding='valid', activation='relu', name='conv1')(x)

    # Layer 2: Conv2D layer with `squash` activation, then reshape to [None, num_capsule, dim_capsule]
    primarycaps = PrimaryCap(conv1, dim_capsule=8, n_channels=32, kernel_size=9, strides=2, padding='valid')

    # Layer 3: Capsule layer. Routing algorithm works here.
    digitcaps = CapsuleLayer(num_capsule=n_class, dim_capsule=16, routings=routings,
                             name='digitcaps')(primarycaps)

    # Layer 4: This is an auxiliary layer to replace each capsule with its length. Just to match the true label's shape.
    # If using tensorflow, this will not be necessary. :)
    out_caps = Length(name='capsnet')(digitcaps)

    # Decoder network.
    y = layers.Input(shape=(n_class,))
    masked_by_y = Mask()(digitcaps, y) # The true label is used to mask the output of capsule layer. For training
    masked = Mask()(digitcaps) # Mask using the capsule with maximal length. For prediction

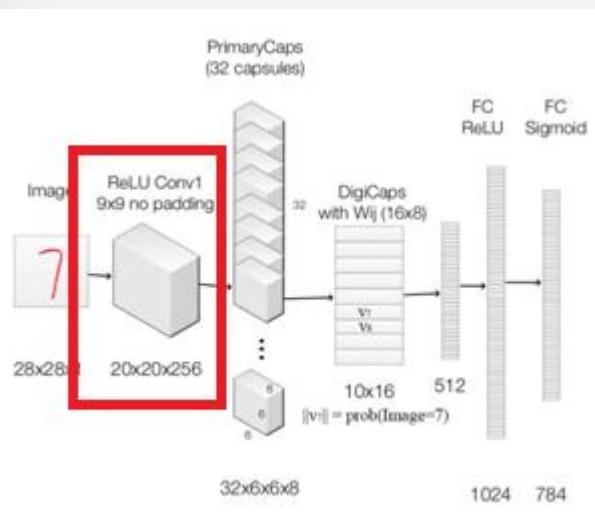
    # Shared Decoder model in training and prediction
    decoder = models.Sequential(name='decoder')
    decoder.add(layers.Dense(512, activation='relu', input_dim=16*n_class))
    decoder.add(layers.Dense(1024, activation='relu'))
    decoder.add(layers.Dense(np.prod(input_shape), activation='sigmoid'))
    decoder.add(layers.Reshape(target_shape=input_shape, name='out_recon'))

    # Models for training and evaluation (prediction)
    train_model = models.Model([x, y], [out_caps, decoder(masked_by_y)])
    eval_model = models.Model(x, [out_caps, decoder(masked)])

    # manipulate model
    noise = layers.Input(shape=(n_class, 16))
    noised_digitcaps = layers.Add()([digitcaps, noise])
    masked_noised_y = Mask()(noised_digitcaps, y)
    manipulate_model = models.Model([x, y, noise], decoder(masked_noised_y))
    return train_model, eval_model, manipulate_model
```

Code Study Dynamic Routing

- ReLu Conv1



```
def CapsNet(input_shape, n_class, routings):
    """
    A Capsule Network on MNIST.
    :param input_shape: data shape, 3d, [width, height, channels]
    :param n_class: number of classes
    :param routings: number of routing iterations
    :return: Two Keras Model, the first one used for training, and the second one for evaluation.
            'eval_model' can also be used for training.
    """

    x = layers.Input(shape=input_shape)

    # Layer 1: Just a conventional Conv2D layer
    conv1 = layers.Conv2D(filters=256, kernel_size=9, strides=1, padding='valid', activation='relu', name='conv1')(x)

    # Layer 2: Conv2D layer with 'squash' activation, then reshape to [None, num_capsule, dim_capsule]
    primarycaps = PrimaryCap(conv1, dim_capsule=8, n_channels=32, kernel_size=9, strides=2, padding='valid')

    # Layer 3: Capsule layer. Routing algorithm works here.
    digitcaps = CapsuleLayer(num_capsule=n_class, dim_capsule=16, routings=routings,
                             name='digitcaps')(primarycaps)

    # Layer 4: This is an auxiliary layer to replace each capsule with its length. Just to match the true label's shape.
    # If using tensorflow, this will not be necessary. ;)
    out_caps = Length(name='capsnet')(digitcaps)

    # Decoder network.
    y = layers.Input(shape=(n_class,))
    masked_by_y = Mask()(digitcaps, y)  # The true label is used to mask the output of capsule layer. For training
    masked = Mask()(digitcaps)  # Mask using the capsule with maximal length. For prediction

    # Shared Decoder model in training and prediction
    decoder = models.Sequential(name='decoder')
    decoder.add(layers.Dense(512, activation='relu', input_dim=16*n_class))
    decoder.add(layers.Dense(1024, activation='relu'))
    decoder.add(layers.Dense(np.prod(input_shape), activation='sigmoid'))
    decoder.add(layers.Reshape(target_shape=input_shape, name='out_recon'))

    # Models for training and evaluation (prediction)
    train_model = models.Model([x, y], [out_caps, decoder(masked_by_y)])
    eval_model = models.Model(x, [out_caps, decoder(masked)])

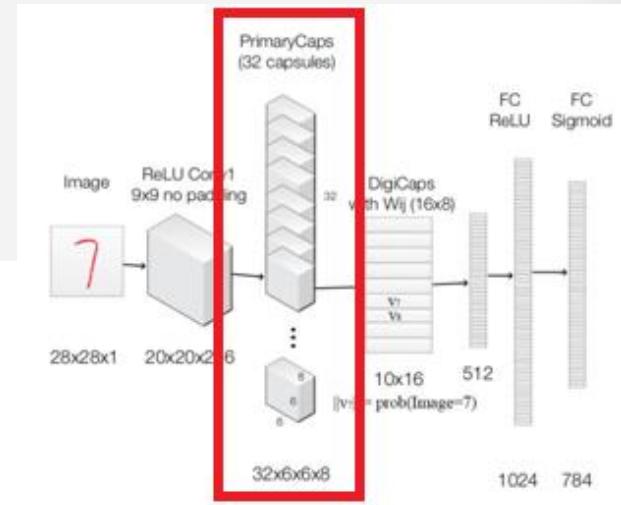
    # manipulate model
    noise = layers.Input(shape=(n_class, 16))
    noised_digitcaps = layers.Add()([digitcaps, noise])
    masked_noised_y = Mask()(noised_digitcaps, y)
    manipulate_model = models.Model([x, y, noise], decoder(masked_noised_y))
    return train_model, eval_model, manipulate_model
```

Code Study Dynamic Routing

- PrimaryCaps

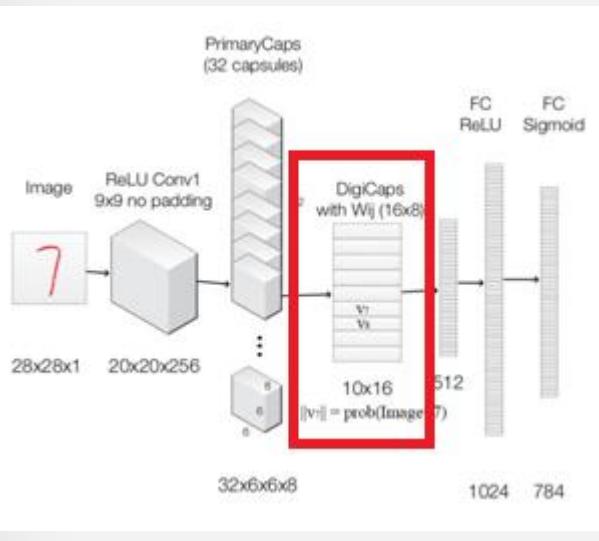
```
def PrimaryCap(inputs, dim_capsule, n_channels, kernel_size, strides, padding):
    """
    Apply Conv2D `n_channels` times and concatenate all capsules
    :param inputs: 4D tensor, shape=[None, width, height, channels]
    :param dim_capsule: the dim of the output vector of capsule
    :param n_channels: the number of types of capsules
    :return: output tensor, shape=[None, num_capsule, dim_capsule]
    """
    output = layers.Conv2D(filters=dim_capsule*n_channels, kernel_size=kernel_size, strides=strides, padding=padding,
                          name='primarycap_conv2d')(inputs)
    outputs = layers.Reshape(target_shape=[-1, dim_capsule], name='primarycap_reshape')(output)
    return layers.Lambda(squash, name='primarycap_squash')(outputs)

