SSD: Single Shot MultiBox Detector

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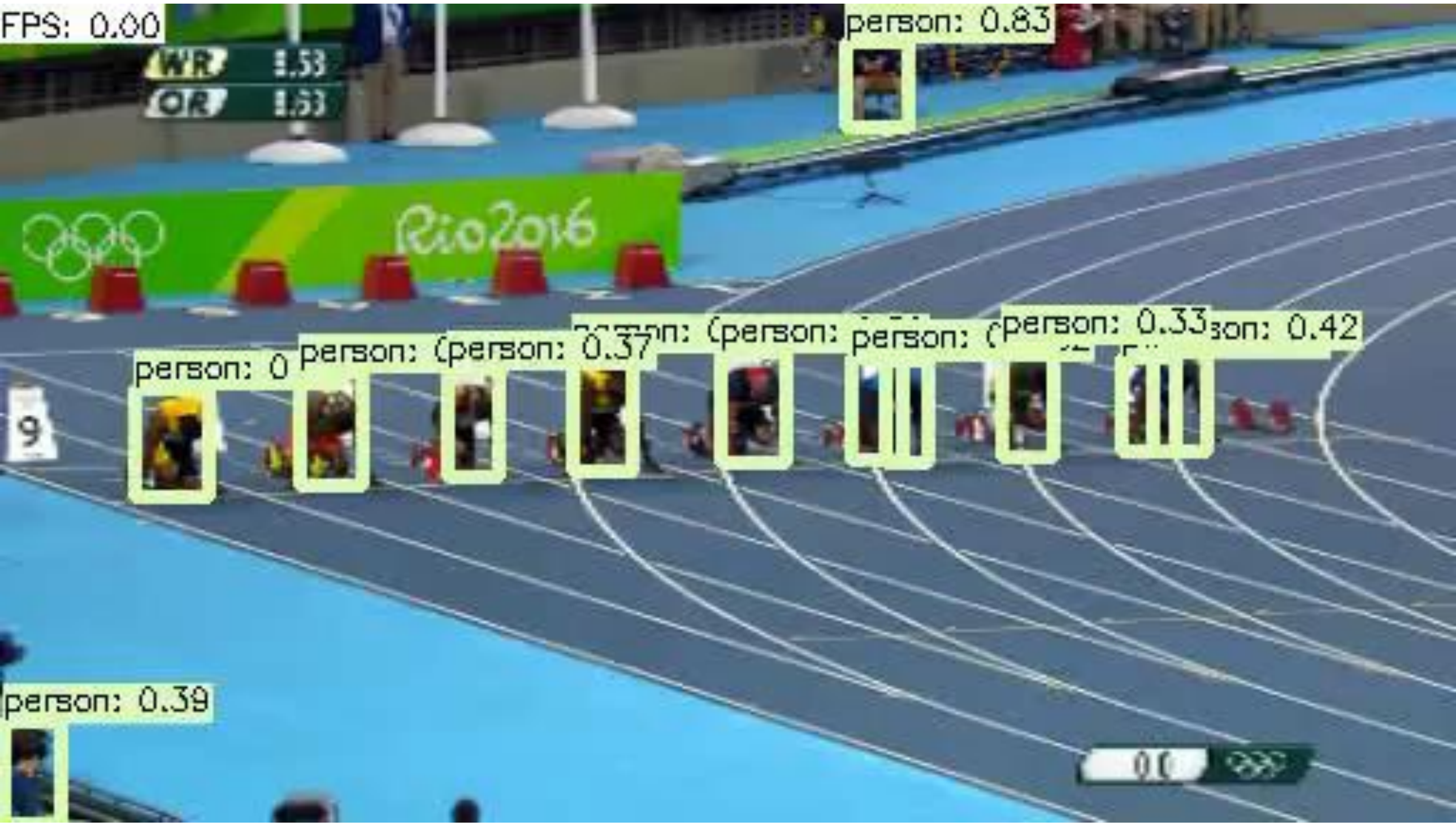
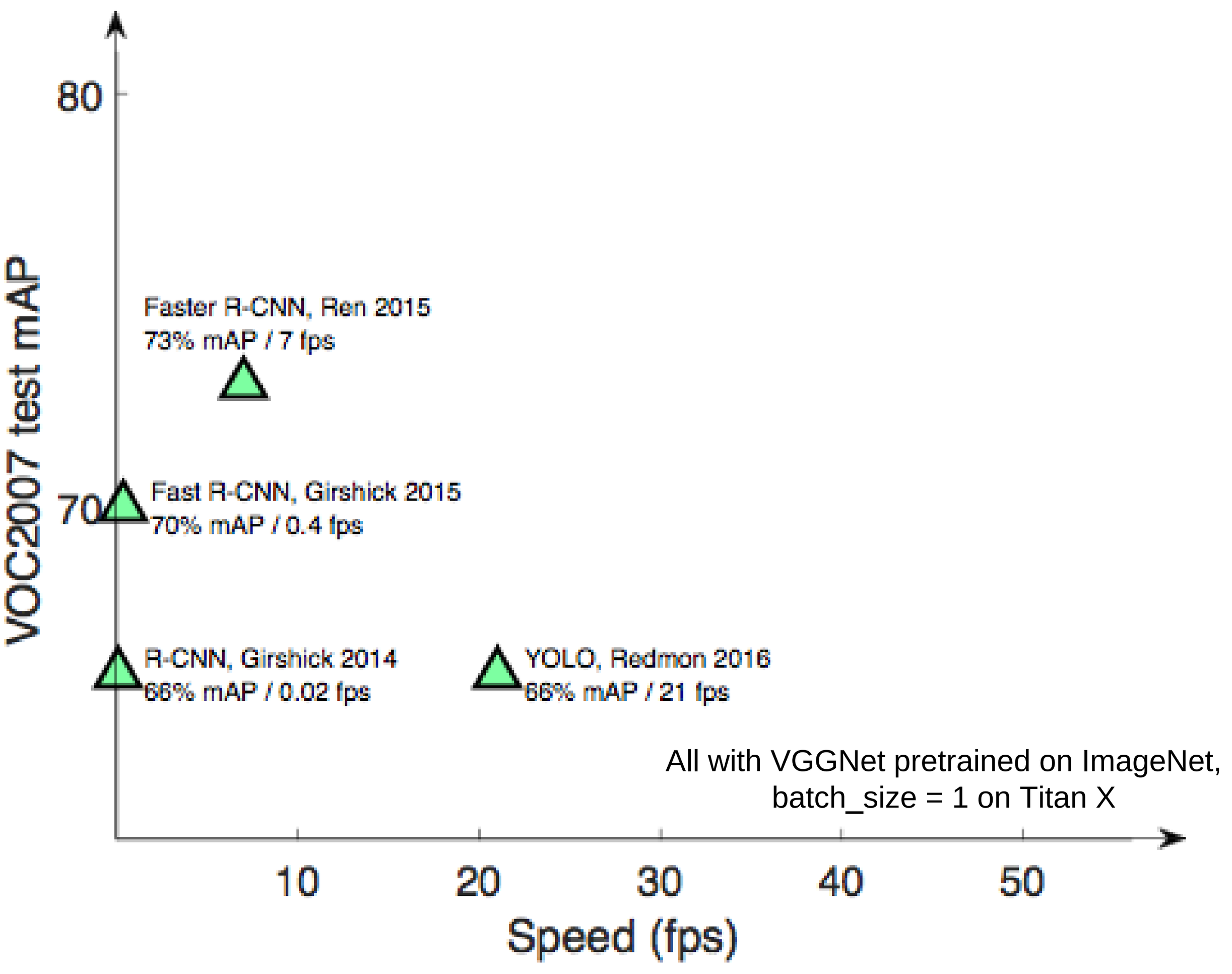
Scott Reed(4), Cheng-Yang Fu(1), Alexander C. Berg(1)

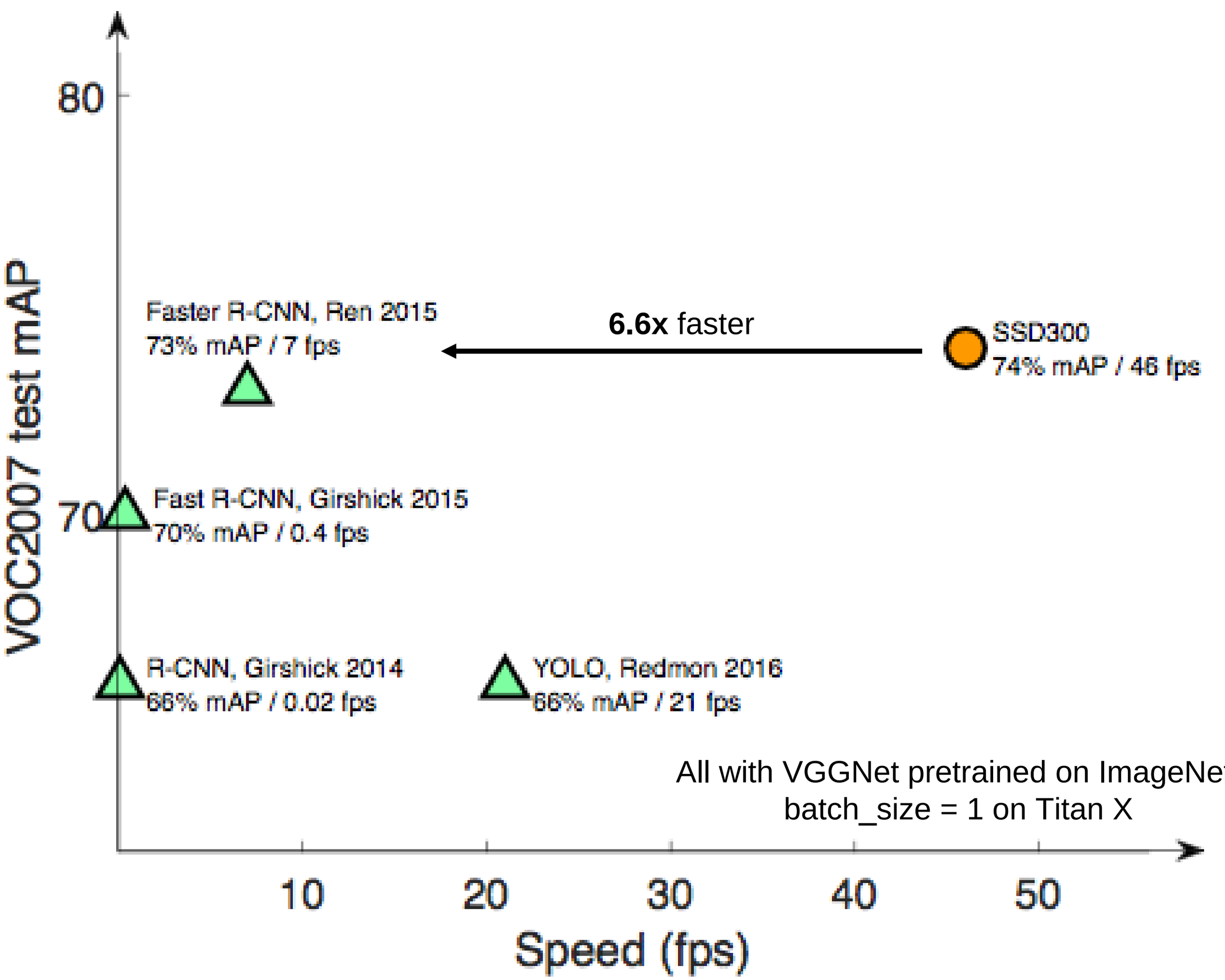
UNC Chapel Hill(1), **Zoox Inc.(2)**, Google Inc.(3),
University of Michigan(4)

THE UNIVERSITY
of NORTH CAROLINA
at CHAPEL HILL



VGGNet
Titan X Pascal


VOC2007 test mAP
80
70
Faster R-CNN, Ren 2015
73% mAP / 7 fps
Fast R-CNN, Girshick 2015
70% mAP / 0.4 fps
R-CNN, Girshick 2014
66% mAP / 0.02 fps
YOLO, Redmon 2016
66% mAP / 21 fps
All with VGGNet pretrained on ImageNet,
batch_size = 1 on Titan X
10
20
30
40
50
Speed (fps)


80
70
VOC2007 test mAP
Faster R-CNN, Ren 2015
73% mAP / 7 fps
6.6x faster
SSD300
74% mAP / 46 fps
Fast R-CNN, Girshick 2015
70% mAP / 0.4 fps
R-CNN, Girshick 2014
66% mAP / 0.02 fps
YOLO, Redmon 2016
66% mAP / 21 fps
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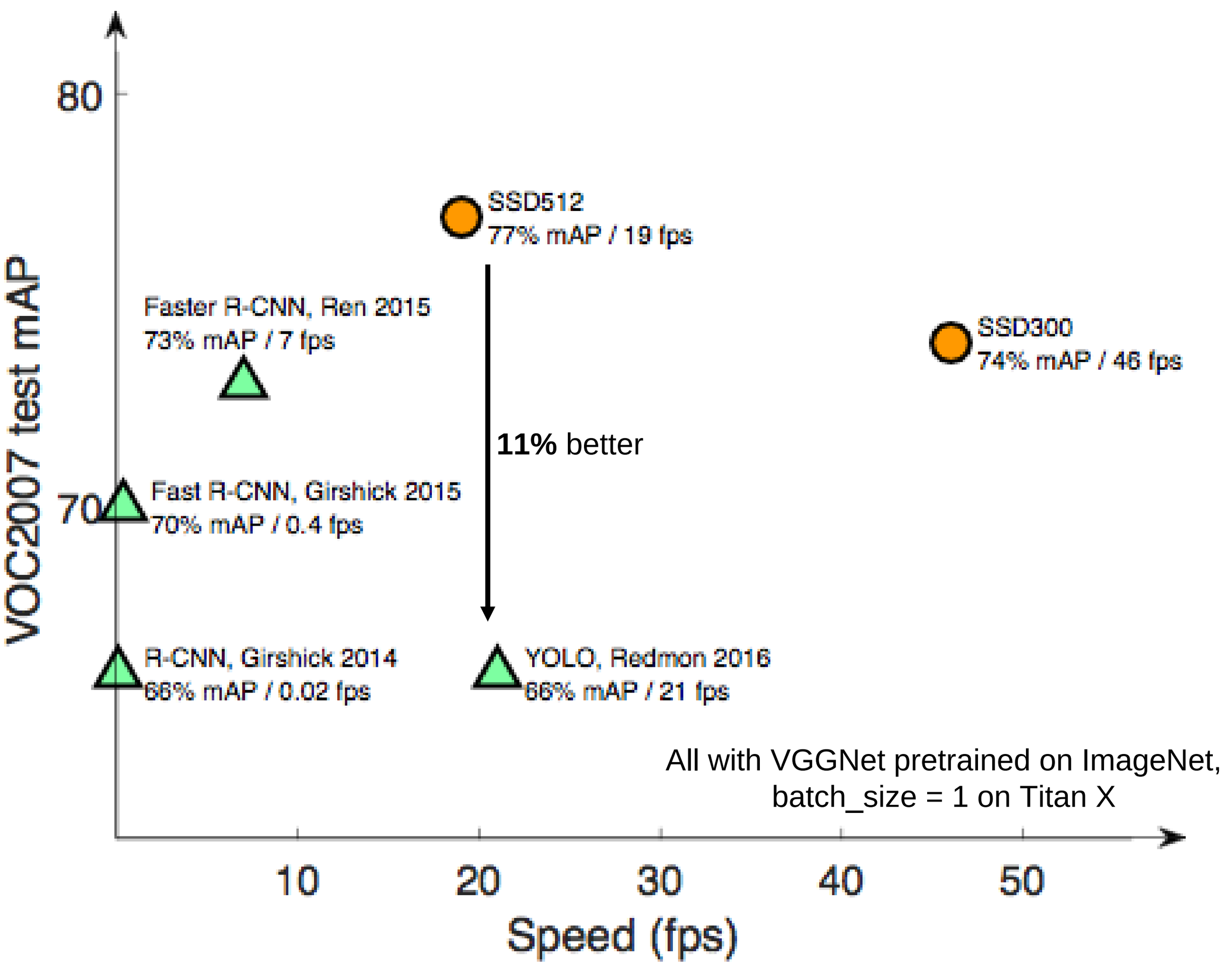
Speed (fps)


VOC2007 test mAP
80
70
SSD512
77% mAP / 19 fps
Faster R-CNN, Ren 2015
73% mAP / 7 fps
SSD300
74% mAP / 46 fps
11% better
Fast R-CNN, Girshick 2015
70% mAP / 0.4 fps
R-CNN, Girshick 2014
66% mAP / 0.02 fps
YOLO, Redmon 2016
66% mAP / 21 fps
All with VGGNet pretrained on ImageNet,
batch_size = 1 on Titan X
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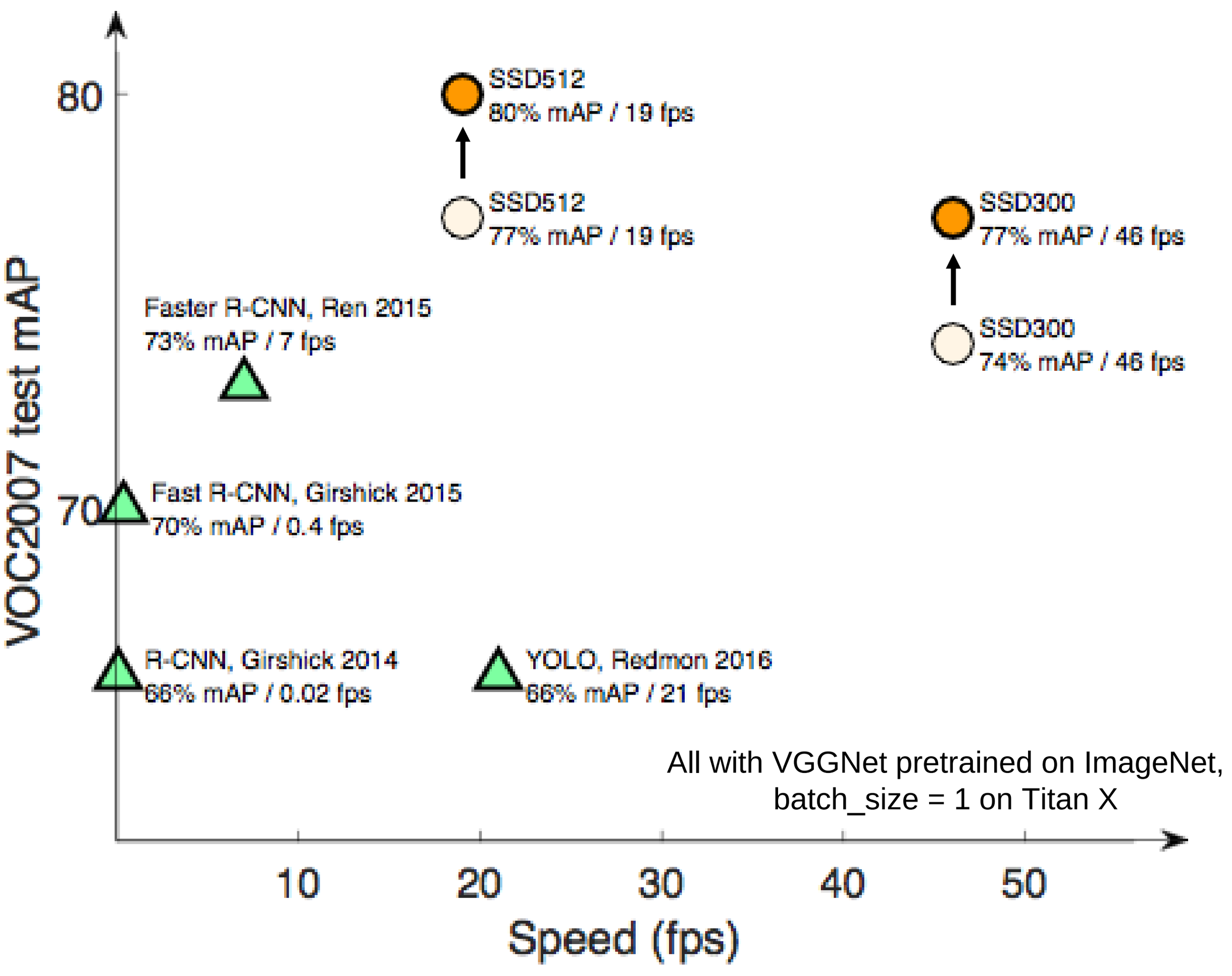
50
Speed (fps)


VOC2007 test mAP
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All with VGGNet pretrained on ImageNet,
batch_size = 1 on Titan X
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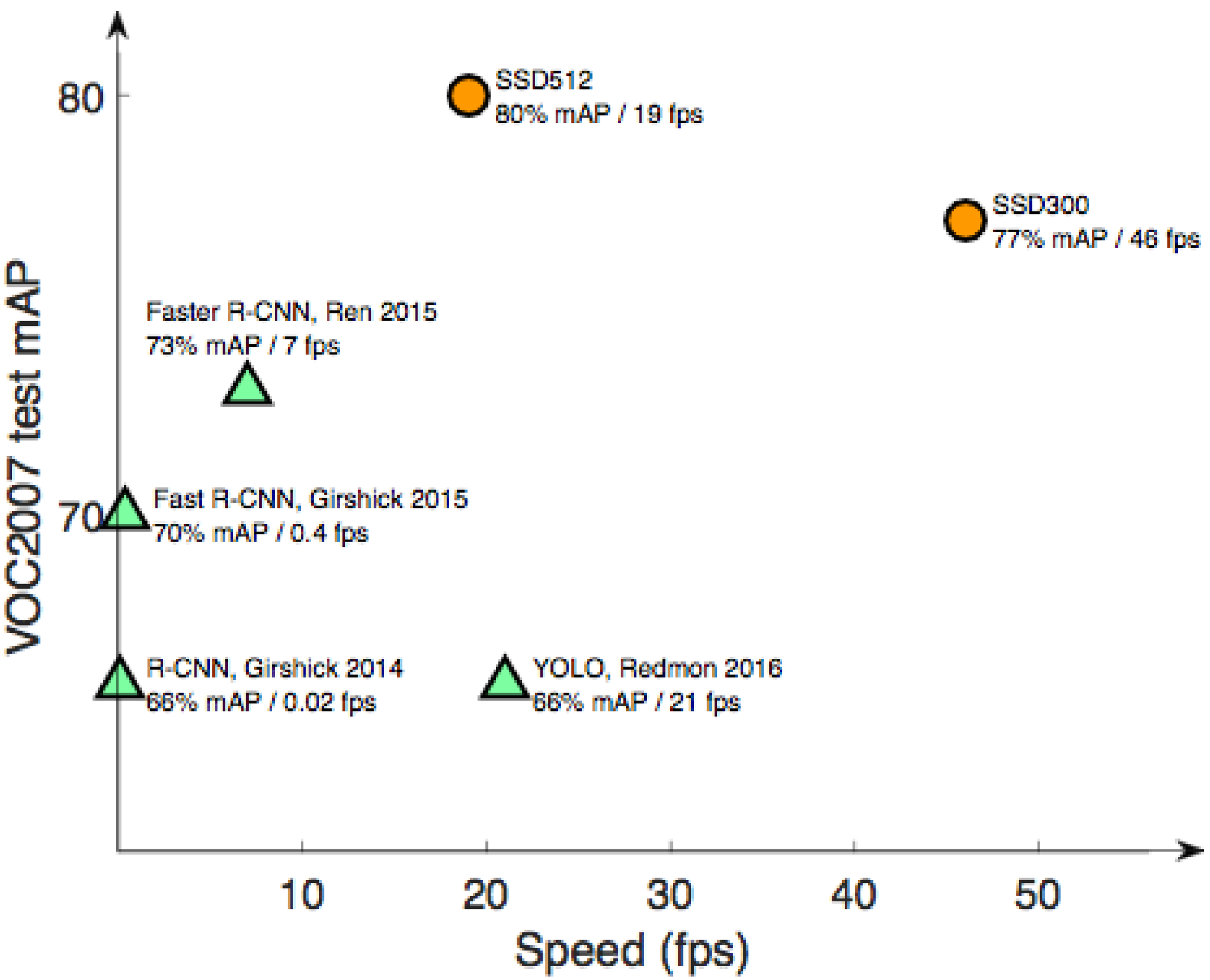
Speed (fps)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66% mAP / 21 fps
10
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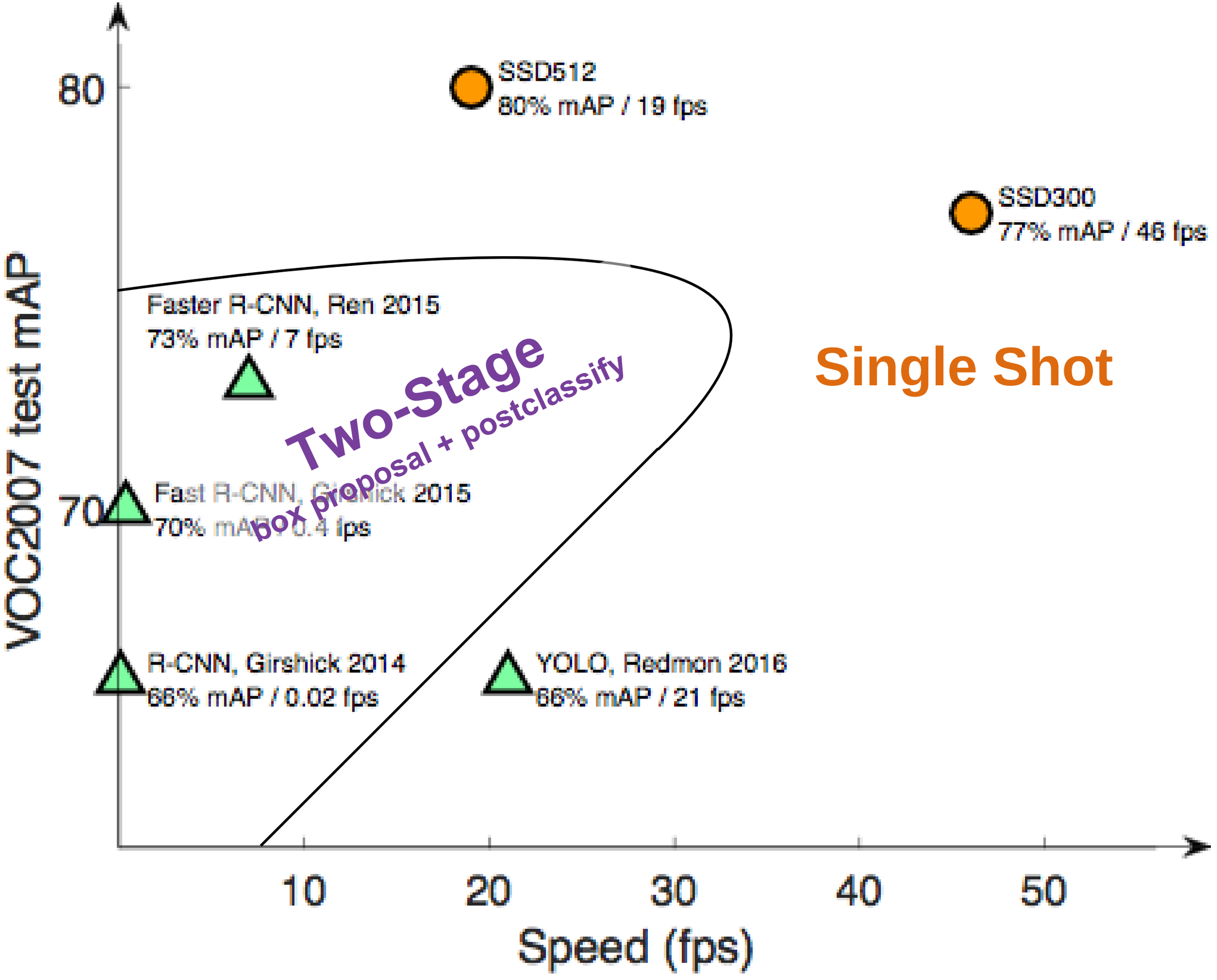
Speed (fps)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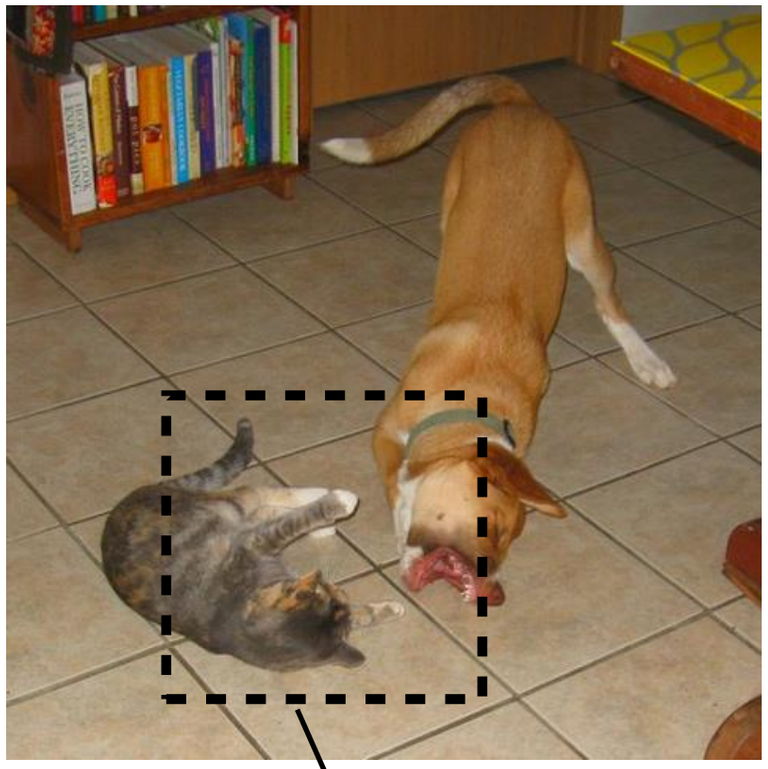
VOC2007 test mAP
SSD512
80% mAP / 19 fps
SSD300
77% mAP / 46 fps
Faster R-CNN, Ren 2015
73% mAP / 7 fps
Two-Stage
box proposal + postclassify
Single Shot
Fast R-CNN, Girshick 2015
70% mAP / 0.4 fps
R-CNN, Girshick 2014
66% mAP / 0.02 fps
YOLO, Redmon 2016
66% mAP / 21 fps
10
20
30
40
50
Speed (fps)

