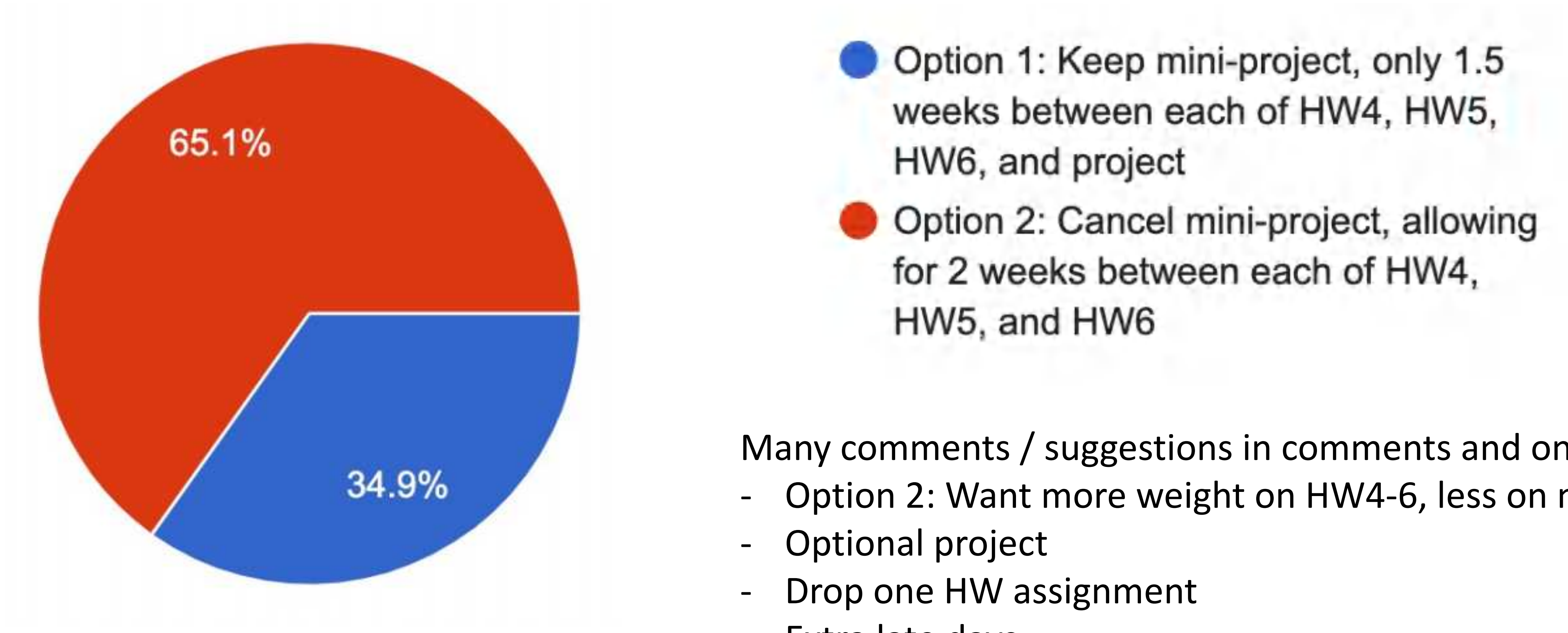
Lecture 14:
Object Detectors

Poll Results



Many comments / suggestions in comments and on Piazza:

- Option 2: Want more weight on HW4-6, less on midterm
- Optional project
- Drop one HW assignment
- Extra late days

Decision

- We will keep 2-week gap between each of HW4-6
- Students can also complete a project if they wish (spec out next week)
- Each student can choose one of the following options:

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Option A:
Do all assignments,
Do not do project.

Grading scheme:
HW1-3: 12%
Midterm: 22%
HW4-6: 14%

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HW4-6: 14%

Option B:
Do 5 or 6 assignments
Do project

Grading scheme (whichever gives you better grade):
HW1-3: 12%
Midterm: 22%
HW4-6: 14%
Project: Replaces lowest HW

Original grading scheme:
HW1-6: 10%
Midterm: 20%
Project: 20%

In addition: Everyone gets +3 late days (cannot be applied to A6 or project)

Decision

- We will keep 2-week gap between each of HW4-6
- Students can also complete a project if they wish (spec out next week)
- Each student can choose one of the following options:

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Do all assignments,
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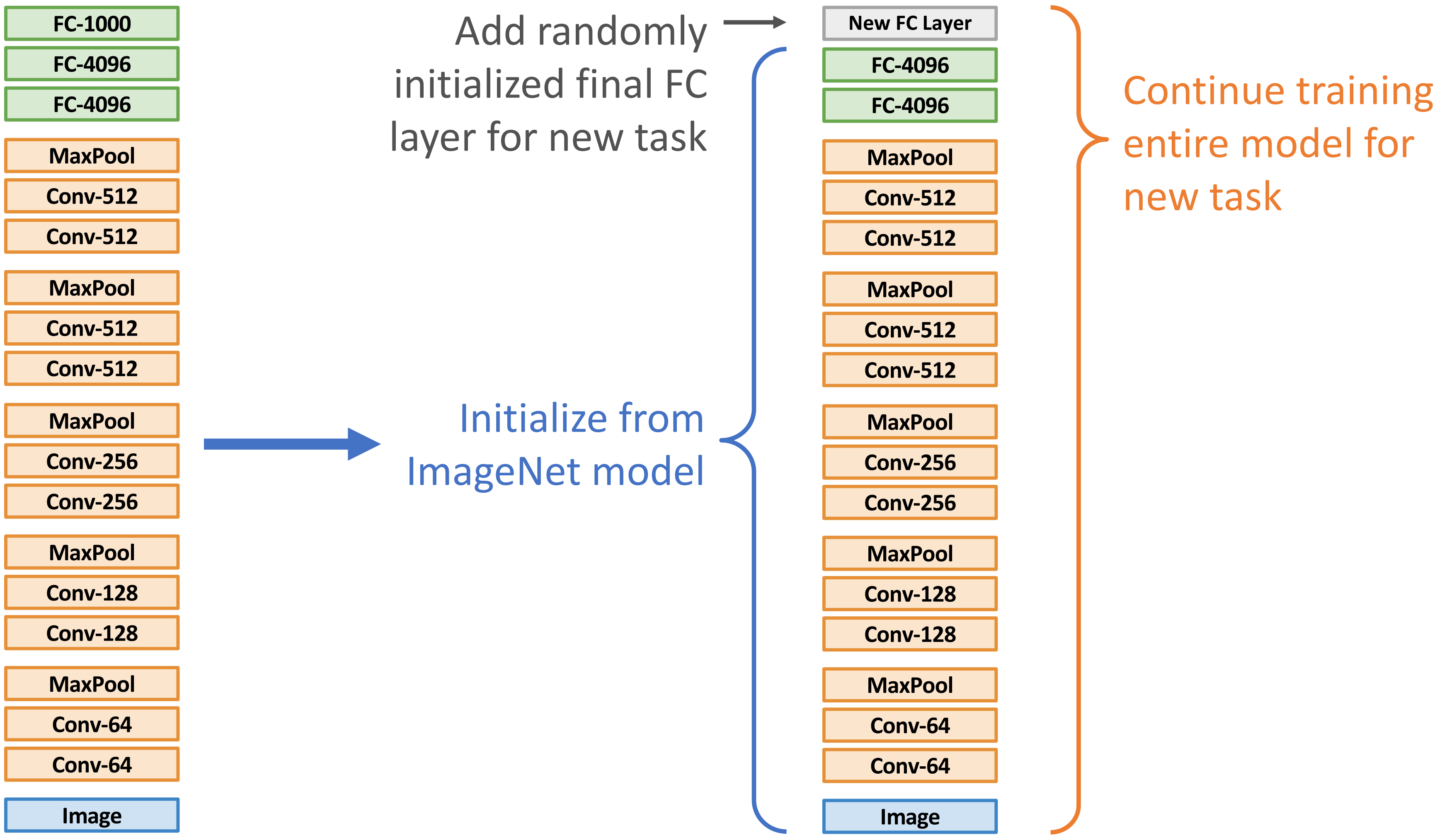
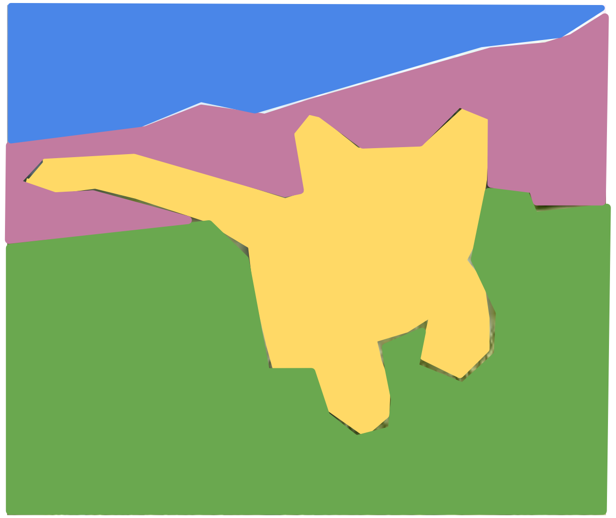
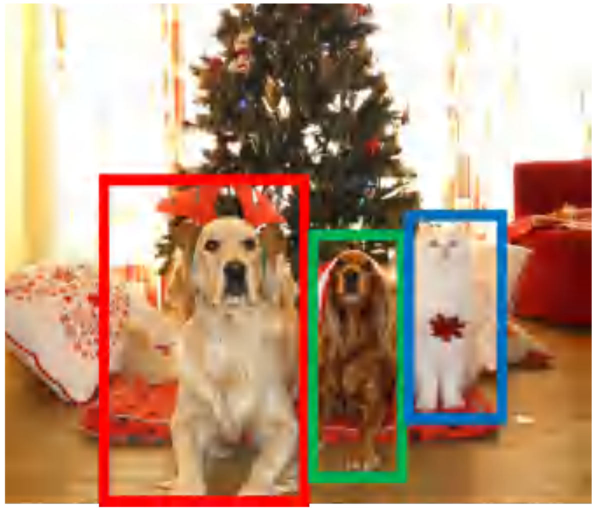
Original grading scheme:
HW1-6: 10%
Midterm: 20%
Project: 20%

