CNN for CV

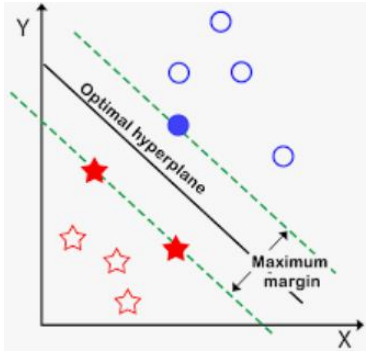
AI for CV Group
2019

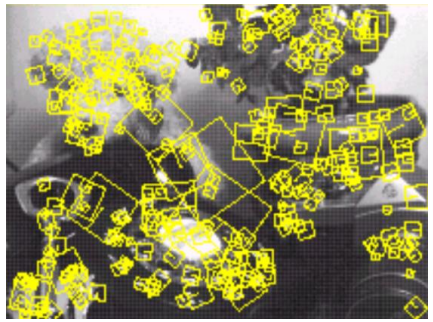
Week 10-11.
Detection

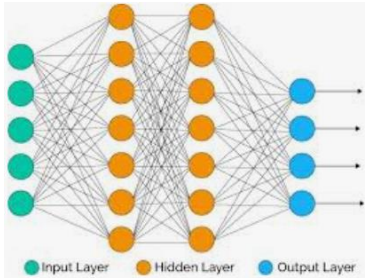
Contents:

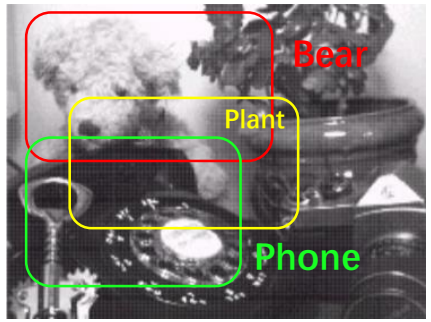
I. Two Stage Detection

Start from:









Input → Feature → Classic ML Tools → Target

Get Manually | Choose Carefully | Use Hopelessly

End up with:

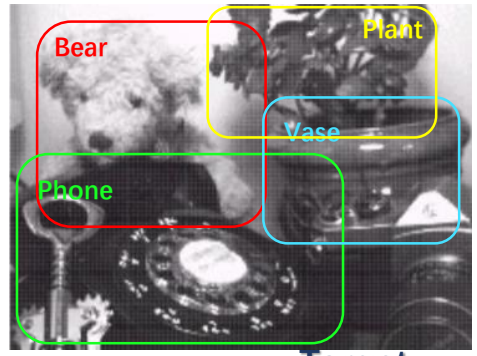
Input

Put In

CNN

Only Focus
On
This Part

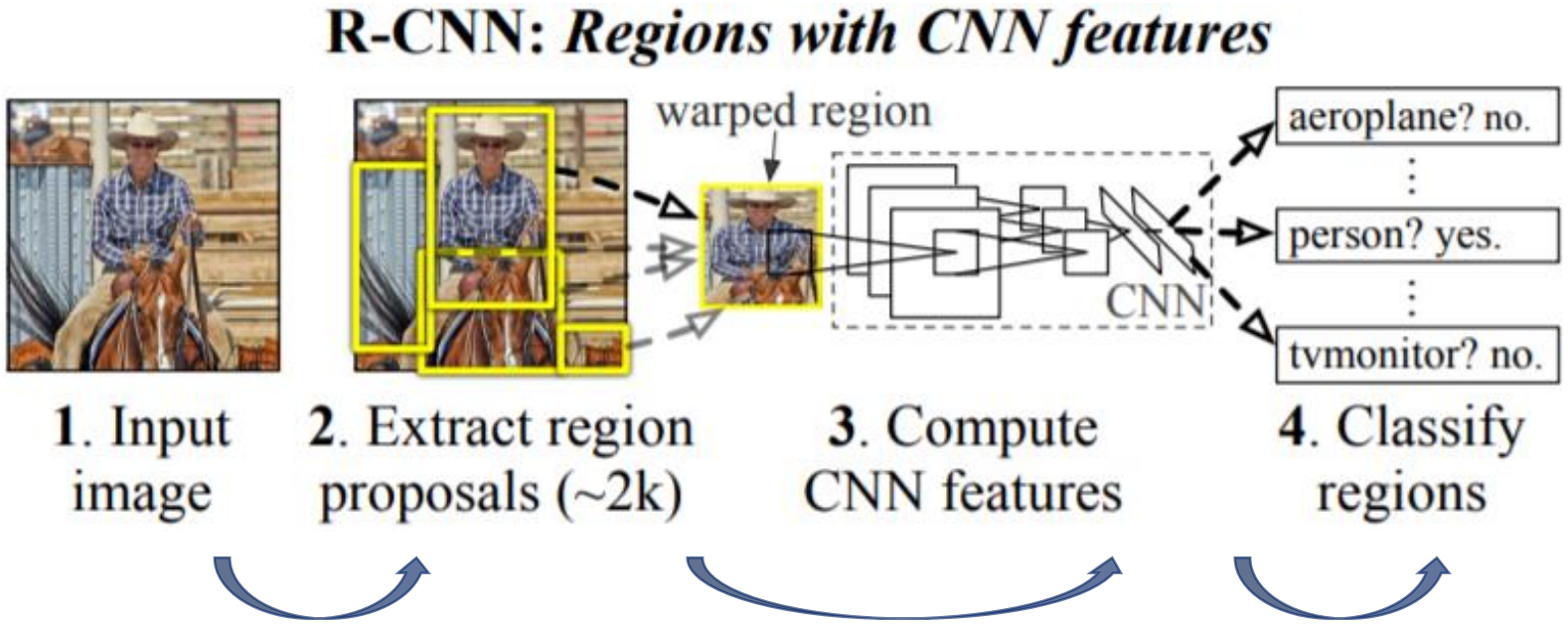
Use It



Target

I. Two Stage Detection

A. First Trial - RCNN [2014 Ross]:



A1. Region Proposal

A2. Feature Extraction

A3. Classification + Detection

A.1 Region Proposal

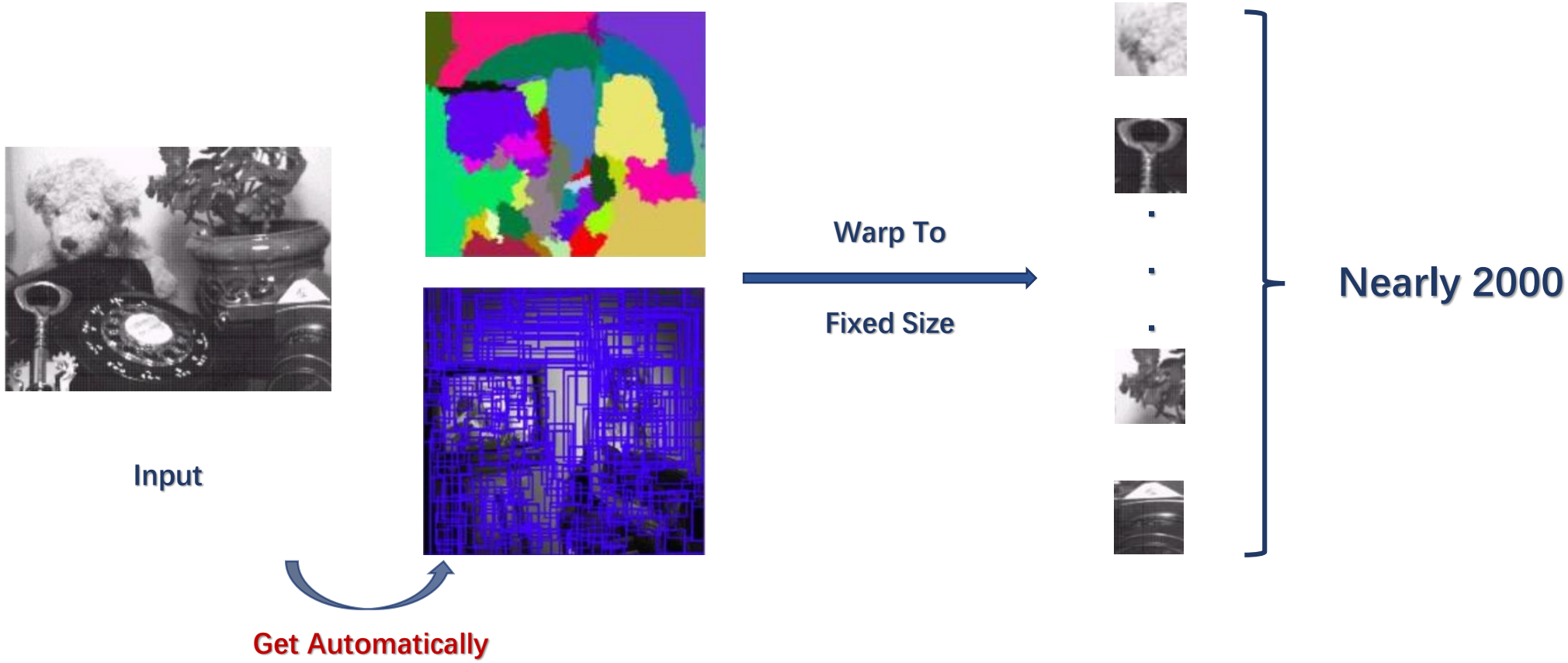
A.2 Feature Extraction

A.3 Cls + Det

I. Two Stage Detection

A. First Trial - RCNN [2014 Ross]:

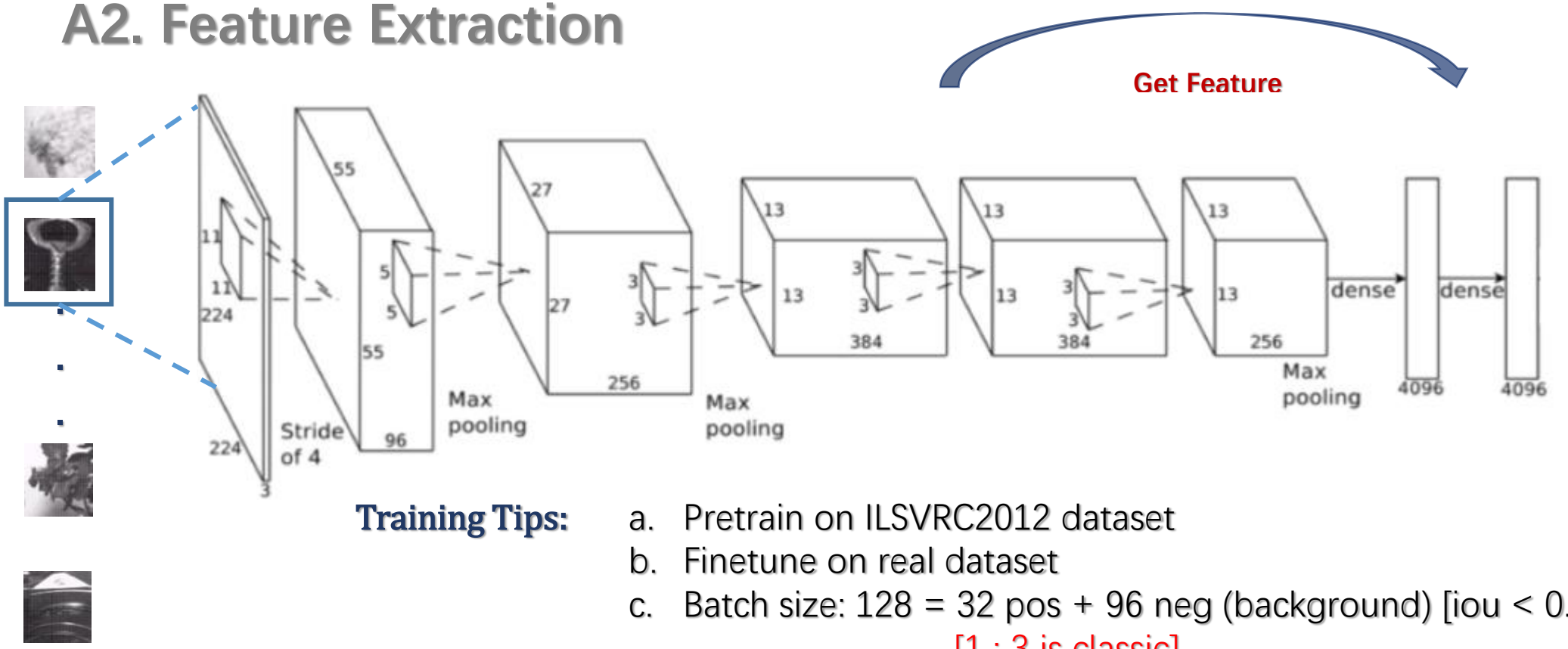
A1. Region Proposal: Selective Search



I. Two Stage Detection

A. First Trial - RCNN [2014 Ross]:

A2. Feature Extraction



Training Tips:

a. Pretrain on ILSVRC2012 dataset
b. Finetune on real dataset
c. Batch size: 128 = 32 pos + 96 neg (background) [iou < 0.5]
[1 : 3 is classic]

I. Two Stage Detection

A. First Trial - RCNN [2014 Ross]:

A3. SVM Classification + NMS + BBox Regression

a. SVM Classification

- Do classification for each class
- Pos: Ground truth
  Neg: iou < 0.3 [others ignored]

[Different from CNN part]

Q: Why iou threshold is different here comparing to training AlexNet?
A: We need more data when training CNN. But here more data may be harmful.