Bounding Box Prediction

Classical sliding windows

Bounding Box Prediction

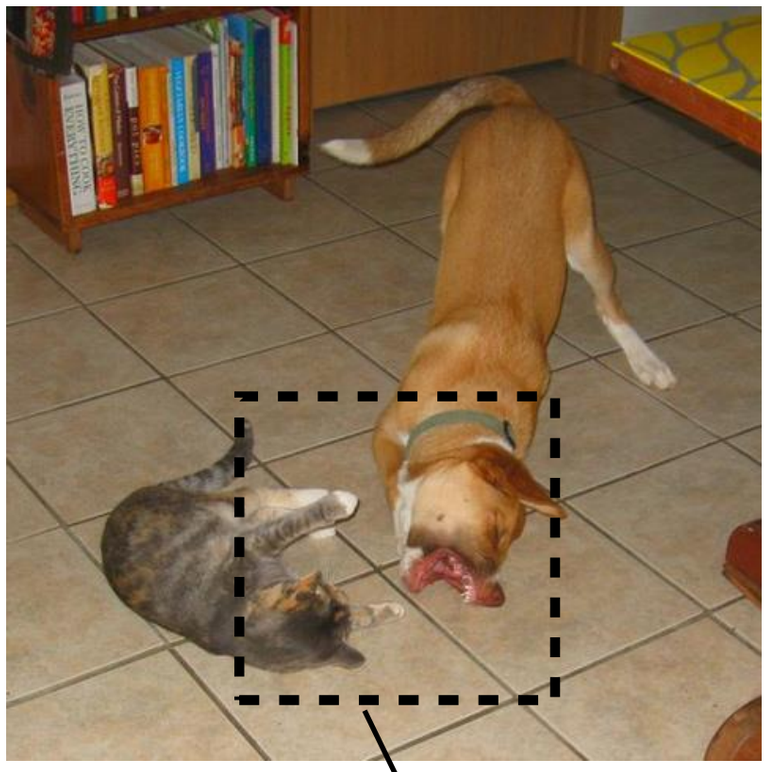
Classical sliding windows



Is it a cat? **No**

Bounding Box Prediction

Classical sliding windows

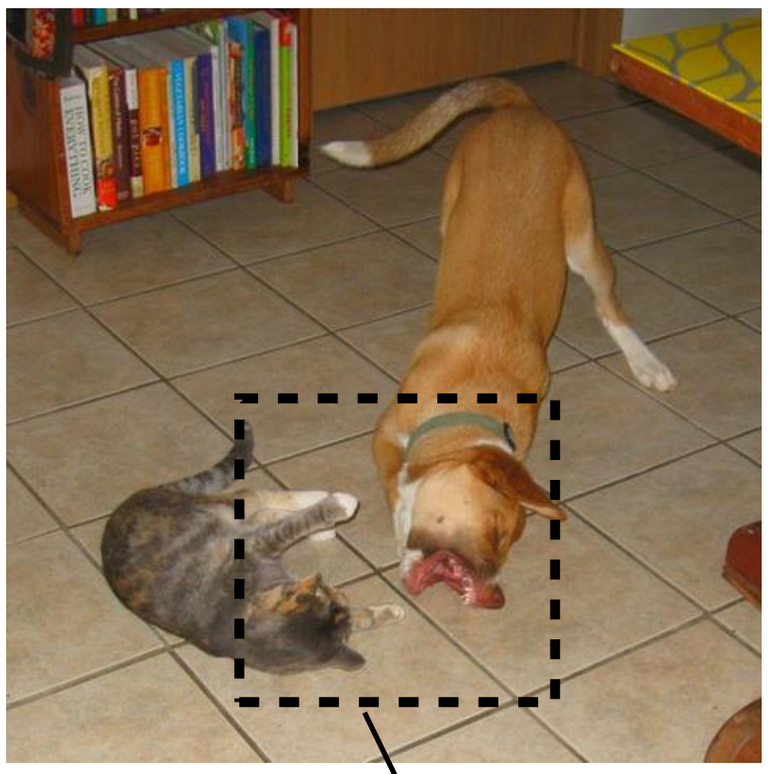


Is it a cat? **No**

Discretize the box space **densely**

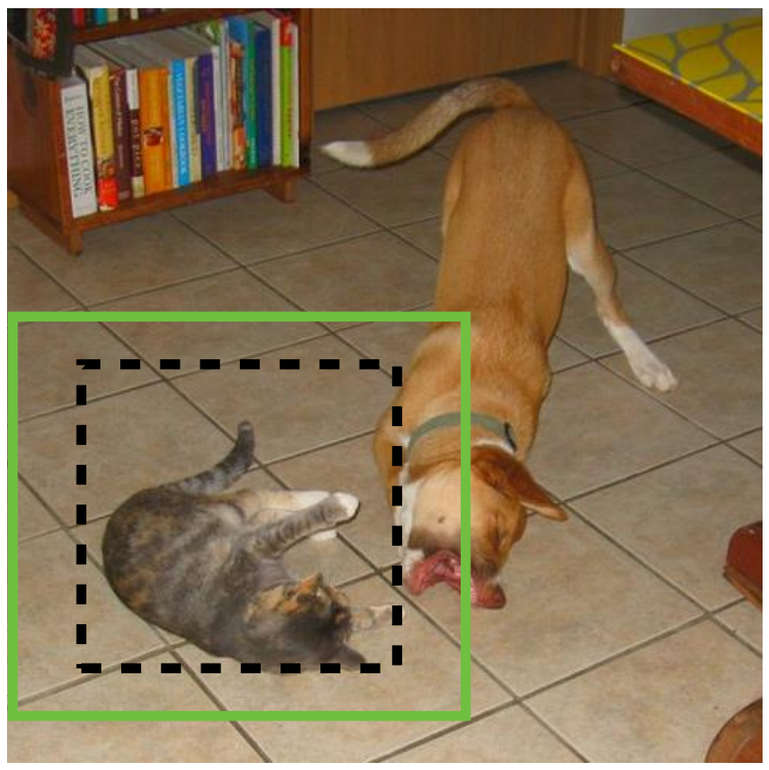
Bounding Box Prediction

Classical sliding windows



Is it a cat? **No**

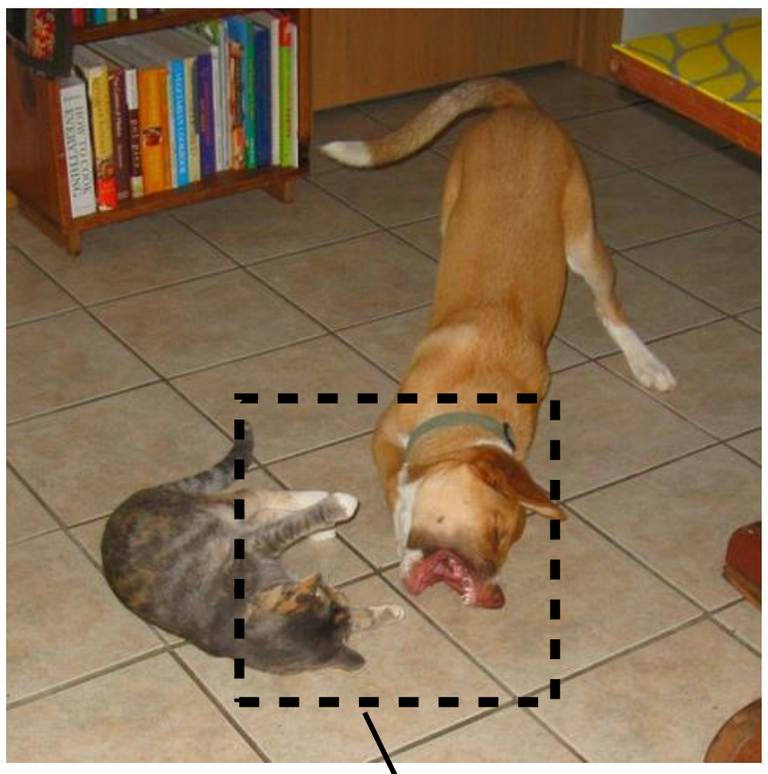
SSD and other deep approaches



Discretize the box space **densely**

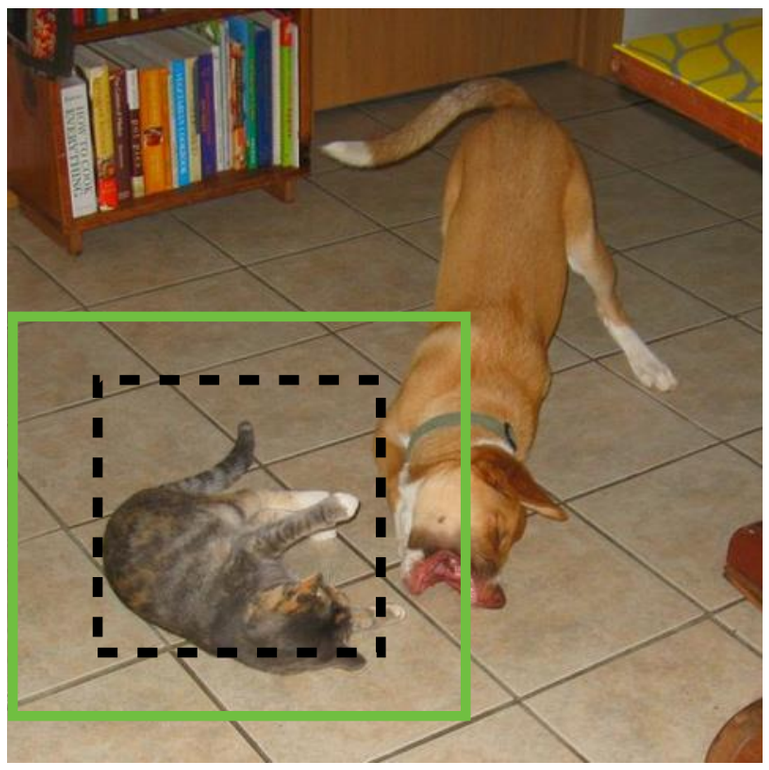
Bounding Box Prediction

Classical sliding windows



Is it a cat? **No**

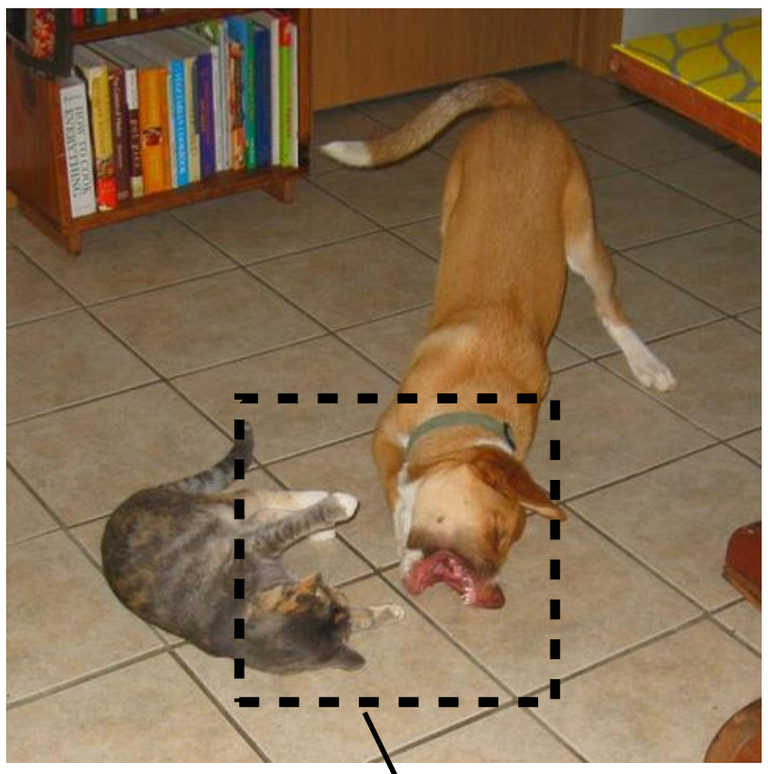
SSD and other deep approaches



Discretize the box space **densely**

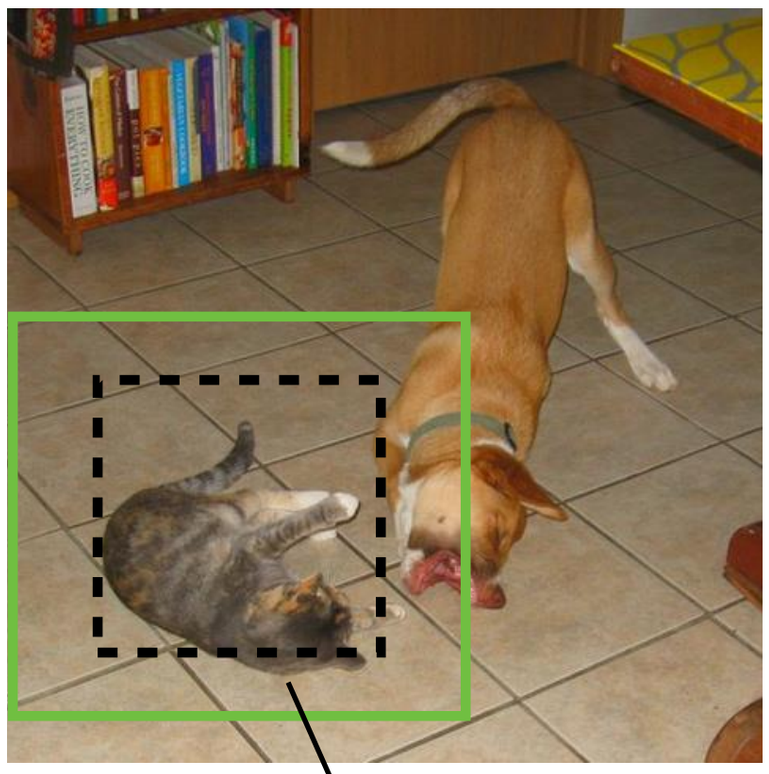
Bounding Box Prediction

Classical sliding windows



Is it a cat? **No**

SSD and other deep approaches

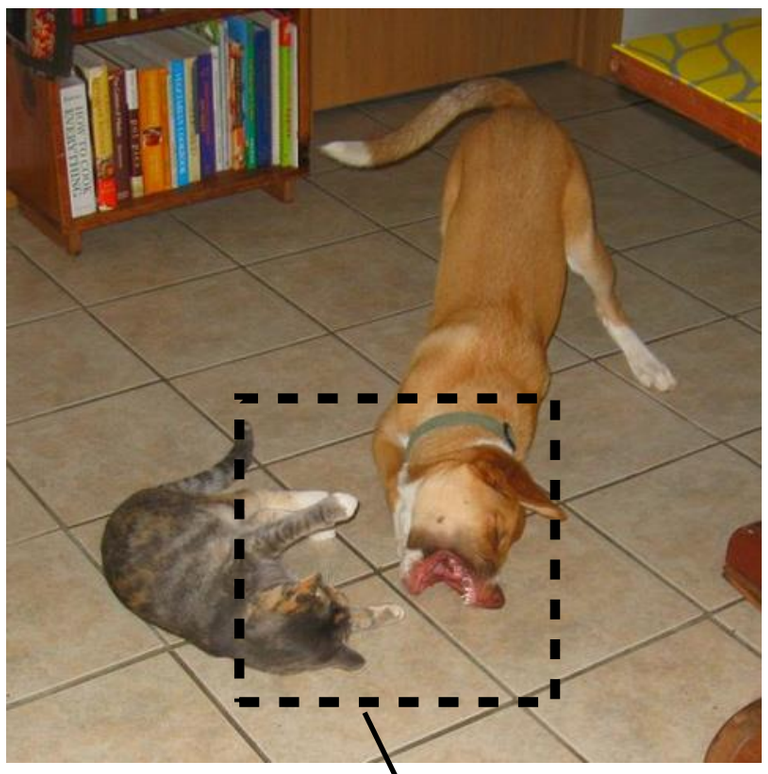


cat: 0.8 dog: 0.1

Discretize the box space **densely**

Bounding Box Prediction

Classical sliding windows



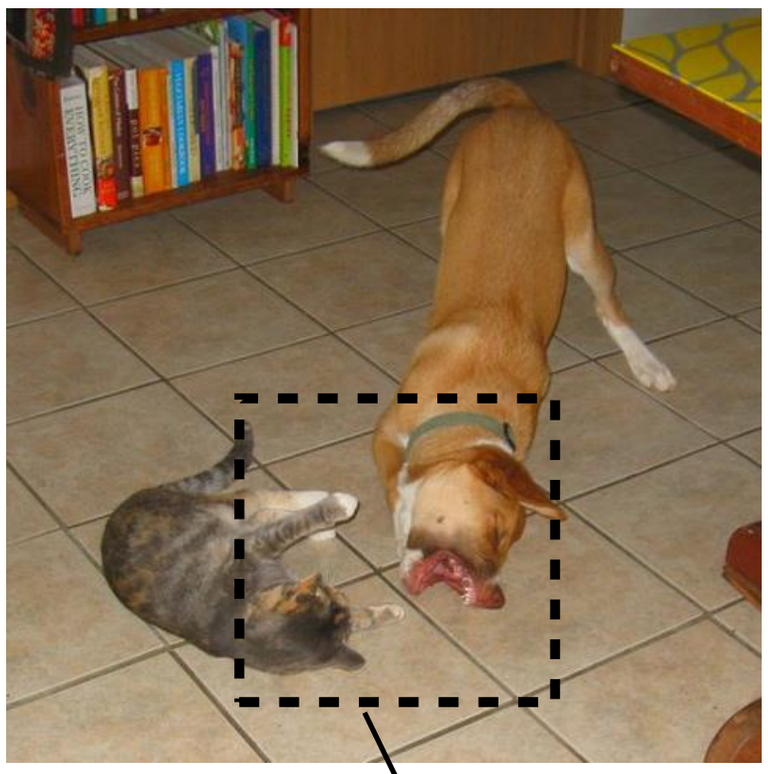
Is it a cat? **No**

SSD and other deep approaches

Discretize the box space **densely**

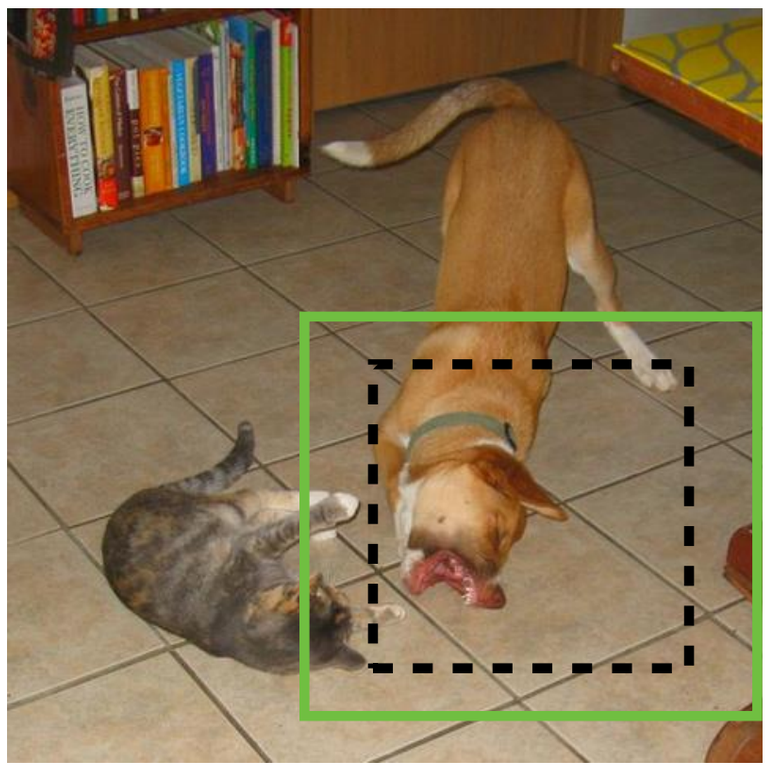
Bounding Box Prediction

Classical sliding windows



Is it a cat? **No**