Last Time: Transfer Learning

1. Train on ImageNet



Last Time: Localization Tasks

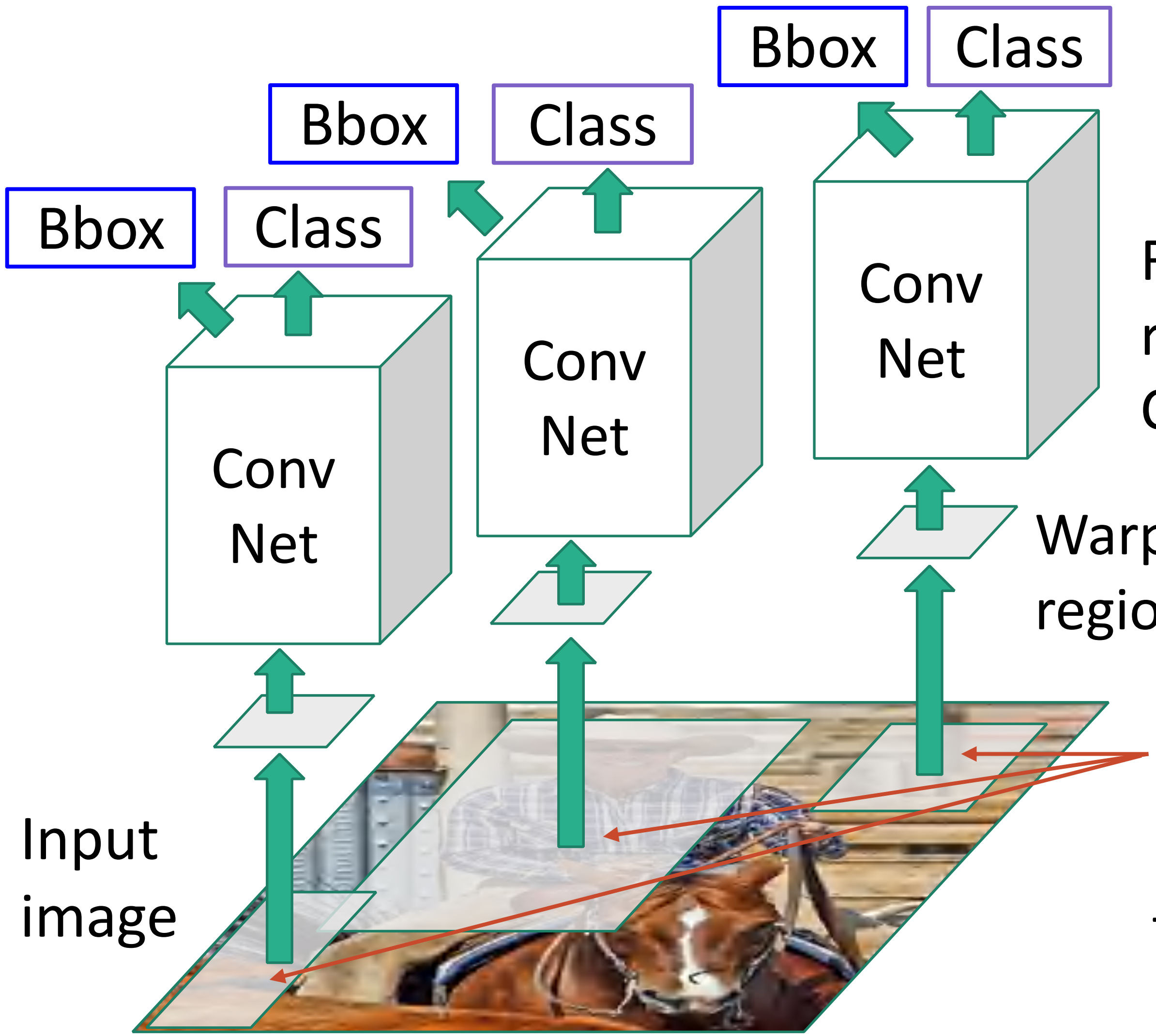
Classification	Semantic Segmentation	Object Detection	Instance Segmentation
			
CAT	**GRASS, CAT, TREE, SKY**	**DOG, DOG, CAT**	**DOG, DOG, CAT**
No spatial extent	No objects, just pixels	Multiple Objects	

This image is CC0 public domain

Last Time: R-CNN

Classify each region

Bounding box regression: Predict "transform" to correct the RoI: 4 numbers (t_x, t_y, t_h, t_w)



Forward each region through ConvNet

Warped image regions (224x224)

Regions of Interest (RoI) from a proposal method (~2k)

Girshick et al, "Rich feature hierarchies for accurate object detection and semantic segmentation", CVPR 2014.
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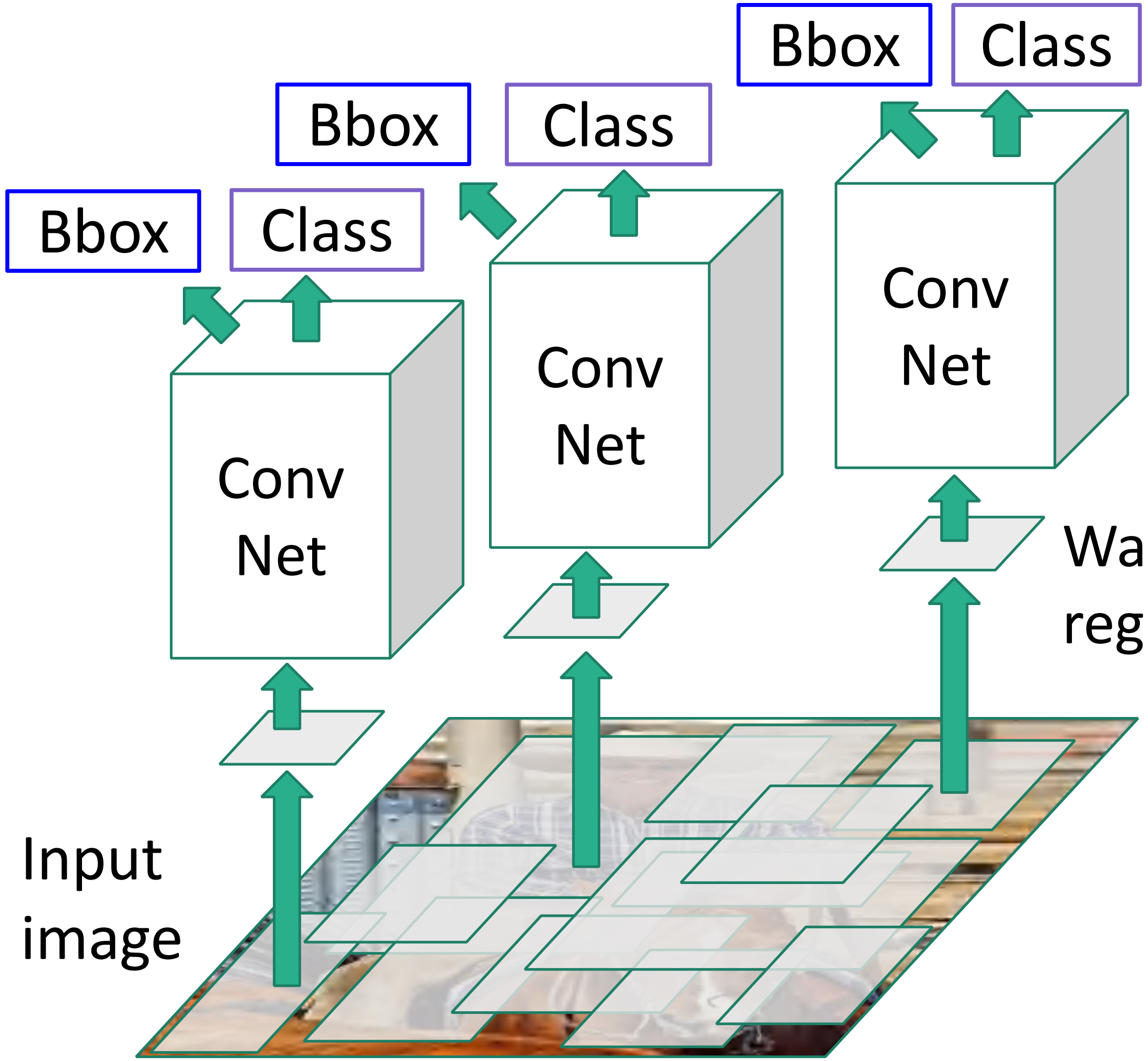

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Problem: Very slow! Need to do 2000 forward passes through CNN per image

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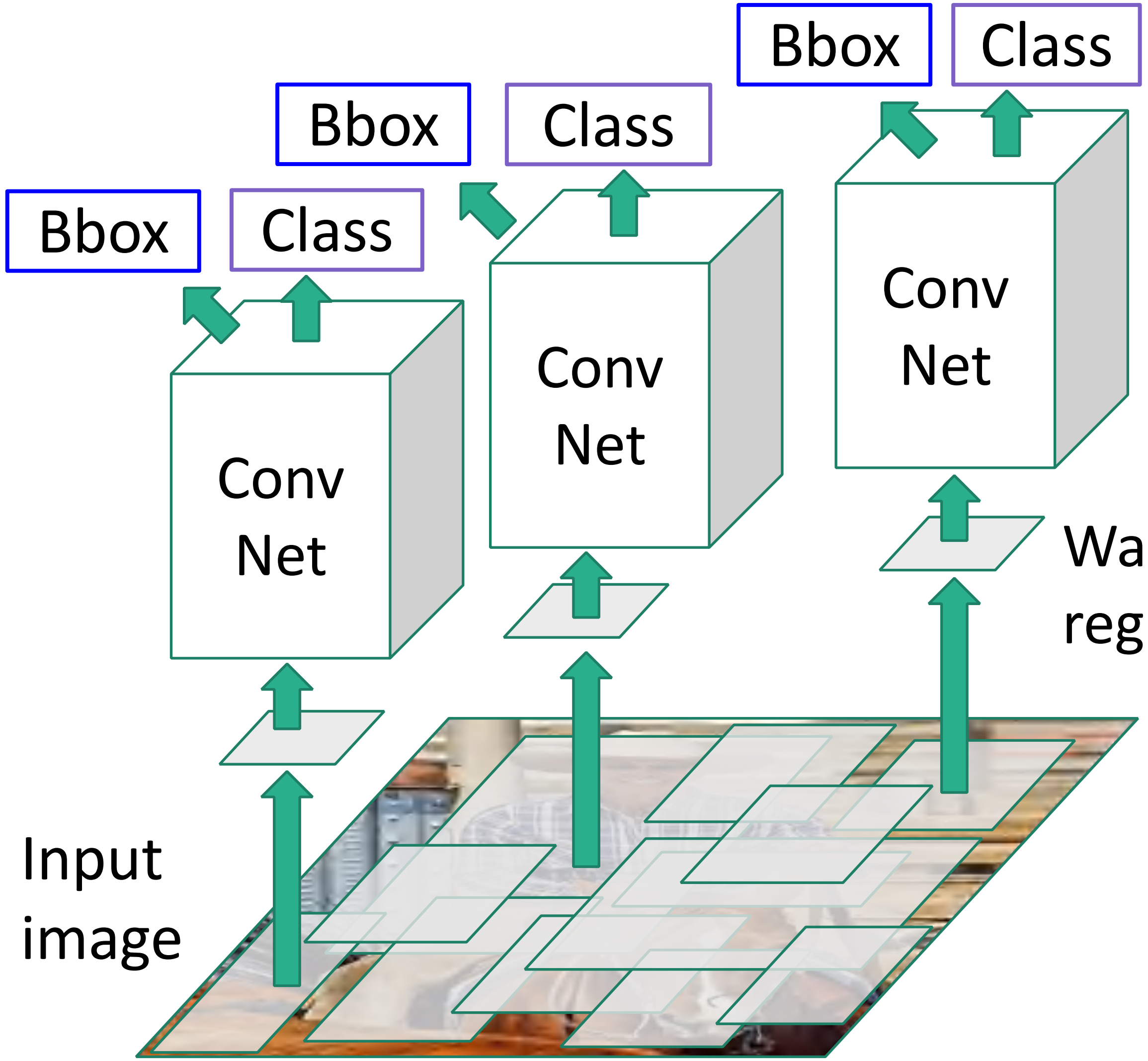
Last Time: R-CNN



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Problem: Very slow! Need to do 2000 forward passes through CNN per image

Idea: Overlapping proposals cause a lot of repeated work: same pixels processed many times. Can we avoid this?