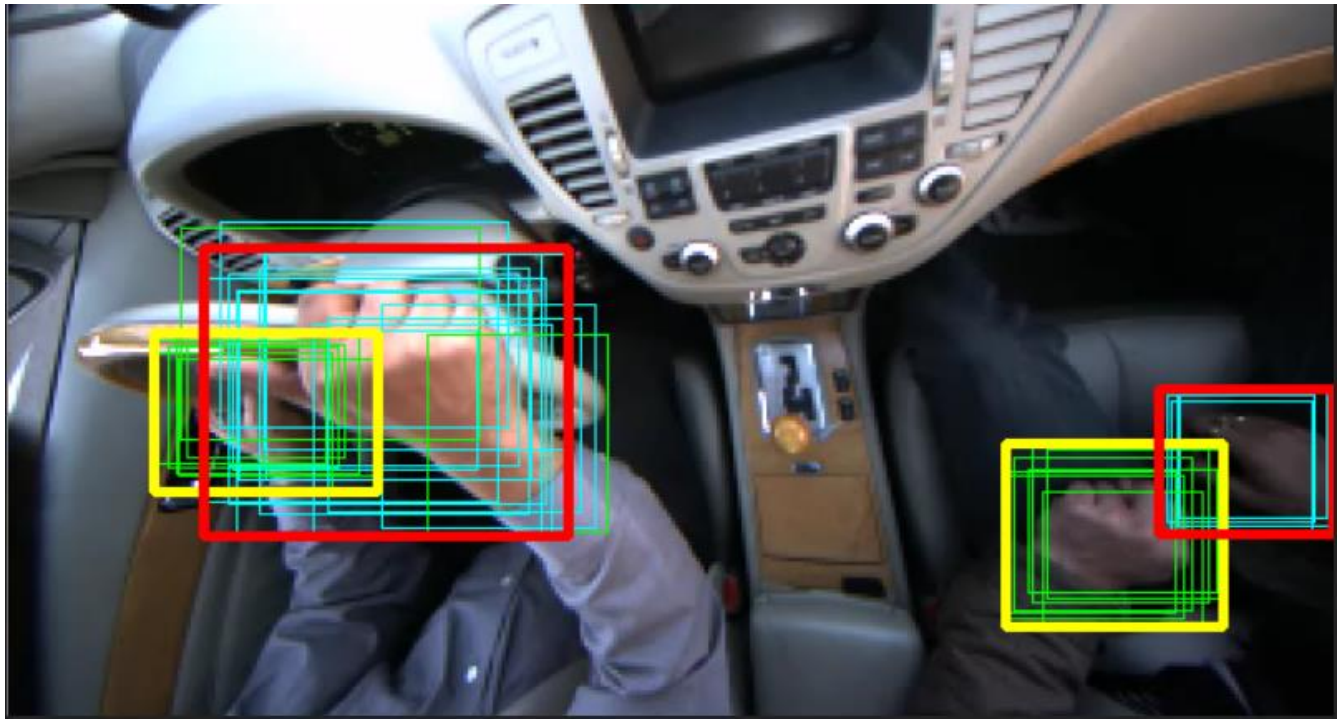
Q: Why use SVM? AlexNet has softmax at last, why not use directly?
A: AlexNet focuses on classification. Not accurate on localization
Use hard negative mining when using SVM

I. Two Stage Detection

A. First Trial - RCNN [2014 Ross]:

A3. SVM Classification + NMS + BBox Regression

b. NMS: Non-Maximum Suppression

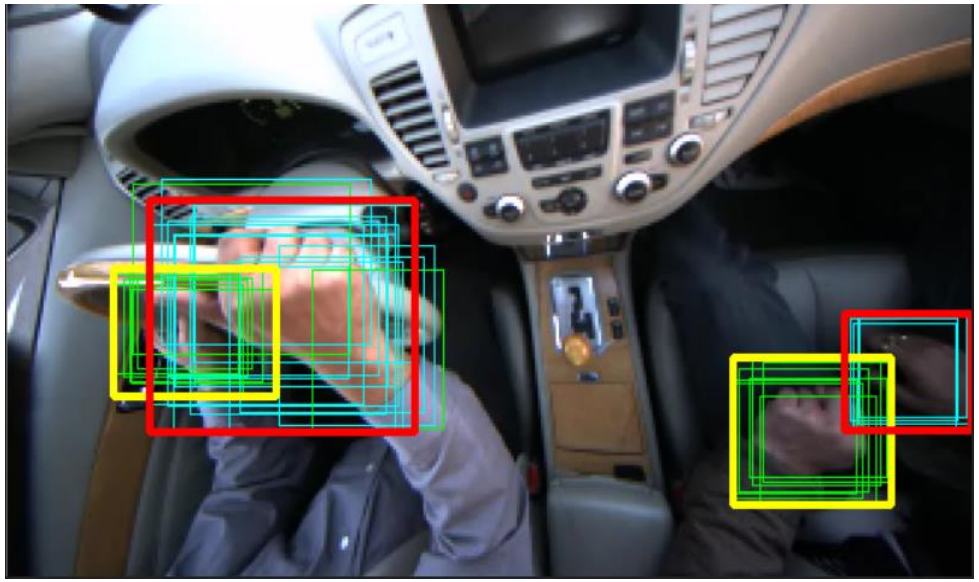


I. Two Stage Detection

A. First Trial - RCNN [2014 Ross]:

A3. SVM Classification + NMS + BBox Regression

b. NMS: Non-Maximum Suppression



- Sort bbox according to score [here class score]
- Get the 1st one. Remove those which has higher iou with it
- Then repeat the last step until there's no bbox

I. Two Stage Detection

A. First Trial - RCNN [2014 Ross]:

A3. SVM Classification + NMS + BBox Regression

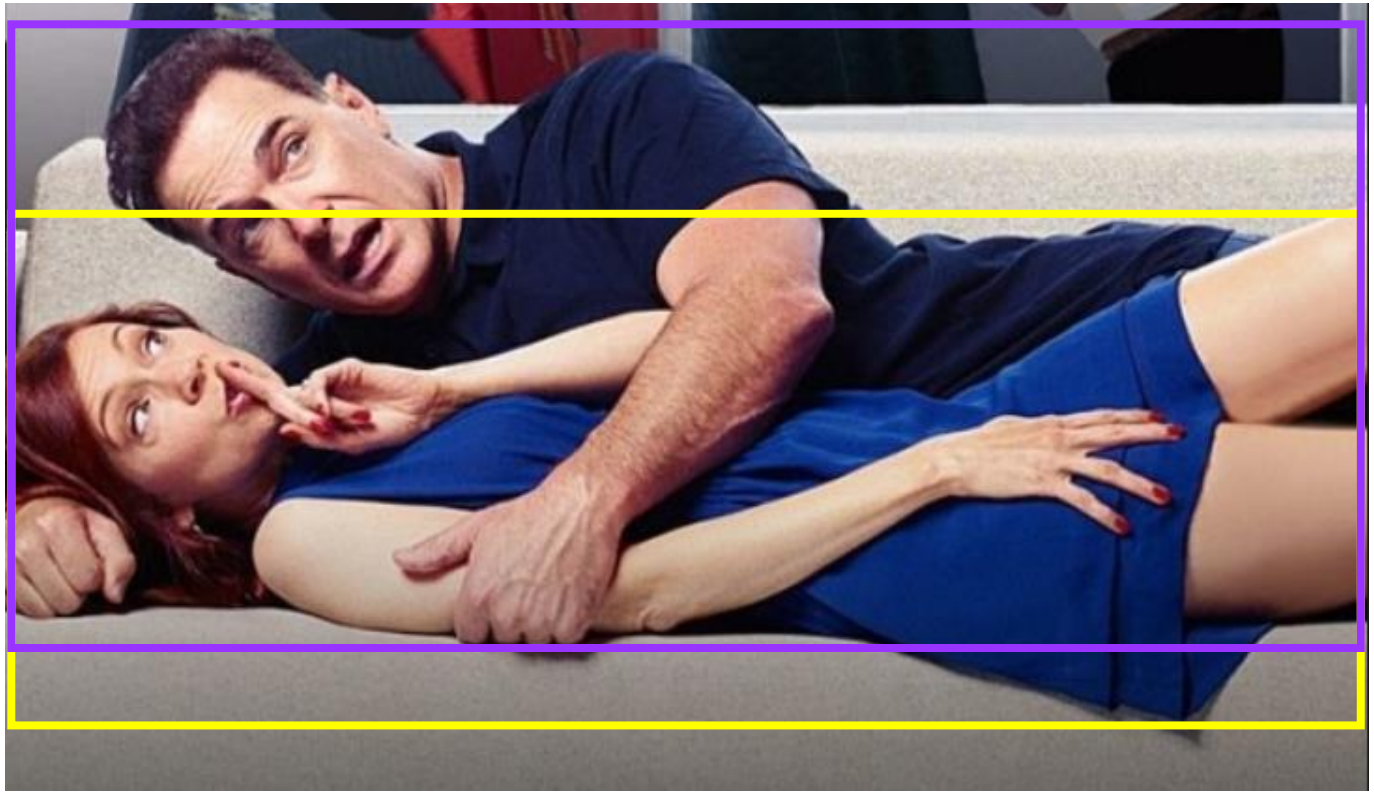
c. Bbox Regression

- Regression targets of (dx, dy, dw, dh)
- Coordinates need to be normalized
- We'll discuss in detail later

I. Two Stage Detection

A. First Trial - RCNN [2014 Ross]:

A*. Rethinking about NMS



I. Two Stage Detection

A. First Trial - RCNN [2014 Ross]:

A*. Rethinking about NMS

- If ▭ has higher score, we'll lose ▭
- If ▭ has higher score, we'll loss ▭
- That's awkward.

Let's Correct It!

I. Two Stage Detection

A. First Trial - RCNN [2014 Ross]:

A*. Rethinking about NMS

- **Brief history about NMS**
  - Traditional NMS [Here we use. Need to know how to code in C++/python]
  - Soft-NMS [2017, better to know]
  - IoU-Net [2018, Localization Confidence + PrROI Pooling, better to know]
  - Softer-NMS [2019, KL-Loss + Softer-NMS, better to know]

Important / Will cover / Remind

I. Two Stage Detection

A. First Trial - RCNN [2014 Ross]:

A*. Rethinking about NMS

- **Soft-NMS**

Input : $\mathcal{B} = \{b_1, .., b_N\}, \mathcal{S} = \{s_1, .., s_N\}, N_t$
$\mathcal{B}$ is the list of initial detection boxes
$\mathcal{S}$ contains corresponding detection scores
N_t is the NMS threshold

begin
  $\mathcal{D} \leftarrow \{\}$
  while $\mathcal{B} \neq$ *empty* **do**
    $m \leftarrow$ argmax $\mathcal{S}$
    $\mathcal{M} \leftarrow b_m$
    $\mathcal{D} \leftarrow \mathcal{D} \bigcup \mathcal{M}; \mathcal{B} \leftarrow \mathcal{B} - \mathcal{M}$
    for b_i *in* $\mathcal{B}$ **do**
      if $iou(\mathcal{M}, b_i) \geq N_t$ **then**
        $\mathcal{B} \leftarrow \mathcal{B} - b_i; \mathcal{S} \leftarrow \mathcal{S} - s_i$
      end — NMS
      $s_i \leftarrow s_i f(iou(\mathcal{M}, b_i))$ — Soft-NMS
    end
  end
  return $\mathcal{D}, \mathcal{S}$
end

I. Two Stage Detection

A. First Trial - RCNN [2014 Ross]:

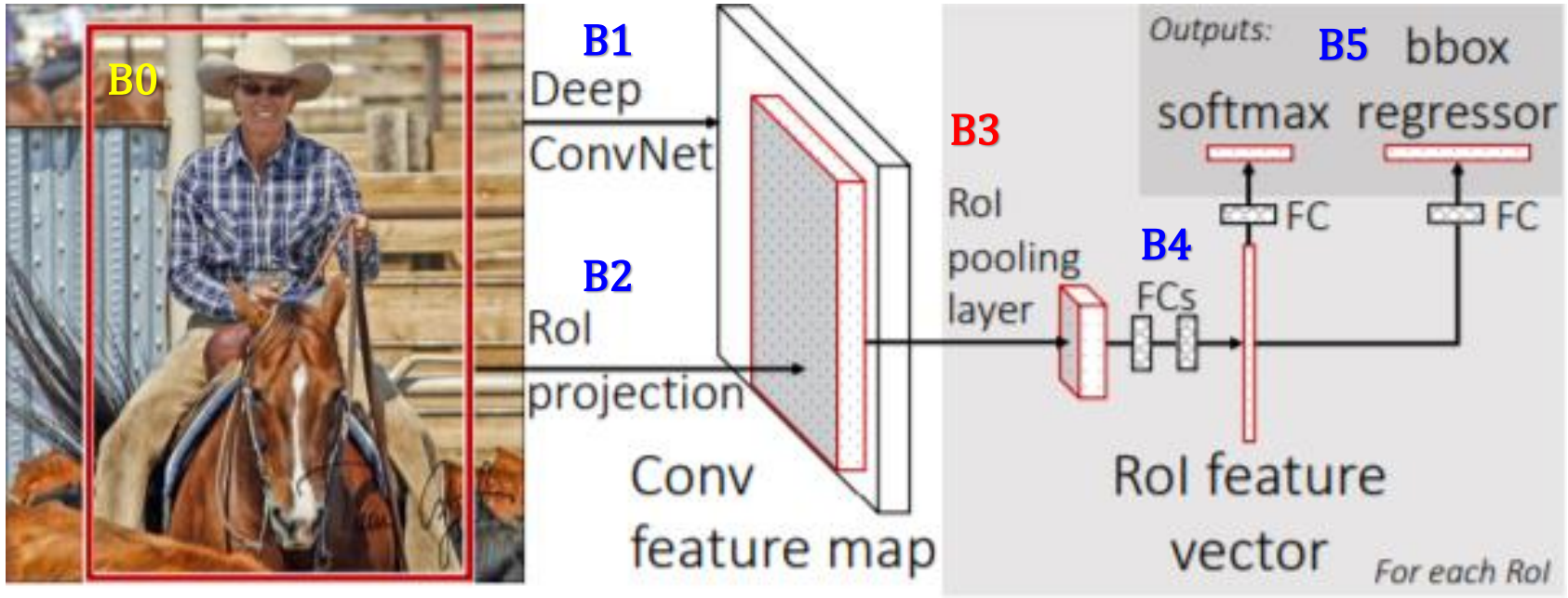
A4. RCNN Problems

- **Slow: need to run full forward pass of CNN for each region proposal**
- **SVMs and regressors are post-hoc: CNN features not updated in response to SVMs and regressors**
- **Complex multistage training pipeline**