def squash(vectors, axis=-1):
    """
    The non-linear activation used in Capsule. It drives the length of a large vector to near 1 and small vector to 0
    :param vectors: some vectors to be squashed, N-dim tensor
    :param axis: the axis to squash
    :return: a Tensor with same shape as input vectors
    """
    s_squared_norm = K.sum(K.square(vectors), axis, keepdims=True)
    scale = s_squared_norm / (1 + s_squared_norm) / K.sqrt(s_squared_norm + K.epsilon())
    return scale * vectors
```



Code Study Dynamic Routing

- DigiCaps



Procedure I Routing algorithm.

```

1: procedure ROUTING( $\hat{u}_{j|i}, r, l$ )
2:   for all capsule  $i$  in layer  $l$  and capsule  $j$  in layer  $(l+1)$ :  $b_{ij} \leftarrow 0$ .
3:   for  $r$  iterations do
4:     for all capsule  $i$  in layer  $l$ :  $c_i \leftarrow \text{softmax}(b_i)$ 
5:     for all capsule  $j$  in layer  $(l+1)$ :  $s_j \leftarrow \sum_i c_{ij} \hat{u}_{j|i}$ 
6:     for all capsule  $j$  in layer  $(l+1)$ :  $v_j \leftarrow \text{squash}(s_j)$ 
7:     for all capsule  $i$  in layer  $l$  and capsule  $j$  in layer  $(l+1)$ :  $b_{ij} \leftarrow b_{ij} + \hat{u}_{j|i} \cdot v_j$ 
return  $v_j$ 
```

```

# inputs_tiled.shape=[None, num_capsule, input_num_capsule, input_dim_capsule]
inputs_tiled = K.tile(inputs_expand, [1, self.num_capsule, 1, 1])

# Compute `inputs * W` by scanning inputs_tiled on dimension 0.
# x.shape=[num_capsule, input_num_capsule, input_dim_capsule]
# W.shape=[num_capsule, input_num_capsule, dim_capsule, input_dim_capsule]
# Regard the first two dimensions as `batch` dimension,
# then matmul: [input_dim_capsule] x [dim_capsule, input_dim_capsule]^T -> [dim_capsule].
# inputs_hat.shape = [None, num_capsule, input_num_capsule, dim_capsule]
inputs_hat = K.map_fn(lambda x: K.batch_dot(x, self.W, [2, 3]), elems=inputs_tiled)

# Begin: Routing algorithm -----
# The prior for coupling coefficient, initialized as zeros.
# b.shape = [None, self.num_capsule, self.input_num_capsule].
b = tf.zeros(shape=[K.shape(inputs_hat)[0], self.num_capsule, self.input_num_capsule])

assert self.routings > 0, 'The routings should be > 0.'
for i in range(self.routings):
    # c.shape=[batch_size, num_capsule, input_num_capsule]
    c = tf.nn.softmax(b, dim=1)

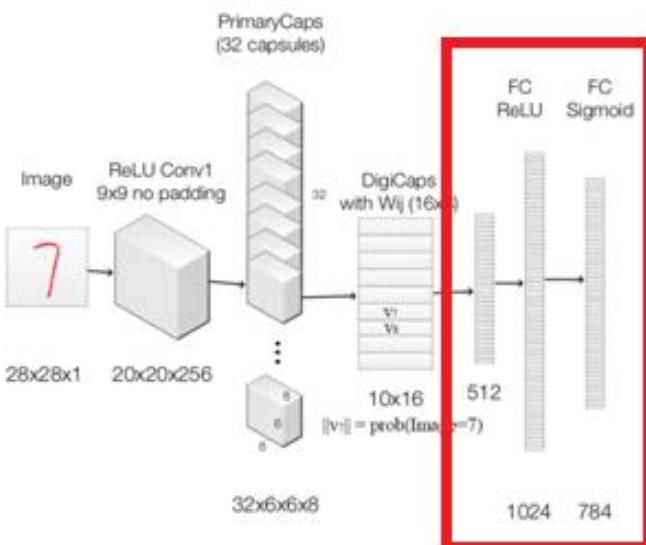
    # c.shape = [batch_size, num_capsule, input_num_capsule]
    # inputs_hat.shape=[None, num_capsule, input_num_capsule, dim_capsule]
    # The first two dimensions as `batch` dimension,
    # then matmul: [input_num_capsule] x [input_num_capsule, dim_capsule] -> [dim_capsule].
    # outputs.shape=[None, num_capsule, dim_capsule]
    outputs = squash(K.batch_dot(c, inputs_hat, [2, 2])) # [None, 10, 16]

if i < self.routings - 1:
    # outputs.shape = [None, num_capsule, dim_capsule]
    # inputs_hat.shape=[None, num_capsule, input_num_capsule, dim_capsule]
    # The first two dimensions as `batch` dimension,
    # then matmul: [dim_capsule] x [input_num_capsule, dim_capsule]^T -> [input_num_capsule].
    # b.shape=[batch_size, num_capsule, input_num_capsule]
    b += K.batch_dot(outputs, inputs_hat, [2, 3])

# End: Routing algorithm -----
```

Code Study Dynamic Routing

- Decode



```
def CapsNet(input_shape, n_class, routings):
    """
    A Capsule Network on MNIST.
    :param input_shape: data shape, 3d, (width, height, channels)
    :param n_class: number of classes
    :param routings: number of routing iterations
    :returns: Two Keras Models, the first one used for training, and the second one for evaluation.
    """
    x = layers.Input(shape=input_shape)

    # Layer 1: Just a conventional Conv2D layer
    conv1 = layers.Conv2D(filters=256, kernel_size=9, strides=1, padding='valid', activation='relu', name='conv1')(x)

    # Layer 2: Conv2D layer with 'squash' activation, then reshape to [None, num_capsule, dim_capsule]
    primarycaps = PrimaryCap(conv1, dim_capsule=8, n_channels=32, kernel_size=9, strides=2, padding='valid')

    # Layer 3: Capsule layer. Routing algorithm works here.
    digitcaps = CapsuleLayer(num_capsules=n_class, dim_capsule=16, routings=routings,
                             name='digitcaps')(primarycaps)

    # Layer 4: This is an auxiliary layer to replace each capsule with its length. Just to match the true label's shape.
    # If using tensorflow, this will not be necessary. ;)
    out_caps = Length(name='capsnet')(digitcaps)