Girshick et al, "Rich feature hierarchies for accurate object detection and semantic segmentation", CVPR 2014.
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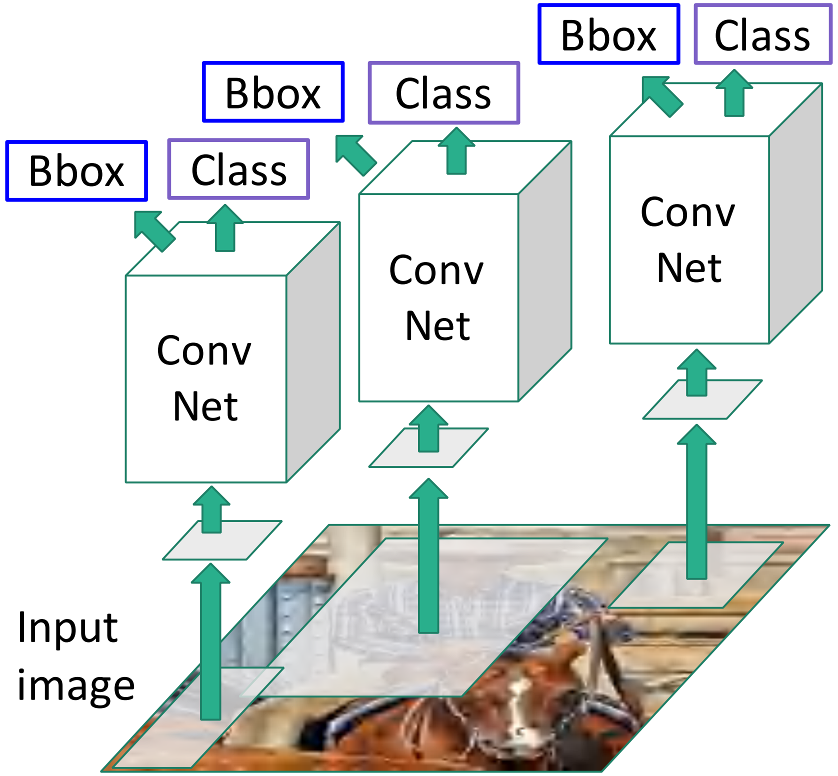
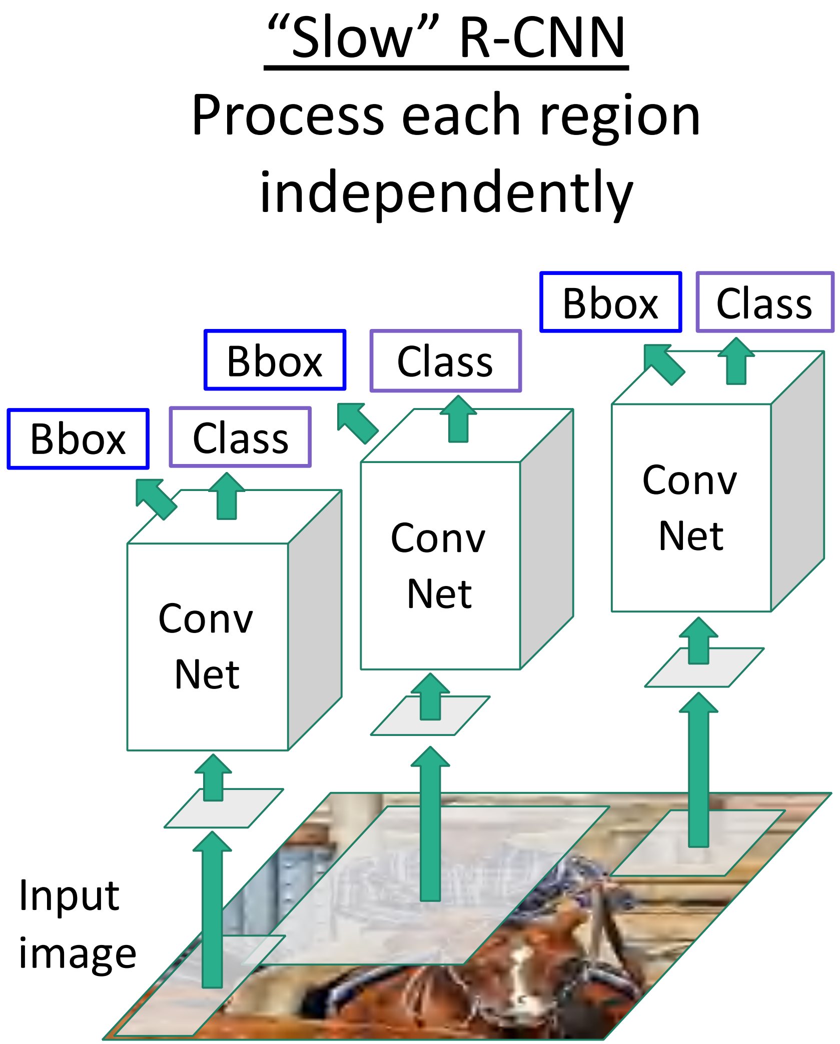
"Slow" R-CNN

Process each region independently



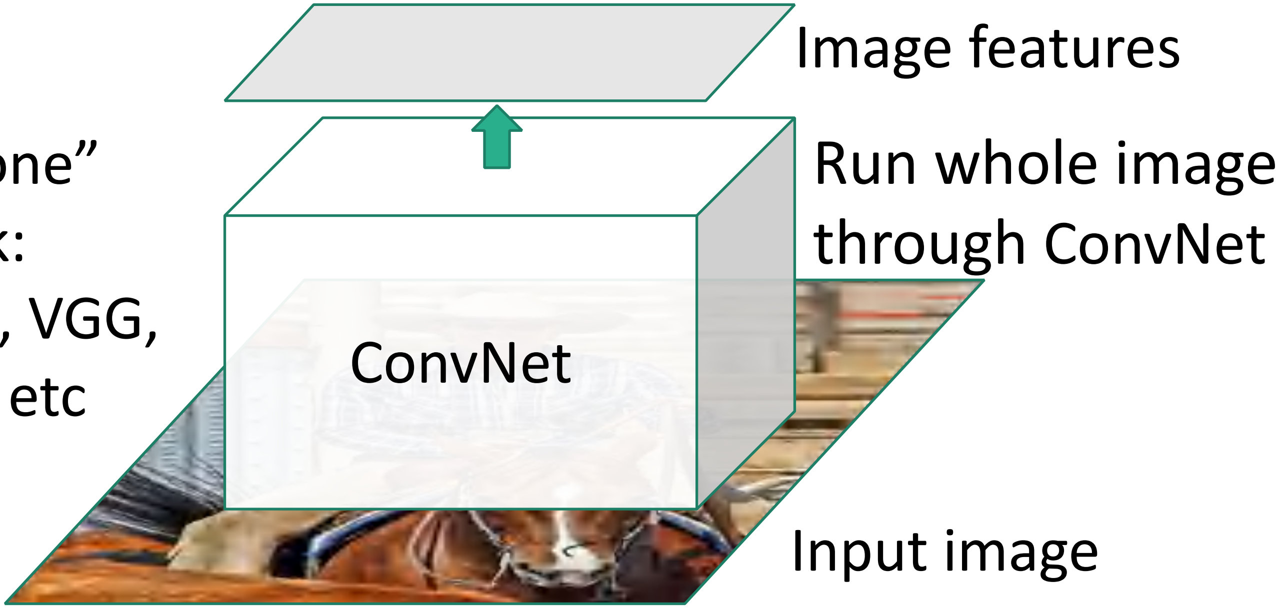
Fast R-CNN



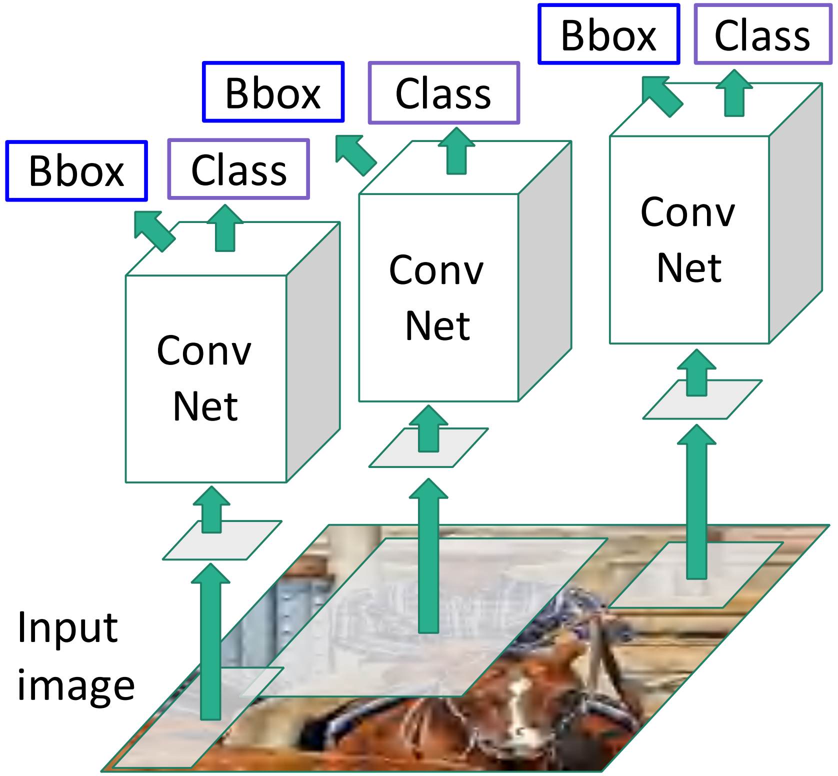
Girshick, “Fast R-CNN”, ICCV 2015. Figure copyright Ross Girshick, 2015; source. Reproduced with permission.