Let's Fix It, Step by Step

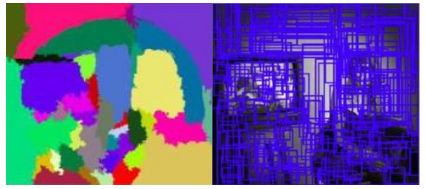
I. Two Stage Detection

B. Fast R-CNN [2015 Ross]:



I. Two Stage Detection

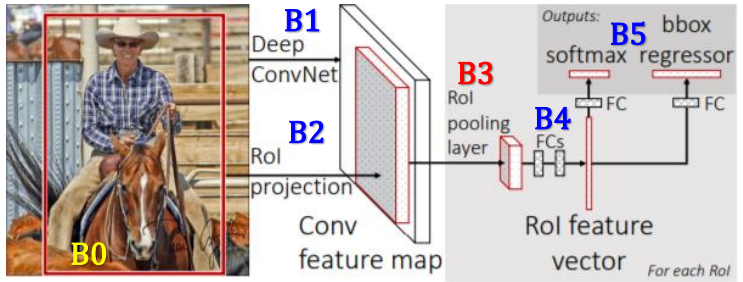
B. Fast R-CNN [2015 Ross]:



B0. Region Proposal: Same as RCNN

- 2k per image. Record location for each ROI

B1 & 2. Convolution & Projection



- Do Conv per ROI. Project location for each ROI
- 3 basic structures provided, use Vgg16 as an E.g.
- 4 max pooling, /16

B3. ROI Pooling

- Grid each ROI in feature map to fixed size, and do max pooling within each grid
- So different size of feature maps can transfer into feature maps with same size.

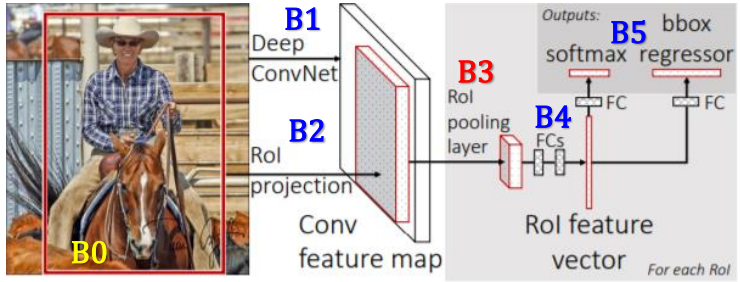
- bs = 2; 64 ROIs / image -> 128 proposals;
- ¼ pos & ¾ neg
- IoU > 0.5 pos, [0.1, 0.5) neg , [0. 0.1) hard neg
- Train on pos & neg. Test use neg. Retrain bad case

I. Two Stage Detection

B. Fast R-CNN [2015 Ross]:

B4. FC Layers

- FC layer cost a lot. Can use SVD to accelerate



B5. Multi-task Loss

- Classification: n + 1(background), softmax + cross entropy, L_{cls}
- Localization: Offset, SmoothL1, L_{loc}
- Total: $L(p, u, t^u, t^v) = L_{cls}(p, u) + \lambda[u \geq 1]\ L_{loc}(t^u, v)$

  p: predicted class score

  u: real class

  t^u: generated bbox [offset]

  t^v: real bbox

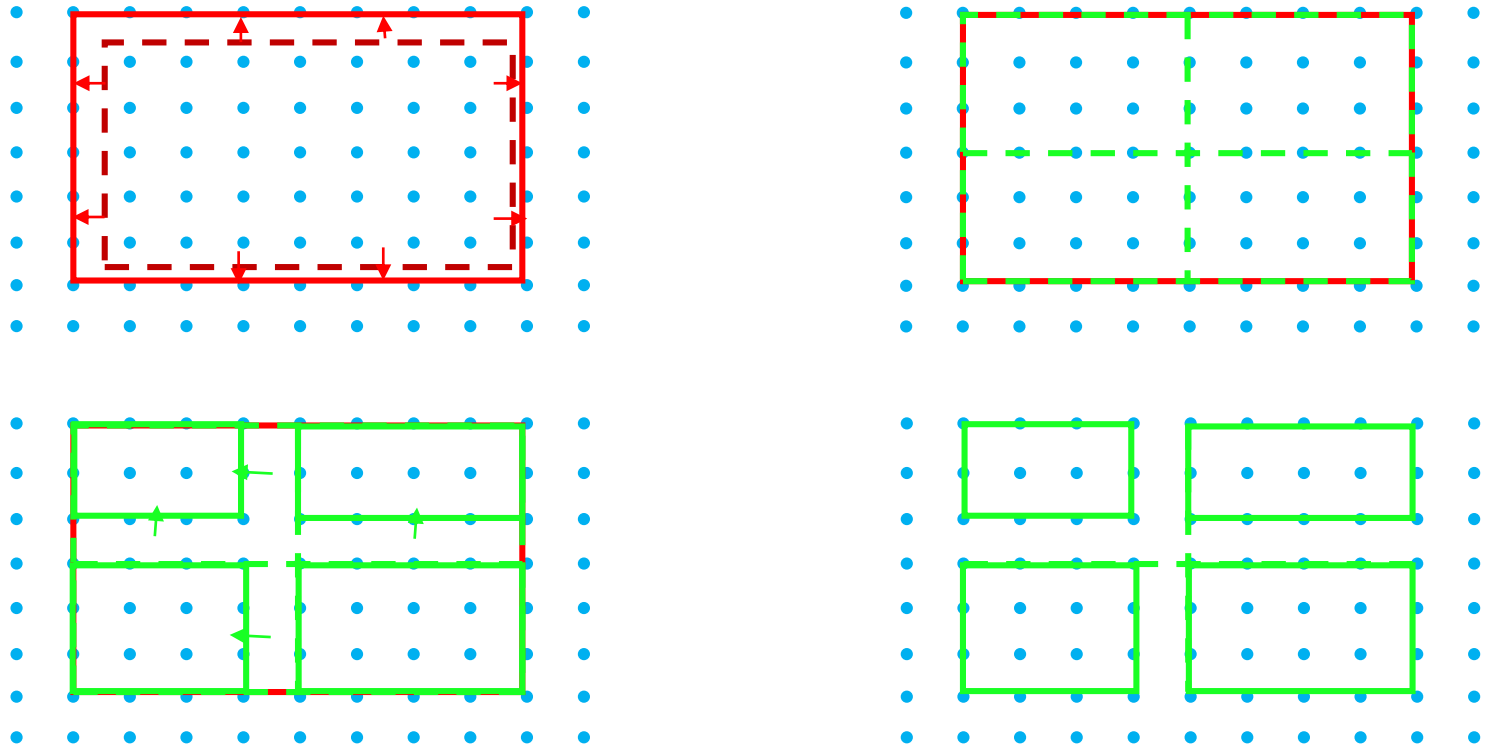
$$\lambda = \begin{cases} 1, u \geq 1 \\ 0, u = 0 \end{cases}$$

SmoothL1 & Offset regression will be discussed in next

I. Two Stage Detection

B. Fast R-CNN [2015 Ross]:

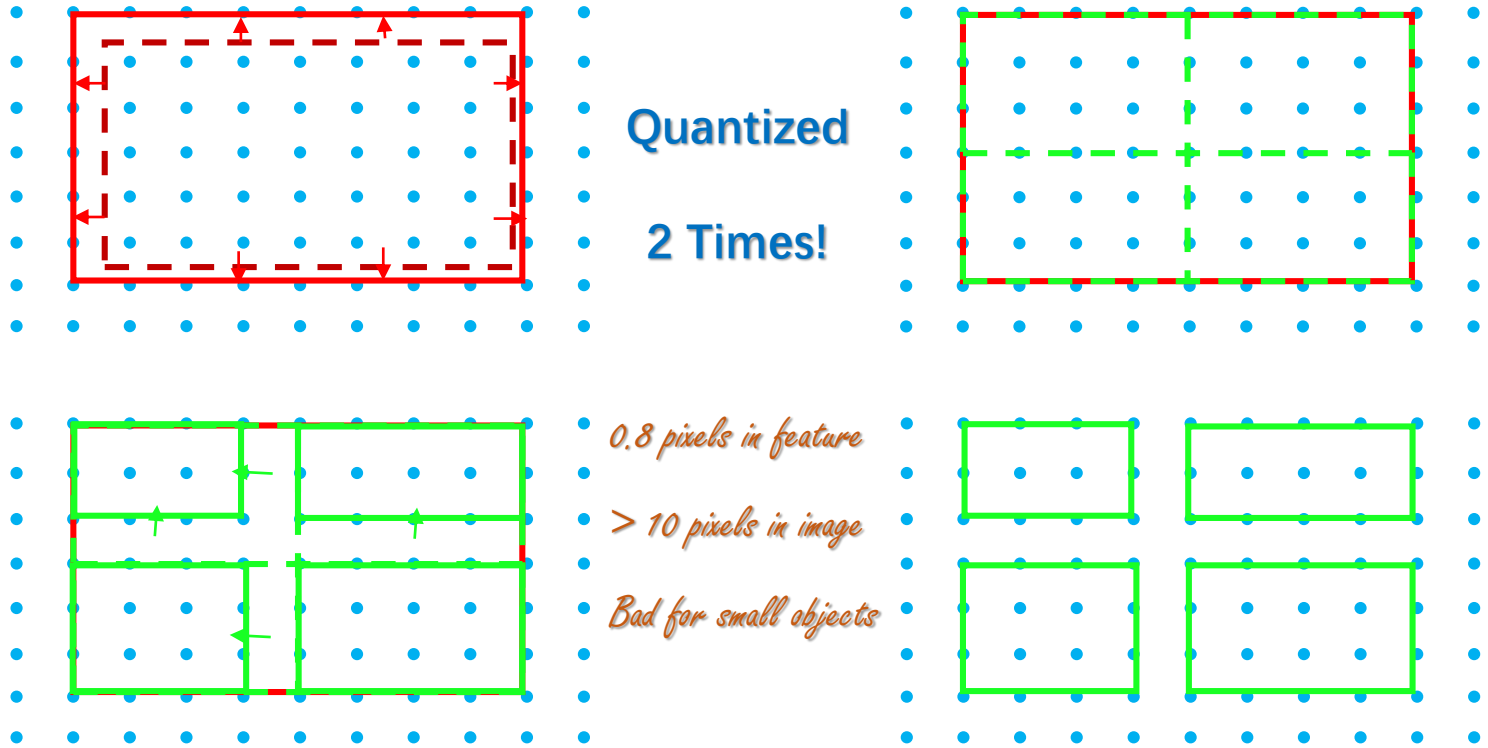
B*. Rethinking ROI Pooling



I. Two Stage Detection

B. Fast R-CNN [2015 Ross]:

B*. Rethinking ROI Pooling



I. Two Stage Detection

B. Fast R-CNN [2015 Ross]:

B*. Rethinking ROI Pooling

- **BP for ROI Pooling**

$$\frac{\partial L}{\partial x_i} = \sum_r \sum_j [i = i^*(r,j)] \frac{\partial L}{\partial y_{r,j}}$$

$y_{r,j}$: rth region, jth feature point

$i^*(r,j)$: the position where $y_{r,j}$ comes from

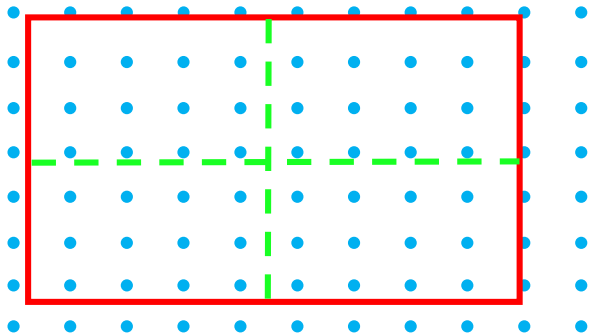
Just one point has loss passed by in each bin.