    # Decoder network.
    y = layers.Input(shape=(n_class,))
    masked_by_y = Mask()([digitcaps, y]) # The true label is used to mask the output of capsule layer. For training
    masked = Mask()(digitcaps) # Mask using the capsule with maximal length. For prediction

    # Shared Decoder model in training and prediction
    decoder = models.Sequential(name='decoder')
    decoder.add(layers.Dense(512, activation='relu', input_dim=16*n_class))
    decoder.add(layers.Dense(1024, activation='relu'))
    decoder.add(layers.Dense(np.prod(input_shape), activation='sigmoid'))
    decoder.add(layers.Reshape(target_shape=input_shape, name='out_recon'))

    # Models for training and evaluation (prediction)
    train_model = models.Model([x, y], [out_caps, decoder(masked_by_y)])
    eval_model = models.Model(x, [out_caps, decoder(masked)])

    # manipulate model
    noise = layers.Input(shape=(n_class, 16))
    noised_digitcaps = layers.Add()([digitcaps, noise])
    masked_noised_y = Mask()([noised_digitcaps, y])
    manipulate_model = models.Model([x, y, noise], decoder(masked_noised_y))

    return train_model, eval_model, manipulate_model
```

Code Study Dynamic Routing

- Training Loss
 - Margin Loss

```
def margin_loss(y_true, y_pred):  
    """  
        Margin loss for Eq. (4). When y_true[i, :] contains not just one `1`, this loss should work too. Not test it.  
    :param y_true: [None, n_classes]  
    :param y_pred: [None, num_capsule]  
    :return: a scalar loss value.  
    """  
  
    L = y_true * K.square(K.maximum(0., 0.9 - y_pred)) + \  
        0.5 * (1 - y_true) * K.square(K.maximum(0., y_pred - 0.1))  
  
    return K.mean(K.sum(L, 1))
```

Loss function (Margin loss)

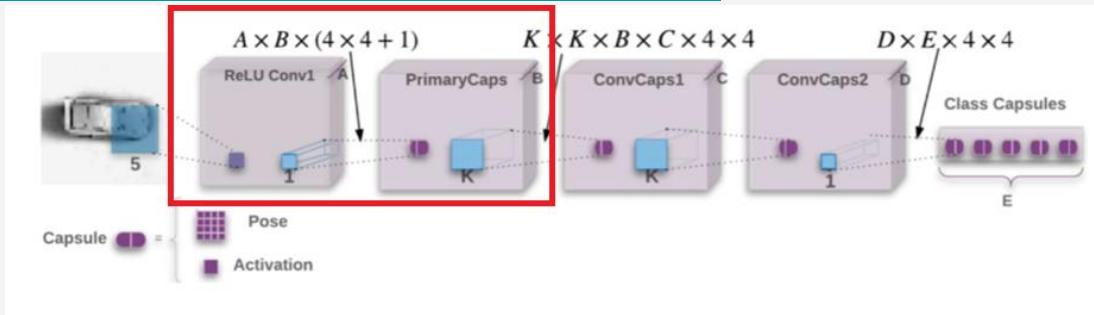
In the paper:
 $m^- = 0.1$
 $m^+ = 0.9$
 $\lambda = 0.5$

In our example, we want to detect multiple digits in a picture. Capsules use a separate margin loss L_c for each category c digit present in the picture:

$$L_c = T_c \max(0, m^+ - \|v_c\|)^2 + \lambda(1 - T_c) \max(0, \|v_c\| - m^-)^2$$

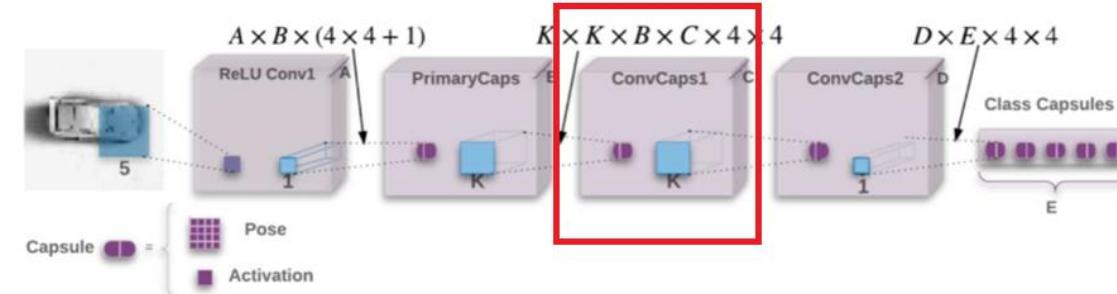
Code Study EM Routing

- <https://github.com/www0wwwjs1/Matrix-Capsules-EM-Tensorflow>



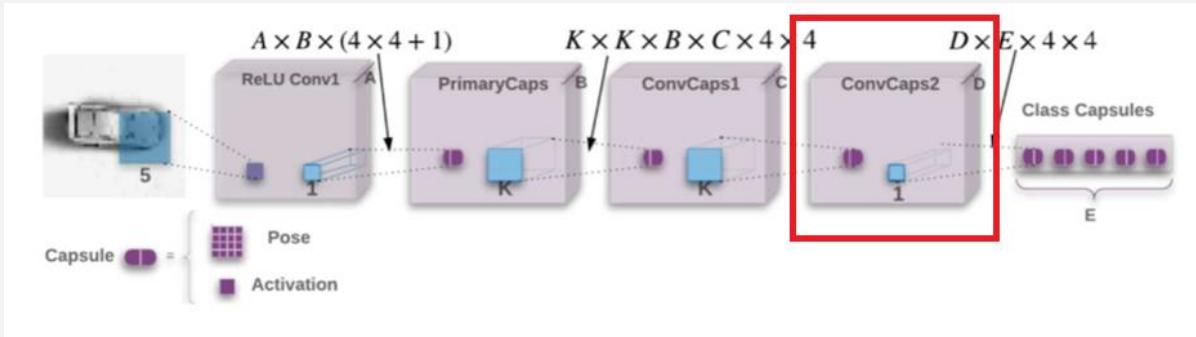
```
with tf.variable_scope('relu_conv1') as scope:  
    output = slim.conv2d(input, num_outputs=cfg.A, kernel_size=[  
        5, 5], stride=2, padding='VALID', scope=scope, activation_fn=tf.nn.relu)  
    data_size = int(np.floor((data_size - 4) / 2))  
  
    assert output.get_shape() == [cfg.batch_size, data_size, data_size, cfg.A]  
    tf.logging.info('conv1 output shape: {}'.format(output.get_shape()))  
  