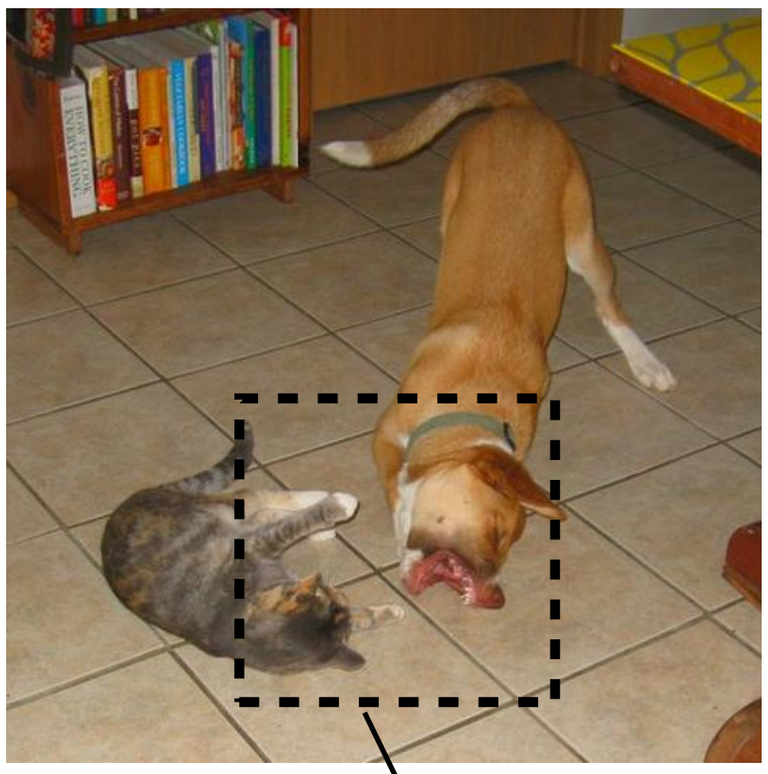
SSD and other deep approaches



Discretize the box space **densely**

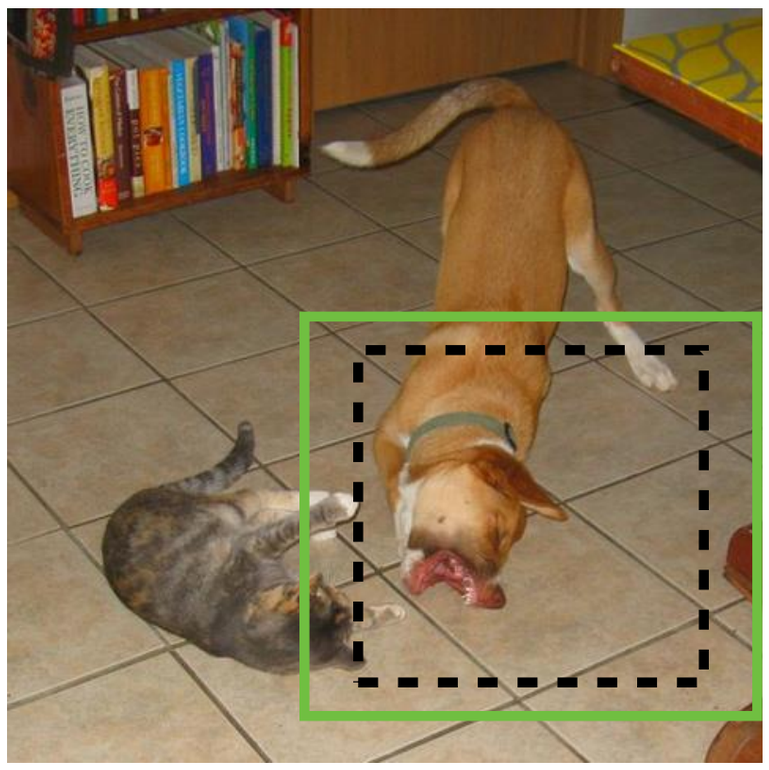
Bounding Box Prediction

Classical sliding windows



Is it a cat? **No**

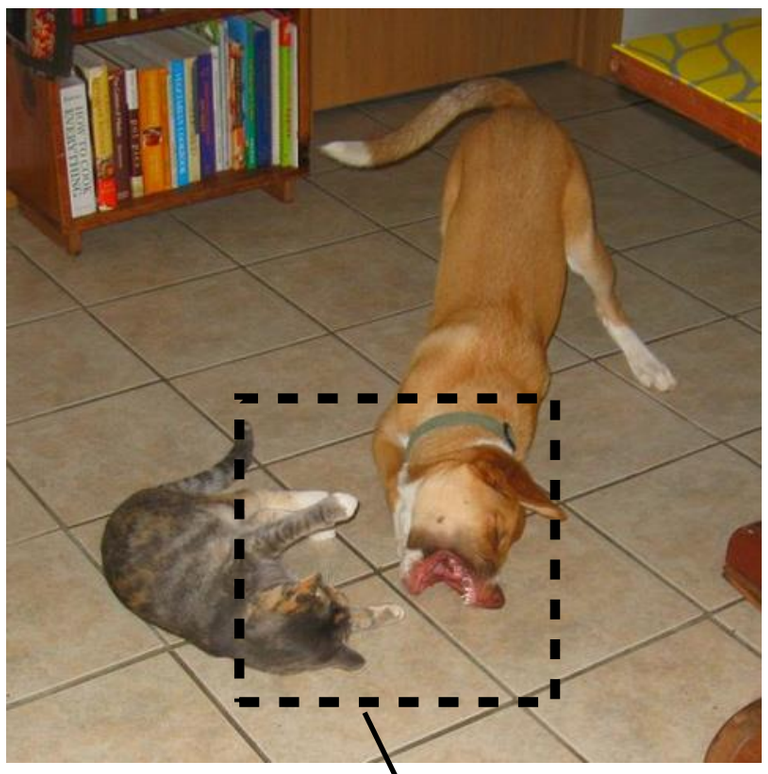
SSD and other deep approaches



Discretize the box space **densely**

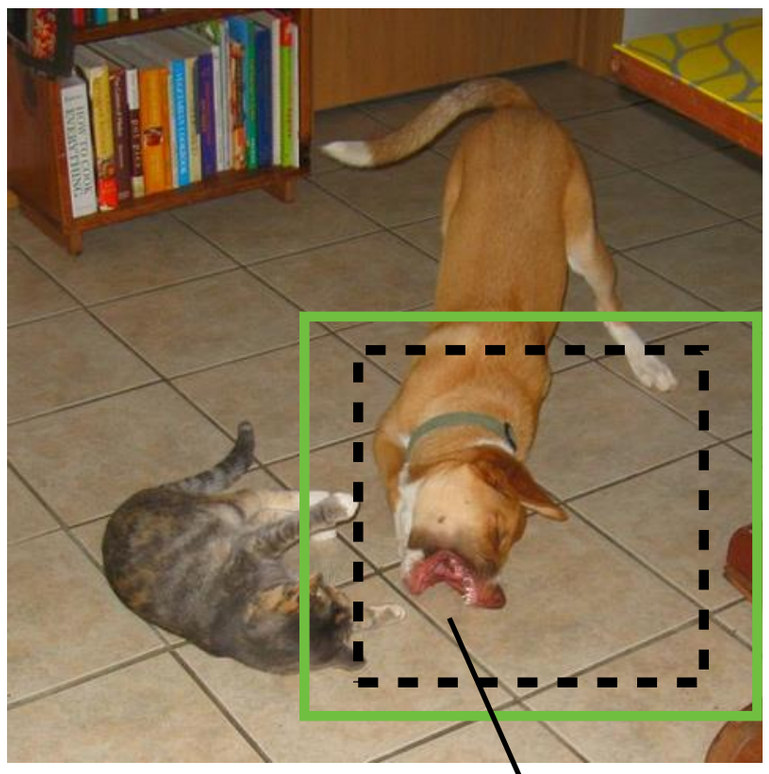
Bounding Box Prediction

Classical sliding windows



Is it a cat? **No**

SSD and other deep approaches

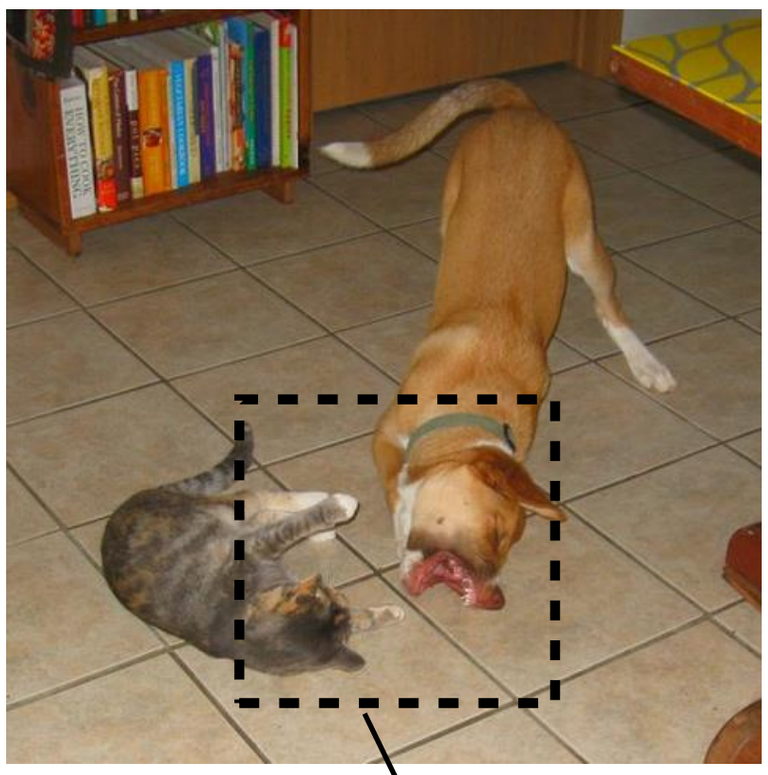


dog: 0.4 cat: 0.2

Discretize the box space **densely**

Bounding Box Prediction

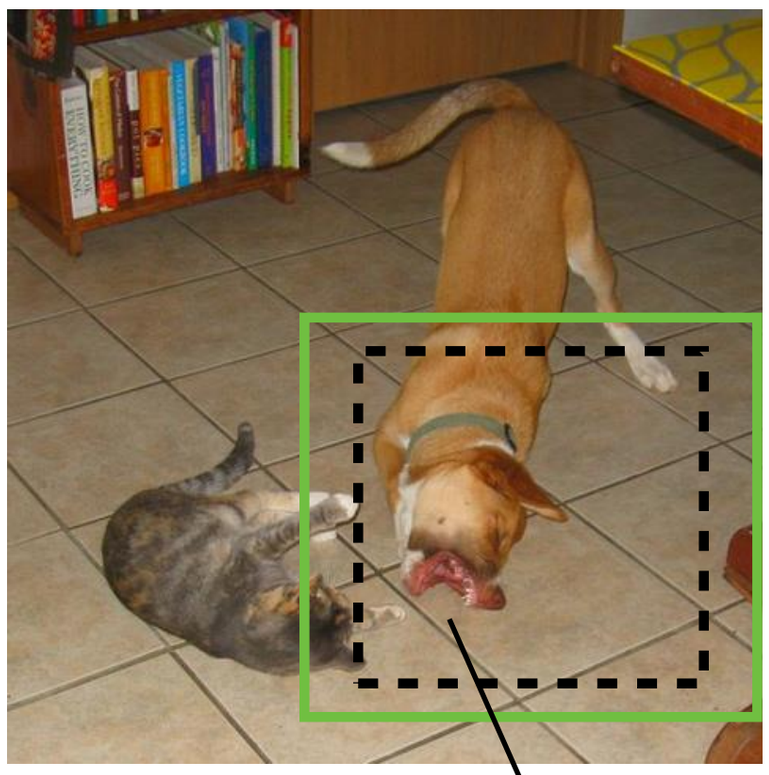
Classical sliding windows



Is it a cat? **No**

Discretize the box space **densely**

SSD and other deep approaches

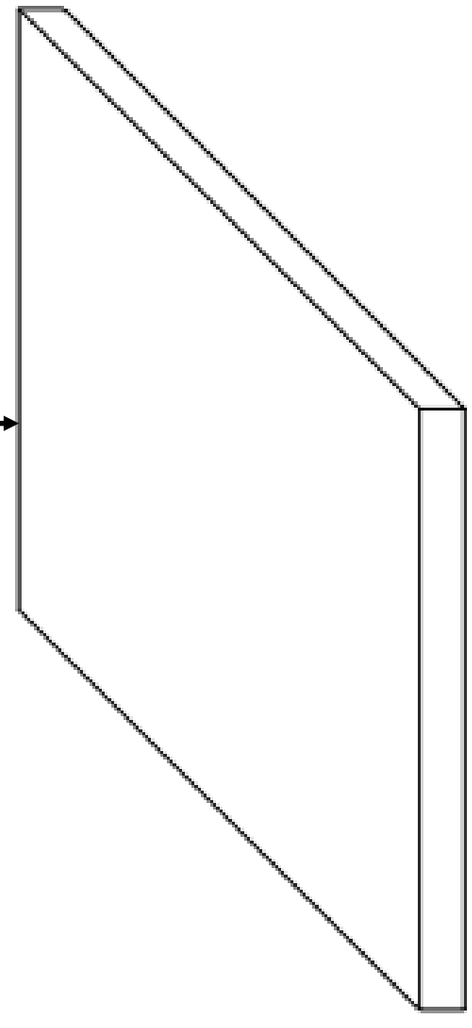


dog: 0.4 cat: 0.2

Discretize the box space more **coarsely**
Refine the coordinates of each box

SSD Output Layer

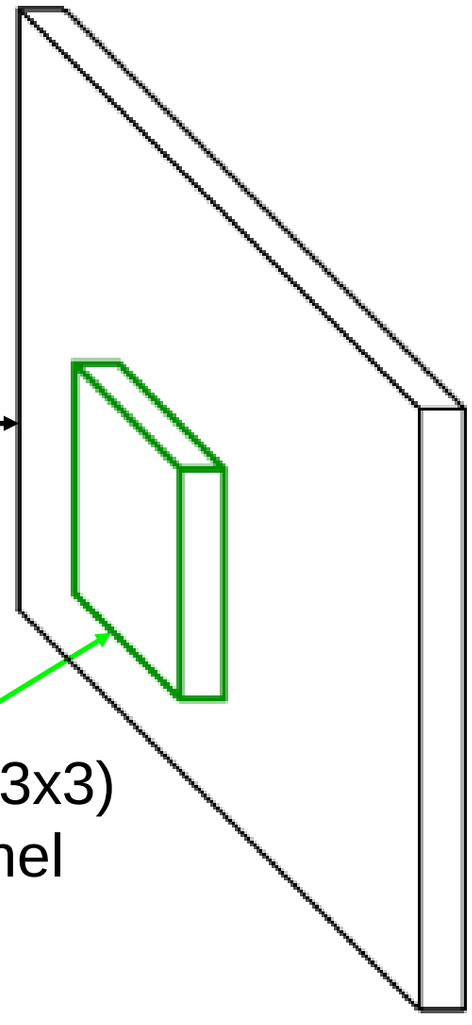
ConvNet



feature map

SSD Output Layer

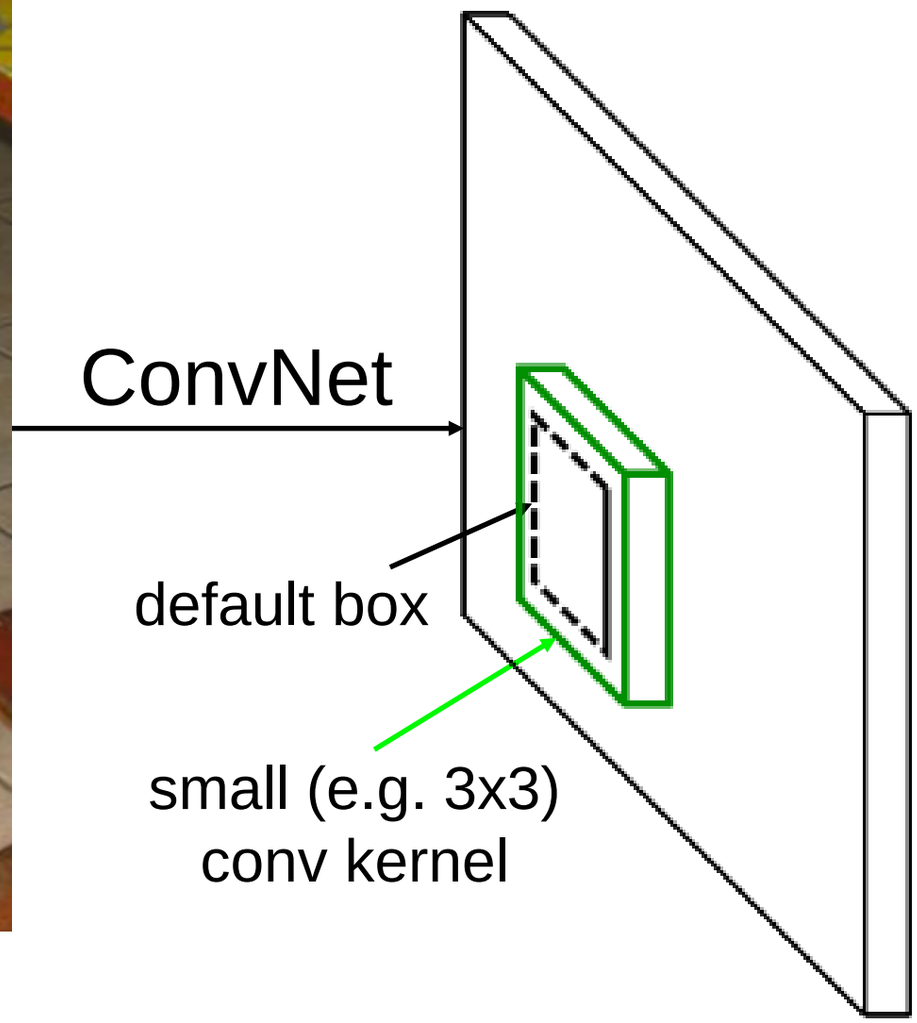
ConvNet



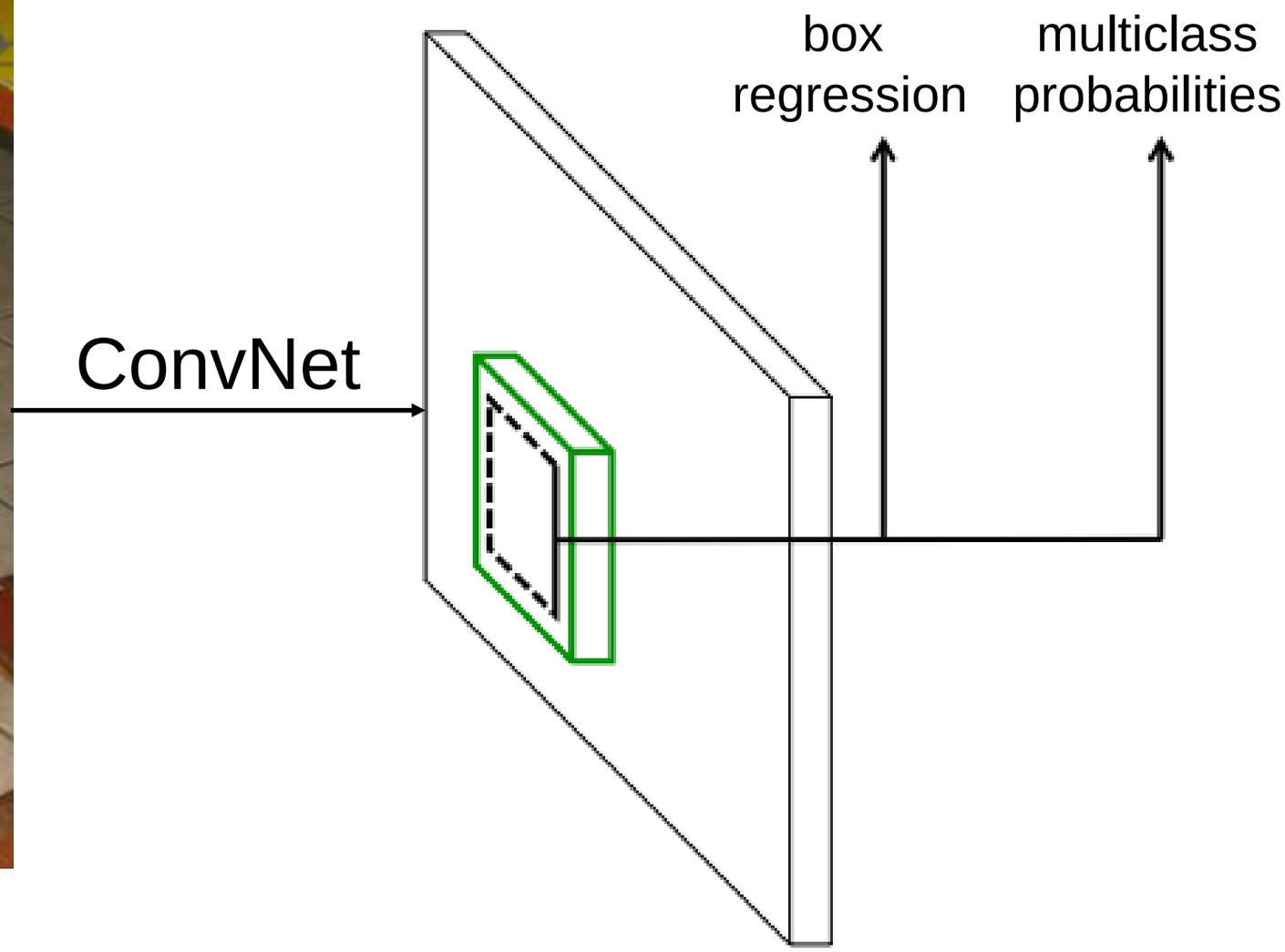
small (e.g. 3x3)
conv kernel

feature map

SSD Output Layer



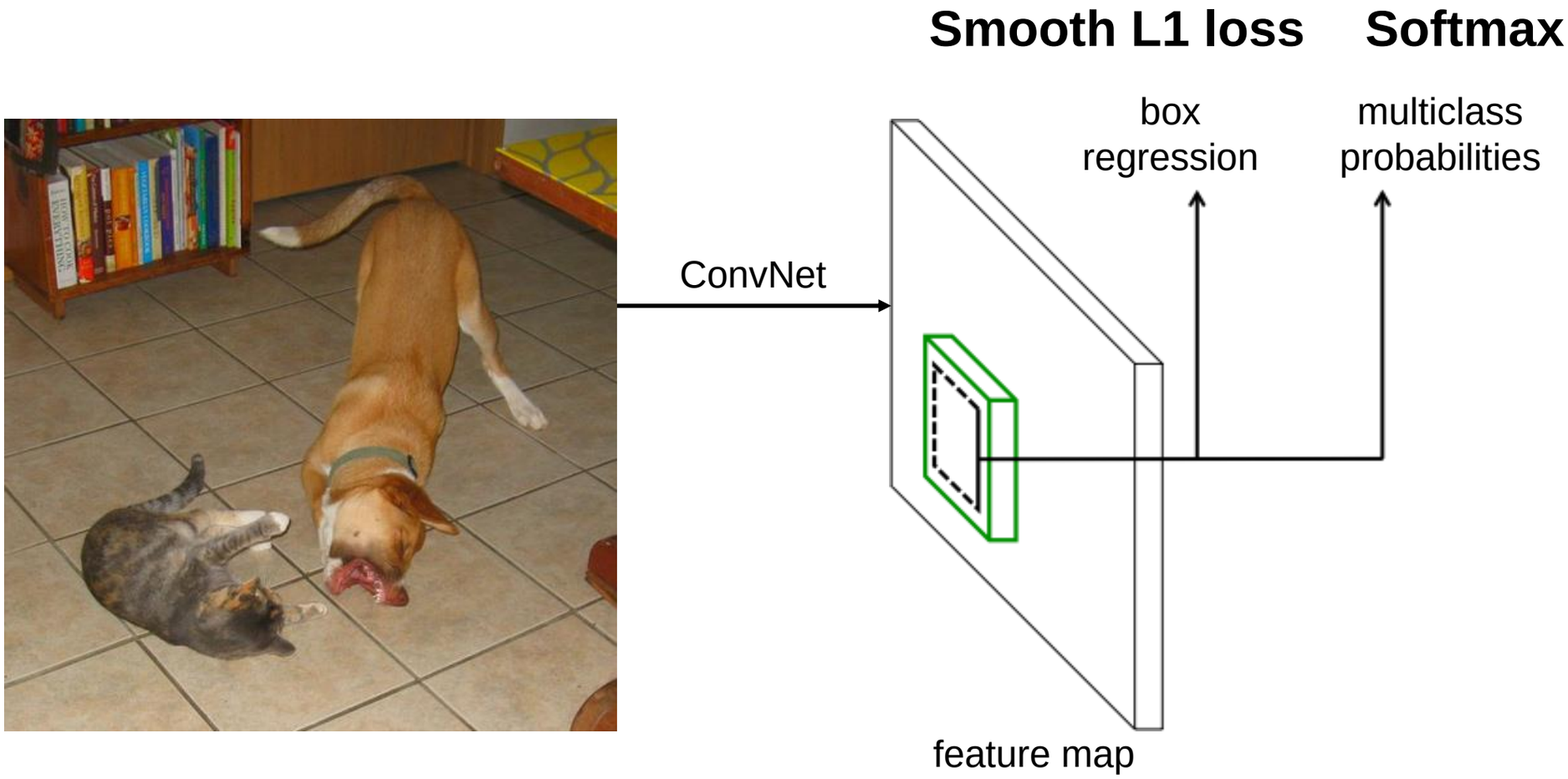
SSD Output Layer



SSD Training

- Match default boxes to ground truth boxes to determine true/false positives.