Fast R-CNN

"Backbone" network: AlexNet, VGG, ResNet, etc



"Slow" R-CNN
Process each region independently



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Fast R-CNN

Regions of Interest (RoIs) from a proposal method

"Backbone" network: AlexNet, VGG, ResNet, etc

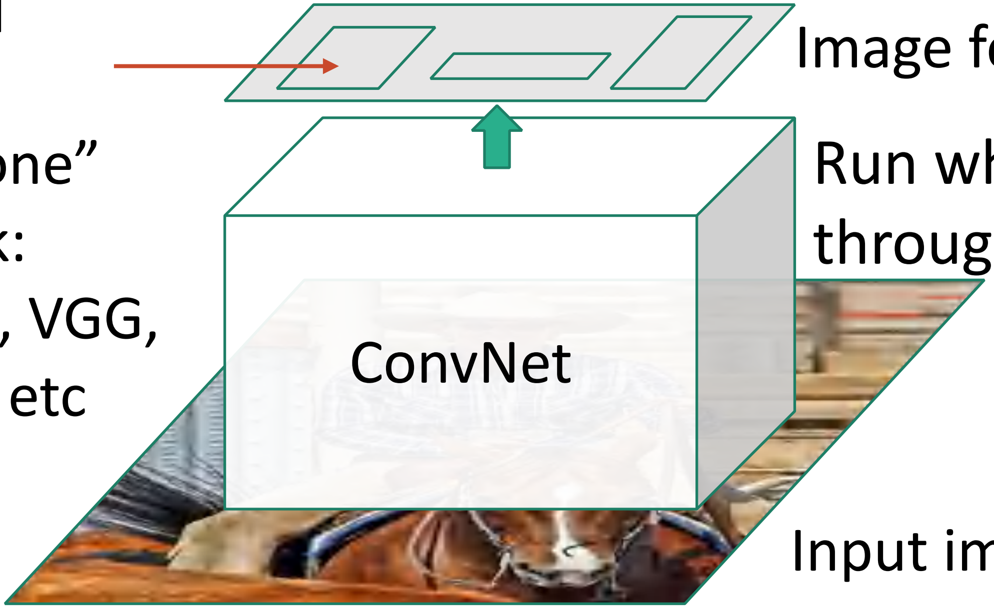


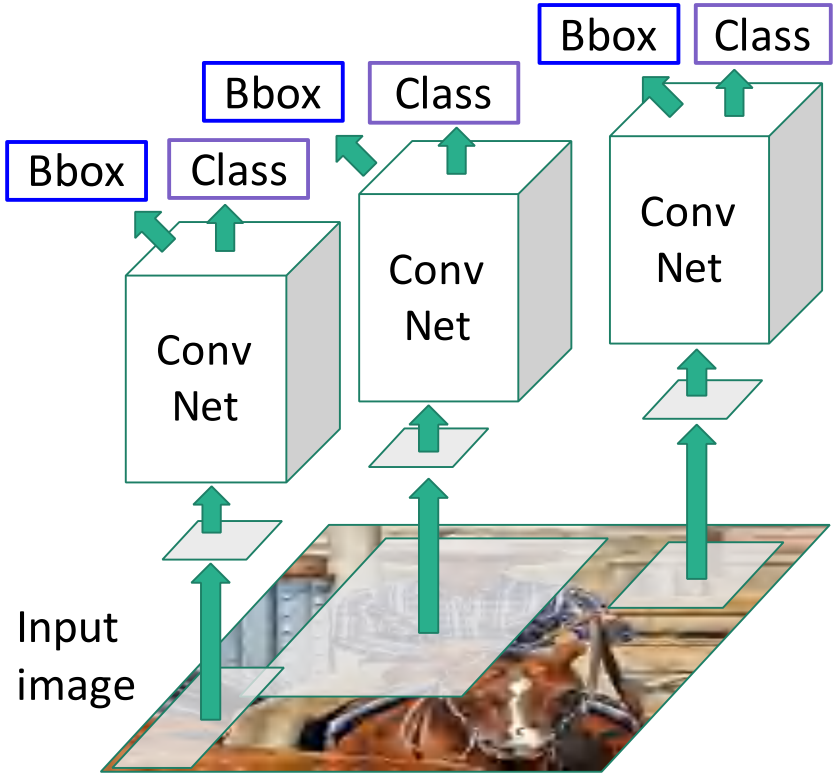
Image features

Run whole image through ConvNet

Input image

"Slow" R-CNN

Process each region independently



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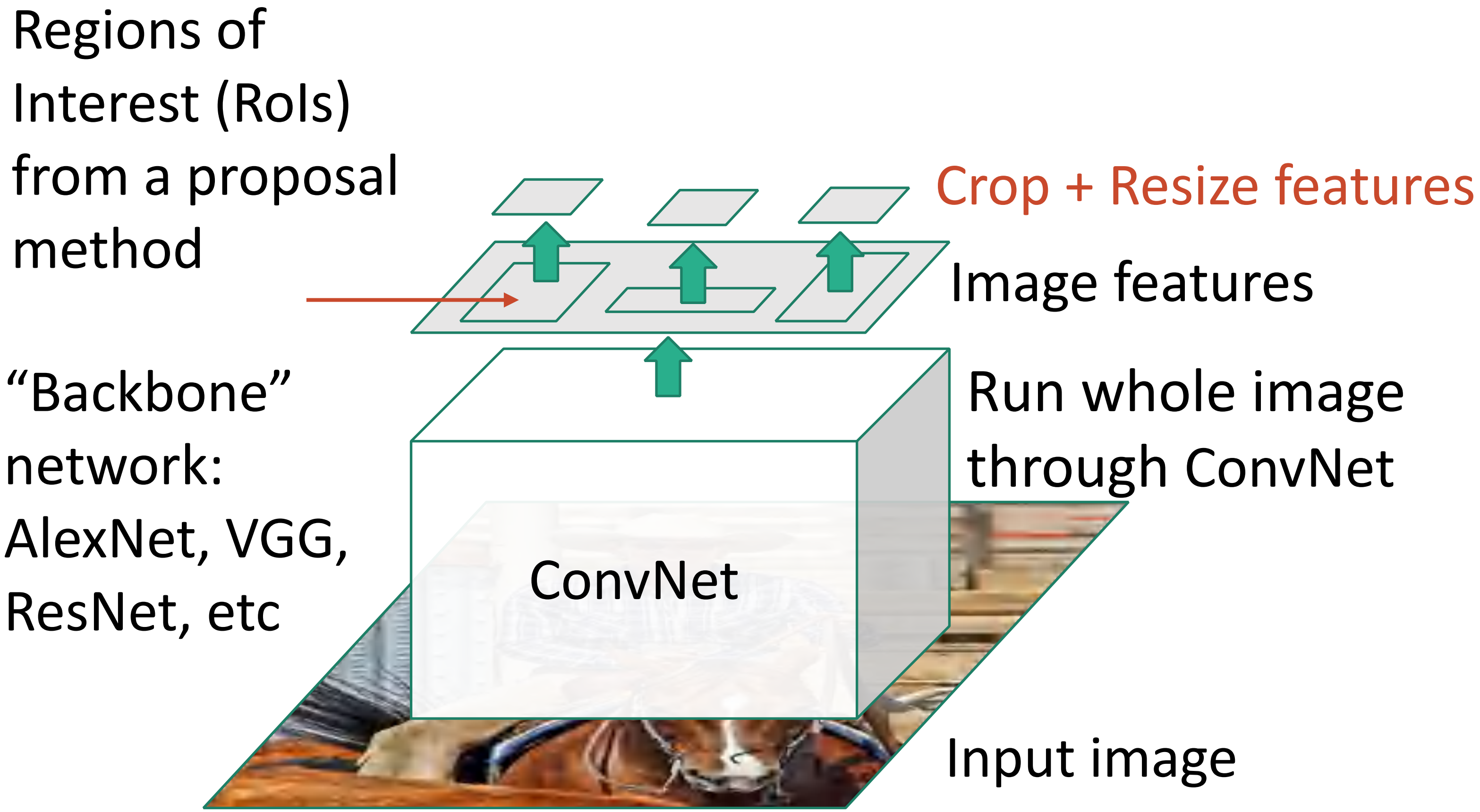
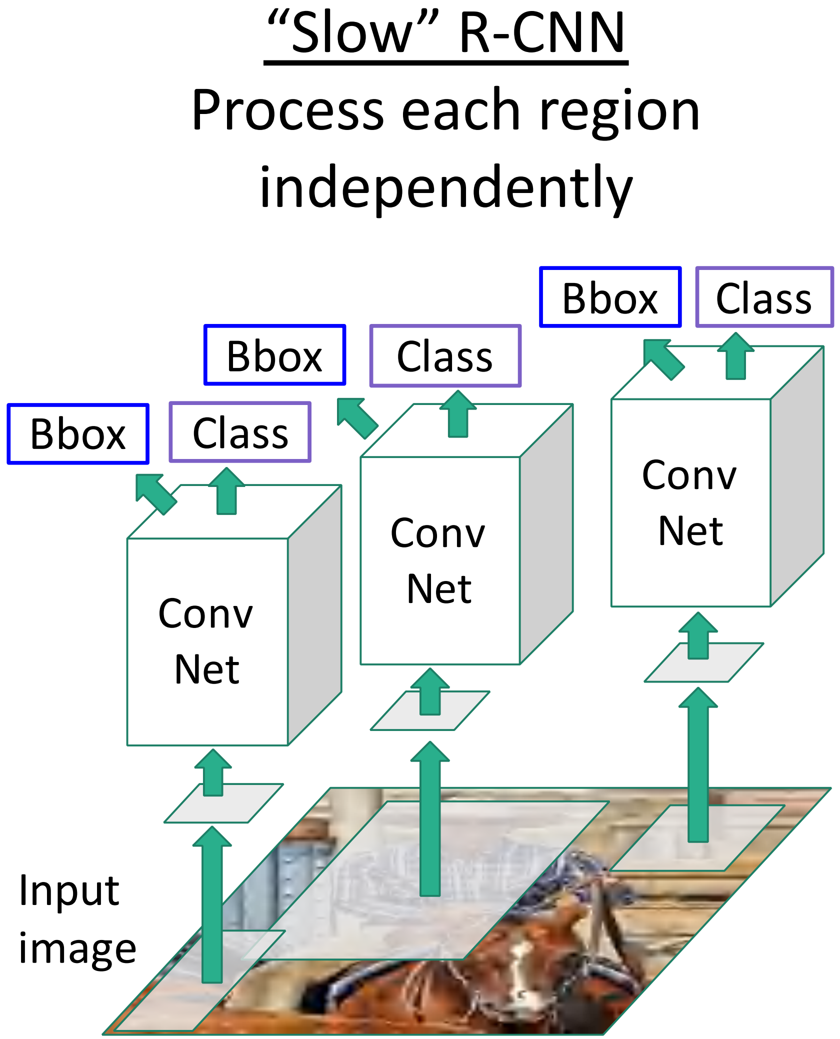
Fast R-CNN





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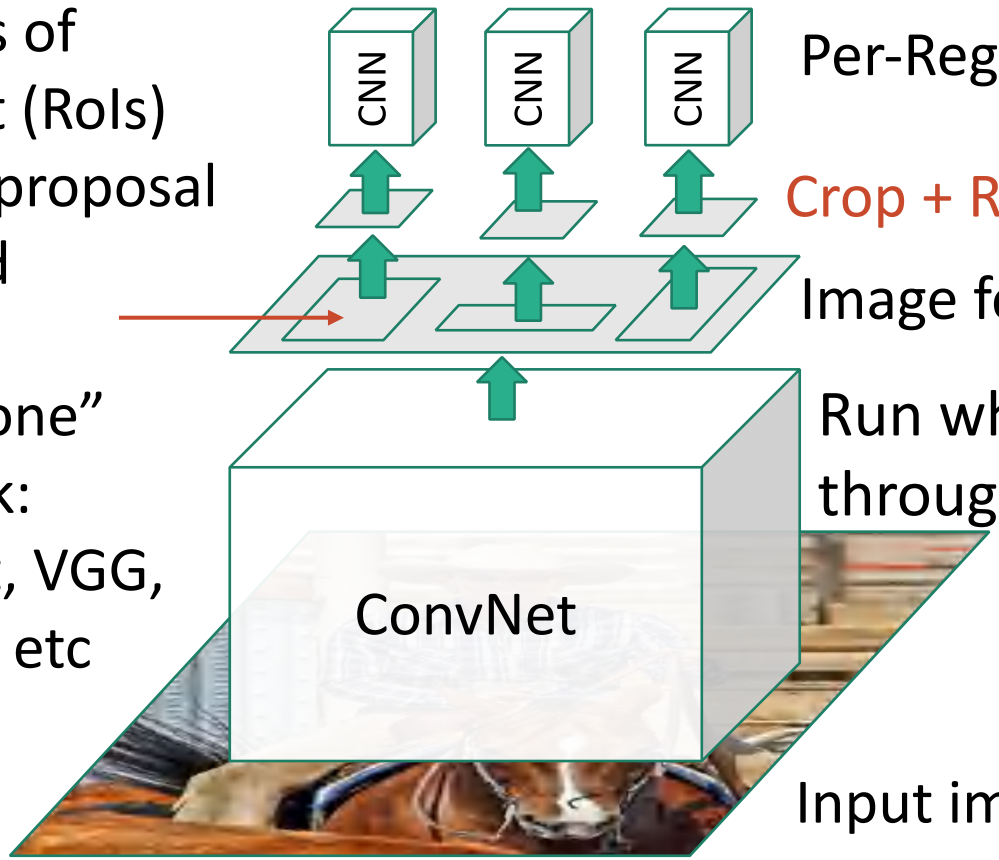