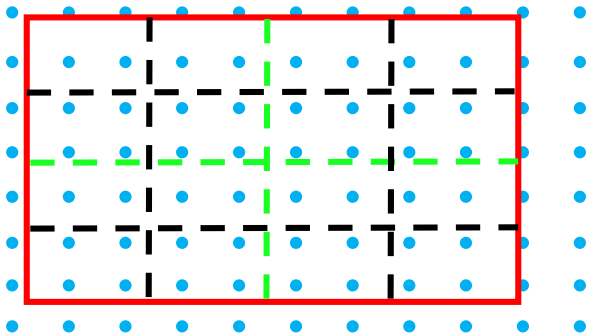
I. Two Stage Detection

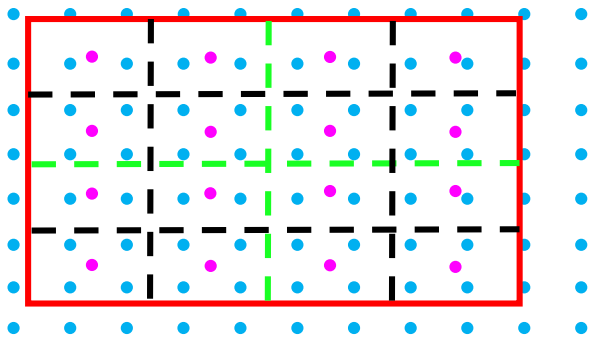
B. Fast R-CNN [2015 Ross]:

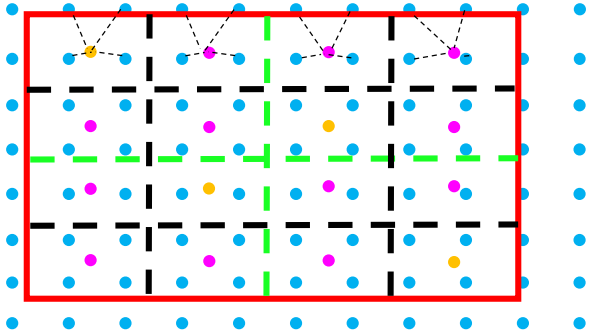
B*. Rethinking ROI Pooling

- ROI Align [2017, Kaiming]







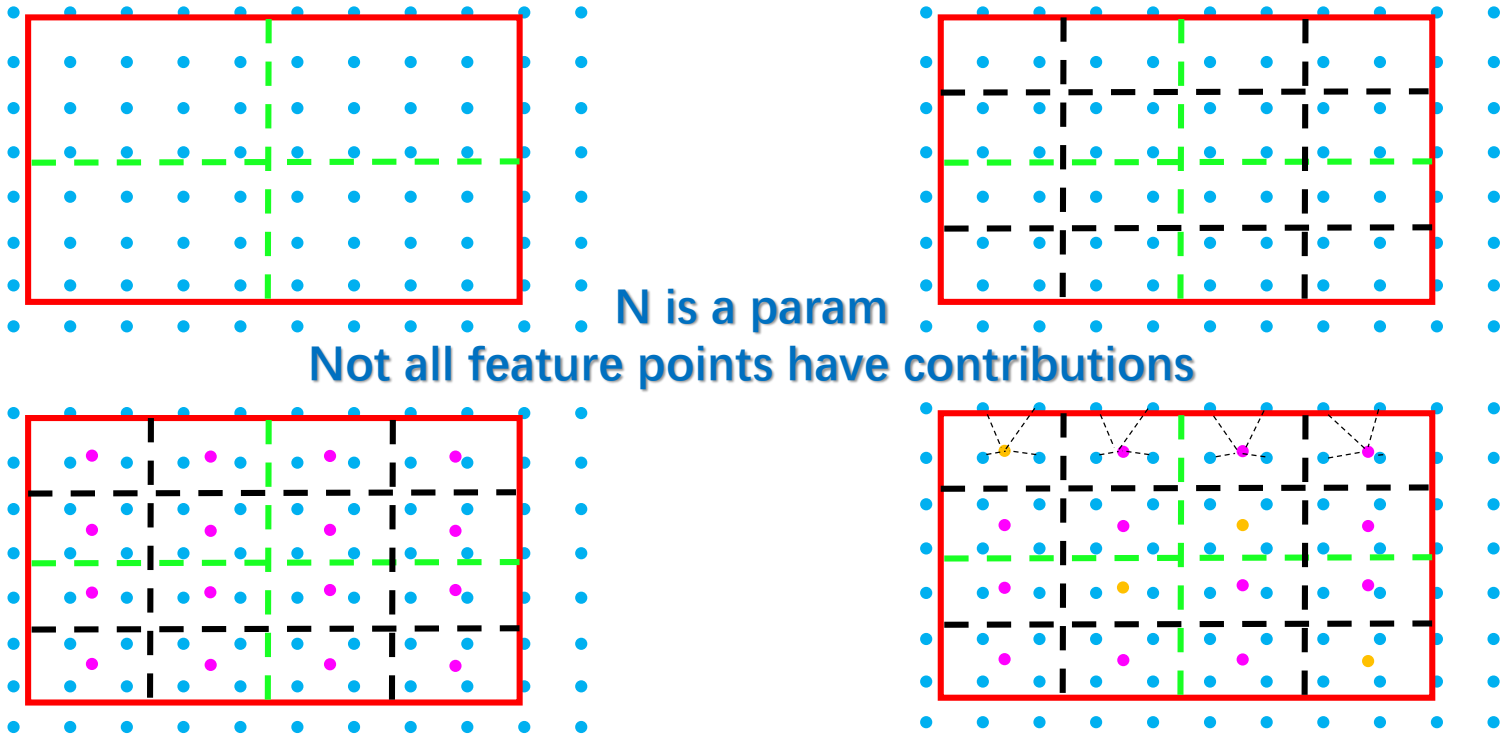


I. Two Stage Detection

B. Fast R-CNN [2015 Ross]:

B*. Rethinking ROI Pooling

- ROI Align [2017, Kaiming]



I. Two Stage Detection

B. Fast R-CNN [2015 Ross]:

B*. Rethinking ROI Pooling

- **ROI Align [2017, Kaiming] – BP**

$$\frac{\partial L}{\partial x_i} = \sum_r \sum_j [d(i, i^*(r,j))](1-\Delta h)(1-\Delta w)\frac{\partial L}{\partial y_{r,j}}$$

$d(x, y)$: distance between x & y

$\Delta w, \Delta h$: width & height difference of x_i & $x_{i^*(r,j)}$

$x_{i^*(r,j)}$: a float value interpolated by the forward pass

x_i: feature point before pooling

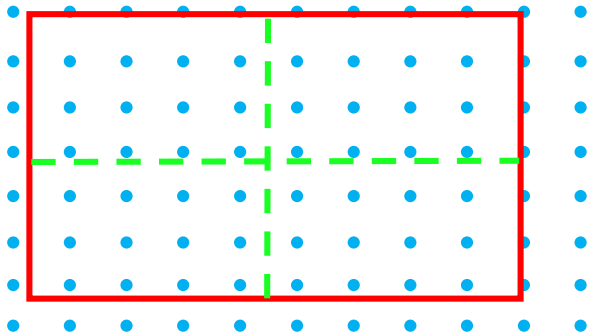
Only several points have losses passed by in each bin.

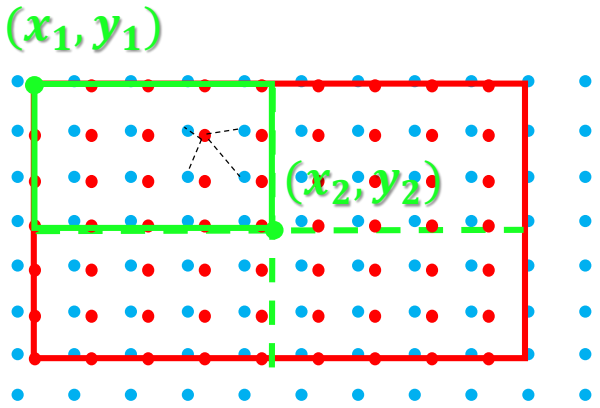
I. Two Stage Detection

B. Fast R-CNN [2015 Ross]:

B*. Rethinking ROI Pooling

- **Precise ROI Pooling [2018, IoU-Net]**





No Quantization

No Parameter

Pass losses for all

$$f(x,y) = \sum_{i,j} IC(x,y,i,j) * w_{i,j}$$

$$IC(x,y,i,j) = \max(0,1-|x-i|) + \max(0,1-|y-j|)$$

Do Pr ROI Pool for $\square$**:**

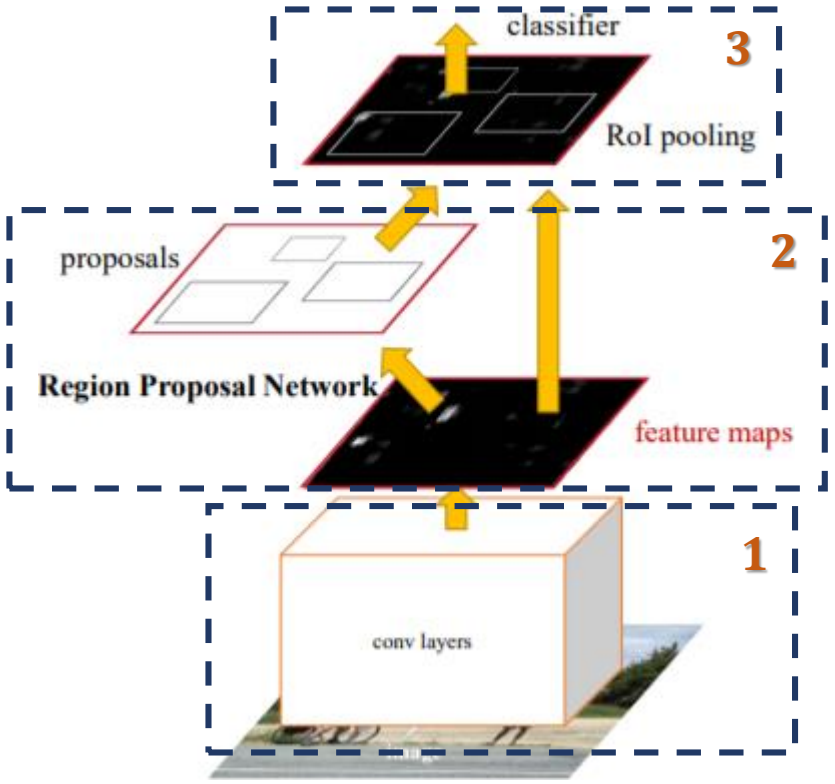
$$PrPool(bin,F) = \frac{\int_{y_1}^{y_2}\int_{x_1}^{x_2} f(x,y)dxdy}{(x_2-x_1)*(y_2-y_1)}$$

BP:

$$\frac{\partial PrPool(bin,F)}{\partial x_1} = \frac{PrPool(bin,F)}{x_2-x_1} - \frac{\int_{y_1}^{y_2} f(x,y)dy}{(x_2-x_1)*(y_2-y_1)}$$

I. Two Stage Detection

C. Faster R-CNN [2015 Ren]:



C0. Structure

3. Fast RCNN: ROI + { Classification, Regression }

2. RPN

1. Backbone

Input

I. Two Stage Detection

C. Faster R-CNN [2015 Ren]:

C1. Backbone

- **Aim:** Extract feature integratedly
  - No need to extract feature per ROI
  - Use generated feature to generate proposals

- **Structure:** ZF / Resnet / VGG16 (13 conv + 13 ReLU + 4 Pooling)
  [Do have the sense of splicing network from now on]

- **Output:**

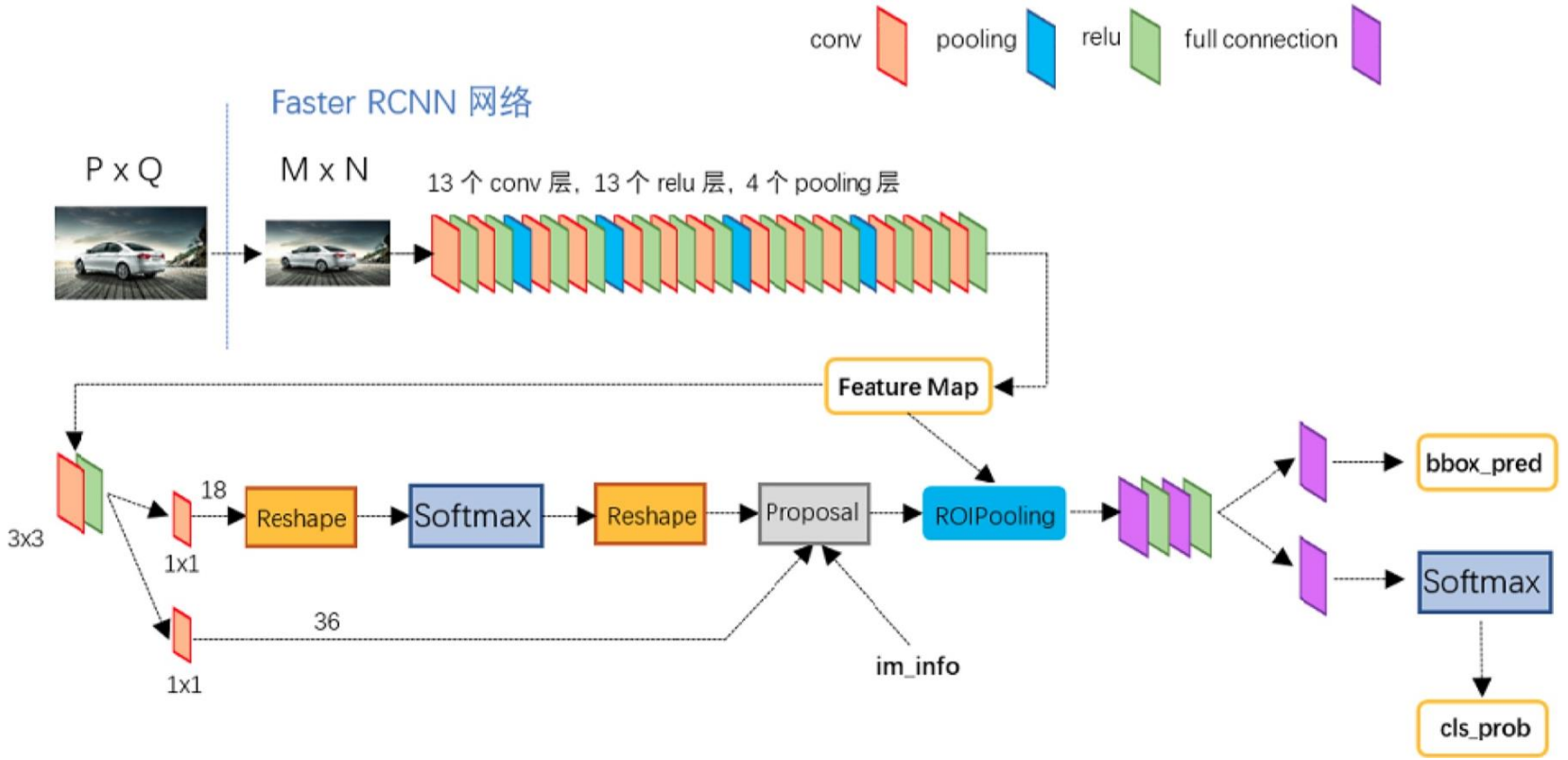
B	x	C	x	H/16	x	W/16
1	x	256	x	38	x	50

[Feature Map]