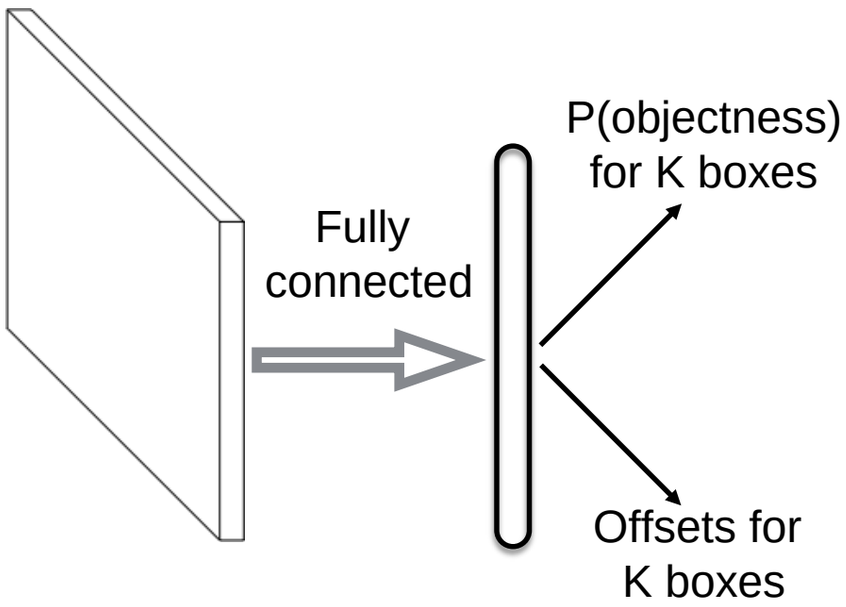
- Loss = **SmoothL1**(box param) + **Softmax**(class prob)



Related Work

Related Work

MultiBox [Erhan et al. CVPR14]



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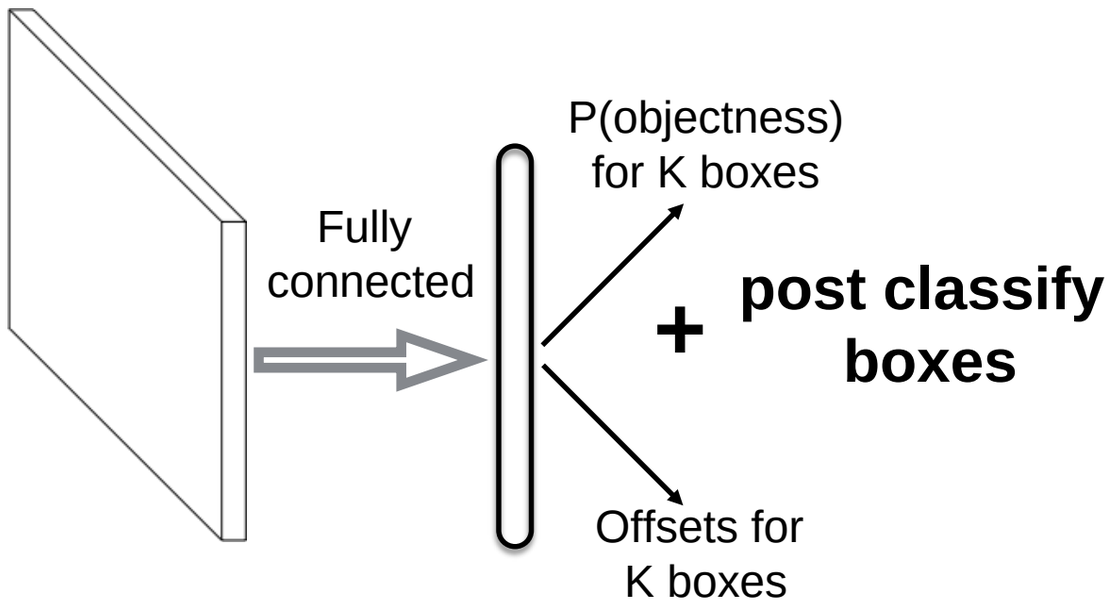

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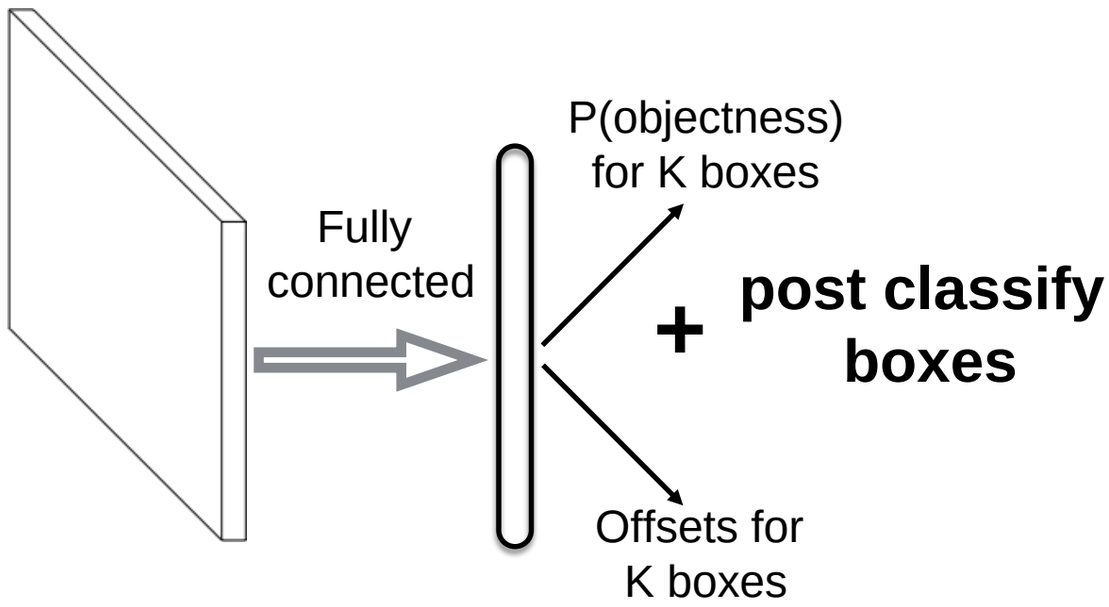
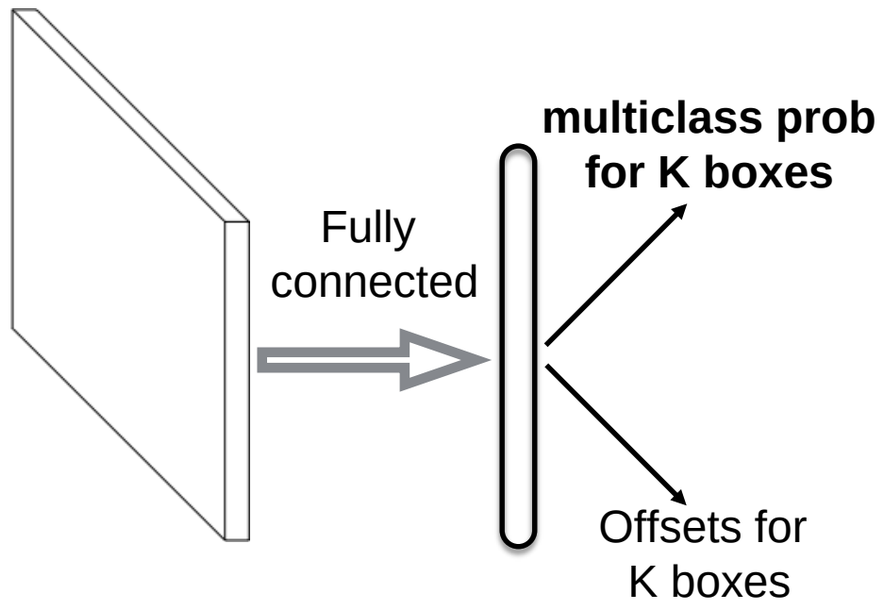


YOLO [Redmon et al. CVPR16]



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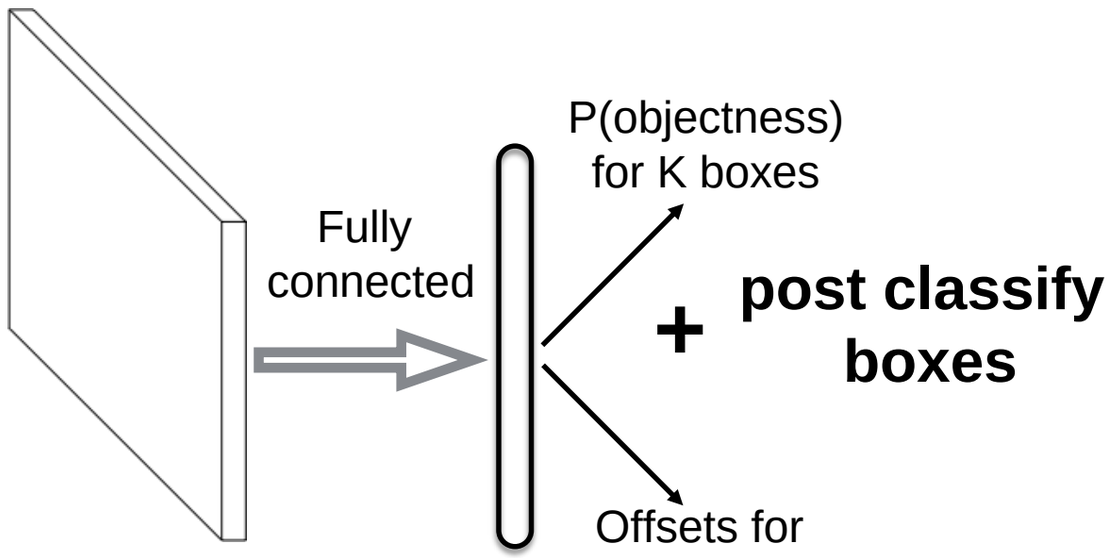

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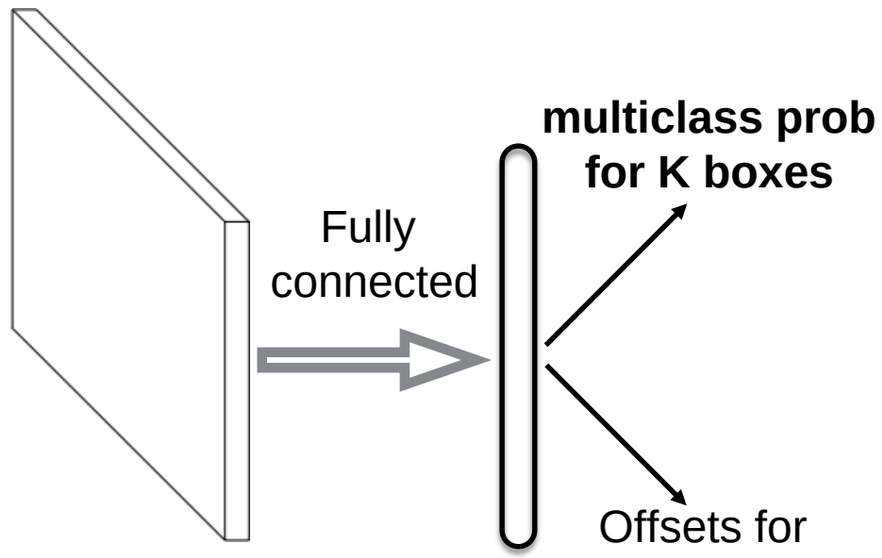
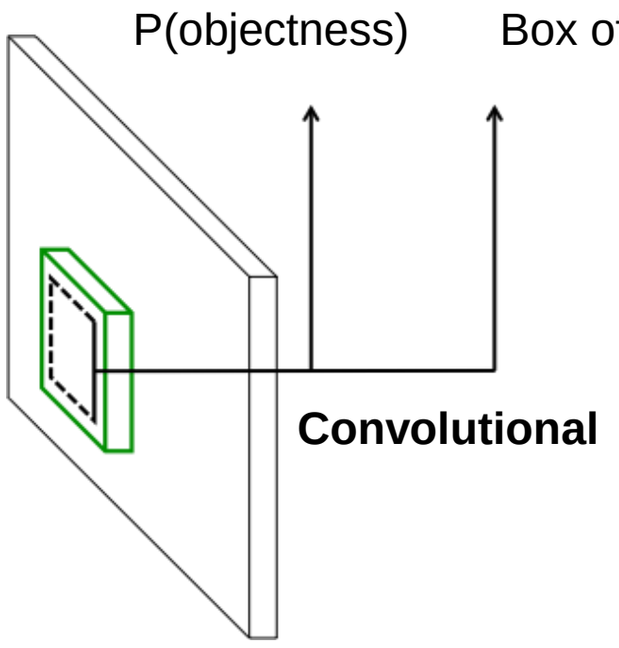


Faster R-CNN [Ren et al. NIPS15]



Related Work

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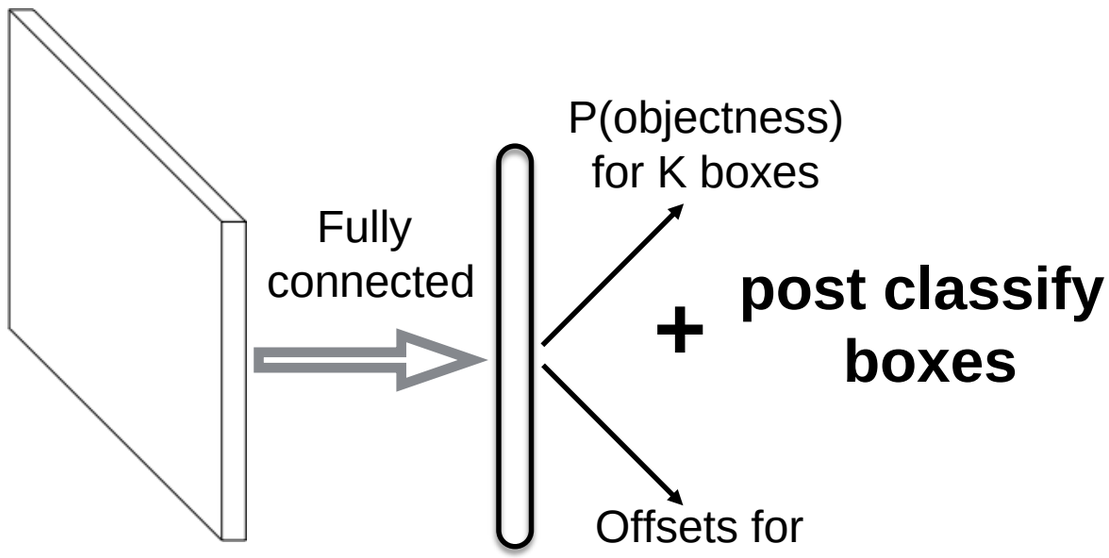
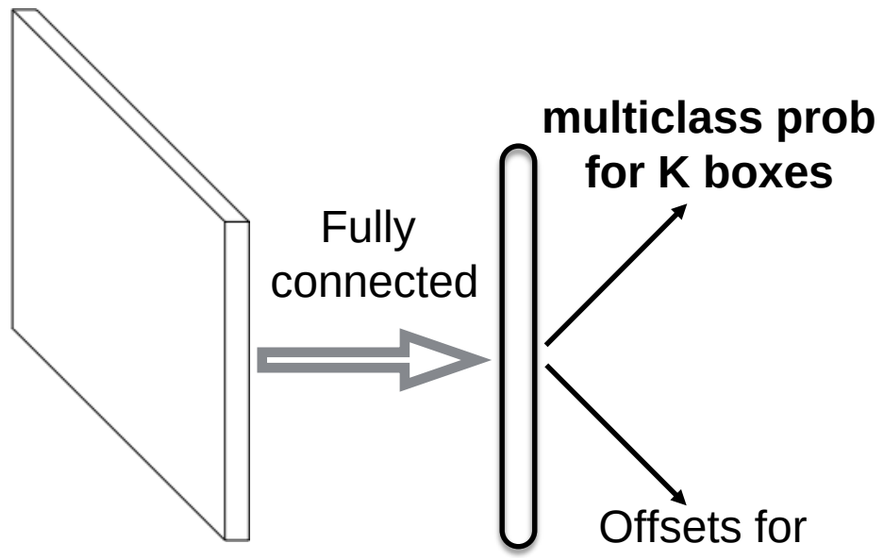
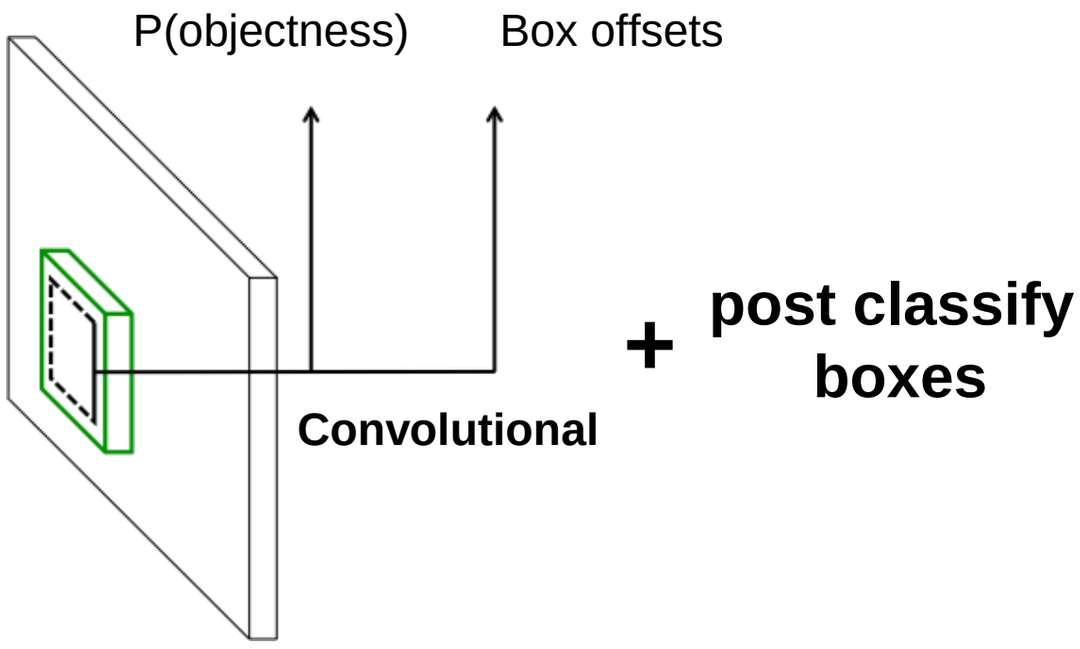


YOLO [Redmon et al. CVPR16]

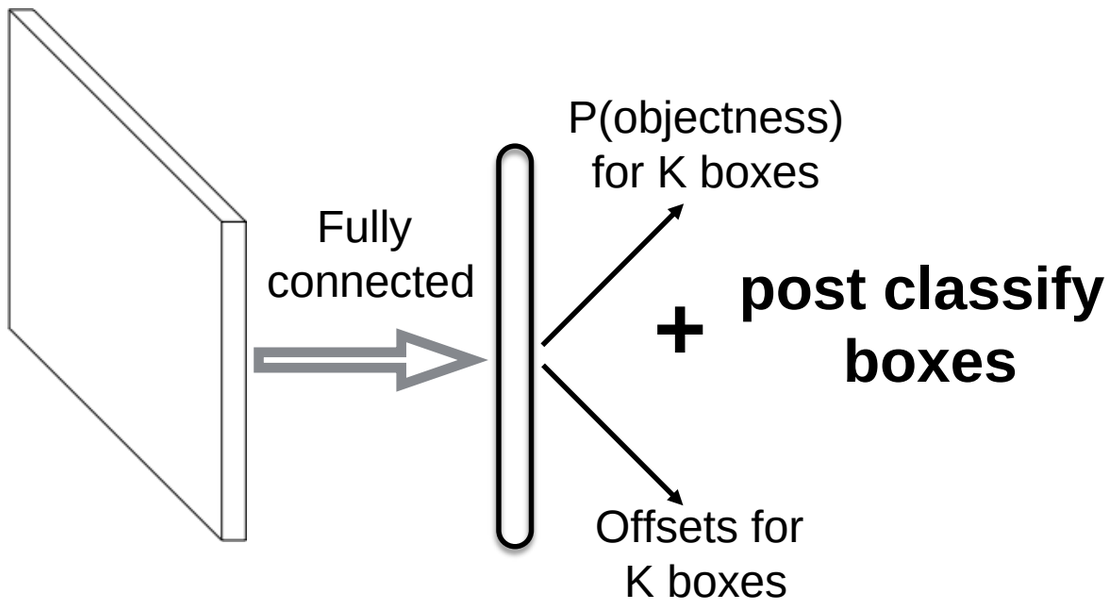


Faster R-CNN [Ren et al. NIPS15]



Related Work

MultiBox [Erhan et al. CVPR14]



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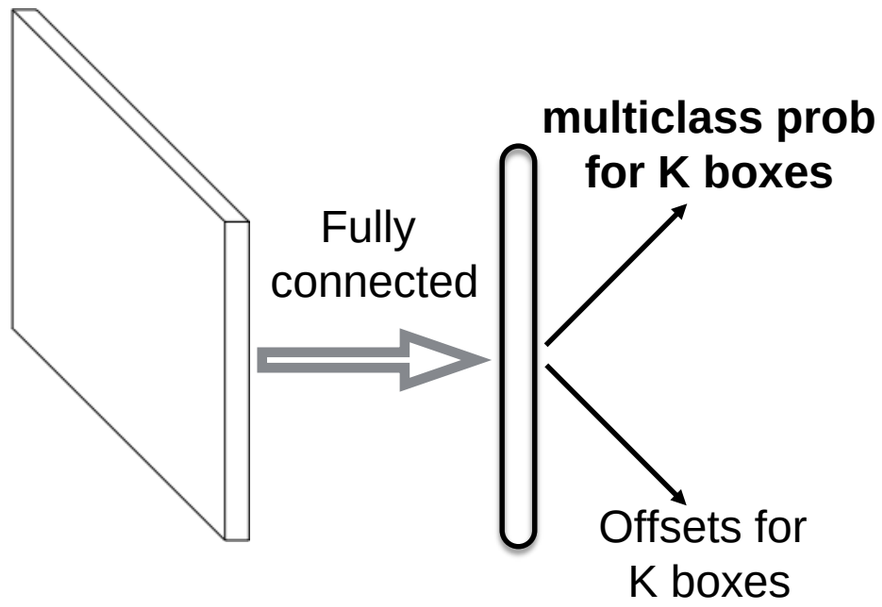
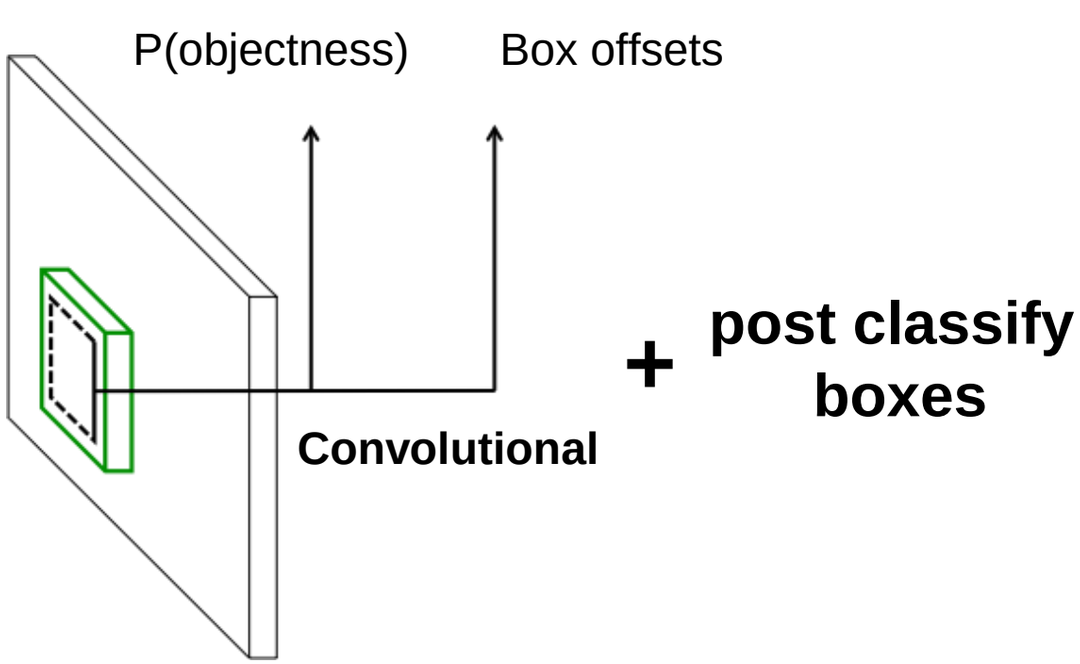
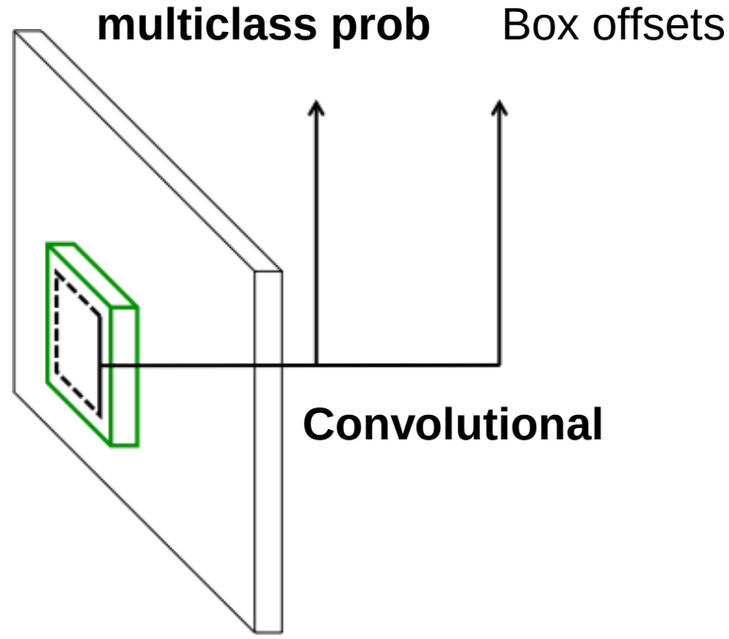


Faster R-CNN [Ren et al. NIPS15]