Per-Region Network

Crop + Resize features

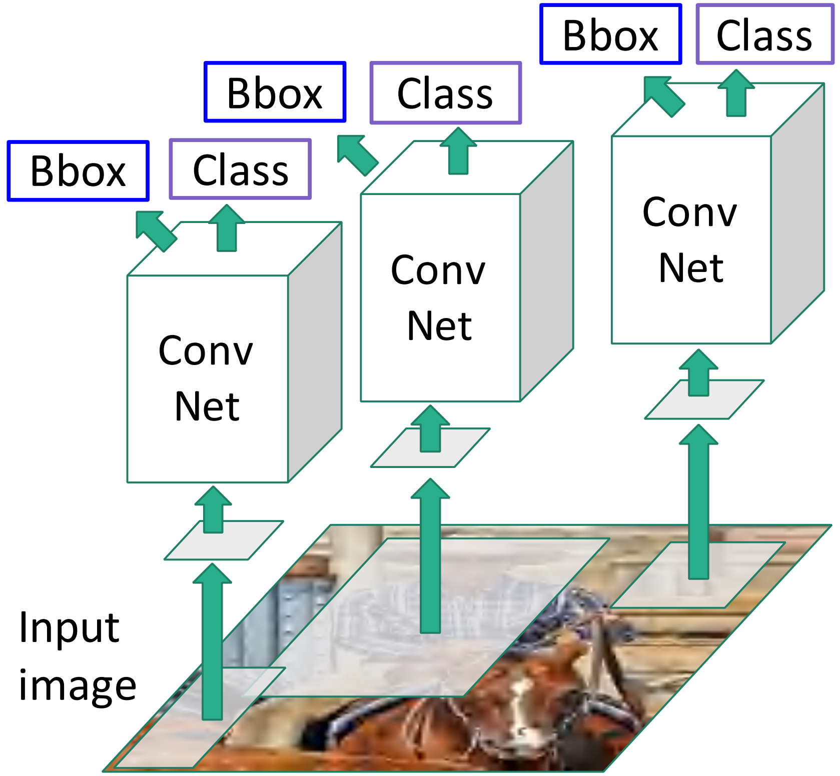
Image features

Run whole image through ConvNet

Input image

"Slow" R-CNN

Process each region independently



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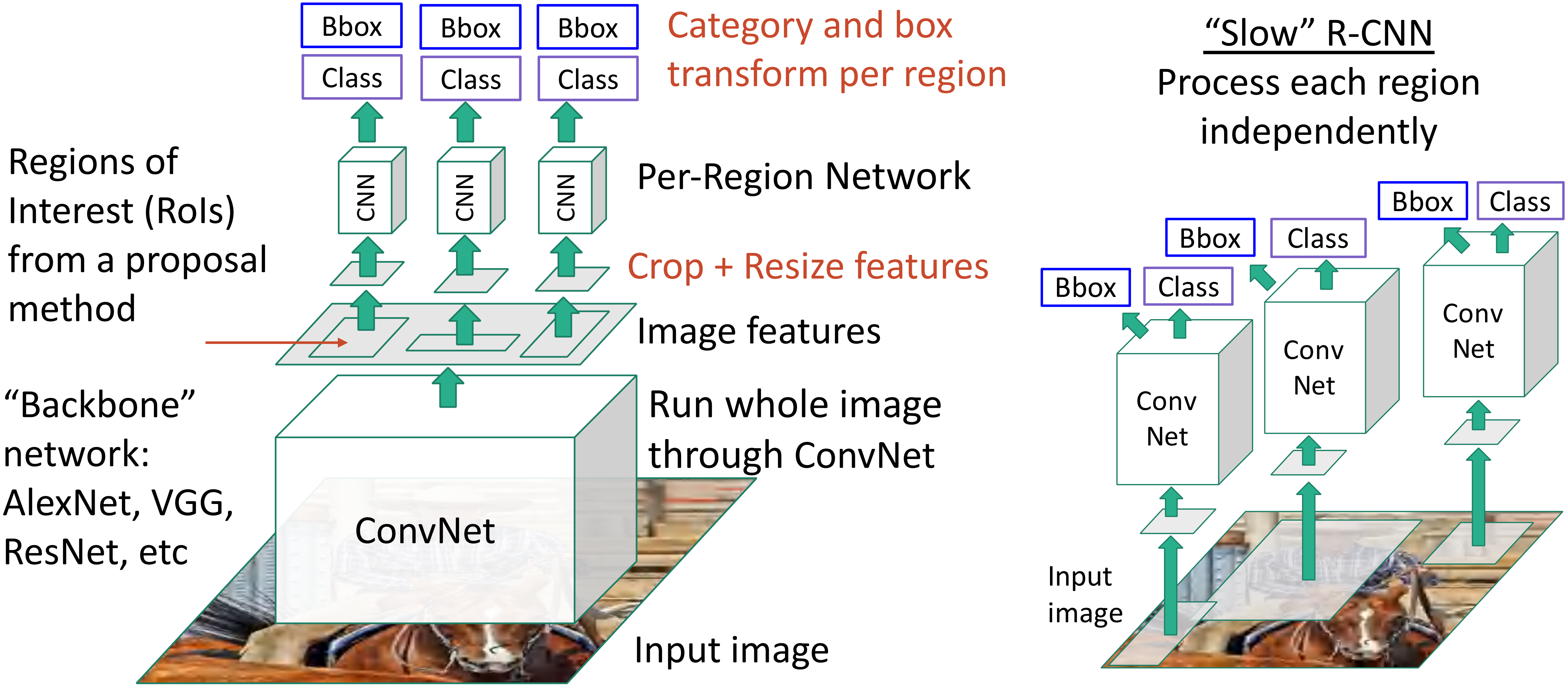
Fast R-CNN



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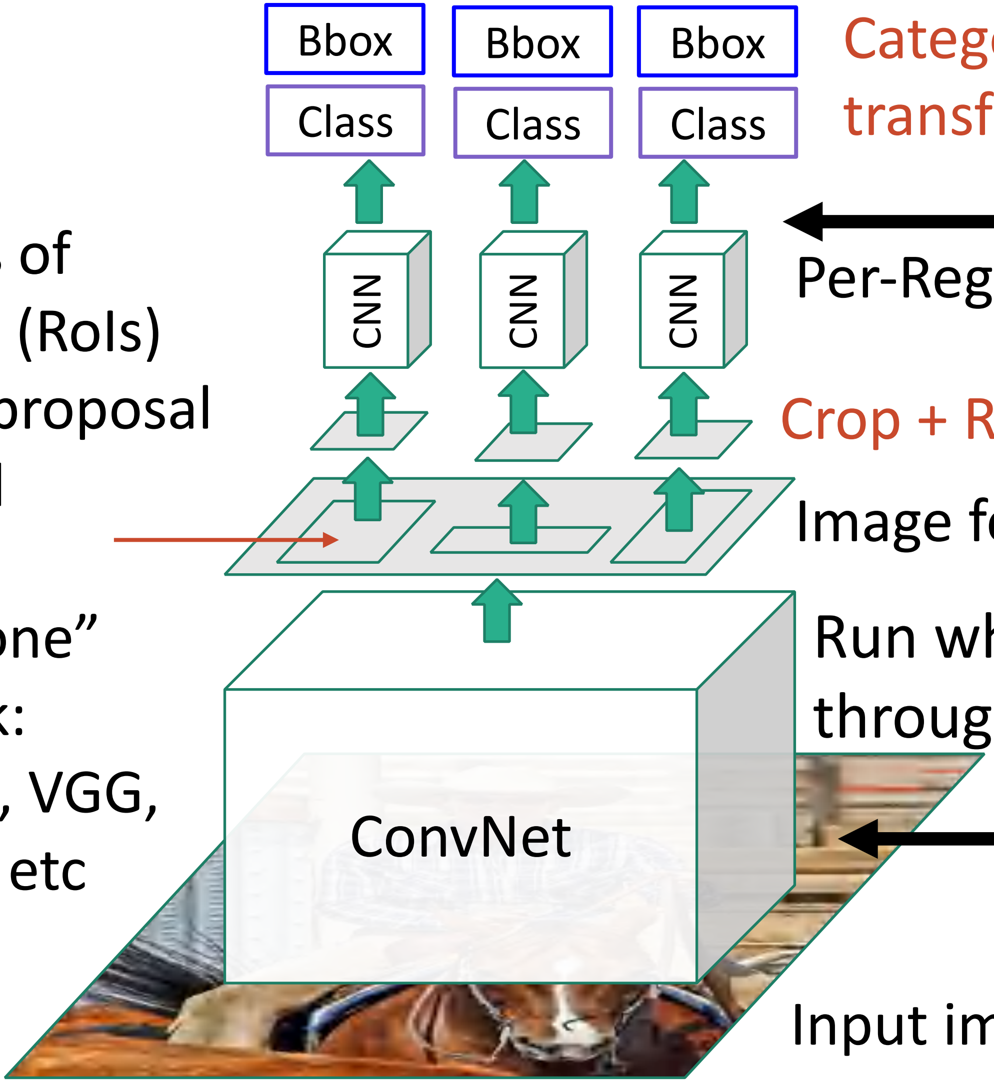
Fast R-CNN



Category and box transform per region

Per-Region network is relatively lightweight

Regions of Interest (RoIs) from a proposal method

Per-Region Network

Crop + Resize features

Image features

"Backbone" network: AlexNet, VGG, ResNet, etc

Run whole image through ConvNet

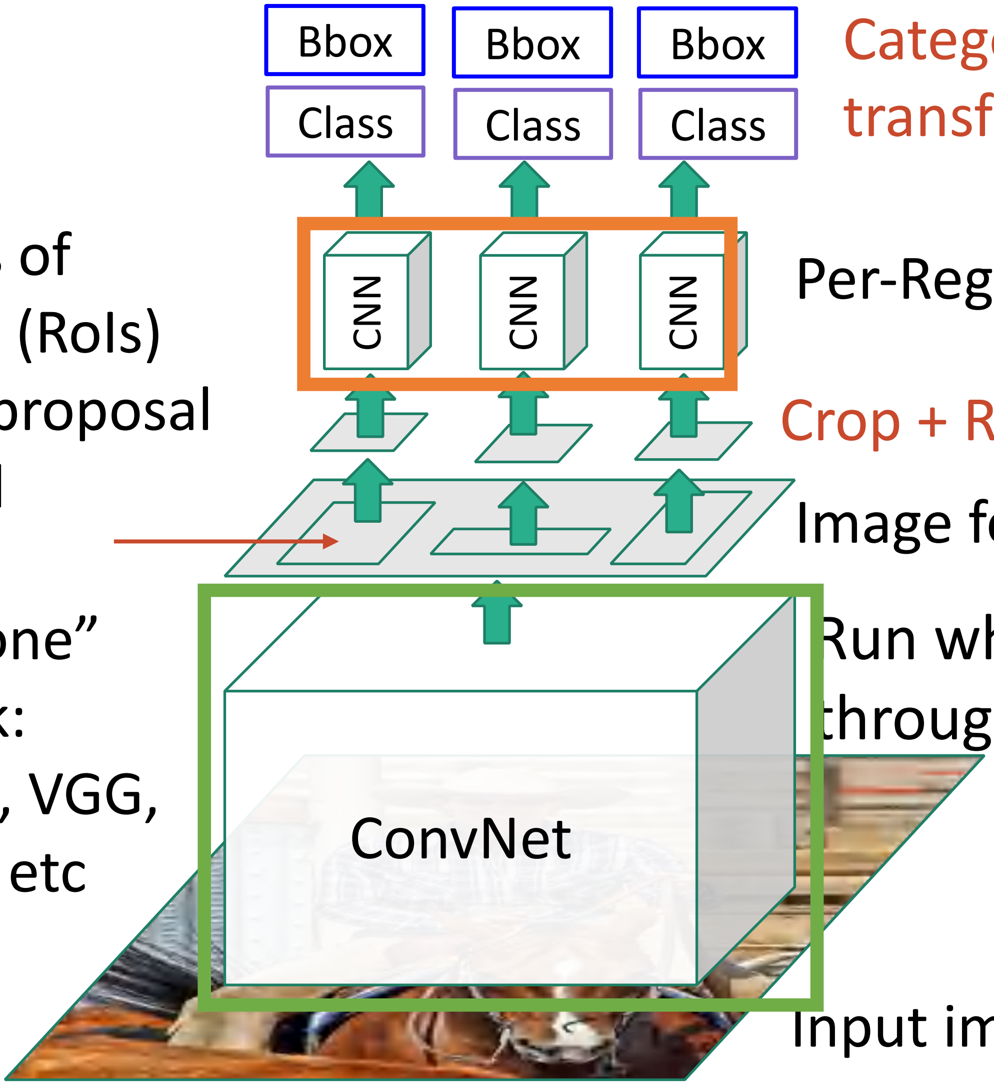
Most of the computation happens in backbone network; this saves work for overlapping region proposals

Input image

Fast R-CNN

Regions of Interest (RoIs) from a proposal method

"Backbone" network: AlexNet, VGG, ResNet, etc



Category and box transform per region

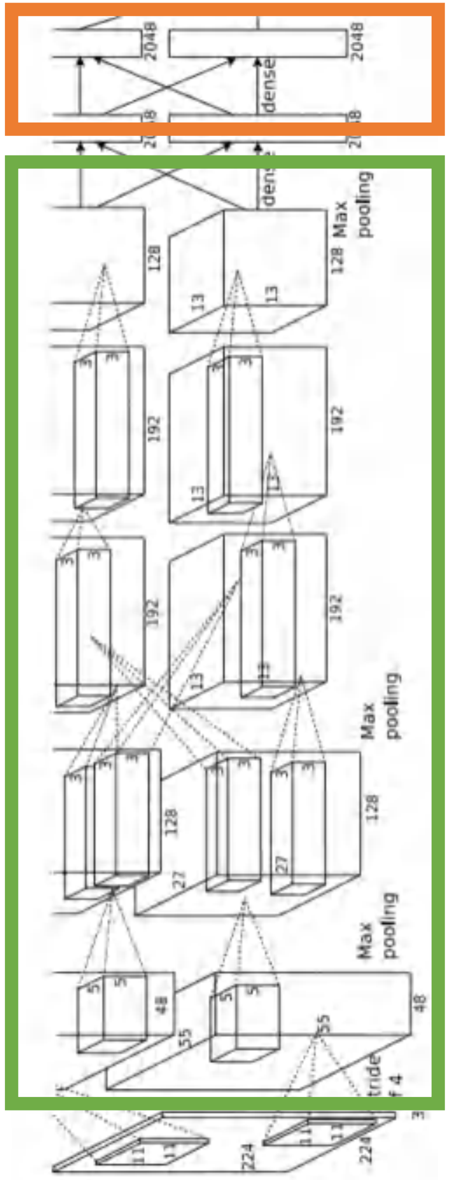
Per-Region Network

Crop + Resize features

Image features

Run whole image through ConvNet

Input image



Example: When using AlexNet for detection, five conv layers are used for backbone and two FC layers are used for per-region network