I. Two Stage Detection

C. Faster R-CNN [2015 Ren]:

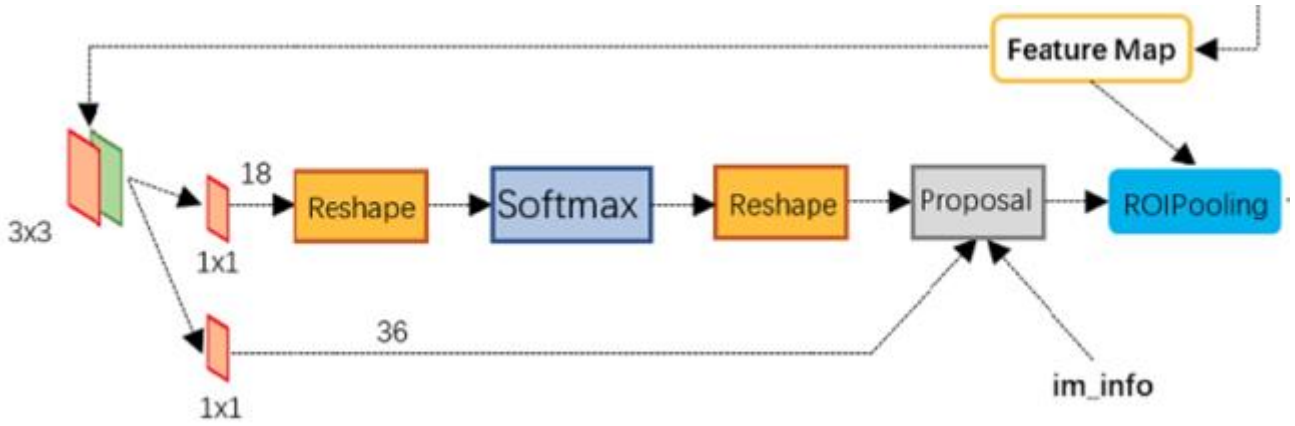
C1. Backbone



I. Two Stage Detection

C. Faster R-CNN [2015 Ren]:

C2. RPN



I. Two Stage Detection

C. Faster R-CNN [2015 Ren]:

C2. RPN

- **Aim: Generate region proposal**
  [Real detected objects are coming from those RPs]

a. **It's the reason where the name "Two-Stage" coming from:**
   RPN + Bbox Regression

b. **It's the reason why some argue two-stage detection has better results then one-stage methods.**

I. Two Stage Detection

C. Faster R-CNN [2015 Ren]:

C2. RPN

- **Output of RPN:**
  a. **ROIs: 128 x 5**
     [0, x1, y1, x2, y2]->physical region proposal

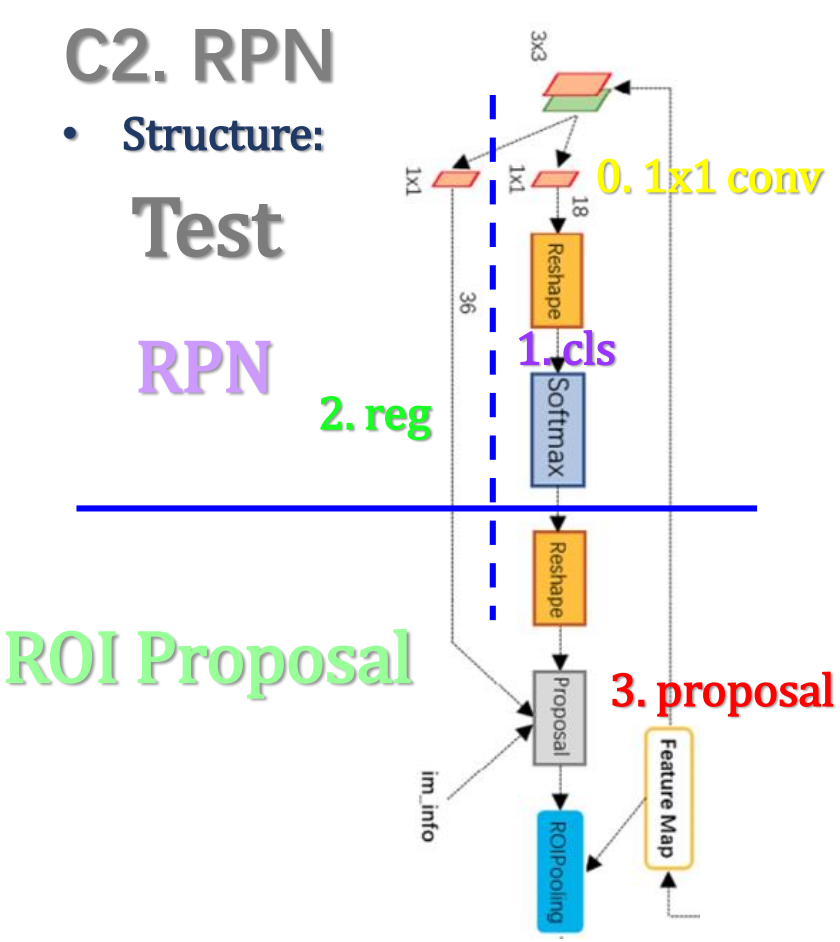
  b. **Label: 128**
     [0 ~ 20]->ROIs' classifications

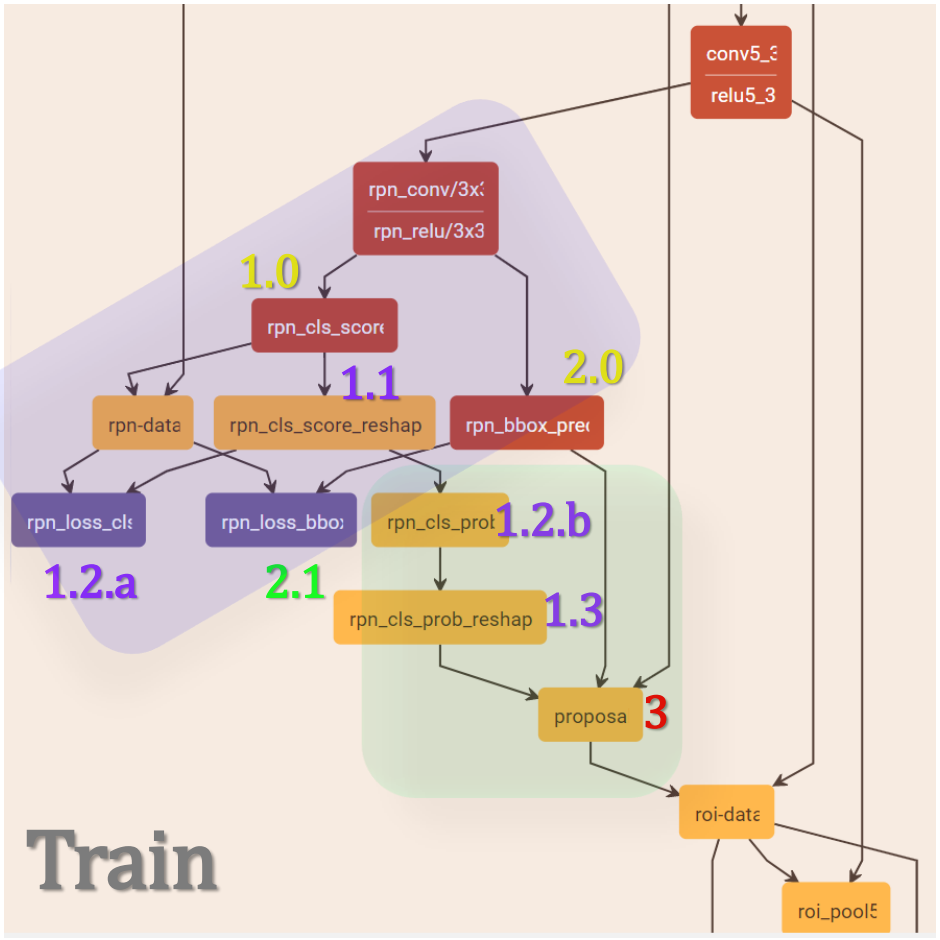
  c. **bbx_target: 128 x 84**
     [(20 + 1) x 4]->targets for bounding box regression

  d. **bbx_weight: 128 x 84**
     [0 0r 1]->weights for bbx_target when box regressing

I. Two Stage Detection

C. Faster R-CNN [2015 Ren]:





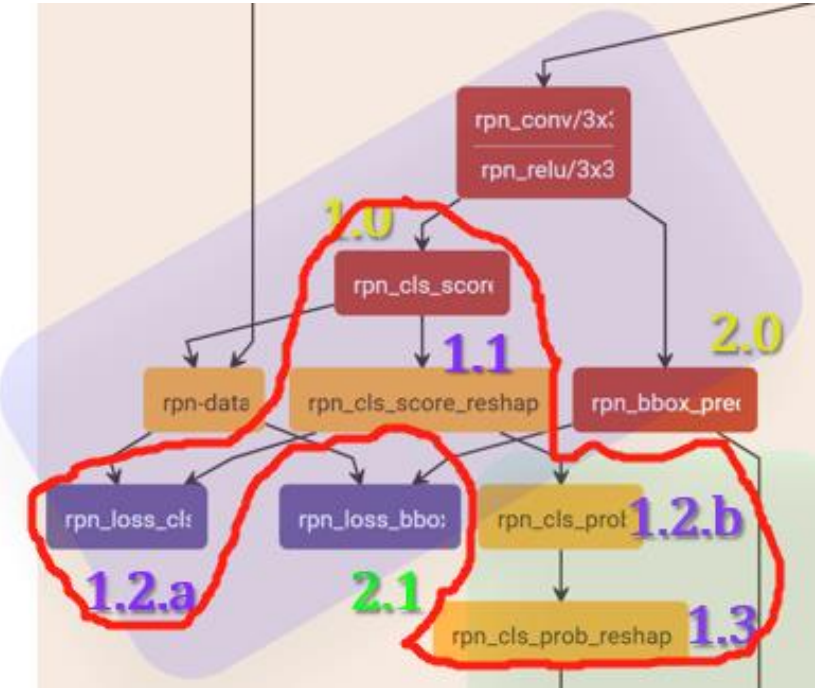
I. Two Stage Detection

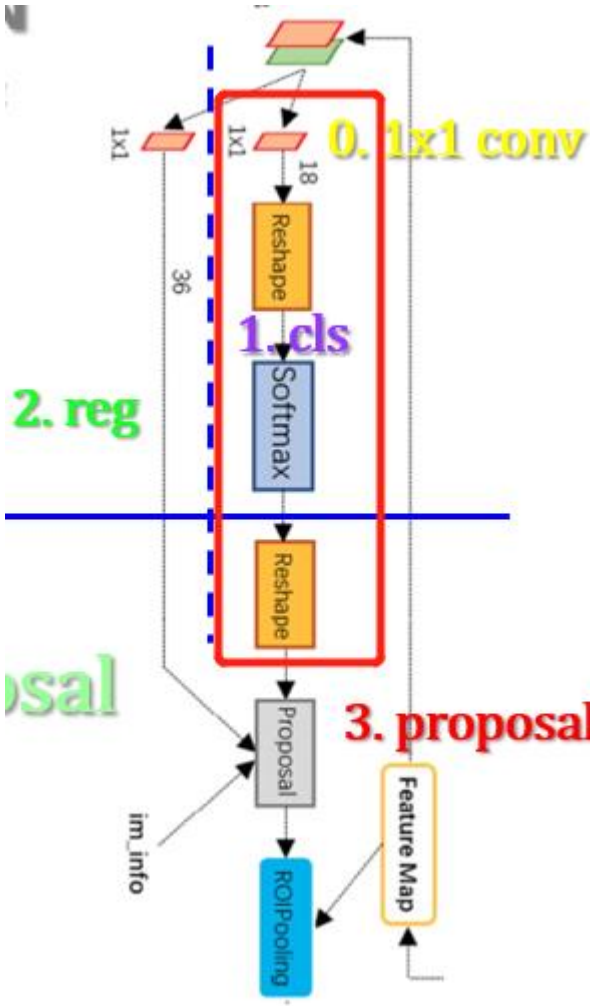
C. Faster R-CNN [2015 Ren]:

C2. RPN

- **Structure:**

C2.1: classification branch





I. Two Stage Detection

C. Faster R-CNN [2015 Ren]:

C2. RPN

- **Structure:**

C2.1.0: 1x1 conv

1 x 18 x 38 x 50

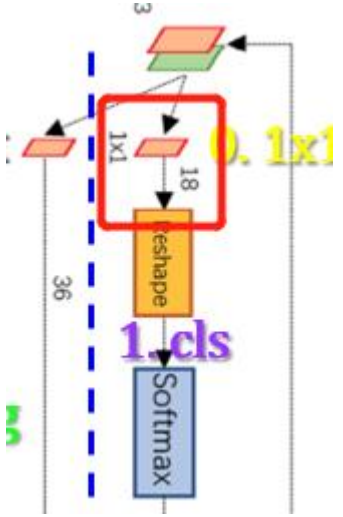
9 x 2

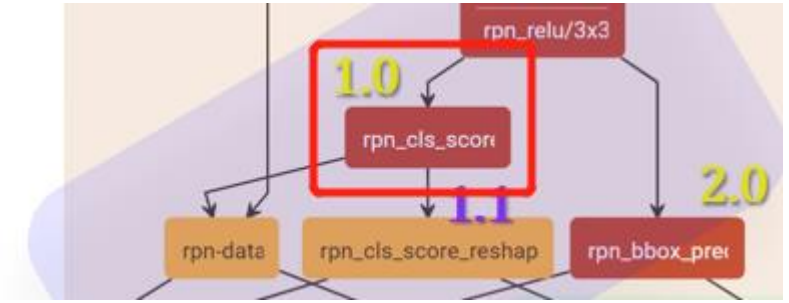
anchors 0|1

50

38

For each feature point,
We generate 9 anchors





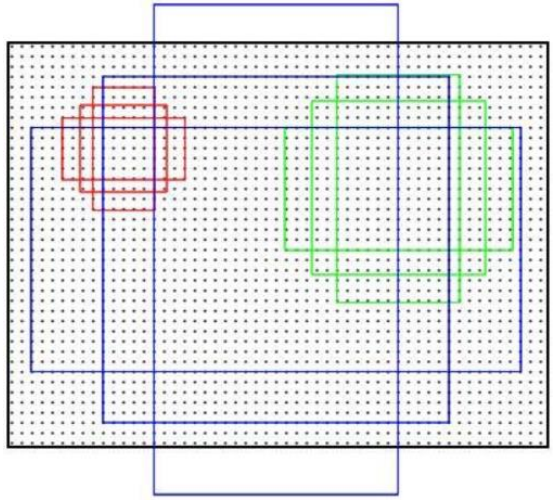
I. Two Stage Detection

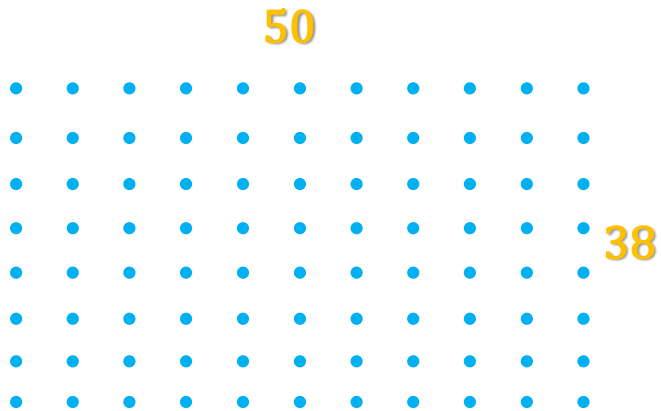
C. Faster R-CNN [2015 Ren]:

C2. RPN

- **Structure - Anchor:**

- ❑ **Represent an area in original image (a.k.a. where objects are)**
- ❑ **Have different scale & ratio to cover all kinds of objects**
- ❑ **9 in total: 3 scales x 3 ratios**
- ❑ **1 x 9 x 38 x 50 = 17100 anchors**
- ❑ **Coords of anchors are of original imgs**





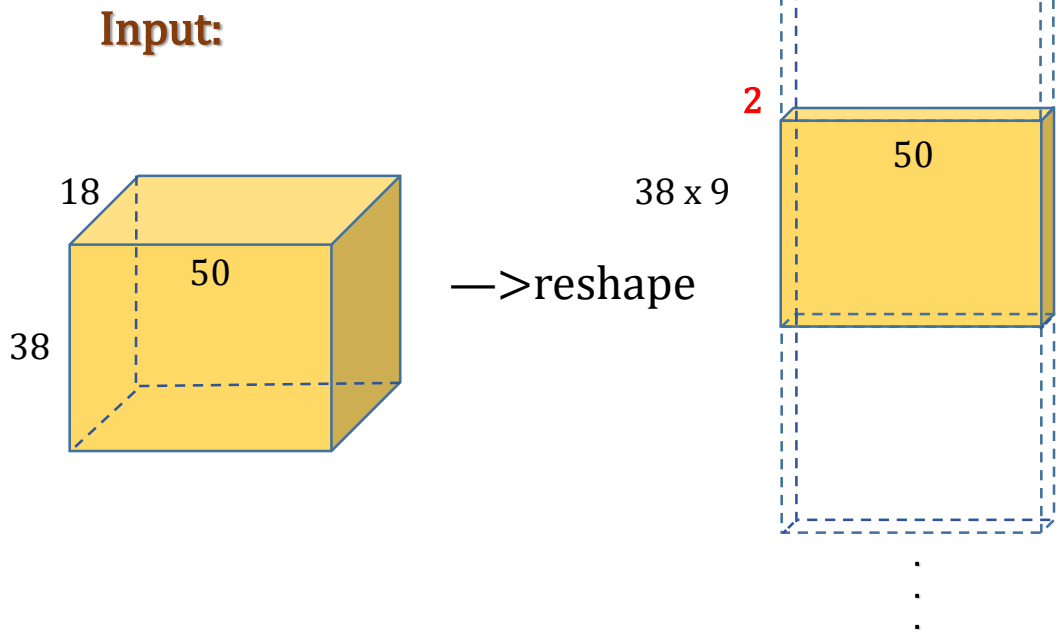
I. Two Stage Detection

C. Faster R-CNN [2015 Ren]:

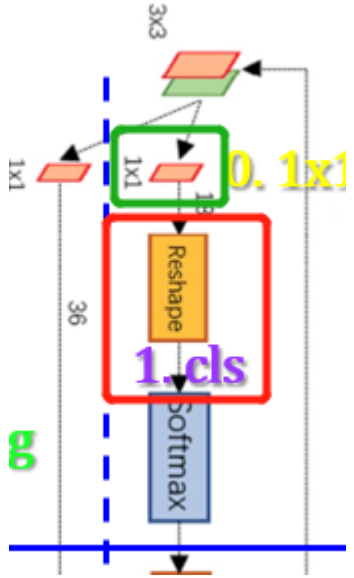
C2. RPN

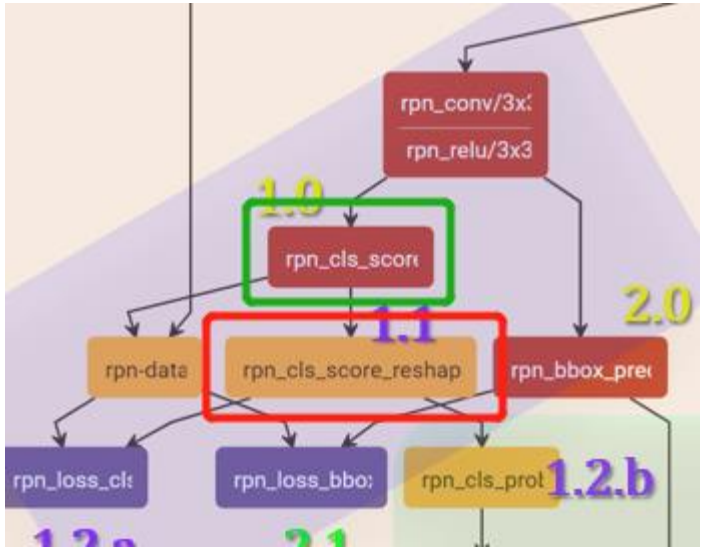
- **Structure:**

C2.1.1: cls reshape



This is for doing **Softmax** to get **fore/background**





I. Two Stage Detection

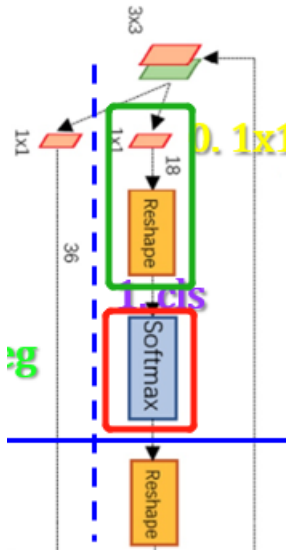
C. Faster R-CNN [2015 Ren]:

C2. RPN

- **Structure:**

C2.1.2: Softmax

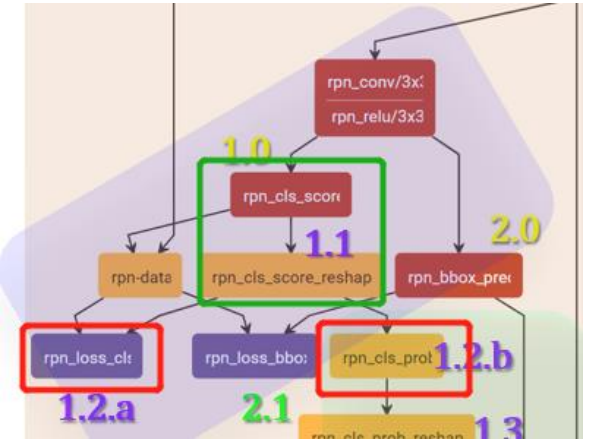
This is for doing **Softmax** to get **fore/background**



2 branches: a. bp loss & b. no loss / get score

- ❑ **a. 1 foreground & 0 background.**
  Get loss with anchor and pass back.
  Use IoU

- ❑ **b. Just do classification and get the score,**
  Use the score to select proposal



I. Two Stage Detection

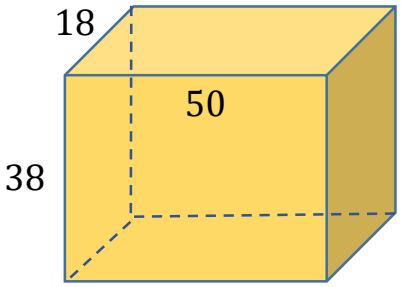
C. Faster R-CNN [2015 Ren]:

C2. RPN

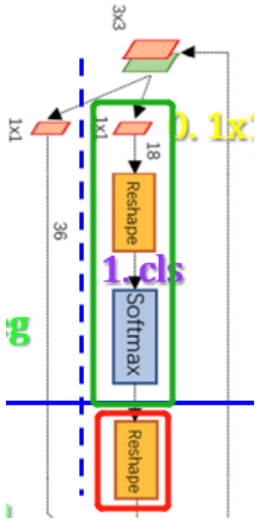
- **Structure:**

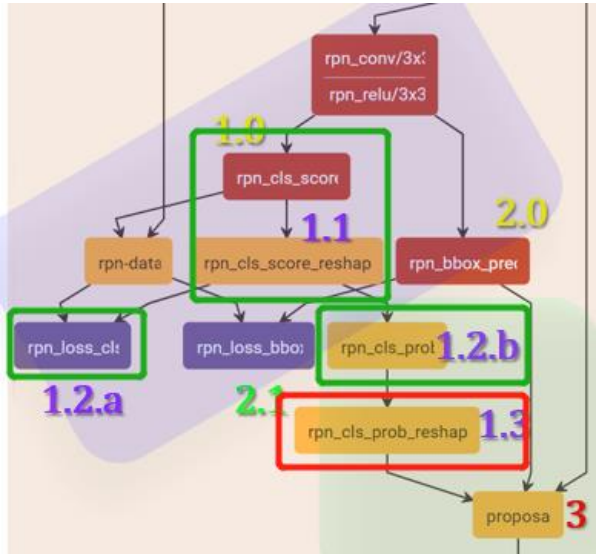
C2.1.3: cls reshape 2

Back to original shape



Each voxel represents the possibility of being a foreground or a background of an anchor





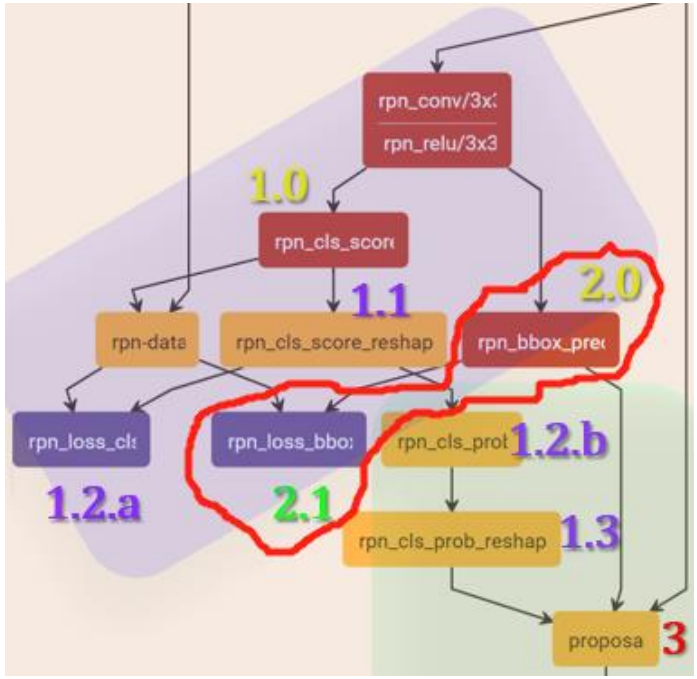
I. Two Stage Detection

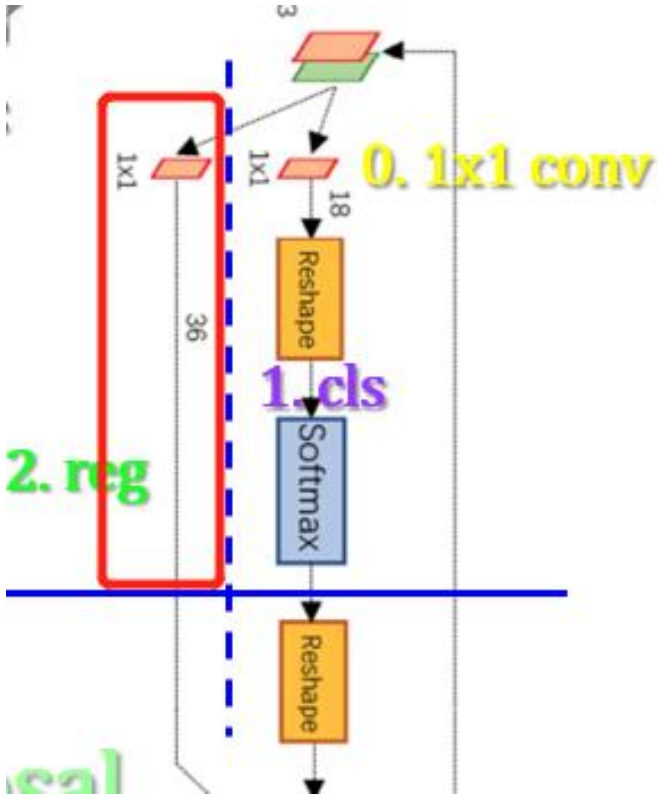
C. Faster R-CNN [2015 Ren]:

C2. RPN

- **Structure:**

C2.2: regression



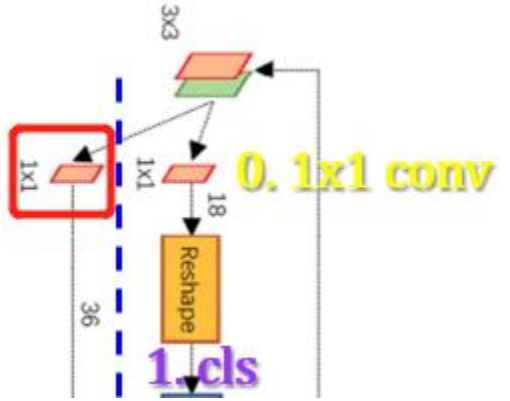


I. Two Stage Detection

C. Faster R-CNN [2015 Ren]:

C2. RPN

- **Structure:**



C2.2.0: 1x1 conv

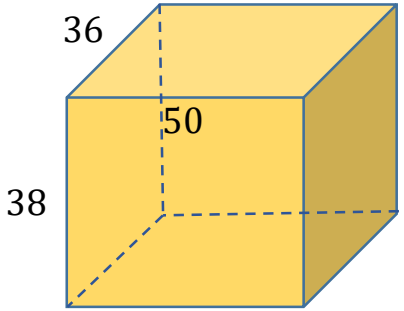
1 x 36 x 38 x 50

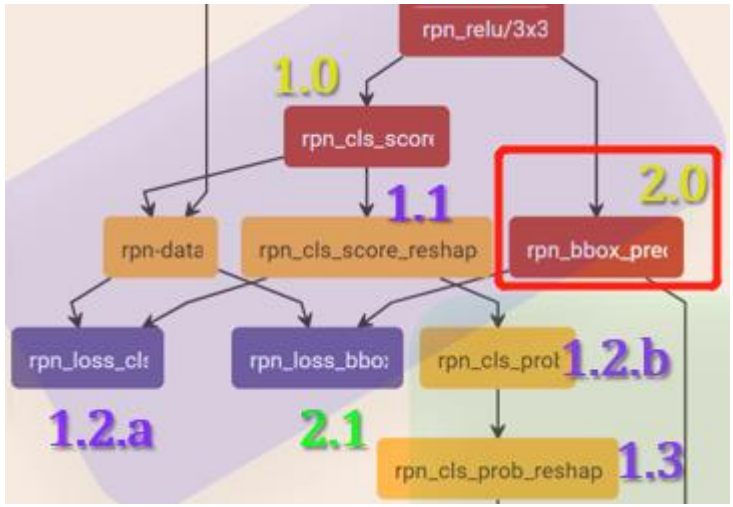
9 x 4

anchors 4 targets

Regress anchor to gt_bbox

Targets: proposals





I. Two Stage Detection

C. Faster R-CNN [2015 Ren]:

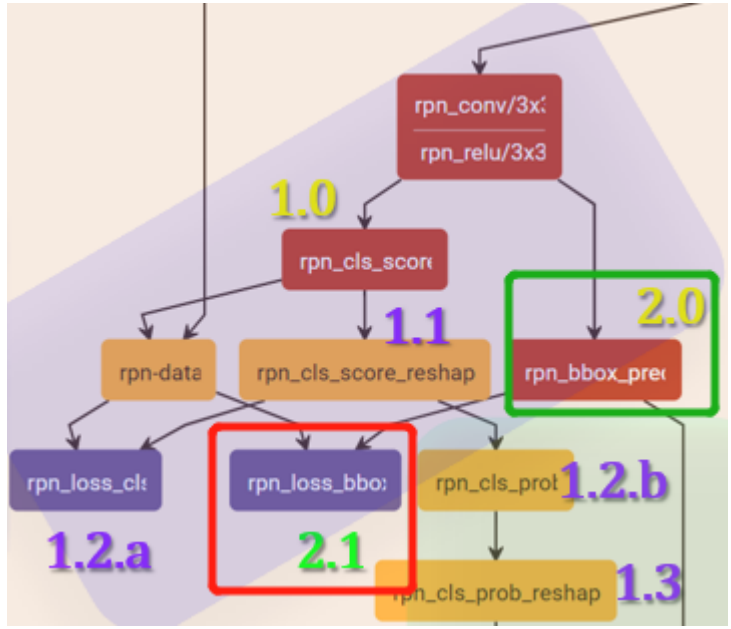
C2. RPN

- **Structure:**

C2.2.1: Smooth L1 Loss

- **Need to multiply the mask**
  - anchor = 1, mask = 1
  - anchor = 0, -1, mask = 0
- **Smooth L1 Loss**

$$f(x) = \begin{cases} \frac{(\sigma x)^2}{2}, & if\ x < 1/\sigma^2 \\ |x| - \frac{0.5}{\sigma^2}, & otherwise \end{cases}$$



I. Two Stage Detection

C. Faster R-CNN [2015 Ren]:

C2. RPN

- **Structure:**

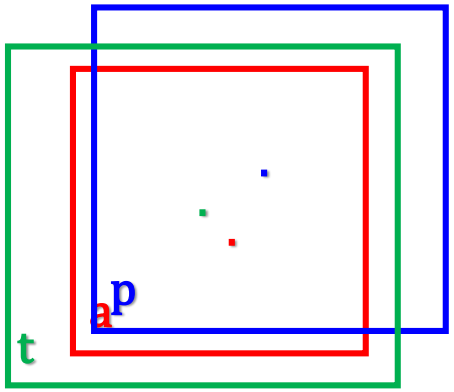
C2.2.1: Smooth L1 Loss

➢ **Regress (center) offset, NOT COORDINATES**

predicated bbox: x, y, w, h

anchor bbox: x_a, y_a, w_a, h_a

true bbox: x^*, y^*, w^*, h^*



We hope a -> t,
but actually a generates p.

So as long as p->t,
We get a good result.

So as long as the offset of
p - a -> t – a
We get a good result

So here we hope $\mathbf{t}_\cdot \rightarrow \mathbf{t}_\cdot^*$

$$f(x) = \begin{cases} t_x = \frac{x - x_a}{w_a}, t_y = \frac{y - y_a}{h_a} \\ t_w = log\left(\frac{w}{w_a}\right), t_h = log\left(\frac{h}{h_a}\right) \\ t_x^* = \frac{x^* - x_a}{w_a}, t_y^* = \frac{y^* - y_a}{h_a} \\ t_w^* = log\left(\frac{w^*}{w_a}\right), t_h = log\left(\frac{h^*}{h_a}\right) \end{cases}$$

I. Two Stage Detection

C. Faster R-CNN [2015 Ren]:

C2. RPN

- Structure:

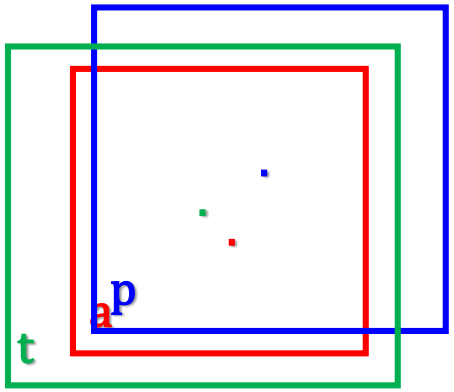
C2.2.1: Smooth L1 Loss

➢ Regress (center) offset, NOT COORDINATES

predicated bbox: x, y, w, h

anchor bbox: x_a, y_a, w_a, h_a

true bbox: x^*, y^*, w^*, h^*



So how to transfer from one box to another?

$$f(x) = \begin{cases} t_x = \frac{x - x_a}{w_a}, t_y = \frac{y - y_a}{h_a} \\ t_w = log\left(\frac{w}{w_a}\right), t_h = log\left(\frac{h}{h_a}\right) \\ t_x^* = \frac{x^* - x_a}{w_a}, t_y^* = \frac{y^* - y_a}{h_a} \\ t_w^* = log\left(\frac{w^*}{w_a}\right), t_h = log\left(\frac{h^*}{h_a}\right) \end{cases}$$

I. Two Stage Detection

C. Faster R-CNN [2015 Ren]:

C2. RPN

- Structure:

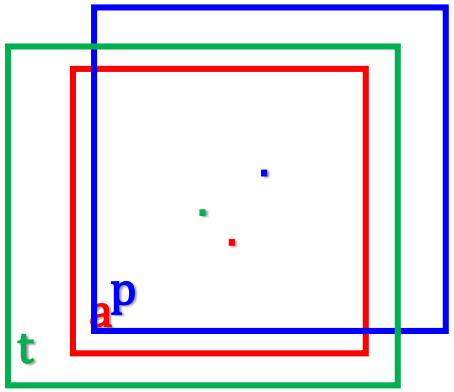
C2.2.1: Smooth L1 Loss

➢ Regress (center) offset, NOT COORDINATES

predicated bbox: x, y, w, h

anchor bbox: x_a, y_a, w_a, h_a

true bbox: x^*, y^*, w^*, h^*



So how to transfer from one box to another?

Shift + Scale

$$f(x) = \begin{cases} t_x = \frac{x - x_a}{w_a}, t_y = \frac{y - y_a}{h_a} \\ t_w = log\left(\frac{w}{w_a}\right), t_h = log\left(\frac{h}{h_a}\right) \\ t_x^* = \frac{x^* - x_a}{w_a}, t_y^* = \frac{y^* - y_a}{h_a} \\ t_w^* = log\left(\frac{w^*}{w_a}\right), t_h = log\left(\frac{h^*}{h_a}\right) \end{cases}$$

I. Two Stage Detection

C. Faster R-CNN [2015 Ren]:

C2. RPN

- **Structure:**

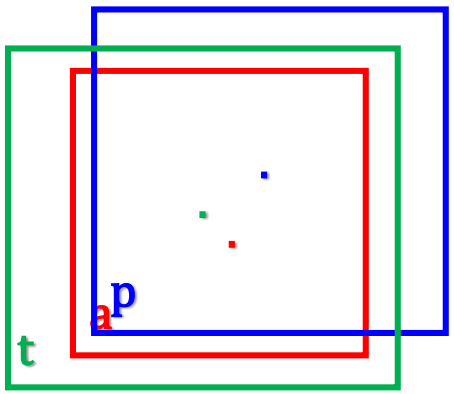
C2.2.1: Smooth L1 Loss

➢ **Regress (center) offset, NOT COORDINATES**

predicated bbox: x, y, w, h

anchor bbox: x_a, y_a, w_a, h_a

true bbox: x^*, y^*, w^*, h^*



$$x = x_a + \Delta x$$
$$y = y_a + \Delta y$$
$$w = w_a \cdot \Delta w$$
$$h = h_a \cdot \Delta h$$

Shift

Scale

$$f(x) = \begin{cases} t_x = \frac{x - x_a}{w_a}, t_y = \frac{y - y_a}{h_a} \\ t_w = log\left(\frac{w}{w_a}\right), t_h = log\left(\frac{h}{h_a}\right) \\ t_x^* = \frac{x^* - x_a}{w_a}, t_y^* = \frac{y^* - y_a}{h_a} \\ t_w^* = log\left(\frac{w^*}{w_a}\right), t_h = log\left(\frac{h^*}{h_a}\right) \end{cases}$$

I. Two Stage Detection

C. Faster R-CNN [2015 Ren]:

C2. RPN

- **Structure:**

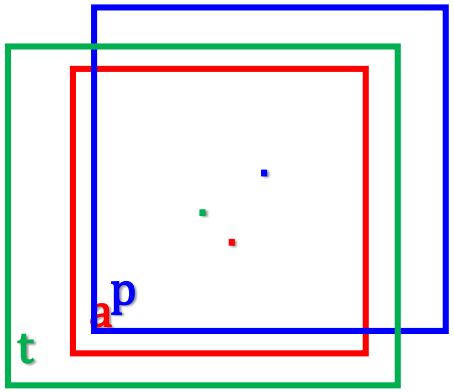
C2.2.1: Smooth L1 Loss

➢ **Regress (center) offset, NOT COORDINATES**

predicated bbox: x, y, w, h

anchor bbox: x_a, y_a, w_a, h_a

true bbox: x^*, y^*, w^*, h^*



$$x = x_a + \Delta x$$
$$y = y_a + \Delta y$$
$$w = w_a \cdot \Delta w$$
$$h = h_a \cdot \Delta h$$

$$\Delta x = w_a \cdot t_x$$
$$\Delta y = h_a \cdot t_y$$
$$\Delta w = w_a \cdot e^{t_w}$$
$$\Delta h = h_a \cdot e^{t_h}$$

Shift

Scale

$$f(x) = \begin{cases} t_x = \frac{x - x_a}{w_a}, t_y = \frac{y - y_a}{h_a} \\ t_w = log\left(\frac{w}{w_a}\right), t_h = log\left(\frac{h}{h_a}\right) \\ t_x^* = \frac{x^* - x_a}{w_a}, t_y^* = \frac{y^* - y_a}{h_a} \\ t_w^* = log\left(\frac{w^*}{w_a}\right), t_h = log\left(\frac{h^*}{h_a}\right) \end{cases}$$

I. Two Stage Detection

C. Faster R-CNN [2015 Ren]:

C2. RPN

- Structure:

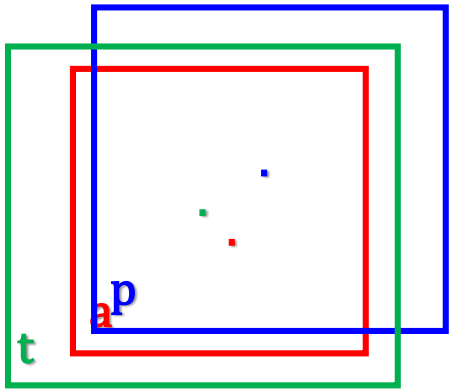
C2.2.1: Smooth L1 Loss

➢ Regress (center) offset, NOT COORDINATES

predicated bbox: x, y, w, h

anchor bbox: x_a, y_a, w_a, h_a

true bbox: x^*, y^*, w^*, h^*



Q: Why use exp

A: tx & ty is used for scaling
we need to ensure scale > 0

Q: Why use log

A: 1. reversing procedure of exp
2. Suppress greater bbox

$$f(x) = \begin{cases} t_x = \frac{x - x_a}{w_a}, t_y = \frac{y - y_a}{h_a} \\ t_w = log\left(\frac{w}{w_a}\right), t_h = log\left(\frac{h}{h_a}\right) \\ t_x^* = \frac{x^* - x_a}{w_a}, t_y^* = \frac{y^* - y_a}{h_a} \\ t_w^* = log\left(\frac{w^*}{w_a}\right), t_h = log\left(\frac{h^*}{h_a}\right) \end{cases}$$

I. Two Stage Detection

C. Faster R-CNN [2015 Ren]:

C2. RPN

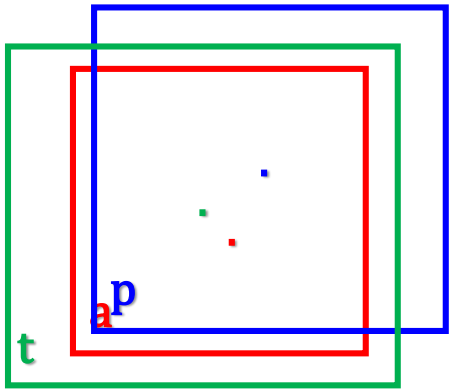
- Structure:

C2.2.1: Smooth L1 Loss

➢ Regress (center) offset, NOT COORDINATES

Q: Why x/y uses linear transferring
but w/h uses non-linear transferring?
Is that reasonable?