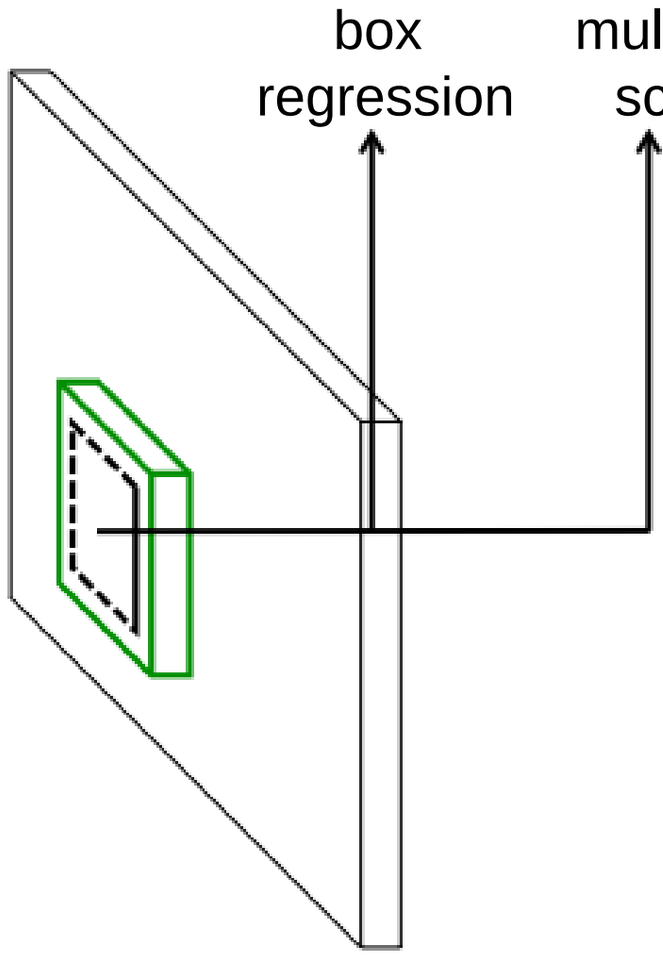


SSD



Contribution #1:
Multi-Scale Feature Maps

ConvNet



Contribution #1:
Multi-Scale Feature Maps

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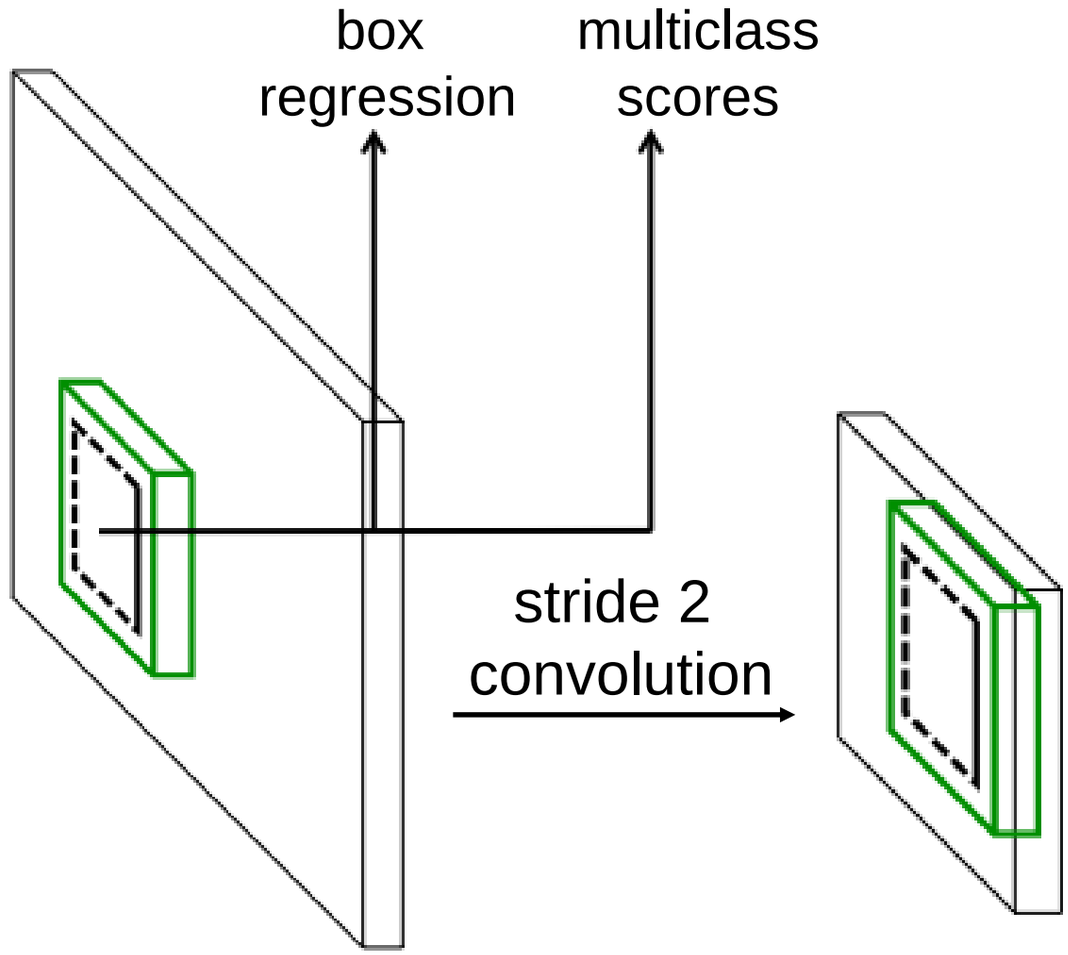
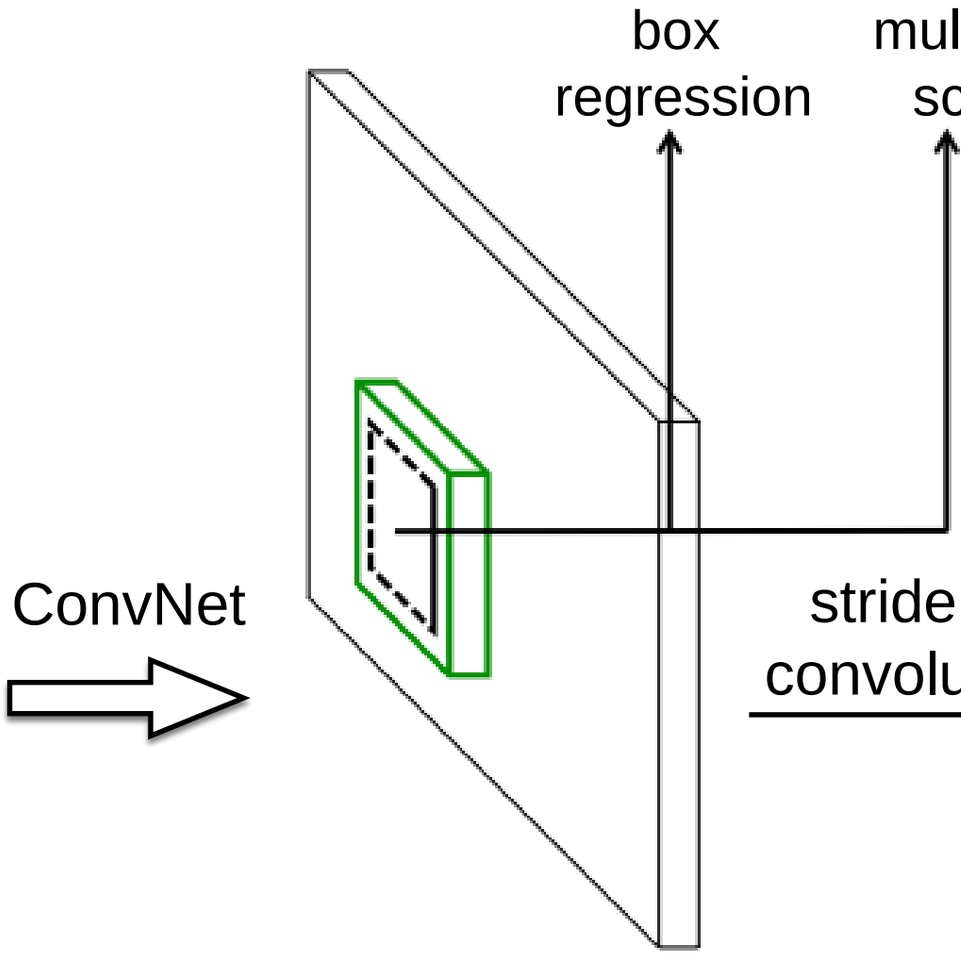
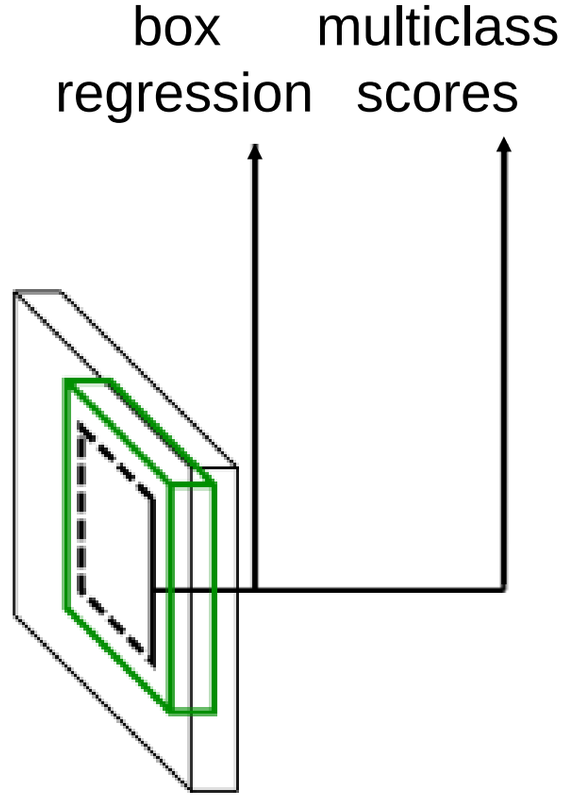


Contribution #1:
Multi-Scale Feature Maps

ConvNet

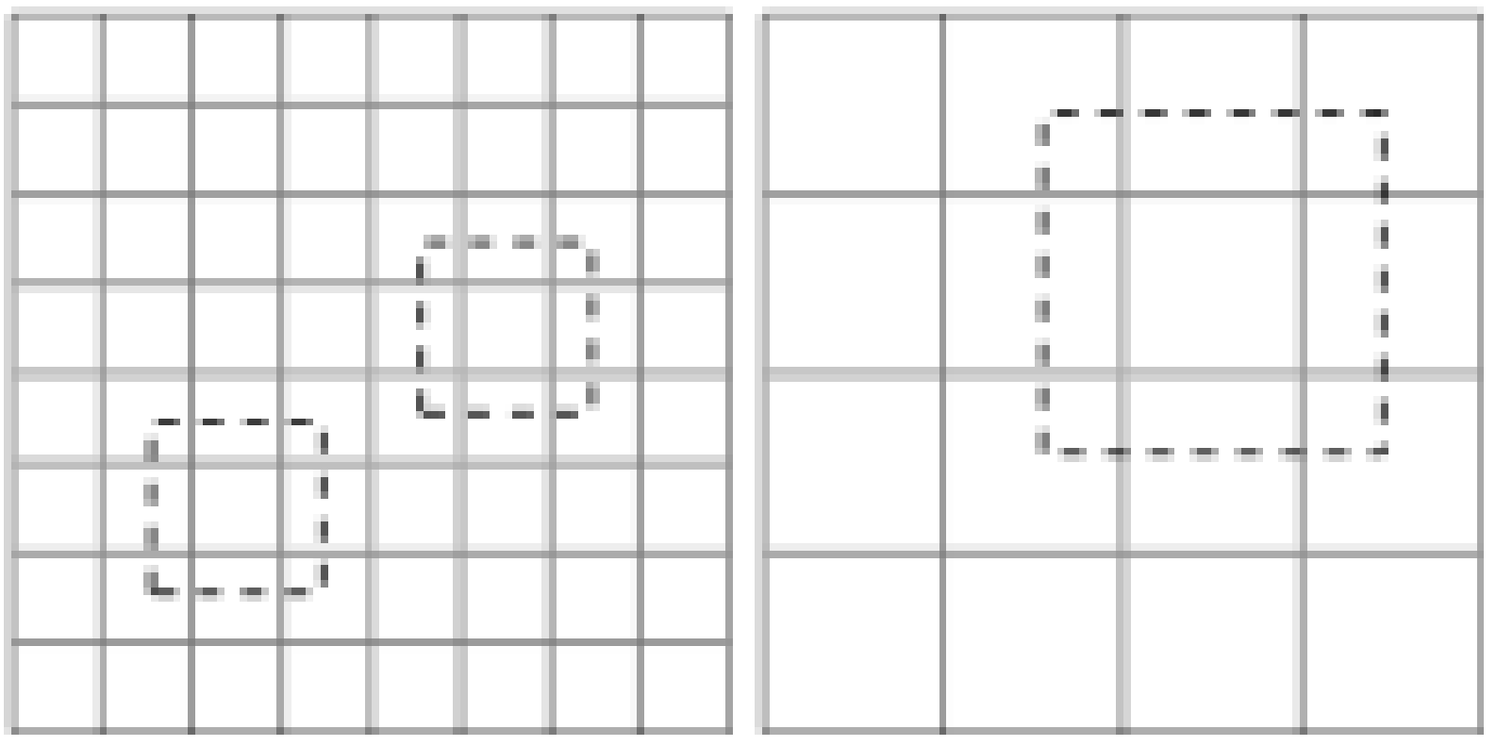


stride 2
convolution



Multi-Scale Feature Maps

SSD



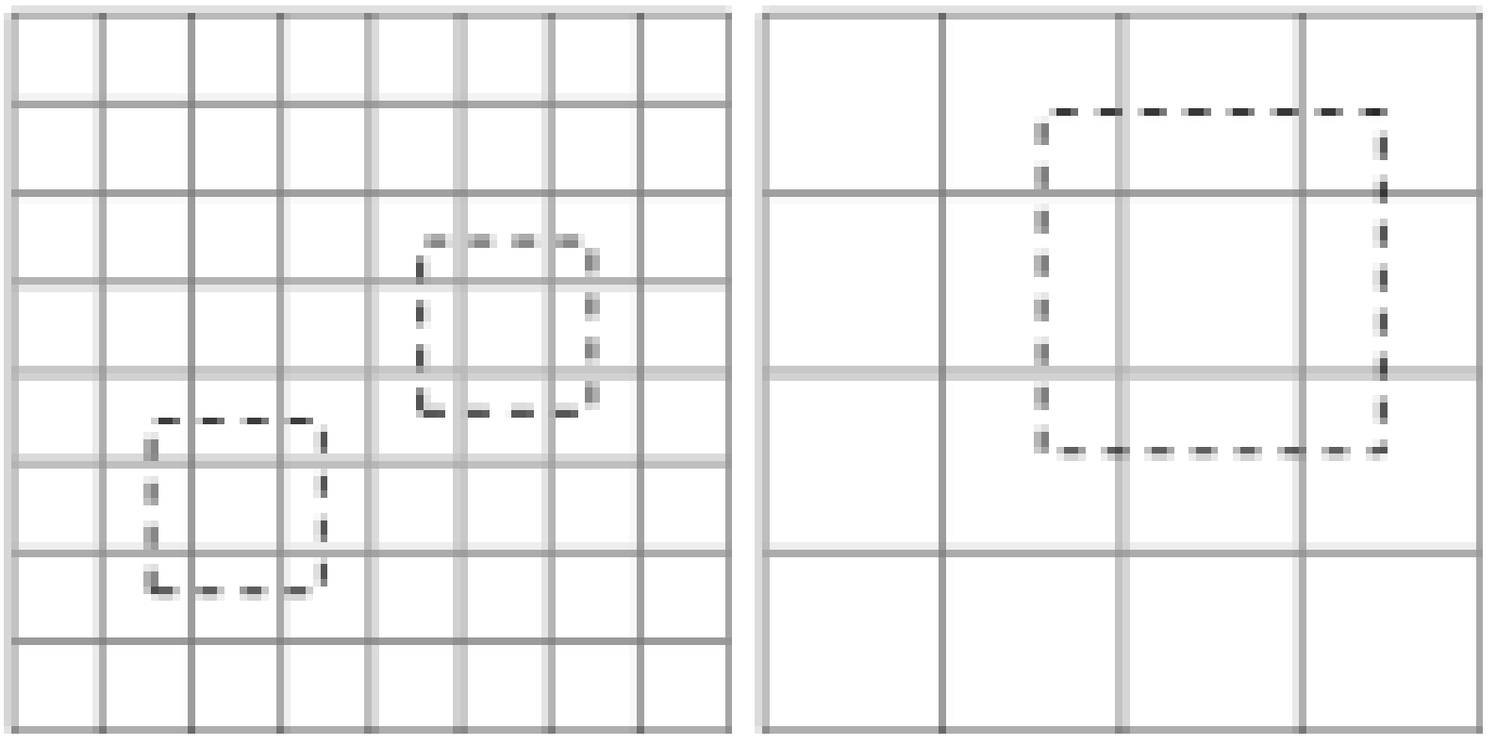
8 × 8 feature map

4 × 4 feature map

Multi-Scale Feature Maps

SSD

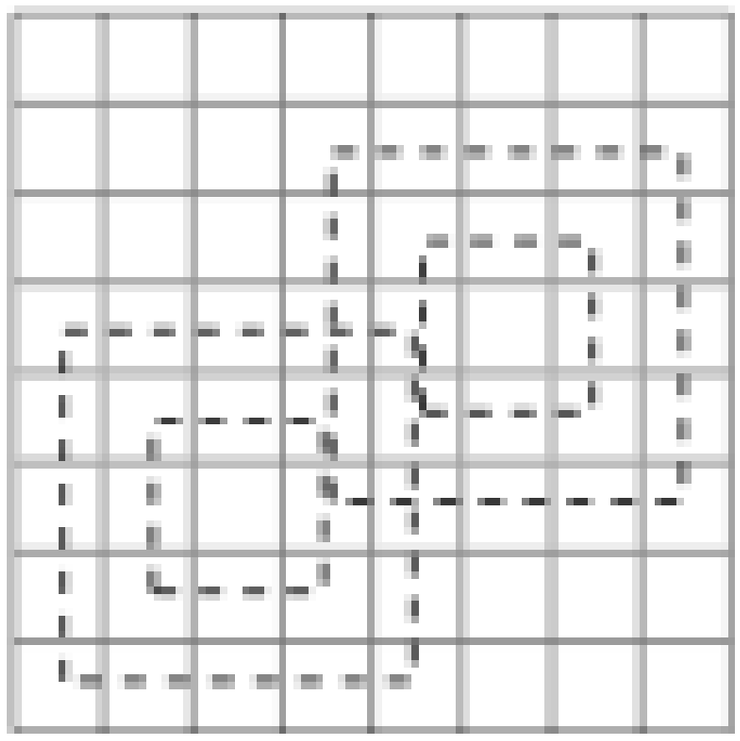
Faster R-CNN Objectness Proposal, Ren 2015



8 × 8 feature map

4 × 4 feature map

vs.



8 × 8 feature map

Multi-Scale Feature Maps Experiment

Prediction source layers from:						mAP use boundary boxes?		# Boxes
38 x 38	19 x 19	10 x 10	5 x 5	3 x 3	1 x 1	Yes	No	
✔	✔	✔	✔	✔	✔	74.3	63.4	8732
✔	✔	✔				70.7	69.2	9864
	✔					62.4	64.0	8664

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						Yes	No	
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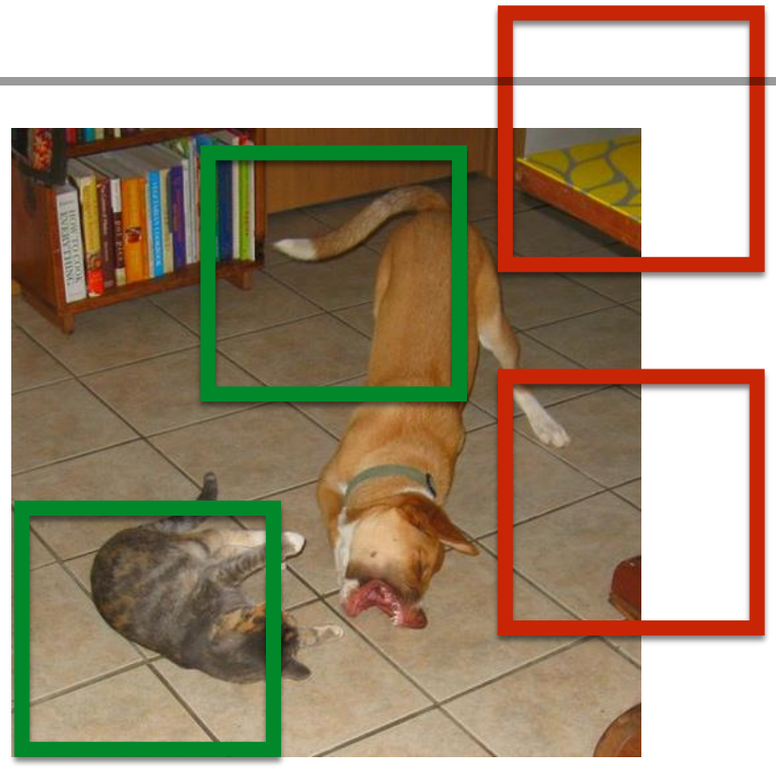

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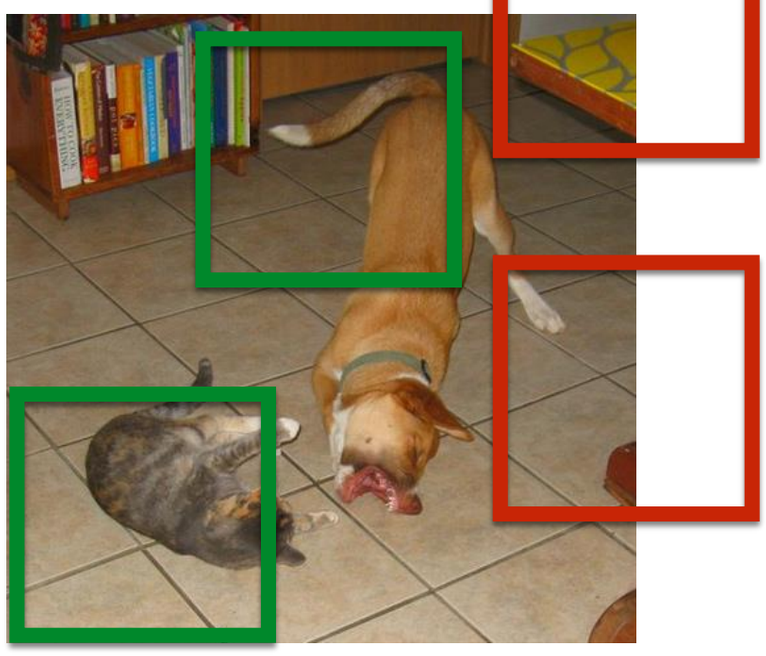

boundary boxes

Multi-Scale Feature Maps Experiment

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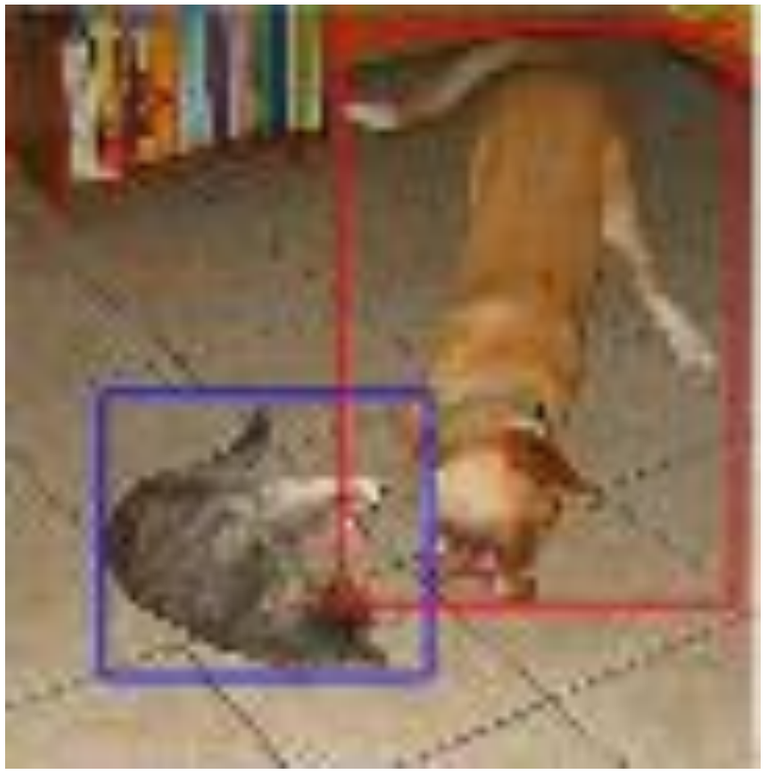
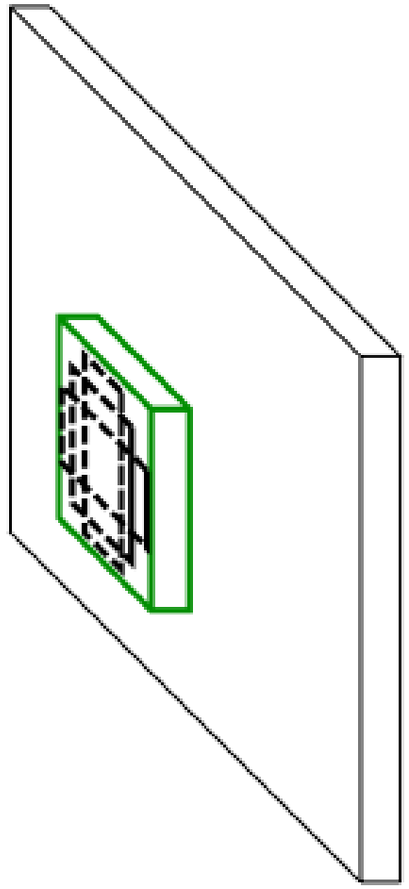
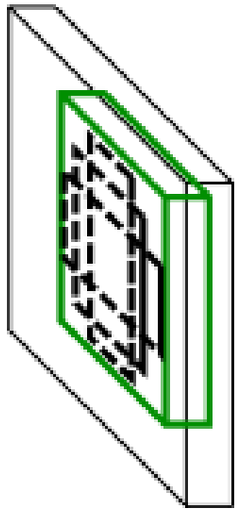
Contribution #2:
Splitting the Region Space