with tf.variable_scope('primary_caps') as scope:  
    pose = slim.conv2d(output, num_outputs=cfg.B * 16,  
                      kernel_size=[1, 1], stride=1, padding='VALID', scope=scope, activation_fn=None)  
    activation = slim.conv2d(output, num_outputs=cfg.B, kernel_size=[  
        1, 1], stride=1, padding='VALID', scope='primary_caps/activation', activation_fn=tf.nn.sigmoid)  
    pose = tf.reshape(pose, shape=[cfg.batch_size, data_size, data_size, cfg.B, 16])  
    activation = tf.reshape(  
        activation, shape=[cfg.batch_size, data_size, data_size, cfg.B, 1])  
    output = tf.concat([pose, activation], axis=4)  
    output = tf.reshape(output, shape=[cfg.batch_size, data_size, data_size, -1])  
    assert output.get_shape() == [cfg.batch_size, data_size, data_size, cfg.B * 17]  
    tf.logging.info('primary capsule output shape: {}'.format(output.get_shape()))
```

Code Study EM Routing



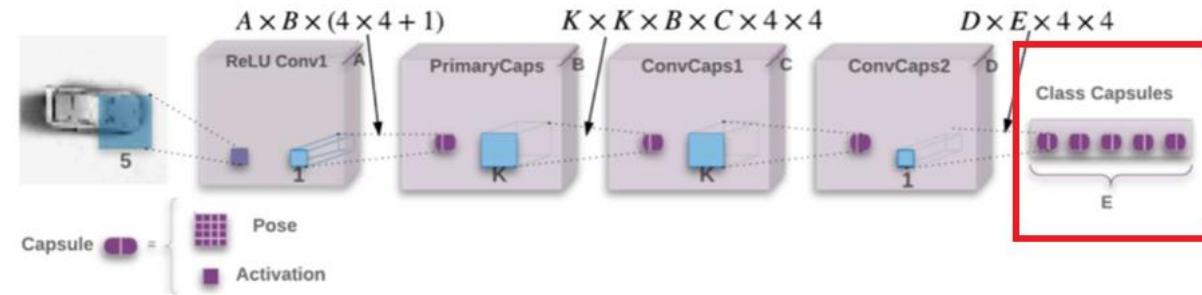
```
with tf.variable_scope('conv_caps1') as scope:  
    output = kernel_tile(output, 3, 2)  
    data_size = int(np.floor((data_size - 2) / 2))  
    output = tf.reshape(output, shape=[cfg.batch_size *  
                                         data_size * data_size, 3 * 3 * cfg.B, 17])  
    activation = tf.reshape(output[:, :, 16], shape=[  
                                         cfg.batch_size * data_size * data_size, 3 * 3 * cfg.B, 1])  
  
    with tf.variable_scope('v') as scope:  
        votes = mat_transform(output[:, :, :16], cfg.C, weights_regularizer, tag=True)  
        tf.logging.info('conv cap 1 votes shape: {}'.format(votes.get_shape()))  
  
    with tf.variable_scope('routing') as scope:  
        miu, activation, _ = em_routing(votes, activation, cfg.C, weights_regularizer)  
        tf.logging.info('conv cap 1 miu shape: {}'.format(miu.get_shape()))  
        tf.logging.info('conv cap 1 activation before reshape: {}'.format(  
            activation.get_shape()))  
  
    pose = tf.reshape(miu, shape=[cfg.batch_size, data_size, data_size, cfg.C, 16])  
    tf.logging.info('conv cap 1 pose shape: {}'.format(pose.get_shape()))  
    activation = tf.reshape(  
        activation, shape=[cfg.batch_size, data_size, data_size, cfg.C, 1])  
    tf.logging.info('conv cap 1 activation after reshape: {}'.format(  
        activation.get_shape()))  
    output = tf.reshape(tf.concat([pose, activation], axis=4), [  
        cfg.batch_size, data_size, data_size, -1])  
    tf.logging.info('conv cap 1 output shape: {}'.format(output.get_shape()))
```

Code Study EM Routing



```
with tf.variable_scope('conv_caps2') as scope:  
    output = kernel_tile(output, 3, 1)  
    data_size = int(np.floor((data_size - 2) / 1))  
    output = tf.reshape(output, shape=[cfg.batch_size *  
                                         data_size * data_size, 3 * 3 * cfg.C, 17])  
    activation = tf.reshape(output[:, :, 16], shape=[  
                                         cfg.batch_size * data_size * data_size, 3 * 3 * cfg.C, 1])  
  
    with tf.variable_scope('v') as scope:  
        votes = mat_transform(output[:, :, :16], cfg.D, weights_regularizer)  
        tf.logging.info('conv cap 2 votes shape: {}'.format(votes.get_shape()))  
  
    with tf.variable_scope('routing') as scope:  
        miu, activation, _ = em_routing(votes, activation, cfg.D, weights_regularizer)  
  
    pose = tf.reshape(miu, shape=[cfg.batch_size * data_size * data_size, cfg.D, 16])  
    tf.logging.info('conv cap 2 pose shape: {}'.format(pose.get_shape()))  
    activation = tf.reshape(  
        activation, shape=[cfg.batch_size * data_size * data_size, cfg.D, 1])  
    tf.logging.info('conv cap 2 activation shape: {}'.format(activation.get_shape()))
```

Code Study EM Routing



```
with tf.variable_scope('class_caps') as scope:  
    with tf.variable_scope('v') as scope:  
        votes = mat_transform(pose, num_classes, weights_regularizer)  
  
        assert votes.get_shape() == [cfg.batch_size * data_size *  
                                     data_size, cfg.D, num_classes, 16]  
        tf.logging.info('class cap votes original shape: {}'.format(votes.get_shape()))  
  
        coord_add = np.reshape(coord_add, newshape=[data_size * data_size, 1, 1, 2])  
        coord_add = np.tile(coord_add, [cfg.batch_size, cfg.D, num_classes, 1])  
        coord_add_op = tf.constant(coord_add, dtype=tf.float32)  
  
        votes = tf.concat([coord_add_op, votes], axis=3)  
        tf.logging.info('class cap votes coord add shape: {}'.format(votes.get_shape()))  
  
    with tf.variable_scope('routing') as scope:  
        miu, activation, test2 = em_routing(  
            votes, activation, num_classes, weights_regularizer)  
        tf.logging.info(  
            'class cap activation shape: {}'.format(activation.get_shape()))  
        tf.summary.histogram(name="class_cap_routing_hist",  
                            values=test2)  
  
    output = tf.reshape(activation, shape=[  
        cfg.batch_size, data_size, data_size, num_classes])
```

Code Study EM Routing

- Loss Function

```
# spread loss
output1 = tf.reshape(output, shape=[cfg.batch_size, 1, num_class])
y = tf.expand_dims(y, axis=2)
at = tf.matmul(output1, y)
"""Paper eq(5)."""
loss = tf.square(tf.maximum(0., m - (at - output1)))
loss = tf.matmul(loss, 1. - y)
loss = tf.reduce_mean(loss)

# reconstruction loss
# pose_out = tf.reshape(tf.matmul(pose_out, y, transpose_a=True), shape=[cfg.batch_size, -1])
pose_out = tf.reshape(tf.multiply(pose_out, y), shape=[cfg.batch_size, -1])
tf.logging.info("decoder input value dimension:{}".format(pose_out.get_shape()))

with tf.variable_scope('decoder'):
    pose_out = slim.fully_connected(pose_out, 512, trainable=True, weights_regularizer=tf.contrib.layers.l2_regularizer(5e-04))
    pose_out = slim.fully_connected(pose_out, 1024, trainable=True, weights_regularizer=tf.contrib.layers.l2_regularizer(5e-04))
    pose_out = slim.fully_connected(pose_out, data_size * data_size,
                                    trainable=True, activation_fn=tf.sigmoid, weights_regularizer=tf.contrib.layers.l2_regularizer(5e-04))

    x = tf.reshape(x, shape=[cfg.batch_size, -1])
    reconstruction_loss = tf.reduce_mean(tf.square(pose_out - x))

if cfg.weight_reg:
    # regularization loss
    regularization = tf.get_collection(tf.GraphKeys.REGULARIZATION_LOSSES)
    # loss+0.0005*reconstruction_loss+regularization#
    loss_all = tf.add_n([loss] + [0.0005 * data_size* data_size * reconstruction_loss] + regularization)
else:
    loss_all = tf.add_n([loss] + [0.0005 * data_size* data_size * reconstruction_loss])
```

Code Study EM Routing

• EM Routing