A: When bbox1->bbox2, then we can.



predicated bbox: x, y, w, h

anchor bbox: x_a, y_a, w_a, h_a

true bbox: x^*, y^*, w^*, h^*

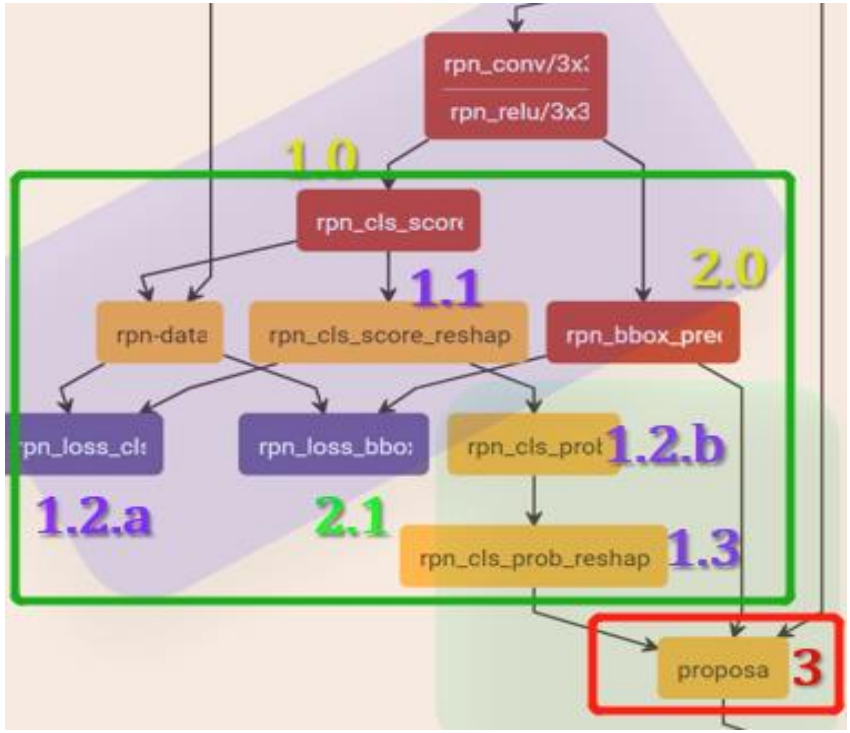
$$f(x) = \begin{cases} t_x = \frac{x - x_a}{w_a}, t_y = \frac{y - y_a}{h_a} \\ t_w = log\left(\frac{w}{w_a}\right), t_h = log\left(\frac{h}{h_a}\right) \\ t_x^* = \frac{x^* - x_a}{w_a}, t_y^* = \frac{y^* - y_a}{h_a} \\ t_w^* = log\left(\frac{w^*}{w_a}\right), t_h = log\left(\frac{h^*}{h_a}\right) \end{cases}$$

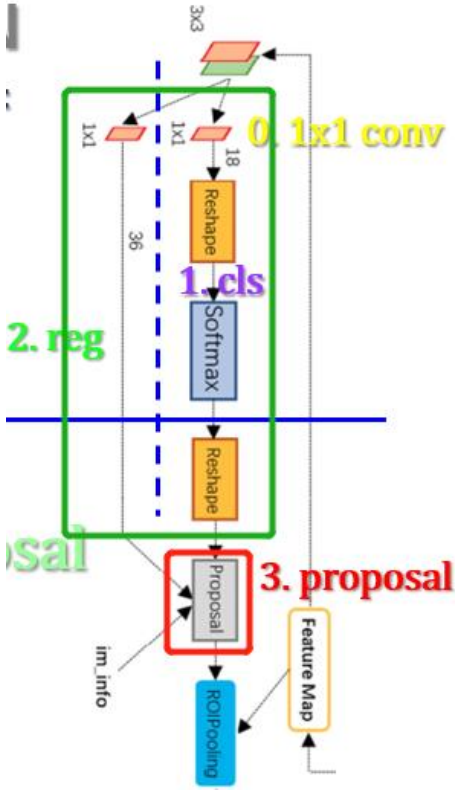
I. Two Stage Detection

C. Faster R-CNN [2015 Ren]:

C2. RPN

- **Structure:** C2.3: Proposal: Get proposal





I. Two Stage Detection

C. Faster R-CNN [2015 Ren]:

C2. RPN

- **Structure:**

C2.3: Proposal: Get proposal

- Regard anchor as FG when IoU > 0.7
- Regard anchor as FG when IoU < 0.3
- Regardless other anchors
- Then just keep 128: 0.25 fg + 0.75 bg anchors

I. Two Stage Detection

C. Faster R-CNN [2015 Ren]:

C3. After RPN

- **Same as Fast RCNN**

C4. How to train

- **Classic: alternatively 4 steps**
  - Use ImageNet finetune our RPN
  - Use trained proposal from step1 to train an Fast RCNN
  - Use detected results to initialize RPN training where we freeze the backbone layers but to train pure RPN-related layers
  - Finetune Fast RCNN-related layers only.
- **Other method:**
  - We can also train Faster RCNN as a whole in just one step

II. One Stage Detection

II. One Stage Detection

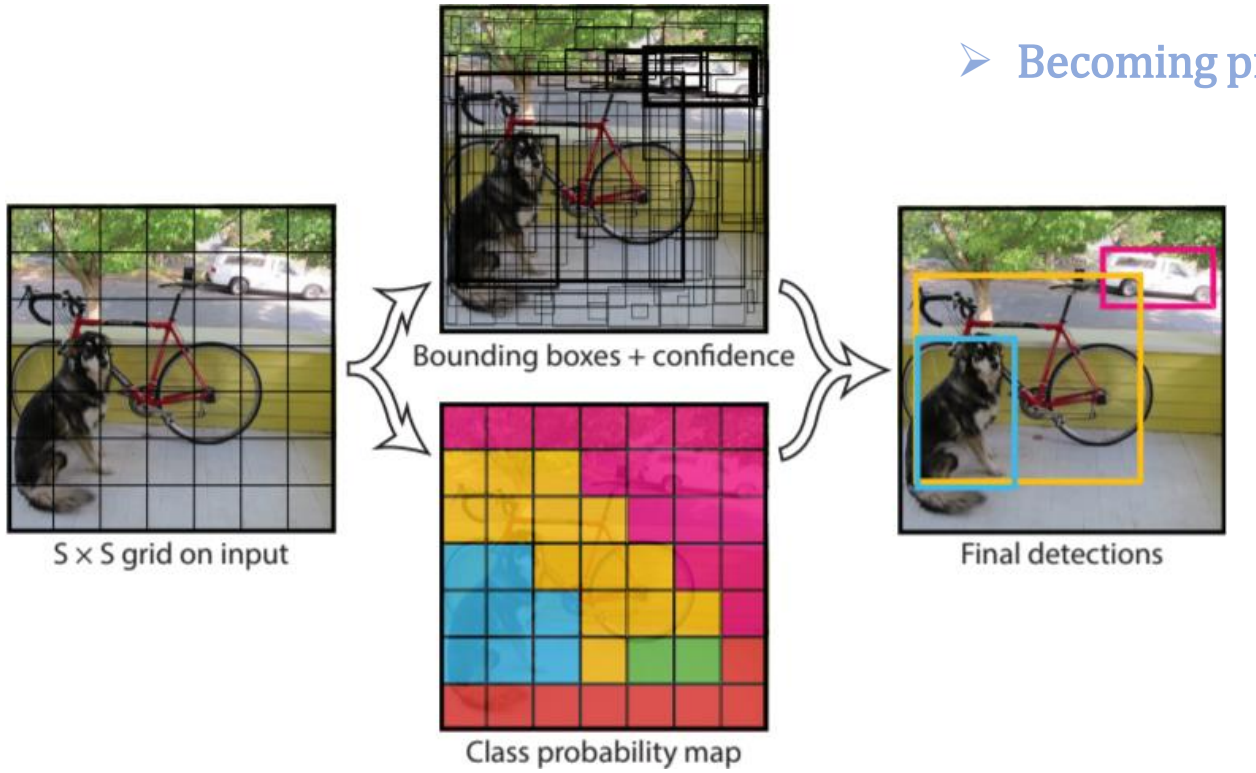
Why we have to use anchors to refine our bounding boxes?

II. One Stage Detection

D. Yolo V1 [2015, Joseph]

D0. You Only Look Once!

- Really fast (18 faster rcnn [ZF] vs 45 yolo)
- Becoming prevalent (62.1 mAP vs 63.4)



II. One Stage Detection

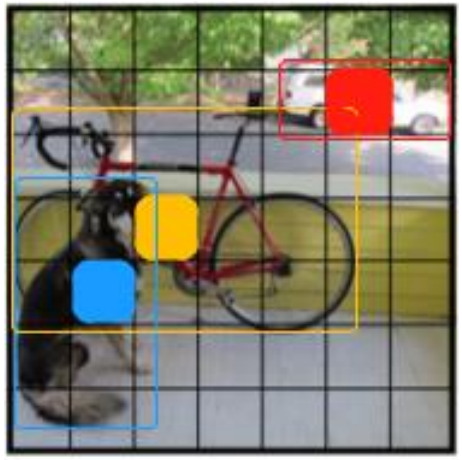
D. Yolo V1 [2015, Joseph]

D1. Procedure

- Grid an image into S x S cells [448 x 448 -> 7 x 7]

One cell will be responsible for predicting an object as long as an object's center locating in that cell.

S × S grid on input



S × S grid on input

II. One Stage Detection

D. Yolo V1 [2015, Joseph]

D1. Procedure

- Each cell predicts B bounding box with a confidence

Bounding Box: x, y, w, h (center)

Confidence: $P_r(object) \cdot IoU_{pred}^{truth}$

Final output tensor: S x S x (5 * B + C)

[7 x 7 x (5 * 2 + 20)] -> v1

II. One Stage Detection

D. Yolo V1 [2015, Joseph]

D2. Loss Function

$$\lambda_{\text{coord}} \sum_{i=0}^{S^2} \sum_{j=0}^{B} \mathbb{1}_{ij}^{\text{obj}} \left[(x_i - \hat{x}_i)^2 + (y_i - \hat{y}_i)^2 \right] \quad (1)$$

2.1

$$+ \lambda_{\text{coord}} \sum_{i=0}^{S^2} \sum_{j=0}^{B} \mathbb{1}_{ij}^{\text{obj}} \left[\left(\sqrt{w_i} - \sqrt{\hat{w}_i} \right)^2 + \left(\sqrt{h_i} - \sqrt{\hat{h}_i} \right)^2 \right] \quad (2)$$

$$+ \sum_{i=0}^{S^2} \sum_{j=0}^{B} \mathbb{1}_{ij}^{\text{obj}} \left(C_i - \hat{C}_i \right)^2 \quad (3)$$

2.2

$$+ \lambda_{\text{noobj}} \sum_{i=0}^{S^2} \sum_{j=0}^{B} \mathbb{1}_{ij}^{\text{noobj}} \left(C_i - \hat{C}_i \right)^2 \quad (4)$$

2.3

$$+ \sum_{i=0}^{S^2} \mathbb{1}_{i}^{\text{obj}} \sum_{c \in \text{classes}} \left(p_i(c) - \hat{p}_i(c) \right)^2 \quad (5)$$

$i: 0 \sim (S^2 - 1)$ [iterate each grid cell (0~48)]

$j: 0 \sim (B - 1)$ [iterate each bbox (0~2)]

$\mathbb{1}_{ij}^{\text{obj}}$ & $\mathbb{1}_{ij}^{\text{noobj}}$:

0	0	0	0	0	0	0
0	0	0	0	0	1	0
0	0	0	0	0	0	0
0	0	1	0	0	0	0
0	1	0	0	0	0	0
0	0	0	0	0	0	0
0	0	0	0	0	0	0

1	1	1	1	1	1	1
1	1	1	1	1	0	1
1	1	1	1	1	1	1
1	1	0	1	1	1	1
1	0	1	1	1	1	0
1	1	1	1	1	1	1
1	1	1	1	1	1	1

III. Other Methods

Summary