ConvNet



convolution



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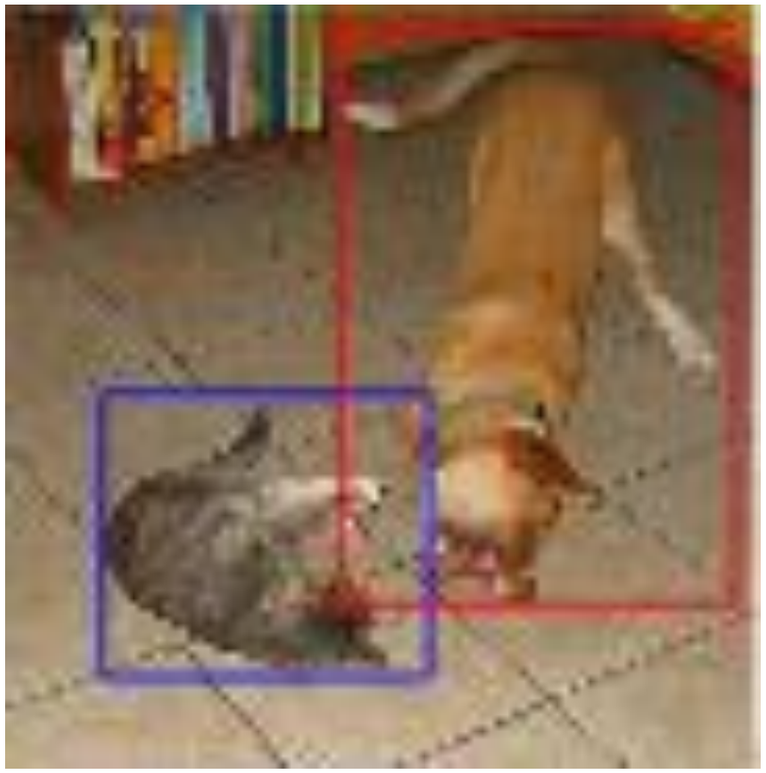
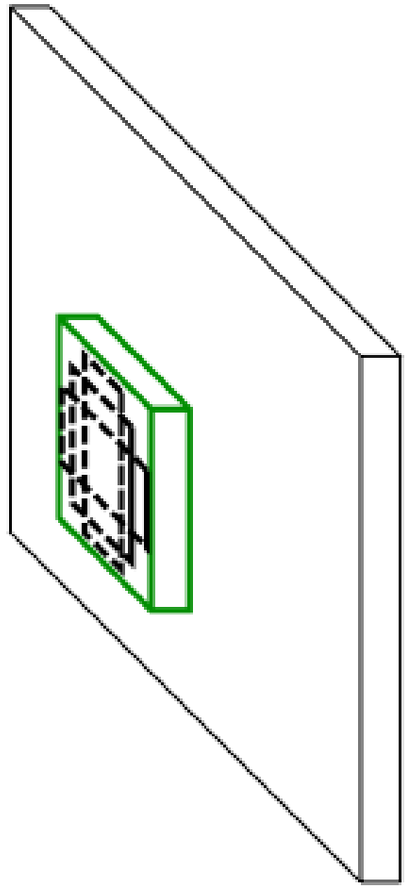
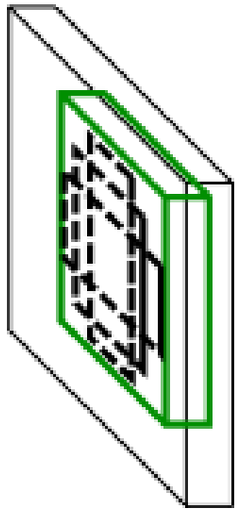


ConvNet

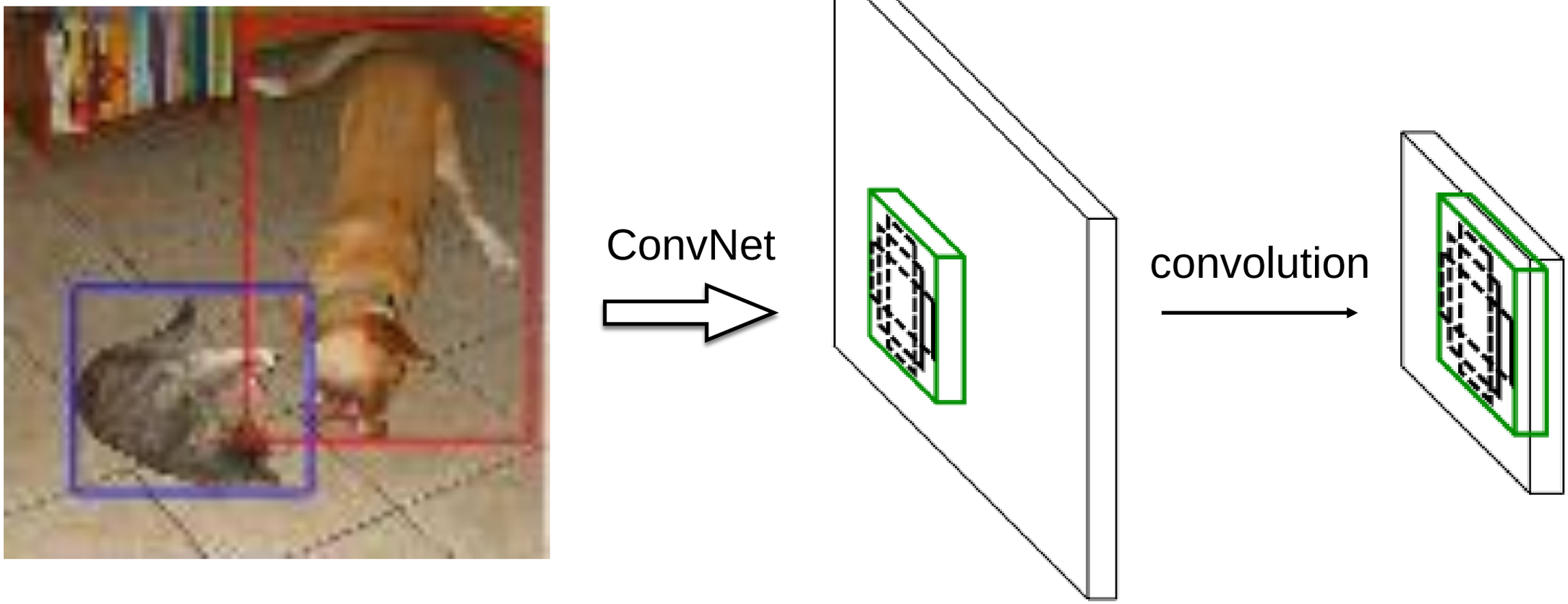


convolution



	SSD300		
include $\{\frac{1}{2}, 2\}$ box?		✔	✔
include $\{\frac{1}{3}, 3\}$ box?			✔
number of Boxes	3880	7760	**8732**
VOC2007 test mAP	71.6	73.7	**74.3**

Contribution #2:
Splitting the Region Space



Use 38x38 feature map : **+2.5 mAP**
(conv4_3)

Why So Many Default Boxes?

	Faster R-CNN	YOLO	SSD300	SSD512
# Default Boxes	6000	98	8732	24564
Resolution	1000x600	448x448	300x300	512x512

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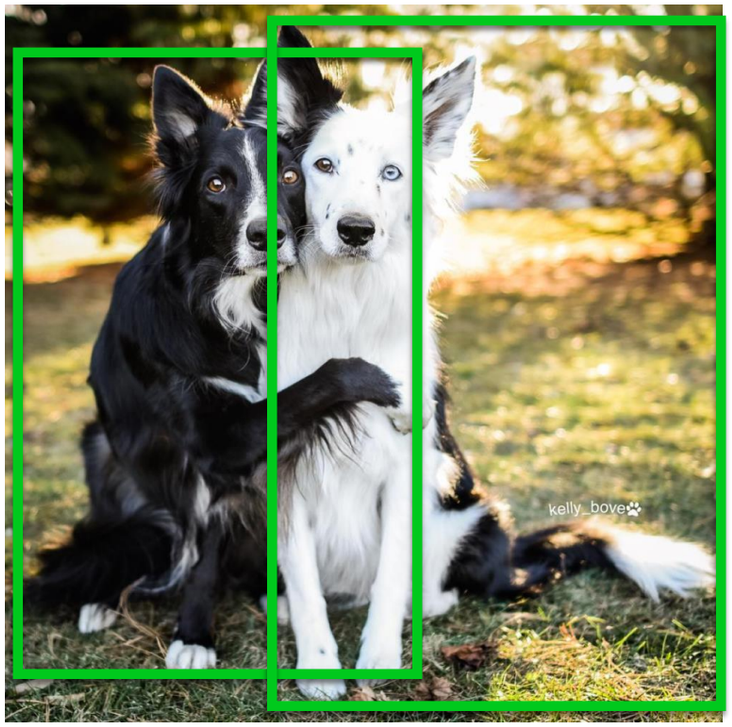
GT



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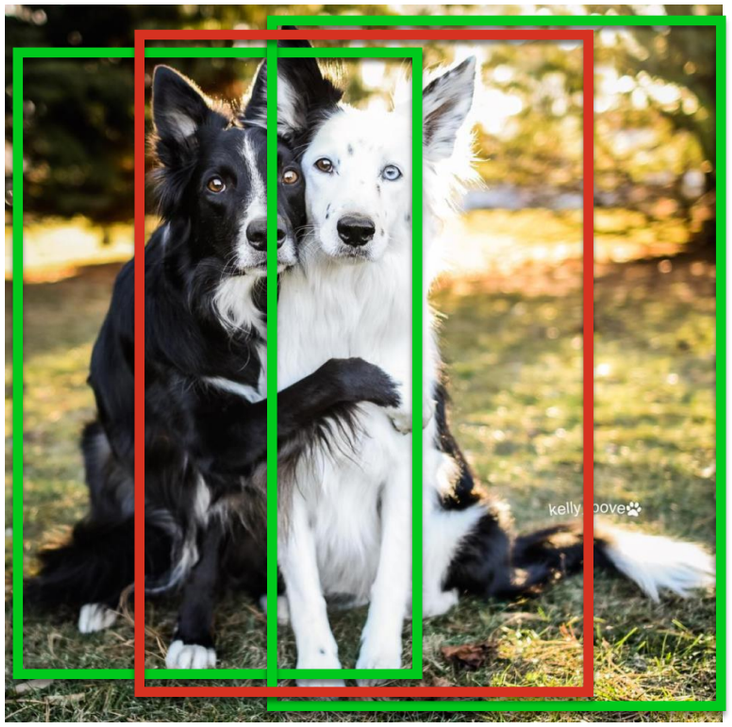
GT **DETECTION**



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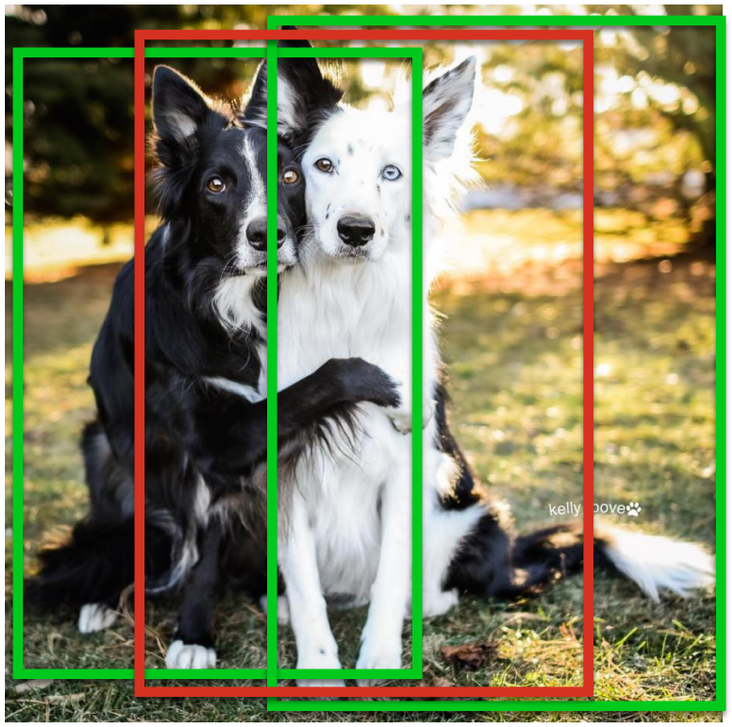

- SmoothL1 or L2 loss for box shape averages among likely hypotheses

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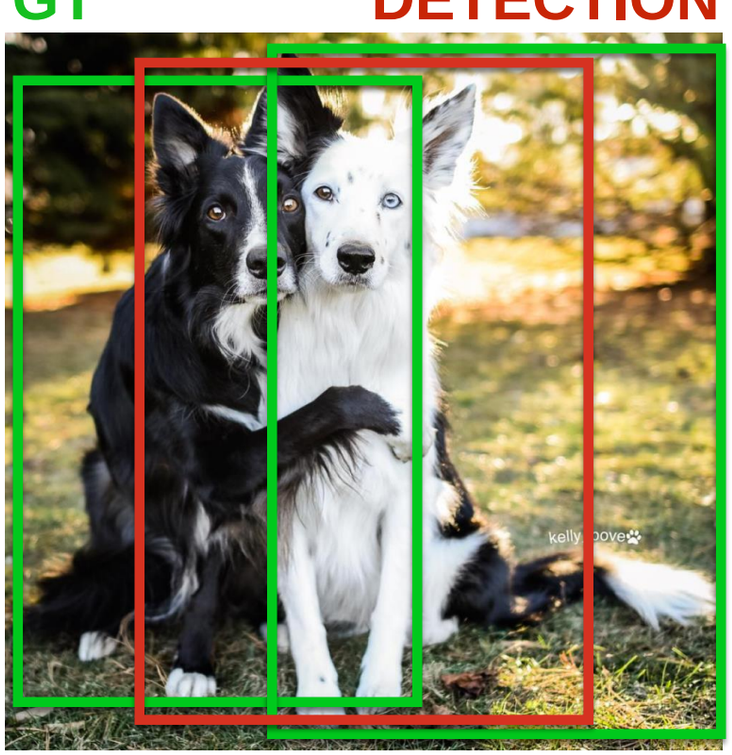

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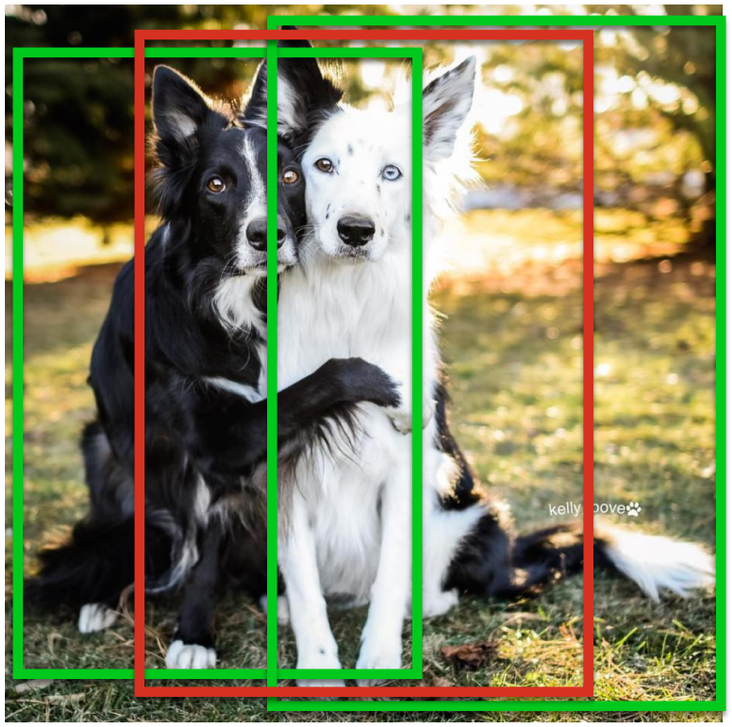

- SmoothL1 or L2 loss for box shape averages among likely hypotheses
- Need to have enough default boxes (discrete bins) to do accurate regression in each
- General principle for regressing complex continuous outputs with deep nets

Handling Many Default Boxes

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- Matching ground truth and default boxes

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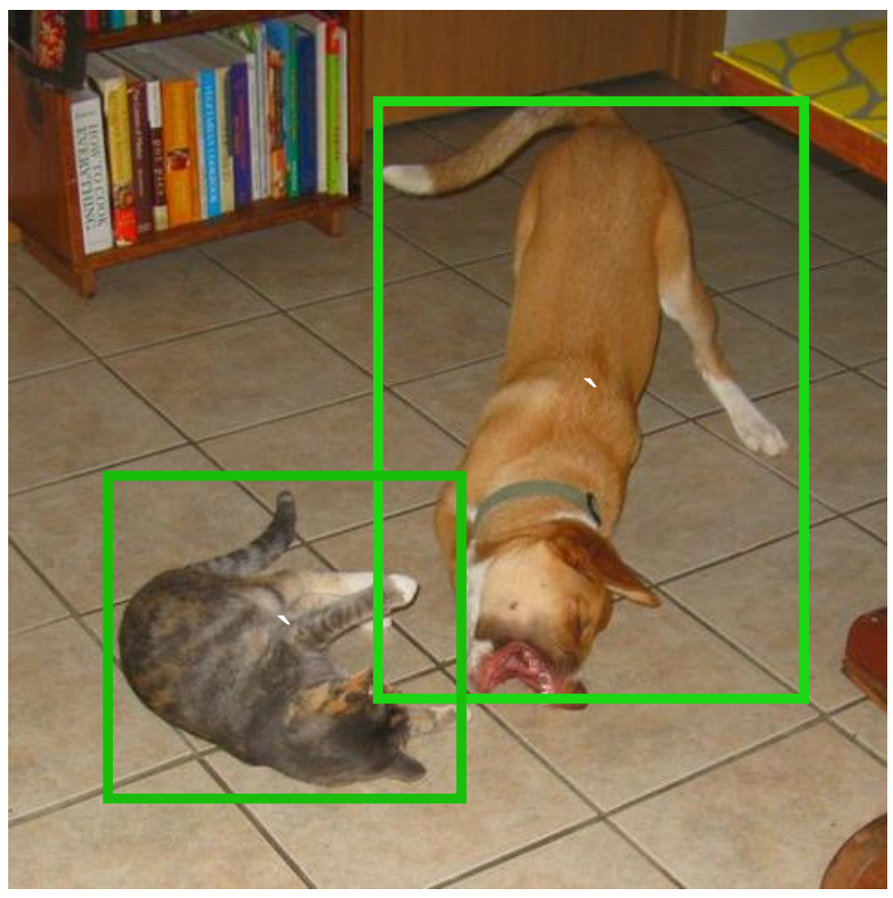

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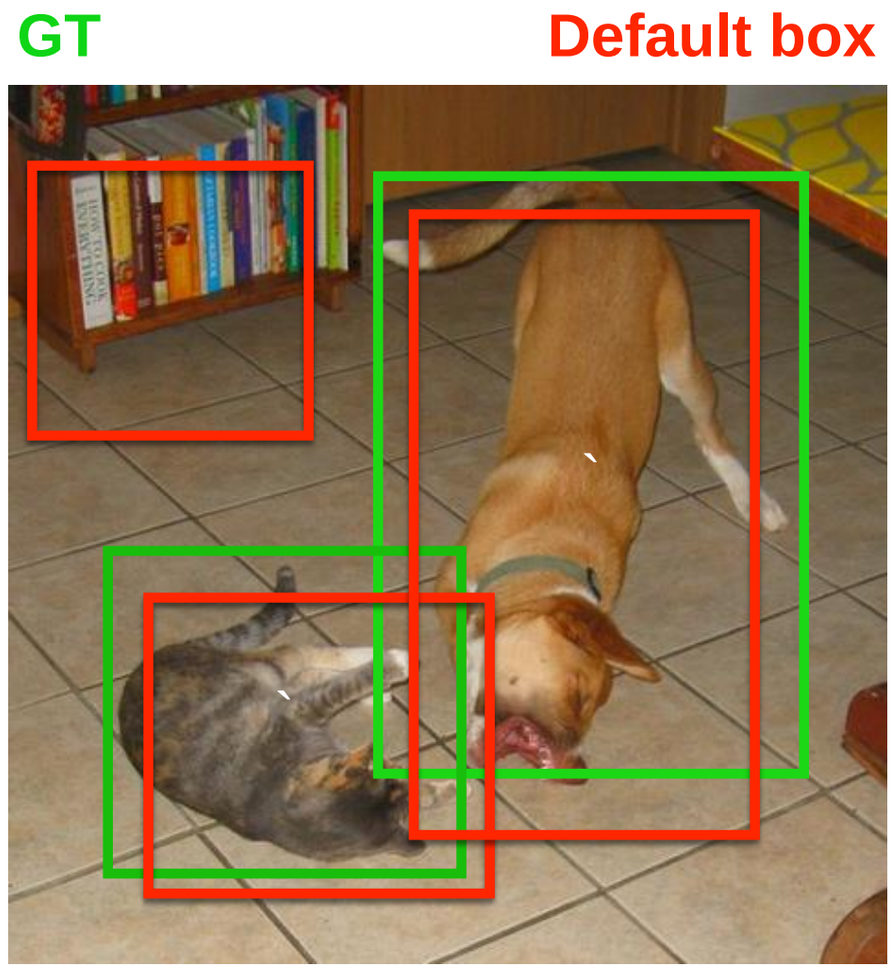

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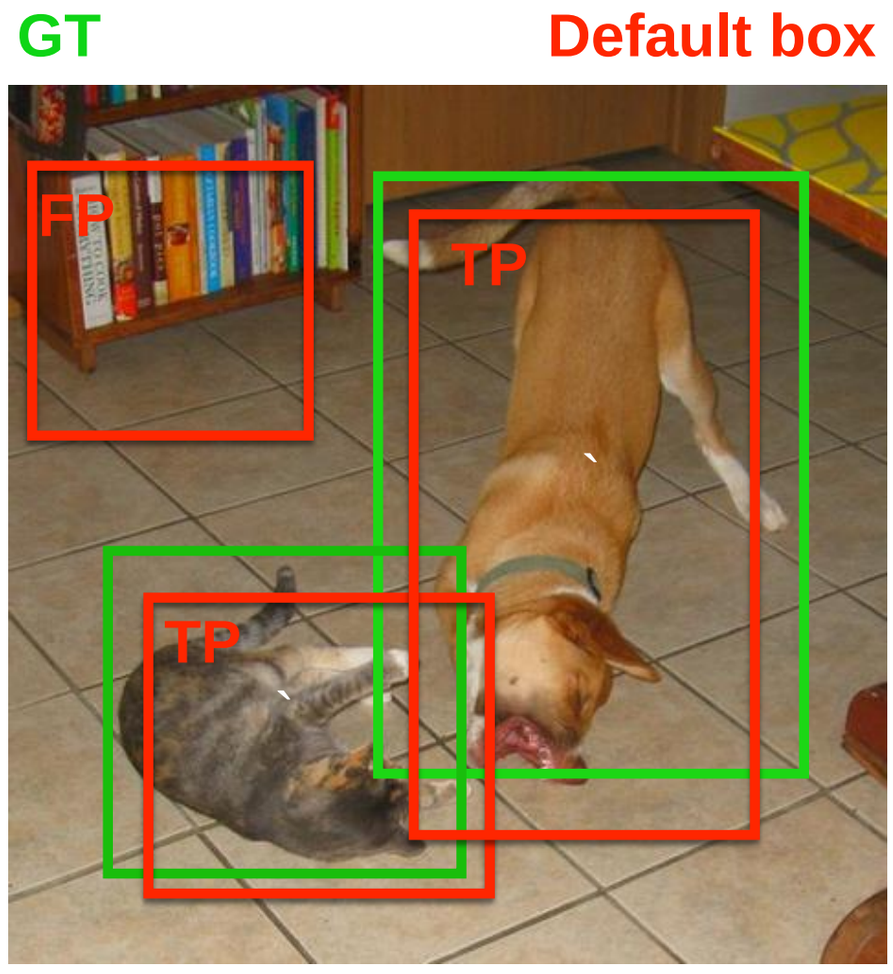