```

for iters in range(cfg.iter_routing):
    # if iters == cfg.iter_routing-1:

        # e-step
        if iters == 0:
            r = tf.constant(np.ones([batch_size, caps_num_i, caps_num_c], dtype=np.float32) / caps_num_c)
        else:
            # Contributor: Yunzhi Shi
            # log and exp here provide higher numerical stability especially for bigger number of iterations
            log_p_c_h = -tf.log(tf.sqrt(sigma_square)) - \
                        tf.square(votes_in - miu) / (2 * sigma_square)
            log_p_c_h = log_p_c_h - \
                        tf.reduce_max(log_p_c_h, axis=[2, 3], keep_dims=True) - tf.log(10.0))
            p_c = tf.exp(tf.reduce_sum(log_p_c_h, axis=3))

            ap = p_c * tf.reshape(activation_out, shape=[batch_size, 1, caps_num_c])

            # ap = tf.reshape(activation_out, shape=[batch_size, 1, caps_num_c])

            r = ap / (tf.reduce_sum(ap, axis=2, keep_dims=True) + cfg.epsilon)

        # m-step
        r = r * activation_in
        r = r / (tf.reduce_sum(r, axis=2, keep_dims=True) + cfg.epsilon)

        r_sum = tf.reduce_sum(r, axis=1, keep_dims=True)
        rl = tf.reshape(r / (r_sum + cfg.epsilon),
                        shape=[batch_size, caps_num_i, caps_num_c, 1])

        miu = tf.reduce_sum(votes_in * rl, axis=1, keep_dims=True)
        sigma_square = tf.reduce_sum(tf.square(votes_in - miu) * rl,
                                    axis=1, keep_dims=True) + cfg.epsilon

        if iters == cfg.iter_routing-1:
            r_sum = tf.reshape(r_sum, [batch_size, caps_num_c, 1])
            cost_h = (beta_v + tf.log(tf.sqrt(tf.reshape(sigma_square,
                                                       shape=[batch_size, caps_num_c, n_channels])))) * r_sum

            activation_out = tf.nn.softmax(cfg.ac_lambda0 * (beta_a - tf.reduce_sum(cost_h, axis=2)))
        else:
            activation_out = tf.nn.softmax(r_sum)

```

Procedure 1 Routing algorithm returns **activation** and **pose** of the capsules in layer $L+1$ given the activations and votes of capsules in layer L . V_{ij}^h is the h^{th} dimension of the vote from capsule i with activation a_i in layer L to capsule j in layer $L+1$. β_a , β_v are learned discriminatively and the inverse temperature λ increases at each iteration with a fixed schedule.

```

1: procedure EM_ROUTING( $a, V$ )
2:    $\forall i \in \Omega_L, j \in \Omega_{L+1}$ :  $R_{ij} \leftarrow 1/|\Omega_{L+1}|$ 
3:   for  $t$  iterations do
4:      $\forall j \in \Omega_{L+1}$ : M-STEP( $a, R, V, j$ )
5:      $\forall i \in \Omega_L$ : E-STEP( $\mu, \sigma, a, V, i$ )
   return  $a, M$ 

```

```

1: procedure M-STEP( $a, R, V, j$ ) ▷ for one higher-level capsule
2:    $\forall i \in \Omega_L$ :  $R_{ij} \leftarrow R_{ij} * a_i$ 
3:    $\forall h$ :  $\mu_j^h \leftarrow \frac{\sum_i R_{ij} V_{ij}^h}{\sum_i R_{ij}}$ 
4:    $\forall h$ :  $(\sigma_j^h)^2 \leftarrow \frac{\sum_i R_{ij} (V_{ij}^h - \mu_j^h)^2}{\sum_i R_{ij}}$ 
5:    $cost^h \leftarrow (\beta_v + \log(\sigma_j^h)) \sum_i R_{ij}$ 
6:    $a_j \leftarrow sigmoid(\lambda(\beta_v - \sum_h cost^h))$ 

1: procedure E-STEP( $\mu, \sigma, a, V, i$ ) ▷ for one lower-level capsule
2:    $\forall j \in \Omega_{L+1}$ :  $p_j \leftarrow \frac{1}{\sqrt{\prod_h 2\pi(\sigma_j^h)^2}} e^{-\sum_h \frac{(V_{ij}^h - \mu_j^h)^2}{2(\sigma_j^h)^2}}$ 
3:    $\forall j \in \Omega_{L+1}$ :  $R_{ij} \leftarrow \frac{a_j p_j}{\sum_{u \in \Omega_{L+1}} a_u p_u}$ 

```

Experience

- <https://github.com/XifengGuo/CapsNet-Keras>

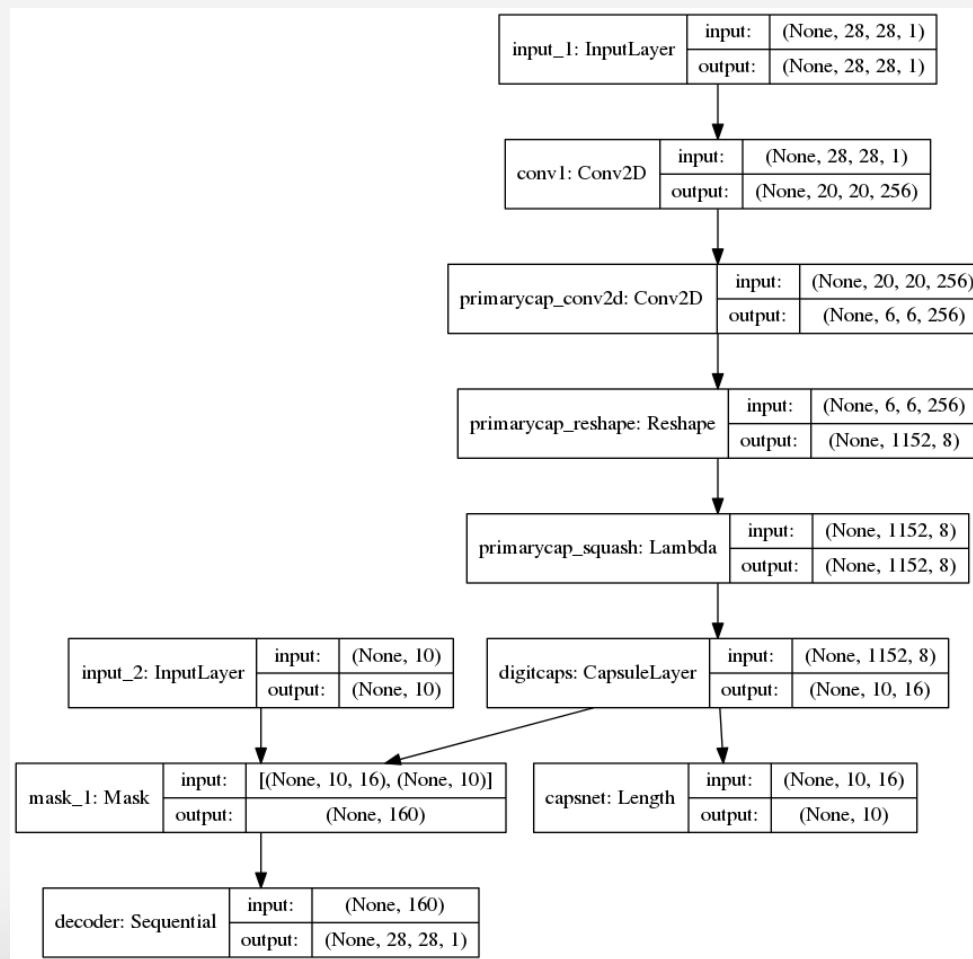
```
jovyan@jupyter-at071080:~/DynamicCapsule$ python capsulenet.py
Using TensorFlow backend.
Namespace(batch_size=100, debug=False, digit=5, epochs=50, lam_recon=0.392, lr=0.001, lr_decay=0.9, routings=3, save_dir='./result', shift_fraction=0.1, testing=False, weights=None)