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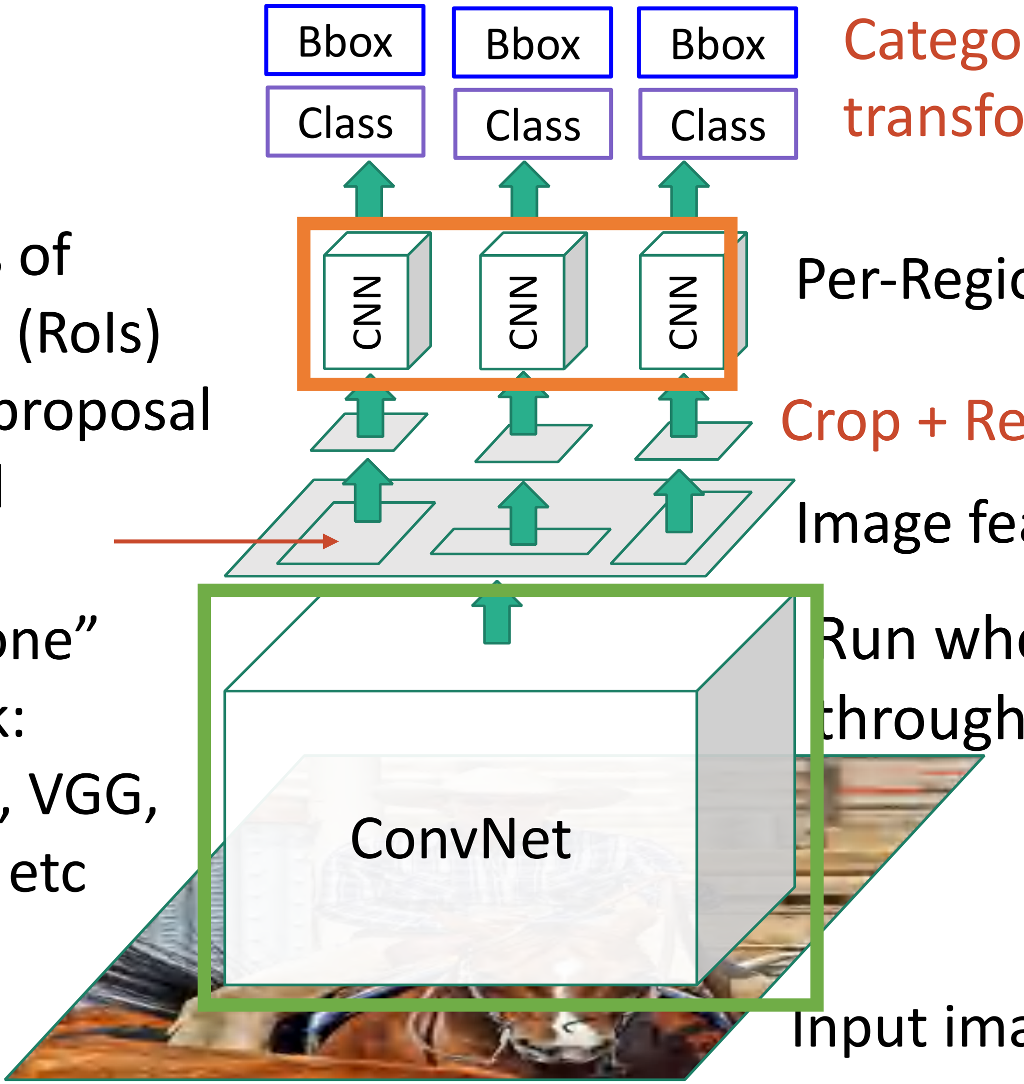
Fast R-CNN



Category and box transform per region

Per-Region Network

Crop + Resize features

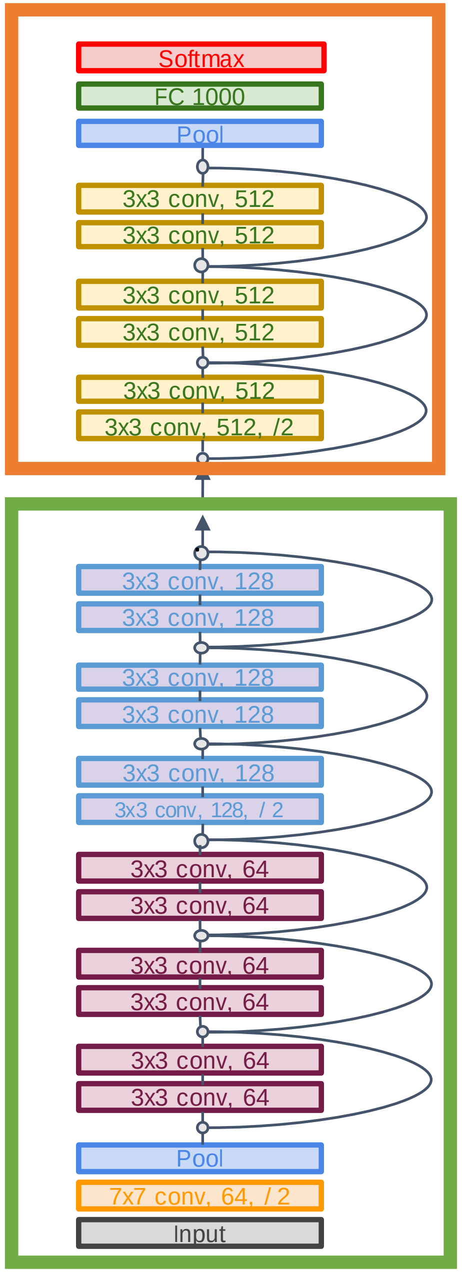
Image features

Run whole image through ConvNet

Input image

Regions of Interest (RoIs) from a proposal method

“Backbone” network: AlexNet, VGG, ResNet, etc



Example:
For ResNet, last stage is used as per-region network; the rest of the network is used as backbone

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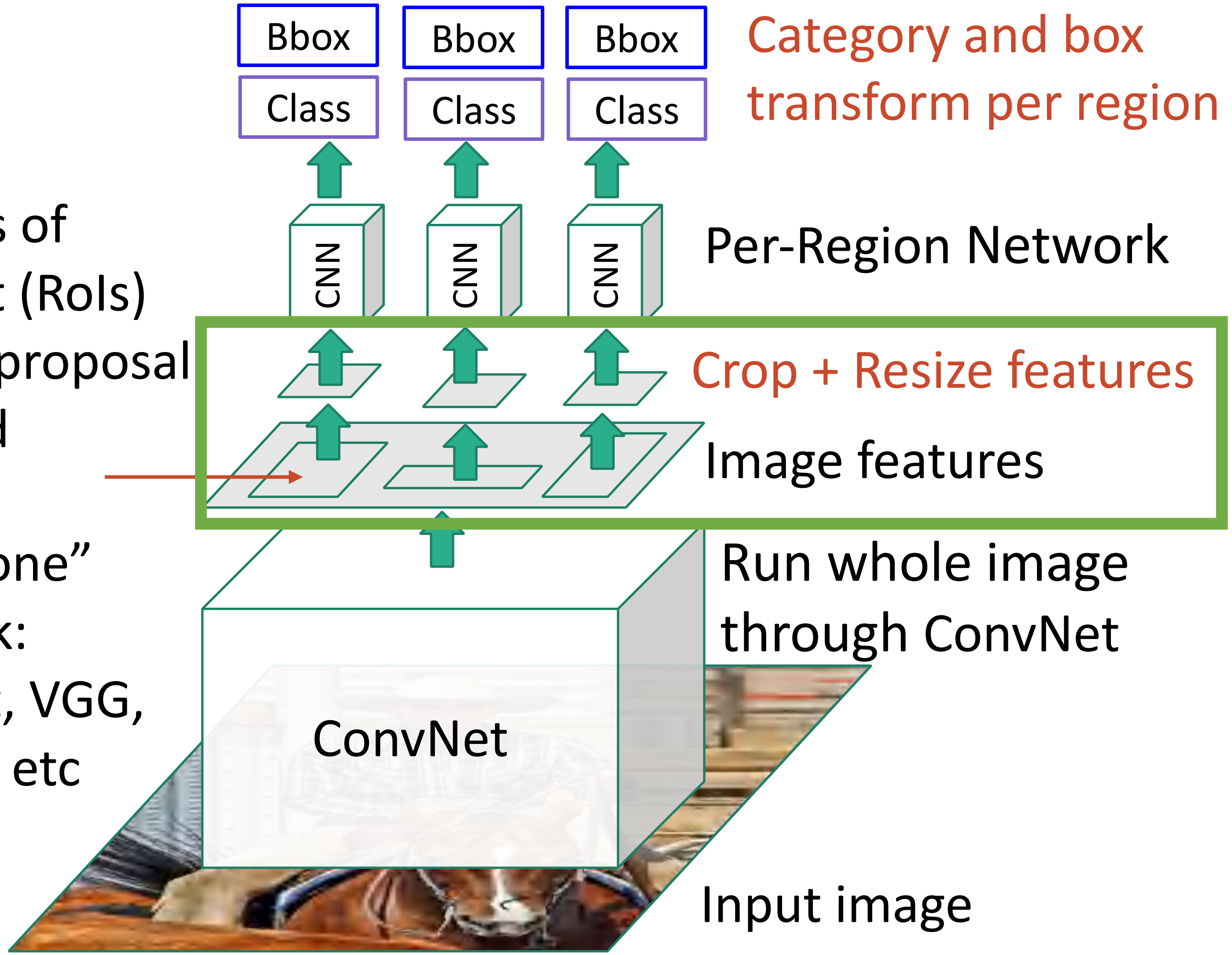
Fast R-CNN



Category and box transform per region

Per-Region Network

Regions of Interest (RoIs) from a proposal method

"Backbone" network: AlexNet, VGG, ResNet, etc

Run whole image through ConvNet

Input image

How to crop features?