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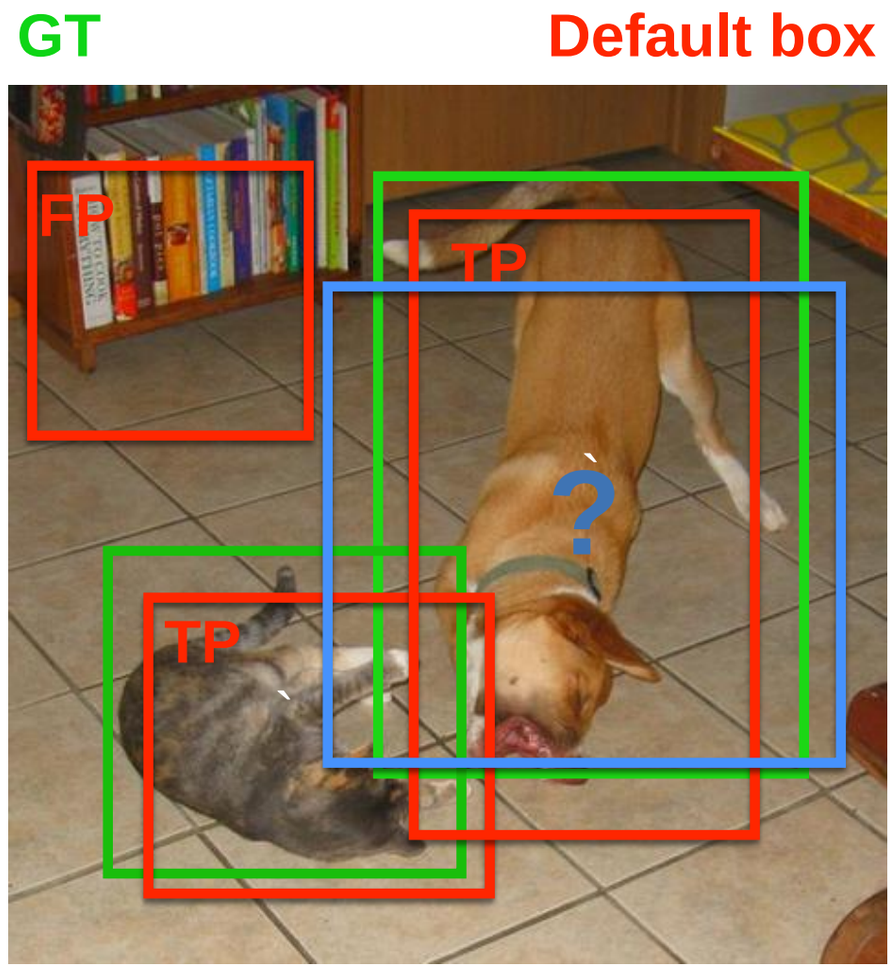
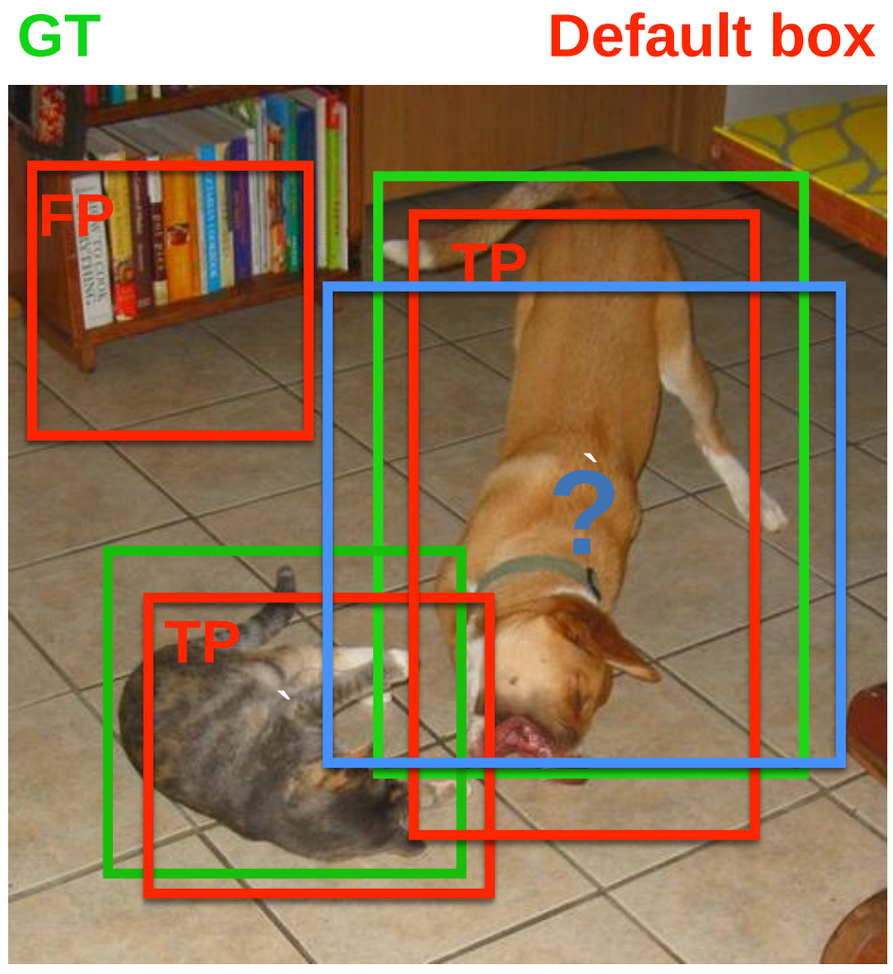


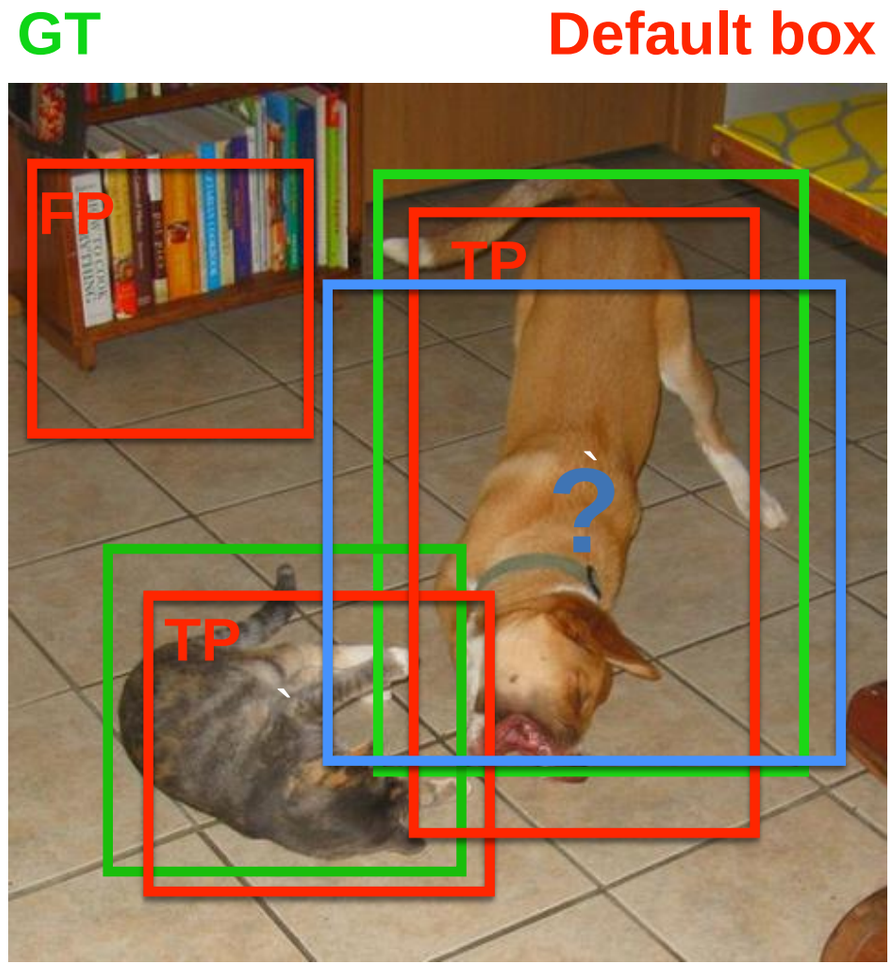
Handling Many Default Boxes

- Matching ground truth and default boxes
  - Match each GT box to closest default box



Handling Many Default Boxes

- Matching ground truth and default boxes
  - Match each GT box to closest default box
  - Also match each GT box to all unassigned default boxes with IoU > 0.5



Handling Many Default Boxes

- Matching ground truth and default boxes
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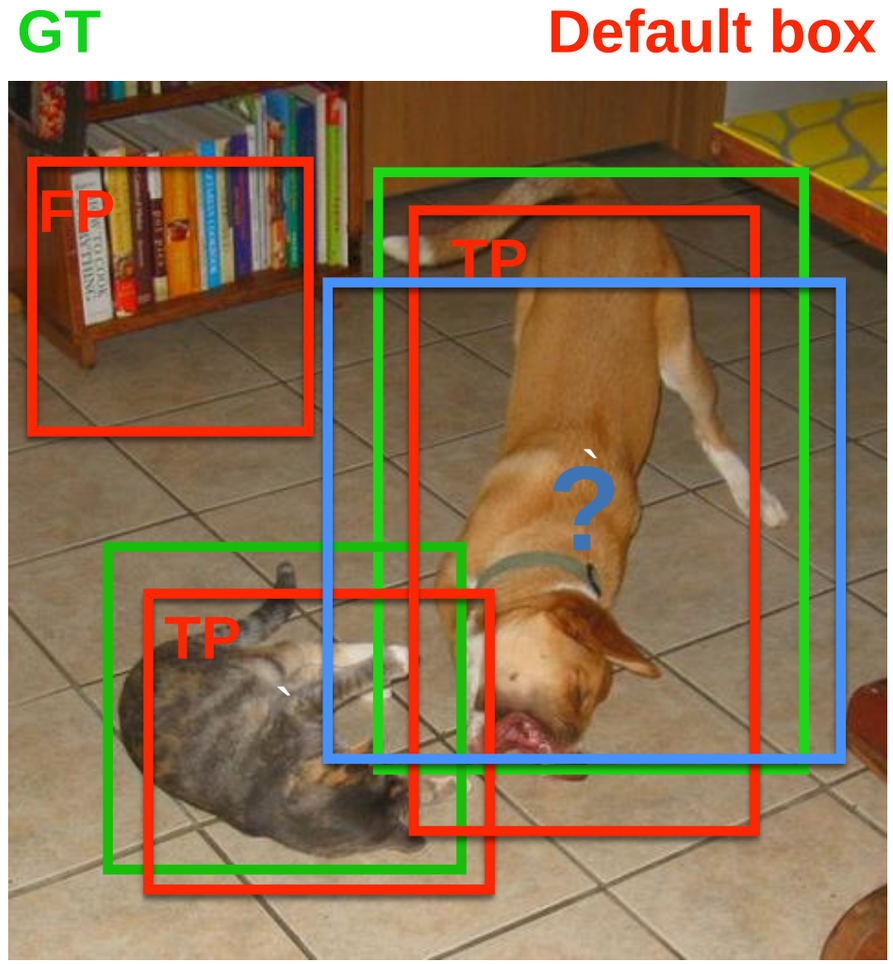
- Hard negative mining



Handling Many Default Boxes

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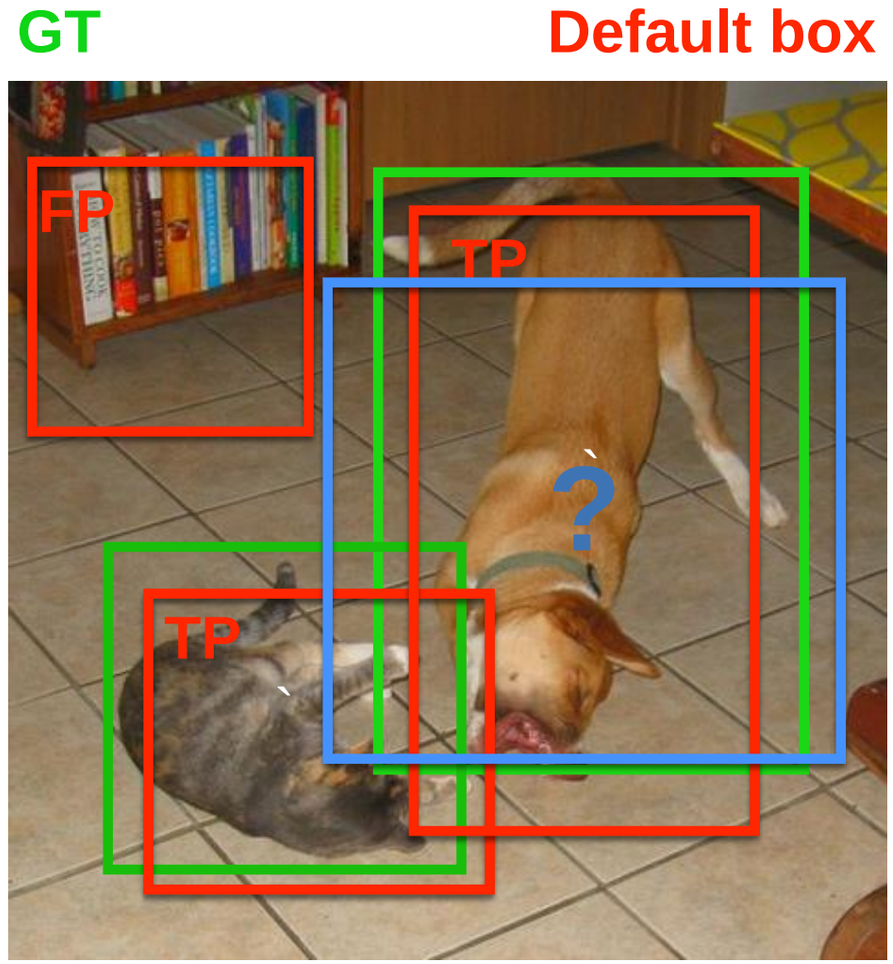
  - Unbalanced training: 1-30 TP, 8k-25k FP



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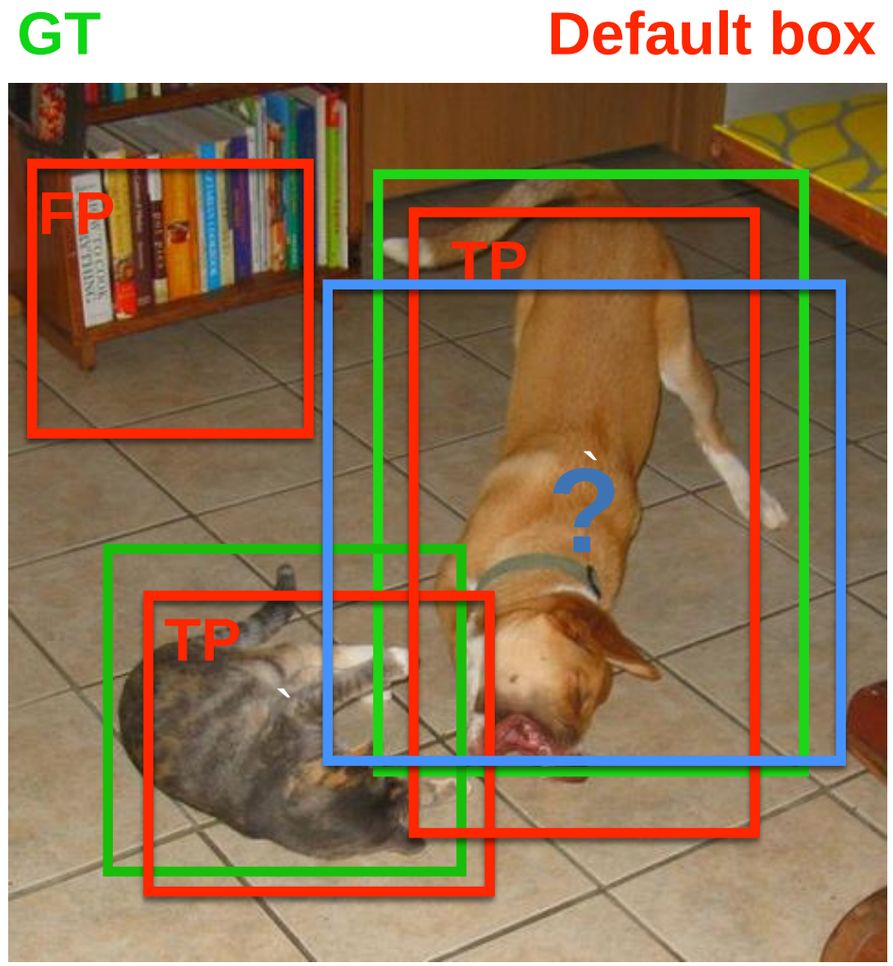
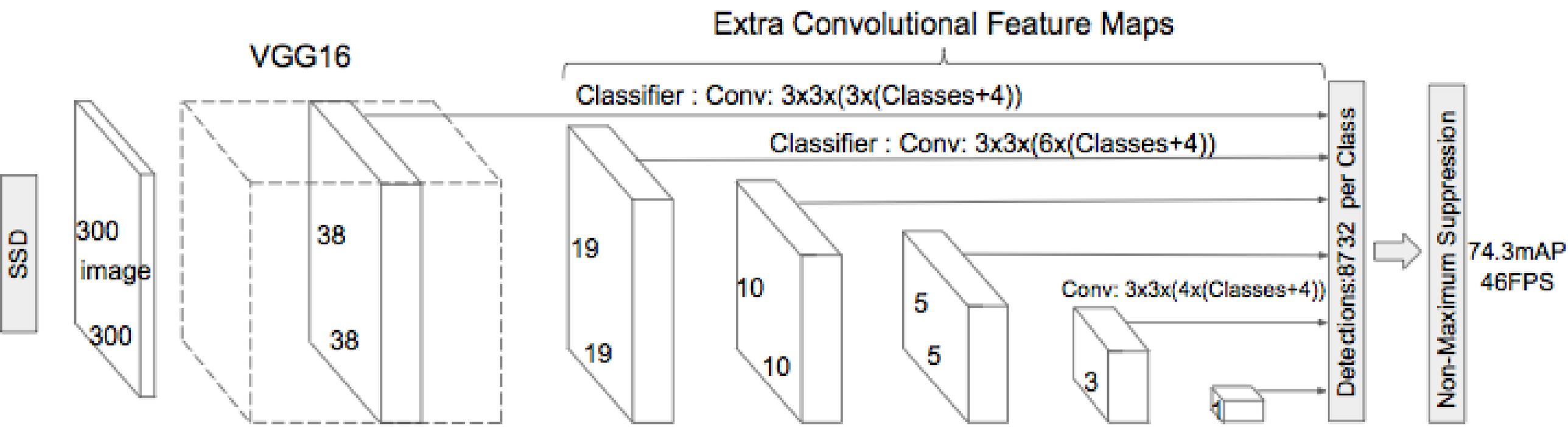
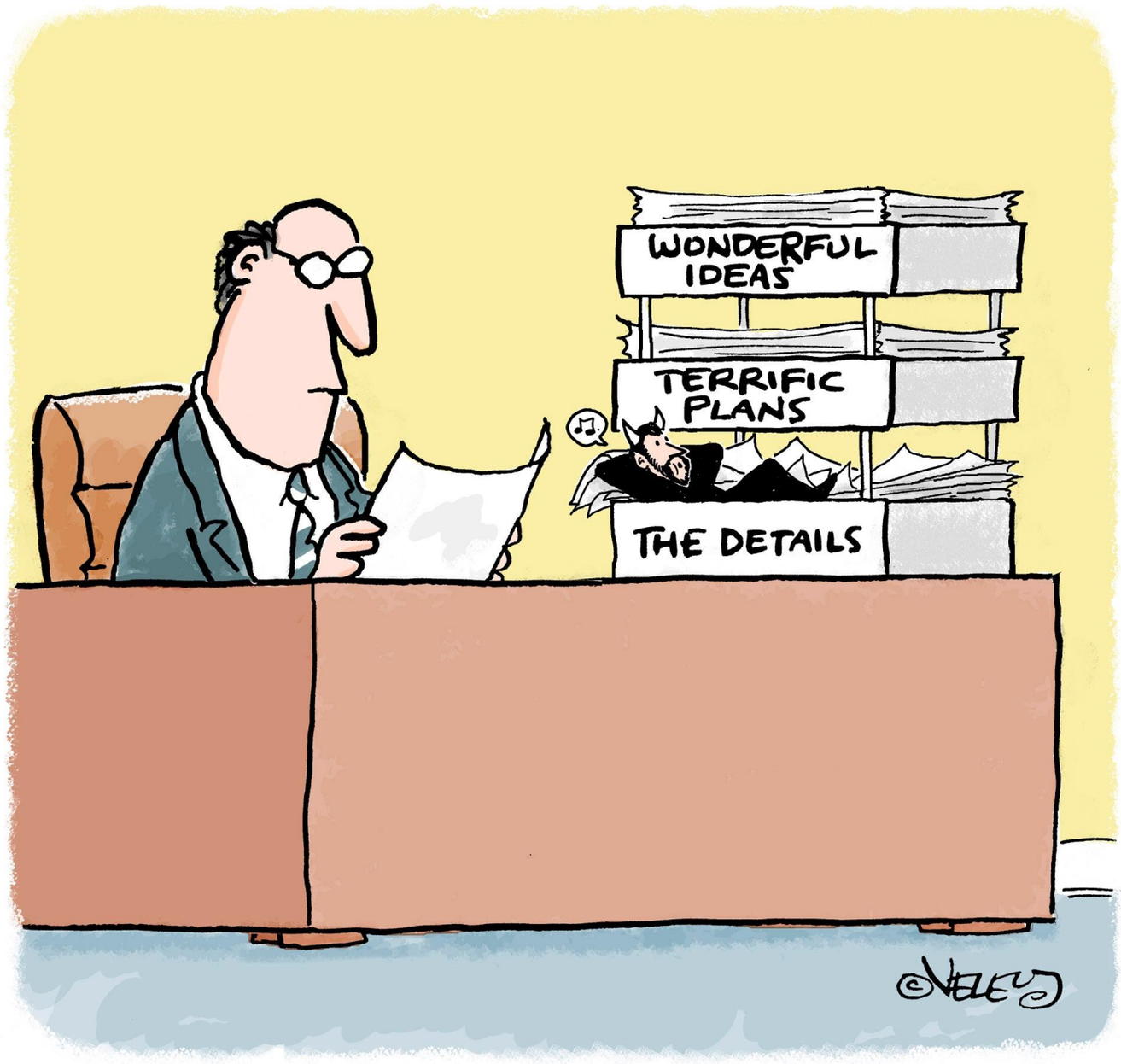
  - Also match each GT box to all unassigned default boxes with IoU > 0.5
- Hard negative mining
  - Unbalanced training: 1-30 TP, 8k-25k FP
  - Keep TP:FP ratio fixed (1:3), use worst-misclassified FPs.



SSD Architecture

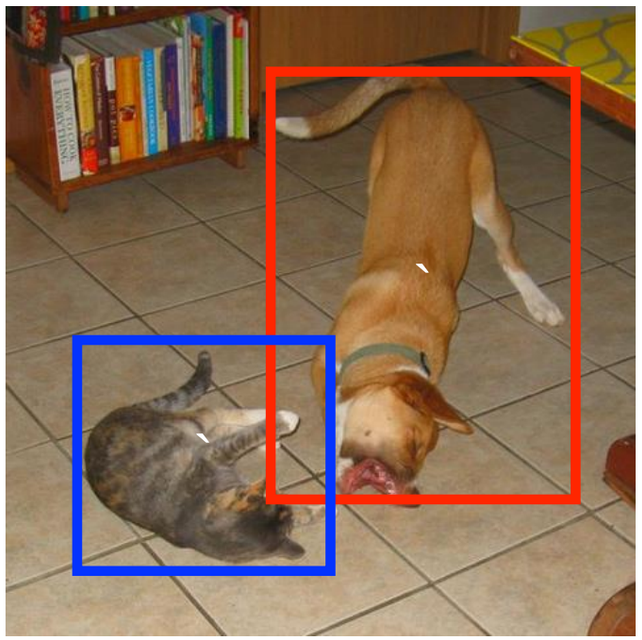


Contribution #3:
The Devil is in the Details



Data Augmentation

Data Augmentation



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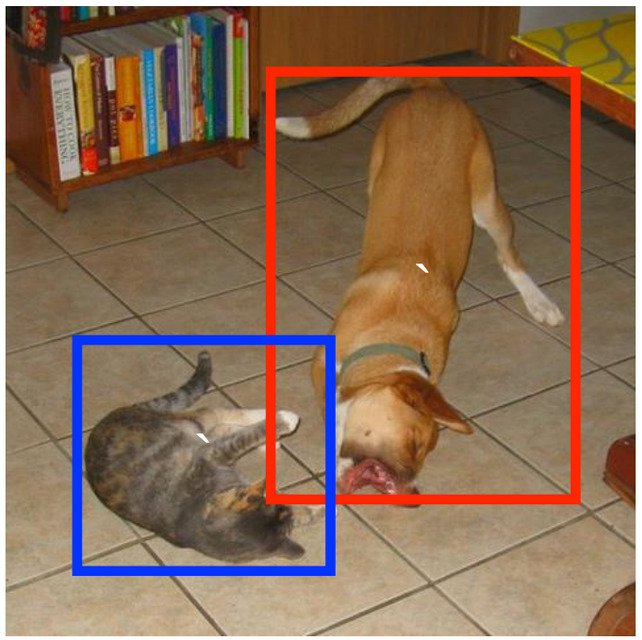

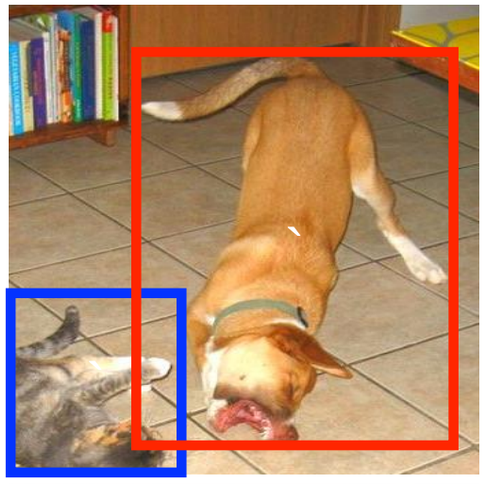

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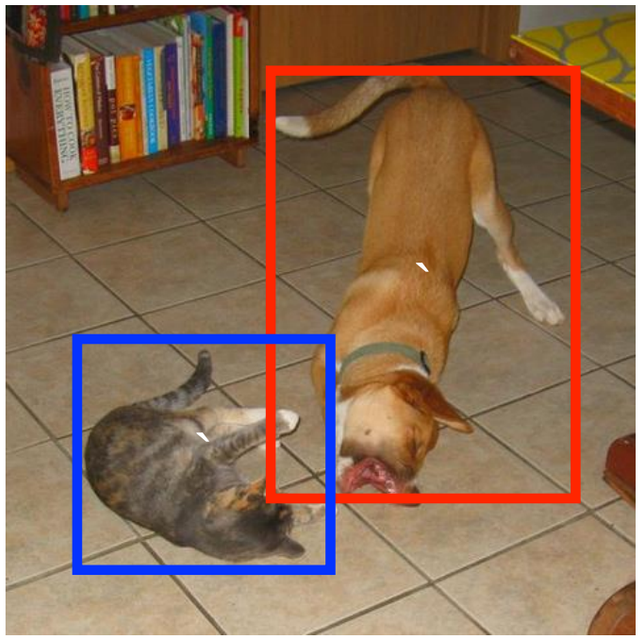