Layer (type)           Output Shape        Param #     Connected to
=====
input_1 (InputLayer)    (None, 28, 28, 1)      0
conv1 (Conv2D)          (None, 20, 20, 256)   28992      input_1[0][0]
primarycap_conv2d (Conv2D) (None, 6, 6, 256)   5308672    conv1[0][0]
primarycap_reshape (Reshape) (None, 1152, 8)      0         primarycap_conv2d[0][0]
primarycap_squash (Lambda) (None, 1152, 8)      0         primarycap_reshape[0][0]
digitcaps (CapsuleLayer) (None, 10, 16)       1474560    primarycap_squash[0][0]
input_2 (InputLayer)    (None, 10)             0
mask_1 (Mask)          (None, 160)            0         digitcaps[0][0]
input_2[0][0]
capsnet (Length)        (None, 10)             0         digitcaps[0][0]
decoder (Sequential)    (None, 28, 28, 1)     1411344    mask_1[0][0]
=====
Total params: 8,215,568
Trainable params: 8,215,568
Non-trainable params: 0

2018-04-13 02:24:32.899705: I tensorflow/core/platform/cpu_feature_guard.cc:137] Your CPU supports instructions that this TensorFlow binary was not compiled to use: SSE4.1
SSE4.2 AVX AVX2 FMA
2018-04-13 02:24:33.508520: I tensorflow/core/common_runtime/gpu/gpu_device.cc:1030] Found device 0 with properties:
name: GeForce GTX 1080 Ti major: 6 minor: 1 memoryClockRate(GHz): 1.582
pciBusID: 0000:0f:00.0
totalMemory: 10.91GiB freeMemory: 10.75GiB
2018-04-13 02:24:33.508578: I tensorflow/core/common_runtime/gpu/gpu_device.cc:1120] Creating TensorFlow device (/device:GPU:0) -> (device: 0, name: GeForce GTX 1080 Ti, pci bus id: 0000:0f:00.0, compute capability: 6.1)
Epoch 1/50
599/600 [=====>.] - ETA: 0s - loss: 0.1370 - capsnet_loss: 0.1093 - decoder_loss: 0.0708 - capsnet_acc: 0.8923
Epoch 00001: val_capsnet_acc improved from -inf to 0.98640, saving model to ./result/weights-01.h5
600/600 [=====] - 147s 244ms/step - loss: 0.1369 - capsnet_loss: 0.1091 - decoder_loss: 0.0708 - capsnet_acc: 0.8925 - val_loss: 0.0433 - val_capsnet_loss: 0.0225 - val_decoder_loss: 0.0529 - val_capsnet_acc: 0.9864
Epoch 2/50
599/600 [=====>.] - ETA: 0s - loss: 0.0485 - capsnet_loss: 0.0275 - decoder_loss: 0.0536 - capsnet_acc: 0.9812
Epoch 00002: val_capsnet_acc improved from 0.98640 to 0.98930, saving model to ./result/weights-02.h5
600/600 [=====] - 143s 238ms/step - loss: 0.0485 - capsnet_loss: 0.0275 - decoder_loss: 0.0536 - capsnet_acc: 0.9812 - val_loss: 0.0332 - val_capsnet_loss: 0.0148 - val_decoder_loss: 0.0468 - val_capsnet_acc: 0.9893
Epoch 3/50
169/600 [==>.....] - ETA: 1:51 - loss: 0.0397 - capsnet_loss: 0.0207 - decoder_loss: 0.0483 - capsnet_acc: 0.9857
```

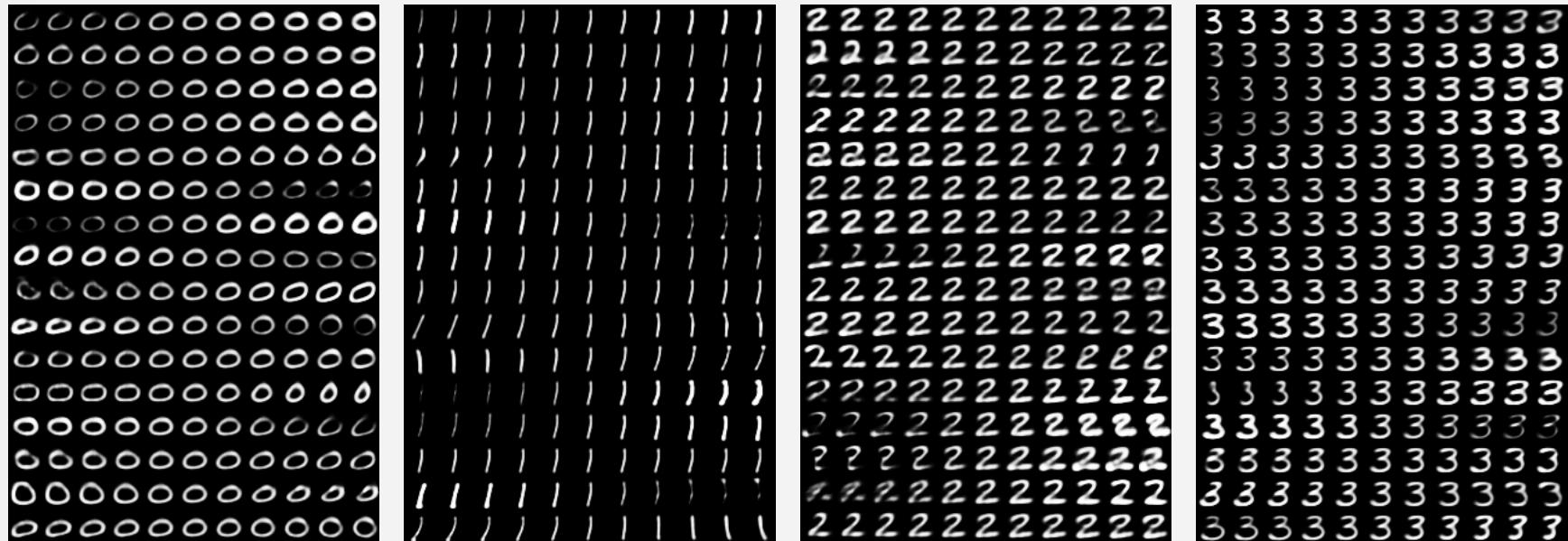
Experience

- <https://github.com/XifengGuo/CapsNet-Keras>



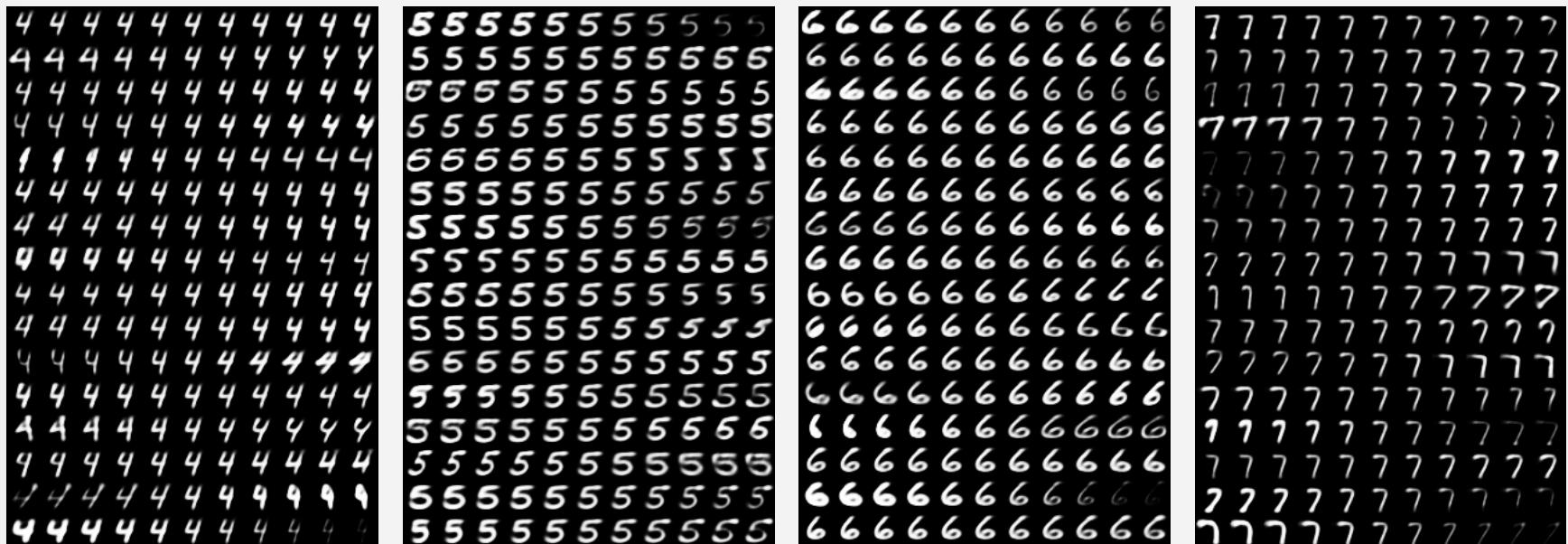
Experience

- <https://github.com/XifengGuo/CapsNet-Keras>



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epoch	capsnet_acc	capsnet_loss	decoder_loss	loss	val_capsnet_acc	val_capsnet_loss	val_decoder_loss	val_loss
0	0.892466671659	0.109148840178	0.0707501581125	0.136882901366	0.986400005817	0.0225033421349	0.0529434316233	0.0432571667805
1	0.981200010578	0.0274706723921	0.0536372451236	0.0484964718949	0.989300008416	0.0148085804627	0.0467900463939	0.0331502781063
2	0.986366676887	0.019316399664	0.0461444876405	0.0374050382897	0.991600005031	0.0131497110368	0.0408325074241	0.0291560534853
3	0.989283342262	0.0154039712976	0.0408928613303	0.0314339724866	0.991500006318	0.0118888985401	0.0360632113554	0.0260256770067
4	0.990916674435	0.0129997884319	0.0366911625055	0.0273827237853	0.990700005293	0.013381741473	0.032674016878	0.0261899557617