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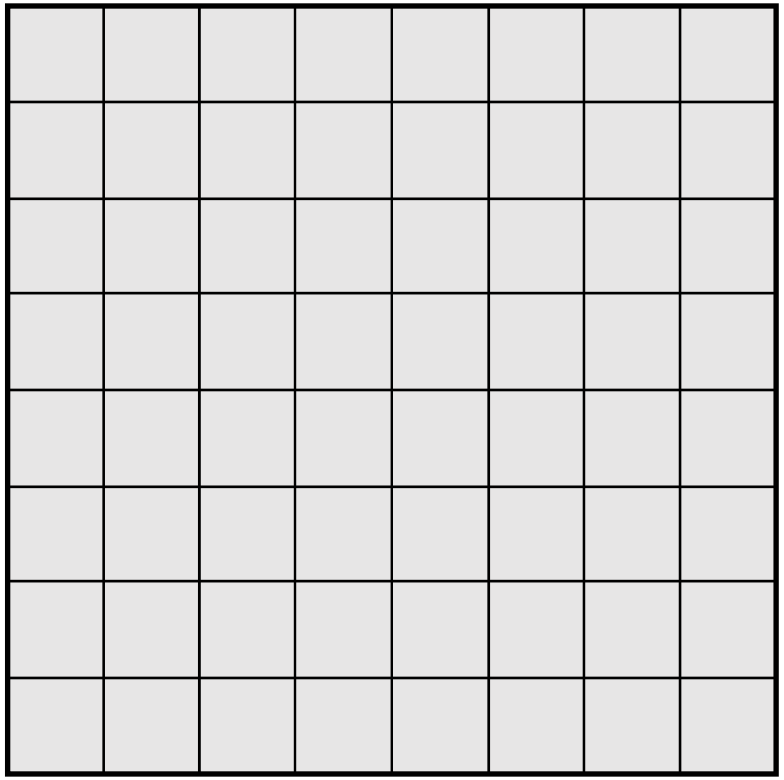
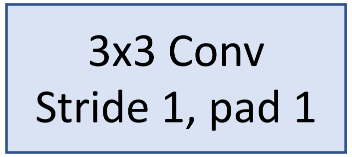
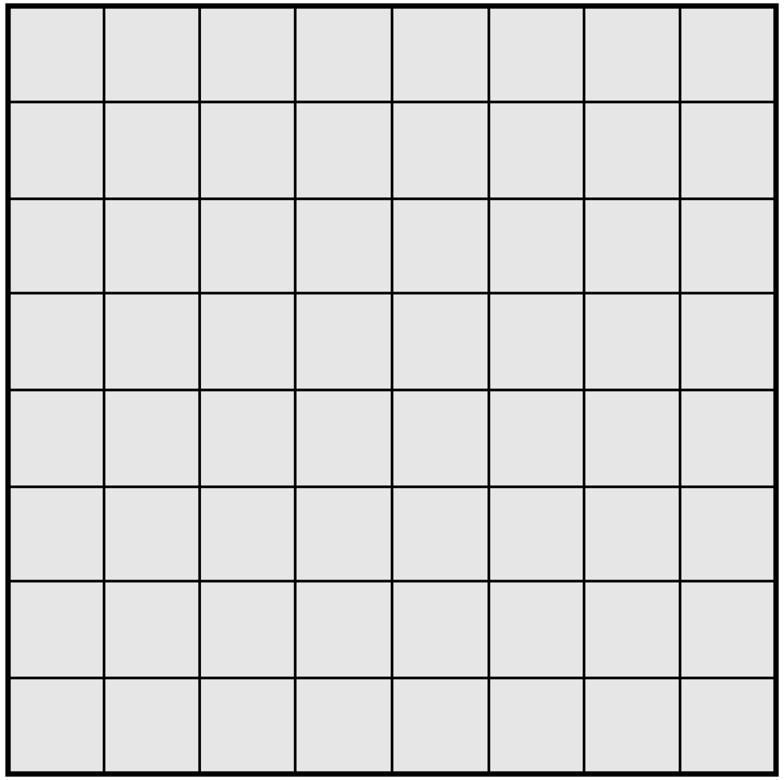
Recall: Receptive Fields



Every position in the output feature map depends on a 3x3 receptive field in the input

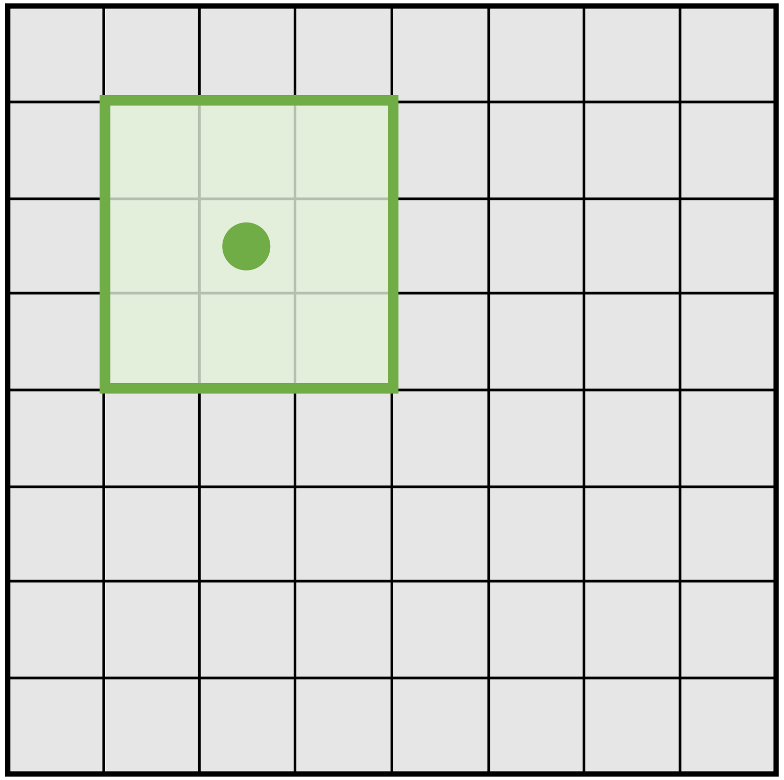




Input Image: 8 x 8

Output Image: 8 x 8

Recall: Receptive Fields



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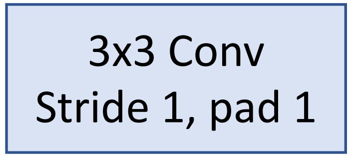
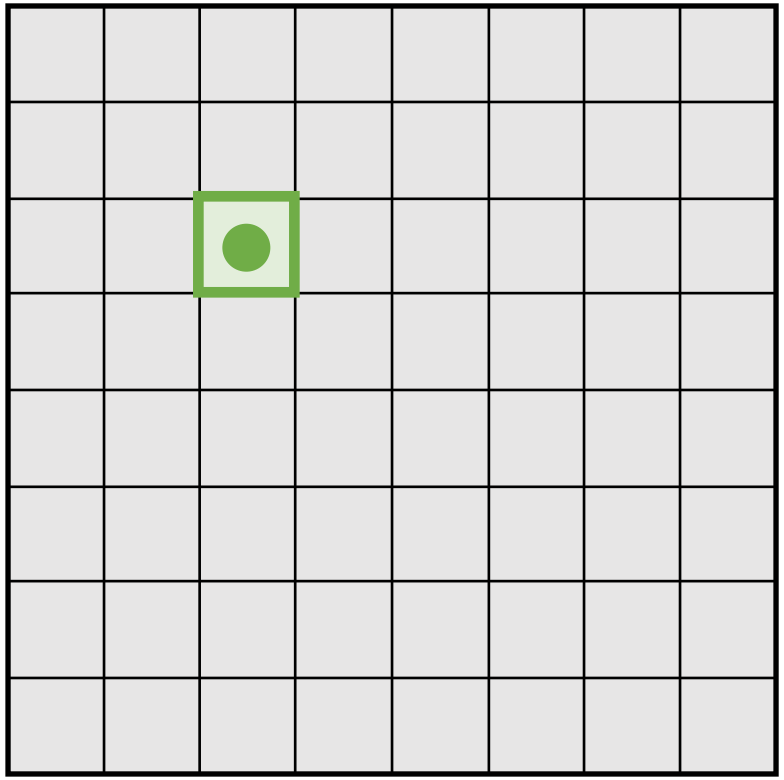
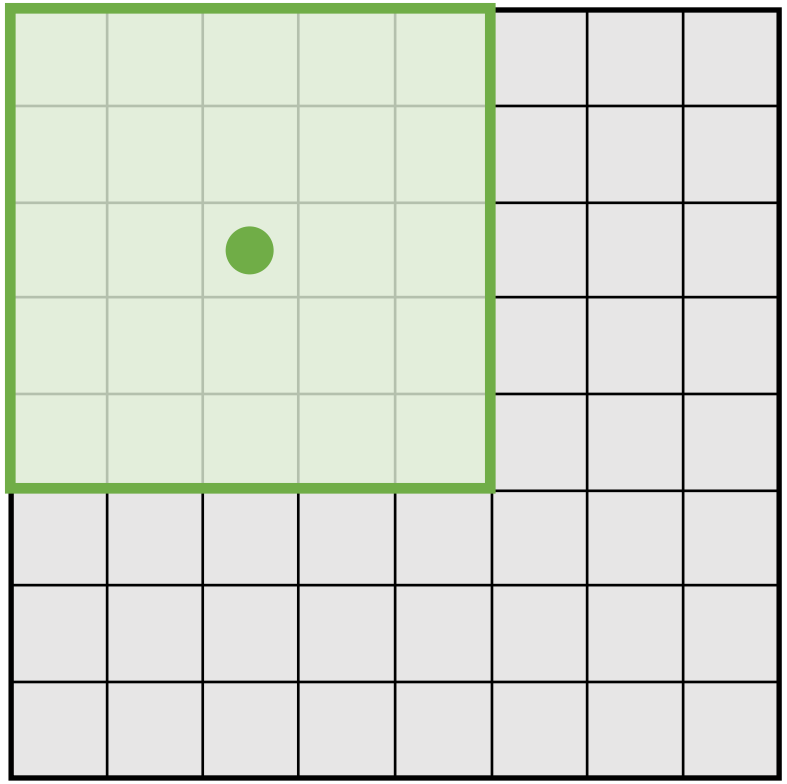




Input Image: 8 x 8

Output Image: 8 x 8

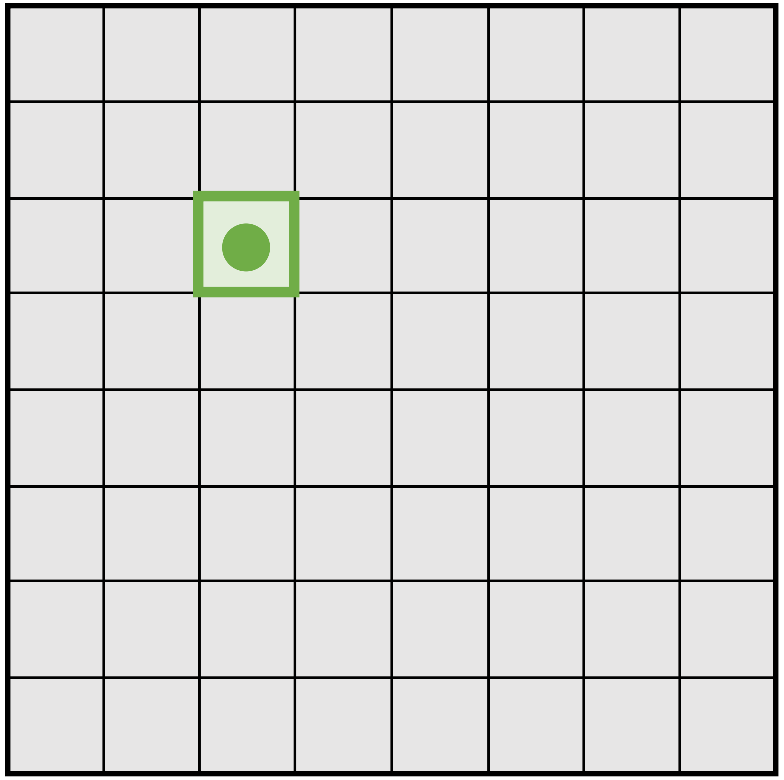
Recall: Receptive Fields



Input Image: 8 x 8

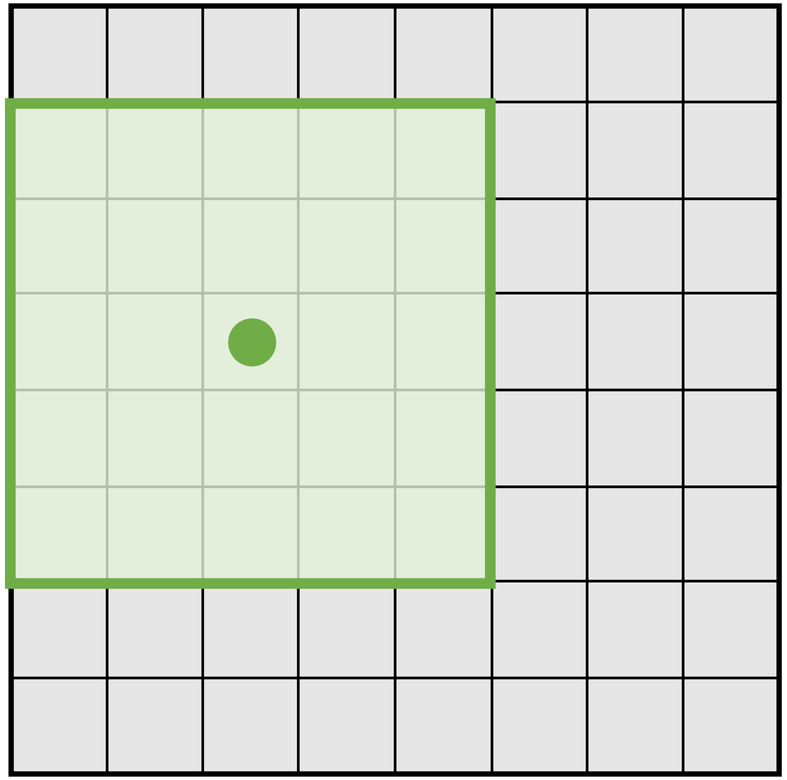
Every position in the output feature map depends on a <u>5x5</u> receptive field in the input