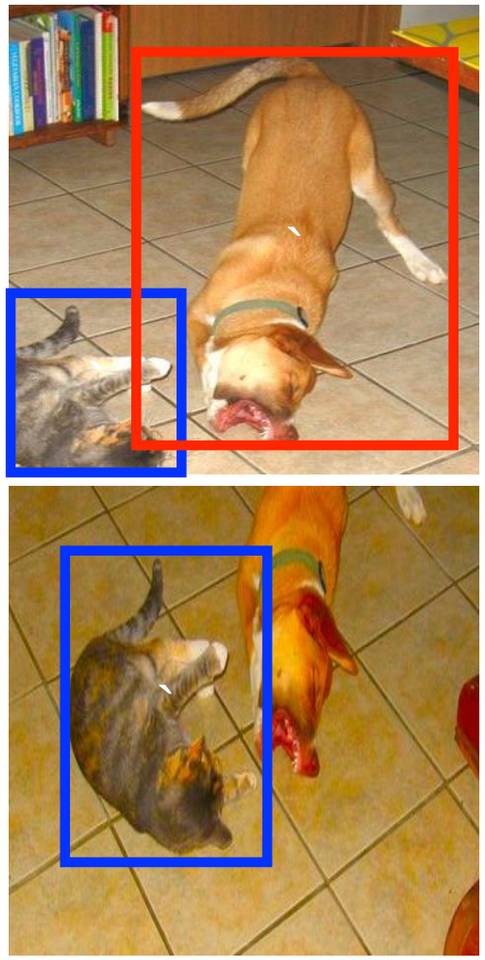

data augmentation	SSD300	
horizontal flip	✔	✔
random crop & color distortion		✔
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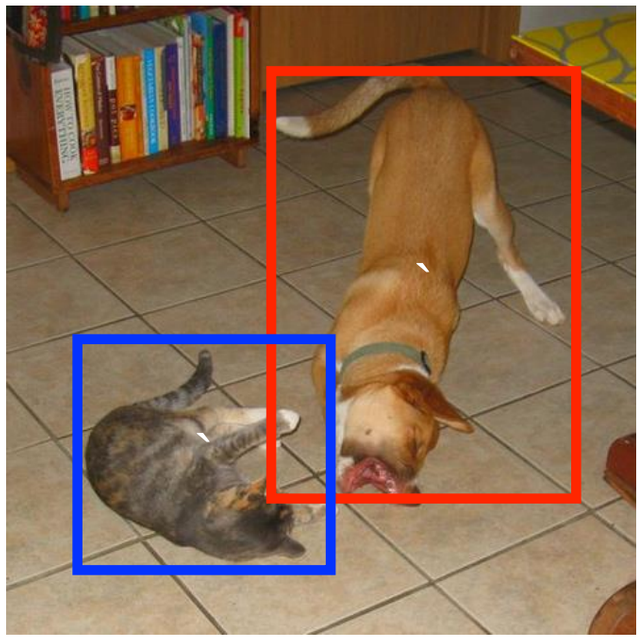

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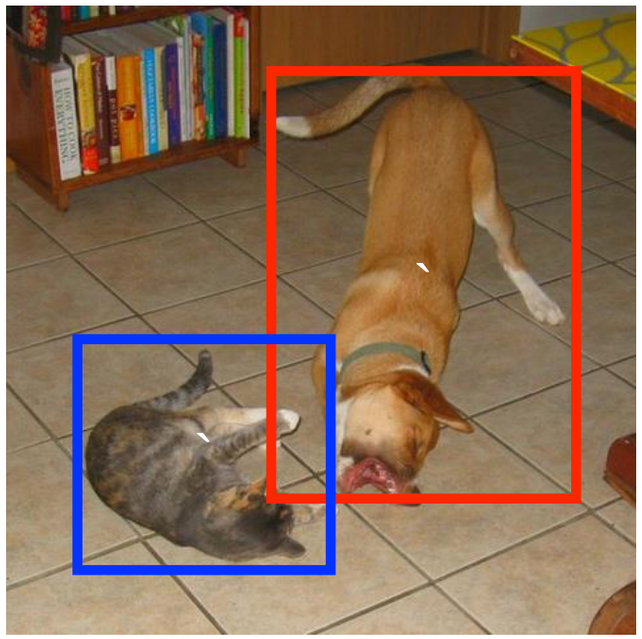
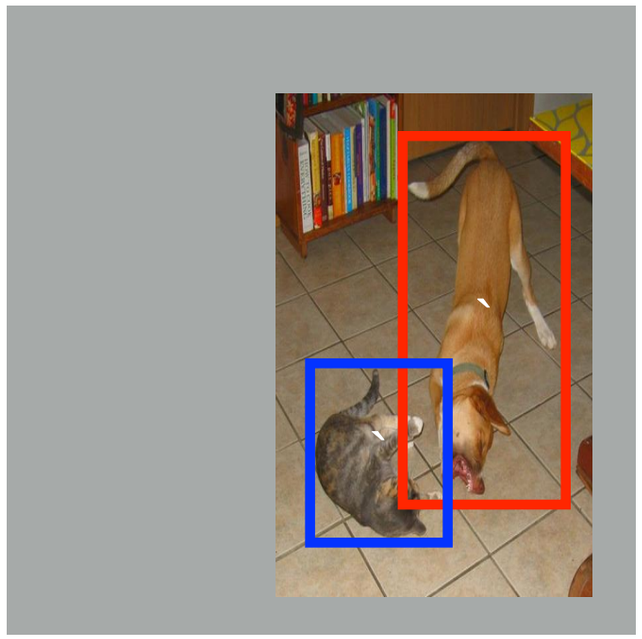
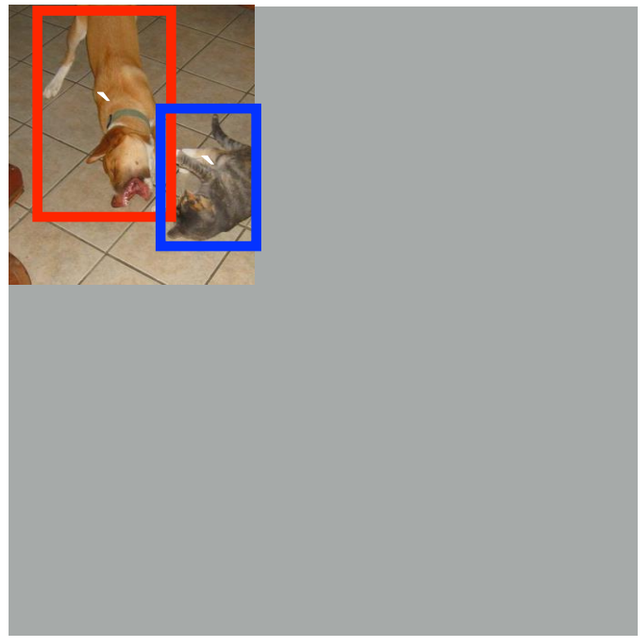
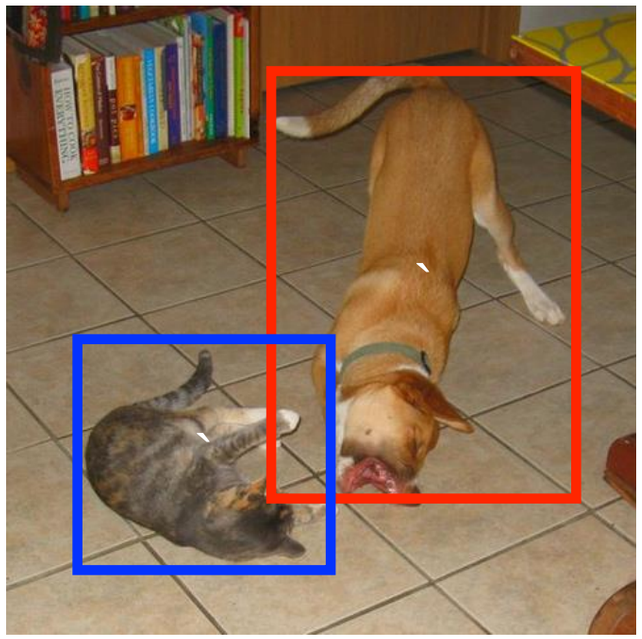


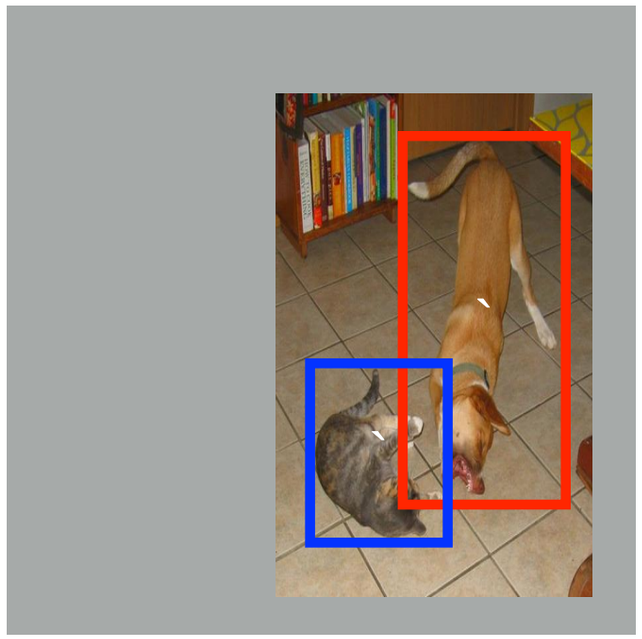


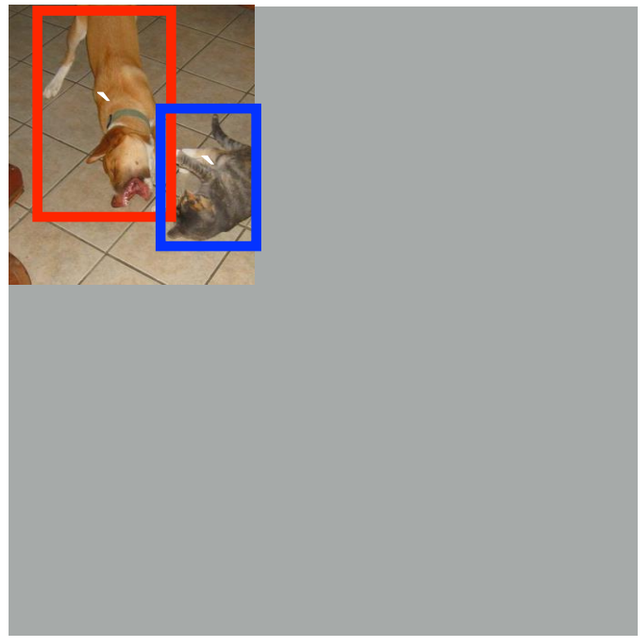


Random expansion creates more **small** training examples

Data Augmentation







Random expansion creates more **small** training examples

data augmentation	SSD300		
horizontal flip	✔	✔	✔
random crop & color distortion		✔	✔
random expansion			✔
VOC2007 test mAP	65.5	74.3	77.2

Results on VOC2007 test

Method	mAP	FPS	batch size	# Boxes	Input resolution
Faster R-CNN (VGG16)	73.2	7	1	~ 6000	$\sim 1000 \times 600$
Fast YOLO	52.7	155	1	98	448×448
YOLO (VGG16)	66.4	21	1	98	448×448
SSD300	74.3	46	1	8732	300×300
SSD512	76.8	19	1	24564	512×512
SSD300	74.3	59	8	8732	300×300
SSD512	76.8	22	8	24564	512×512

Results on VOC2007 test

Method	mAP	FPS	batch size	# Boxes	Input resolution
Faster R-CNN (VGG16)	73.2	7	1	~ 6000	~ 1000 × 600
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6.6x

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10% ↑

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Results on More Datasets

Results on More Datasets

Method	VOC2007 test	VOC2012 test	MS COCO test-dev	ILSVRC2014 val2
Fast R-CNN	70,0	68,4	19,7	N/A
Faster R-CNN	**73,2**	**70,4**	**21,9**	N/A
YOLO	63,4	57,9	N/A	N/A

Results on More Datasets

Method	VOC2007 test	VOC2012 test	MS COCO test-dev	ILSVRC2014 val2
Fast R-CNN	70,0	68,4	19,7	N/A
Faster R-CNN	73,2	70,4	21,9	N/A
YOLO	63,4	57,9	N/A	N/A
SSD300	**74,3**	**72,4**	**23,2**	**43,4**

Results on More Datasets

Method	VOC2007 test	VOC2012 test	MS COCO test-dev	ILSVRC2014 val2
Fast R-CNN	70,0	68,4	19,7	N/A
Faster R-CNN	73,2	70,4	21,9	N/A
YOLO	63,4	57,9	N/A	N/A
SSD300	74,3	72,4	23,2	43,4
SSD512	**76,8**	**74,9**	**26,8**	**46,4**

Results on More Datasets

Method	VOC2007 test	VOC2012 test	MS COCO test-dev	ILSVRC2014 val2
Fast R-CNN	70,0	68,4	19,7	N/A
Faster R-CNN	73,2	70,4	21,9	N/A
YOLO	63,4	57,9	N/A	N/A
SSD300*	77,2	75,8	25,1	N/A
SSD512*	**79,8**	**78,5**	**28,8**	N/A

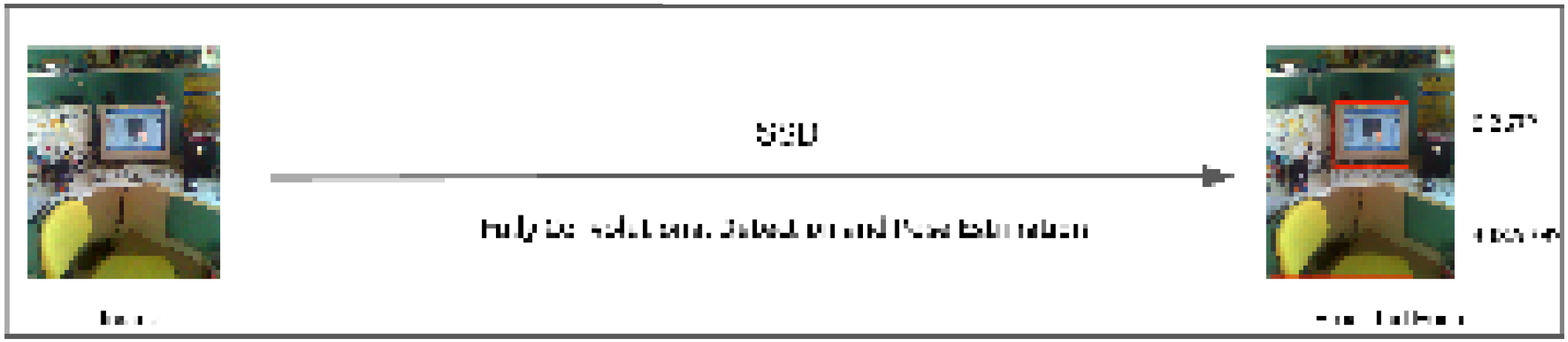
COCO Bounding Box precision

COCO Bounding Box precision

mAP @ IoU	0,5	0,75	0.5:0.95
Faster R-CNN	45,3	23,5	24,2
SSD512*	48,5	30,3	28,8
gain	**+3.2**	**+6.8**	**+4.6**

Future Work

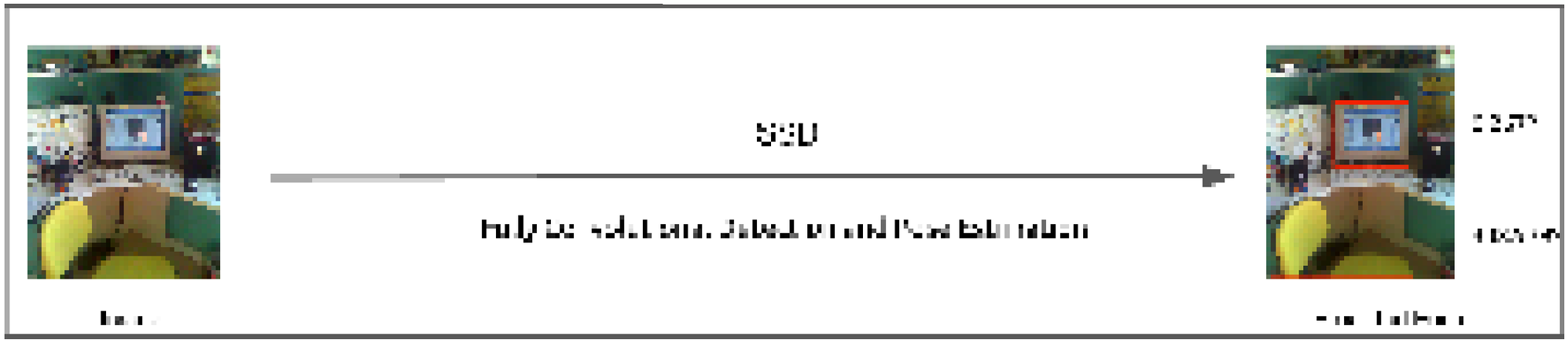
[Poirson et al, coming out at 3DV, 2016]



Future Work

- Object detection + pose estimation

[Poirson et al, coming out at 3DV, 2016]



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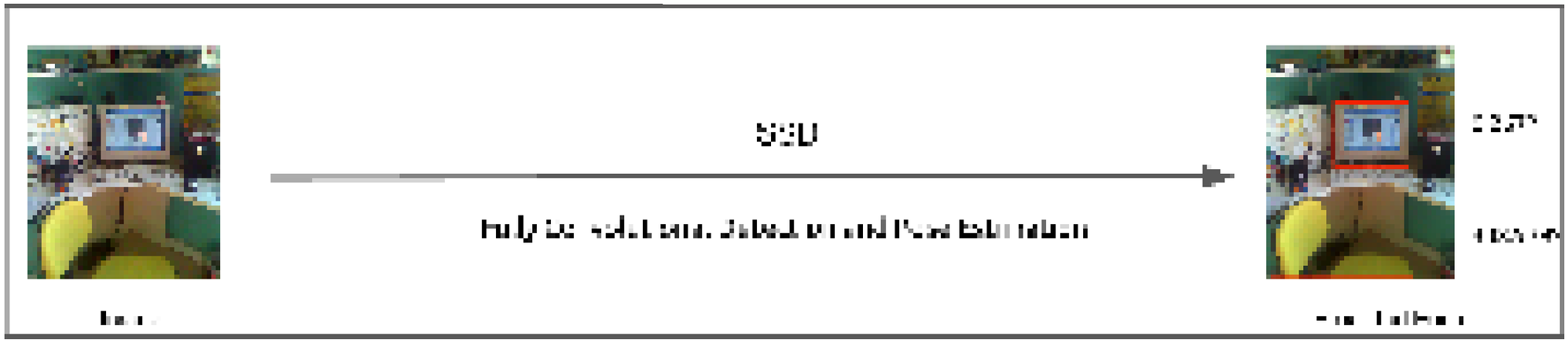

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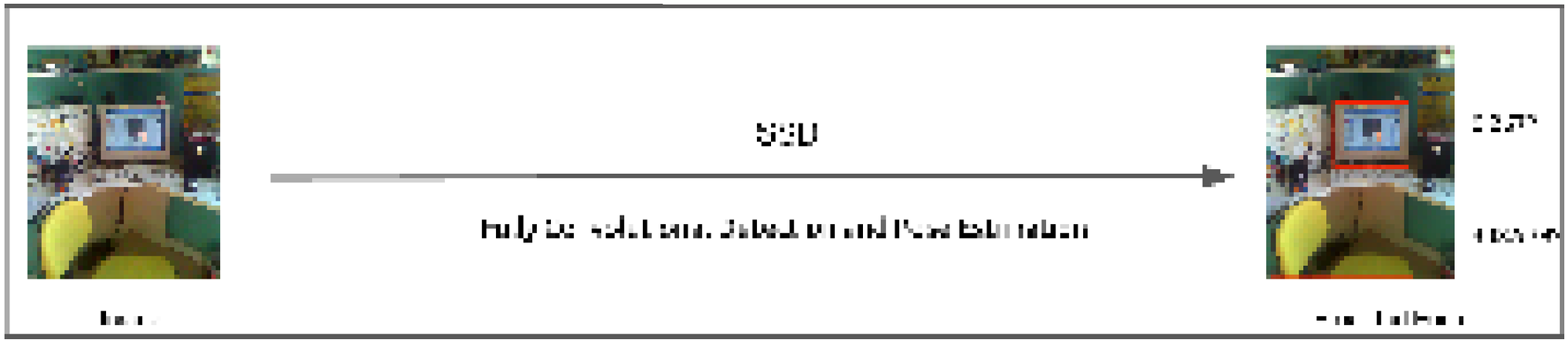

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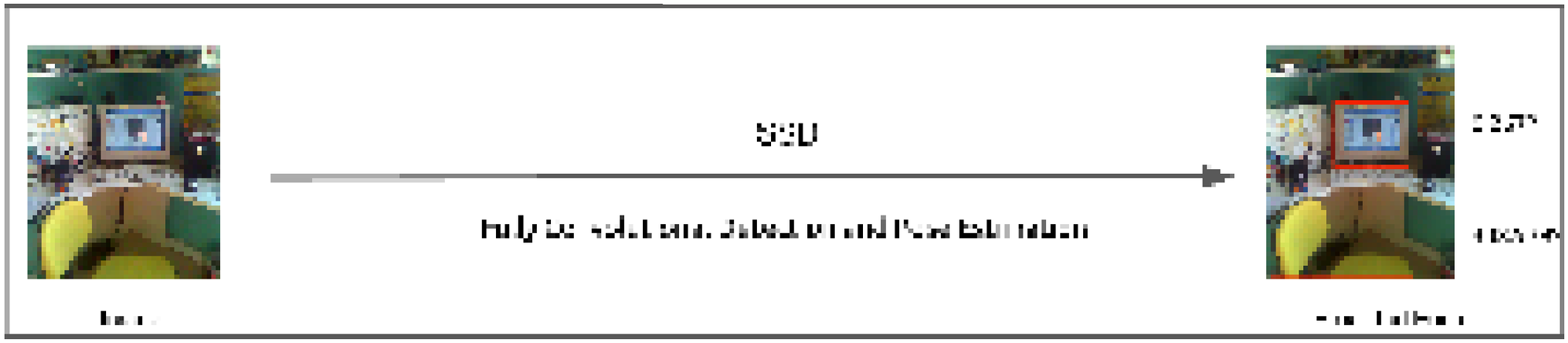

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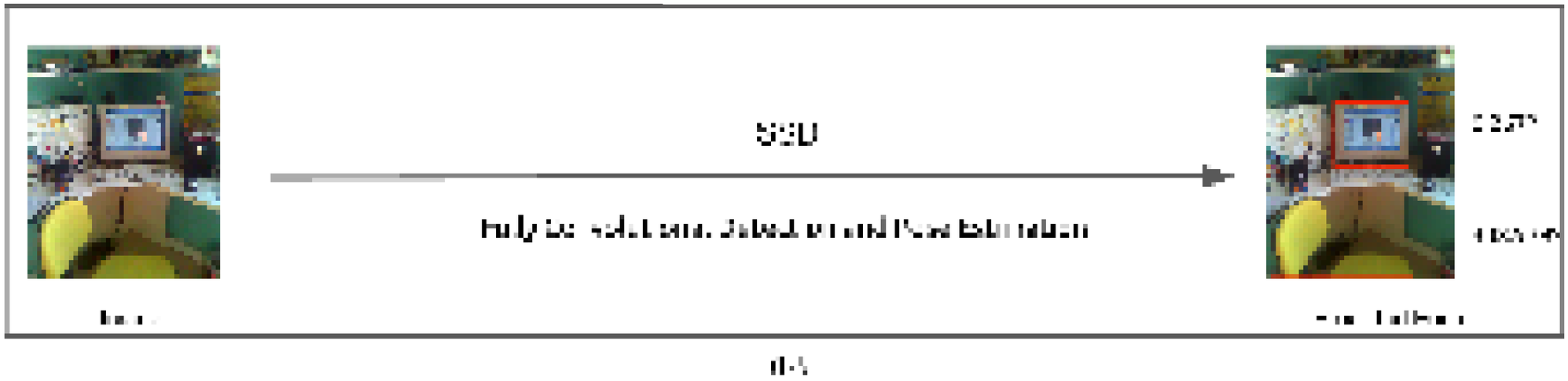
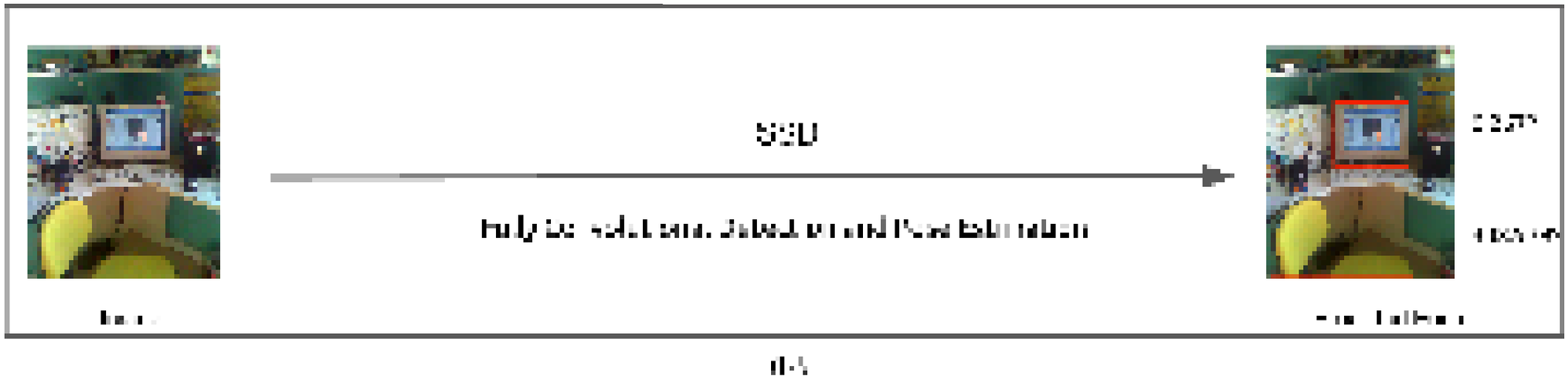


- Single shot 3D bounding box detection

Future Work

- Object detection + pose estimation

[Poirson et al, coming out at 3DV, 2016]



- Single shot 3D bounding box detection
- Joint object detection + tracking model

Check out the code/models

https://github.com/weiliu89/caffe/tree/ssd

Thank you!

Come by our poster O-1A-02