5	0.991150007447	0.0118292274085	0.0343199532355	0.0252826487413	0.993500005007	0.00786436403176	0.0310601744801	0.0200399522111
6	0.992233340343	0.0101946678552	0.0323827537894	0.0228887069893	0.993700005412	0.0076677835462	0.0289617005736	0.0190207698382
7	0.993033339977	0.00915096157289	0.0308871039096	0.0212587060003	0.994000005126	0.00709067733478	0.0272203556262	0.0177610563952
8	0.99395000577	0.00824728587545	0.0295962760629	0.0198490257794	0.994400004745	0.00671544760371	0.026353442464	0.0170459969202
9	0.994550005098	0.00729937177035	0.0282353789515	0.0183676400657	0.993900005221	0.00693653874652	0.0251231774315	0.0167848239699
10	0.99521667103	0.00662011678059	0.0271365647422	0.0172576498815	0.992900005579	0.00680795754477	0.0240484762751	0.0162349600391
11	0.995550004244	0.00611202797299	0.026331816949	0.016434100033	0.99430000484	0.00574103198749	0.0235015578568	0.0149536423571
12	0.996150003672	0.00553094113808	0.0256144279397	0.0155717966178	0.99370000422	0.00686147416243	0.0230121857859	0.0158822506899
13	0.996433336735	0.00502015791504	0.0249555919475	0.0148027496599	0.994600004554	0.00586726075482	0.0224781134725	0.0146786810365
14	0.996633336544	0.00469180526901	0.0244473080275	0.0142751497729	0.99590000391	0.00516301001771	0.0216513847373	0.0136503525916
15	0.996833336353	0.00436084558091	0.0239595583578	0.0137529922044	0.994500005245	0.00513398719444	0.0214218221977	0.0135313411942
16	0.99740000248	0.00396758965966	0.0234627198521	0.013164975609	0.995000004172	0.00558514707323	0.0209319275152	0.0137904624362
17	0.99740000248	0.00368685063731	0.0230618410309	0.0127270920908	0.995600004196	0.00493689138525	0.0204660956841	0.0129596007662
18	0.997566668987	0.00351604991784	0.0227407636897	0.0124304290613	0.995300004482	0.00534062215767	0.0201285806298	0.0132310255244
19	0.997883335352	0.00318453587492	0.0223999047776	0.0119652983003	0.995600004196	0.00442407563246	0.0198843458481	0.0122187390365
20	0.99805000186	0.00298910651848	0.0221229587868	0.01166130614	0.996200003624	0.00412068158922	0.0195659430139	0.0117905310588
21	0.998000001907	0.00287518299509	0.0218231462066	0.0114298561115	0.996200003624	0.00421903324181	0.0193294107262	0.0117961621052
22	0.998233335018	0.00265088861803	0.0215644397649	0.0111041487947	0.996100003719	0.00412899824444	0.0190710794087	0.0116048611933
23	0.997966668606	0.00271109613054	0.0213831856102	0.0110933046578	0.995100004673	0.00436583812031	0.0189360378496	0.0117887646984
24	0.998600001335	0.0024031641879	0.0211702859153	0.0107019160471	0.995100004077	0.00431962292765	0.0186805772036	0.0116424089344
25	0.99870000124	0.00226795530609	0.0209722044847	0.0104890592427	0.996400003433	0.00402965317771	0.0184919796232	0.0112785089668

Experience

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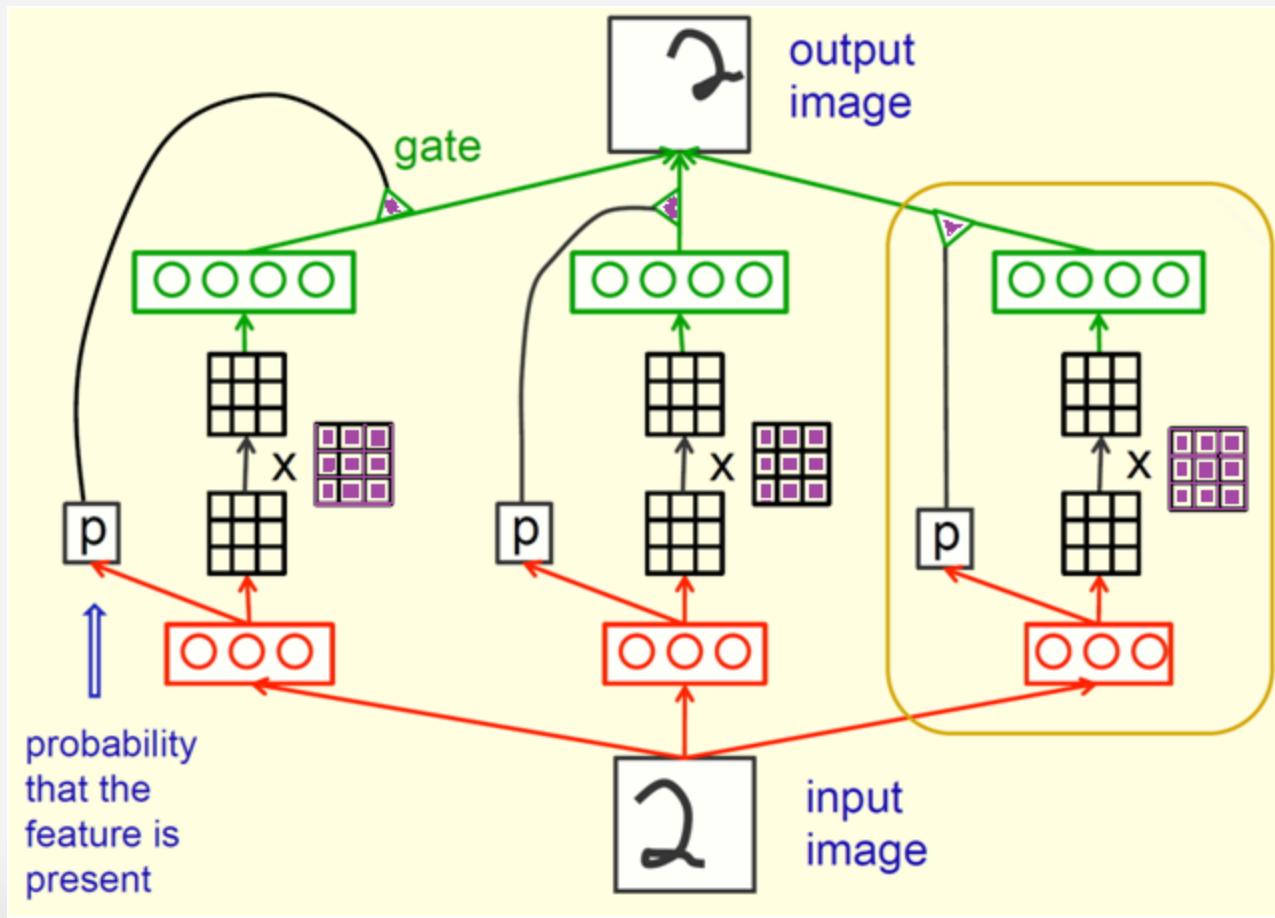
epoch	capsnet_acc	capsnet_loss	decoder_loss	loss	val_capsnet_acc	val_capsnet_loss	val_decoder_loss	val_loss
26	0.998666667938	0.00213878616829	0.0207916882914	0.0102891277491	0.996100003719	0.00419416185155	0.0183845353313	0.0114008994773
27	0.998750001192	0.0021319204799	0.0206323033789	0.0102197832071	0.996000003815	0.00397314476663	0.0182389038708	0.0111227949057
28	0.998750001192	0.00198122190386	0.020489101264	0.0100129493784	0.996300003529	0.00392191253529	0.0181614222378	0.0110411898652
29	0.998900001049	0.00189226556726	0.0203707392172	0.009877595151	0.99590000391	0.00396375482942	0.0180554731283	0.0110415000748
30	0.998900001049	0.0018603248365	0.0202827231803	0.00981115212198	0.995800004005	0.00390505666823	0.0179257639125	0.0109319559392
31	0.998983334303	0.00180153825375	0.020170000776	0.0097081783639	0.996400003433	0.00382352402803	0.0178575434536	0.0108236808889
32	0.998966667652	0.00173002508111	0.0201060889196	0.00961161173725	0.996200003624	0.00384986427661	0.0177674497571	0.0108147043874
33	0.999150000811	0.00160303286662	0.0200016955379	0.00944369732713	0.996700003147	0.00366642986288	0.0176556177624	0.010587431821
34	0.999016667604	0.00166224532279	0.0199270729162	0.00947365767788	0.996600003242	0.00364638662754	0.0176231258269	0.0105546517577
35	0.999083334208	0.00163958035269	0.019898353514	0.009439734711	0.996700003147	0.00367538379634	0.0175900329463	0.0105706765689
36	0.99913333416	0.00159540262537	0.0198342076658	0.00937041182925	0.996400003433	0.00379610536755	0.0175464352965	0.0106743077748
37	0.999116667509	0.0015783284914	0.0197679037228	0.00932734653819	0.996400003433	0.00374213233749	0.0175156023353	0.010608248366
38	0.999216667414	0.0014805961443	0.0197017338717	0.00920367560893	0.99590000391	0.00398182968838	0.0174515323341	0.0108228302235
39	0.999183334112	0.00146983555336	0.0196774502471	0.00918339584256	0.996400003433	0.00368869624186	0.017430311786	0.0105213782657
40	0.999233334064	0.00143750537921	0.0196449256316	0.00913831601152	0.996900002956	0.00366910350312	0.0173789045215	0.0104816338746
41	0.999183334112	0.00143629903909	0.0196305198005	0.00913146259418	0.996600003242	0.00359874600707	0.0173525169492	0.0104009324638
42	0.999183334112	0.00138541804232	0.0195688047229	0.00905638928836	0.996500003338	0.00362582973976	0.0173221322056	0.0104161053896
43	0.999216667414	0.00141484177555	0.019563437008	0.00908370886852	0.996200003624	0.0037017574371	0.0173072920181	0.0104862157023
44	0.999066667557	0.00149529826683	0.0195341958882	0.00915270284129	0.996300003529	0.00371963856634	0.0172774996702	0.0104924182873
45	0.999250000715	0.0013420471771	0.0194841579348	0.0089798368987	0.996500003338	0.00363574467001	0.0172553548124	0.0103998435382
46	0.999333333969	0.00129521021498	0.0194638637422	0.00892504459945	0.996300003529	0.00363931271802	0.0172398396395	0.0103973297309
47	0.999216667414	0.00136688152784	0.0194504401522	0.00899145386725	0.996500003338	0.00359818145701	0.017210362535	0.0103446434438
48	0.999266667366	0.00131019270123	0.0194419459331	0.00893143532177	0.996400003433	0.00362343545656	0.017199526038	0.0103656494571
49	0.999216667414	0.00132540212258	0.0194367229597	0.00894459730868	0.996400003433	0.00363531410995	0.0171967412252	0.0103764364542

Discuss

- Proposed Methods proposed still use **Conv2D** to extract **features** and formulate **Capsule Units**.
- And then apply **routing** algorithm to learn **part-whole relationships**.
- Not solve all invariance problem, Proposed methods are **Viewpoint-Invariant**.
- Not Solution for One-Shot or Zero Shot Learning.
- Maybe need to add **label** for features.
- Problem now assume objects are **Rigid** and maybe cause **problem** while applying on flexible object that maybe good at CNN treating as invariance. (**maybe node explosion**)

EM Routing Method

- Think about different rotation combination



Discuss

- Maybe add **flexible** or **joint** consideration in the following version.
- It's **high computing consuming** algorithm which now only apply on toy problem.
- It is clammed to reduce attack for image classification compared to CNN.
- The Capsule Network is an idea and maybe more methods will be proposed.