3x3 Conv Stride 1, pad 1	3x3 Conv Stride 1, pad 1



Output Image: 8 x 8

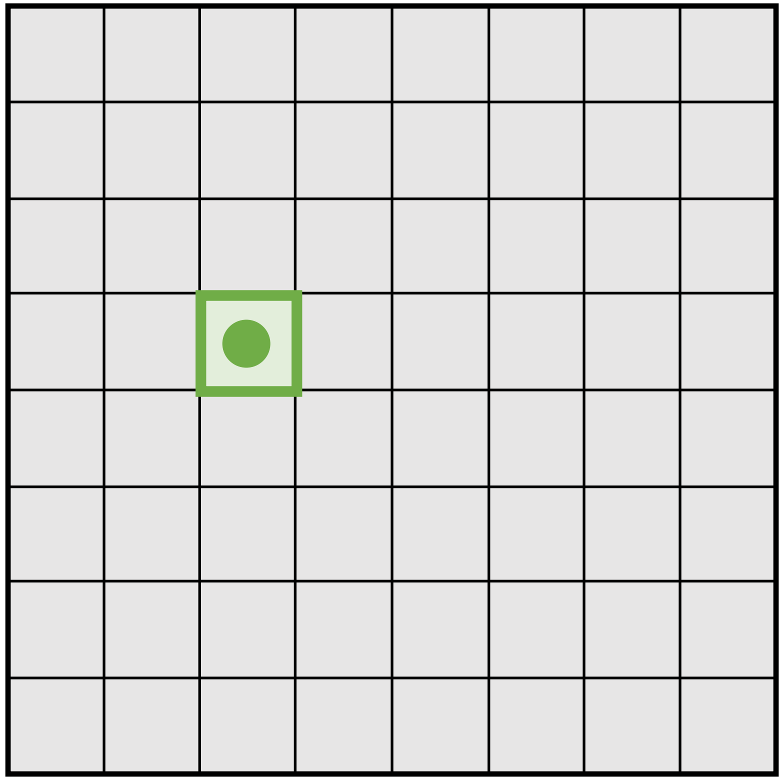
Recall: Receptive Fields



Moving one unit in the output space also moves the receptive field by one

3x3 Conv
Stride 1, pad 1

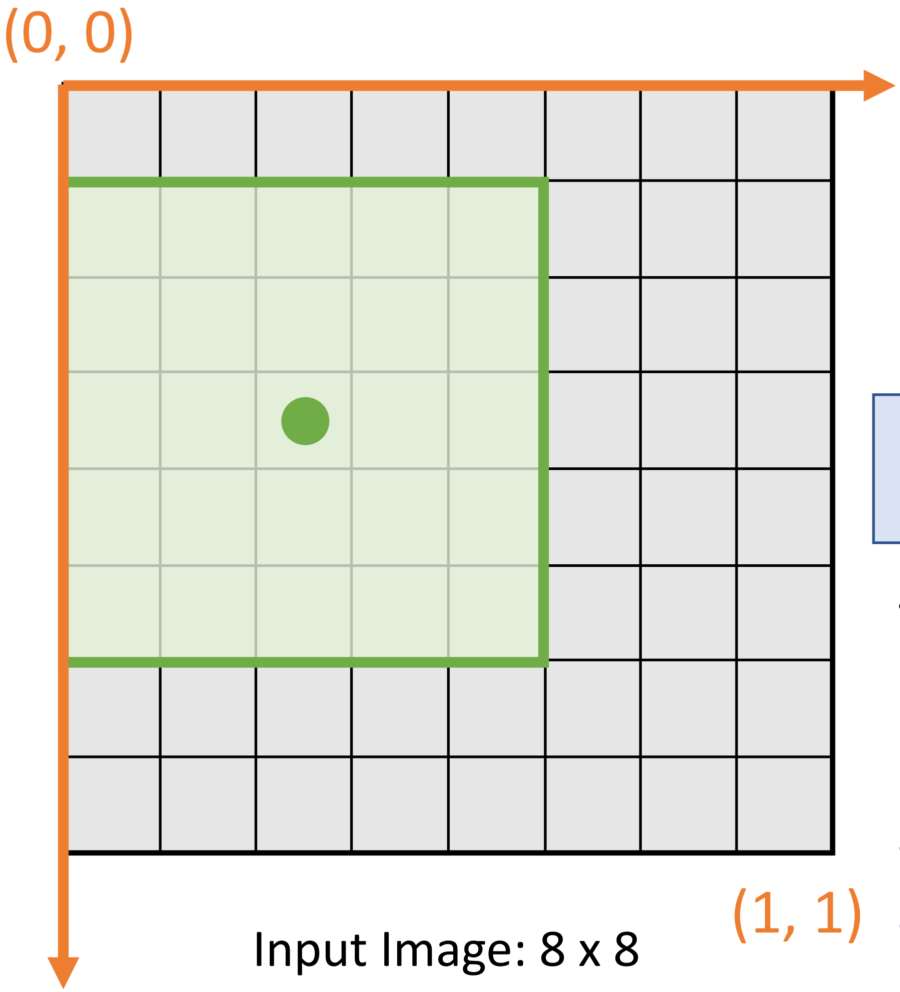
3x3 Conv
Stride 1, pad 1



Input Image: 8 x 8

Output Image: 8 x 8

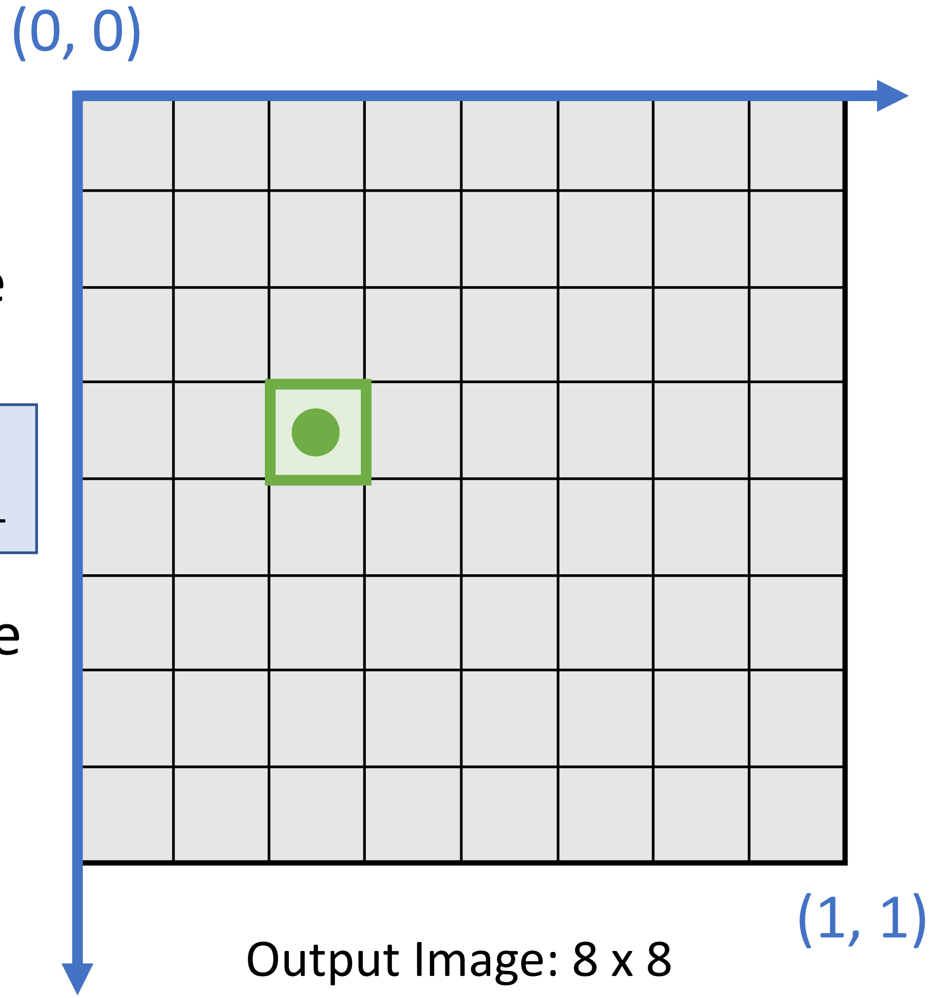
Recall: Receptive Fields



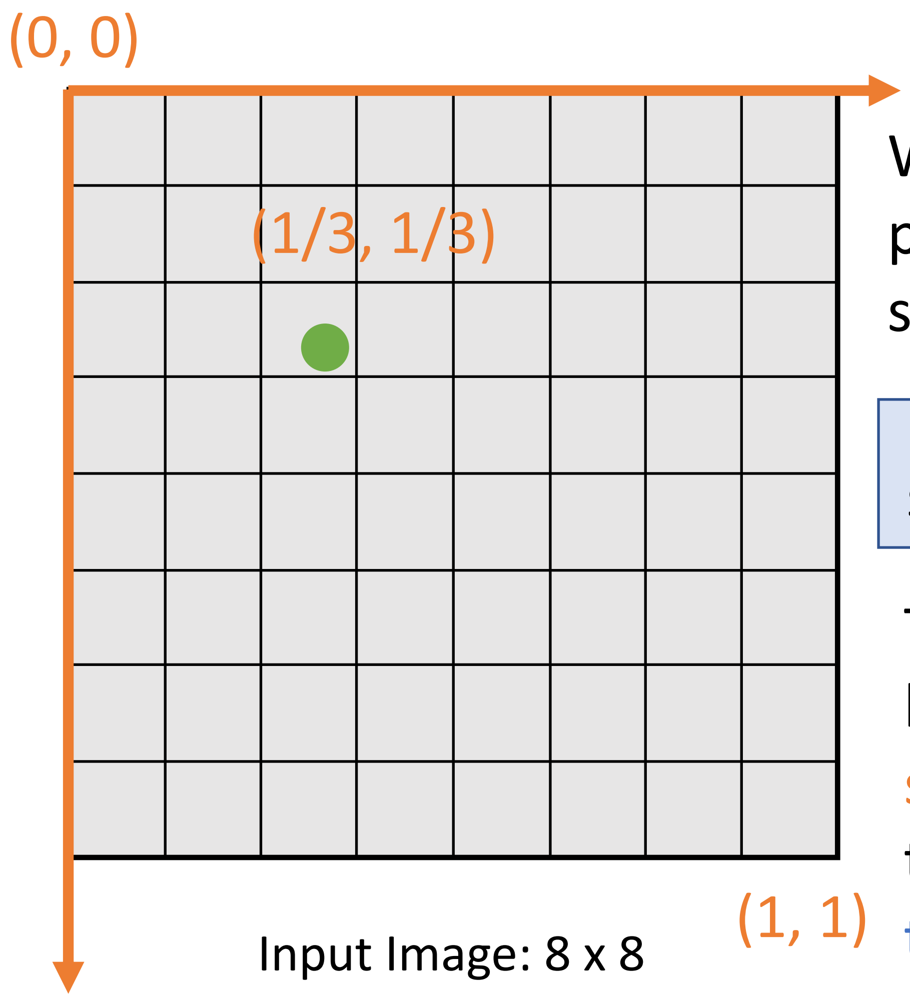
Moving one unit in the output space also moves the receptive field by one

3x3 Conv Stride 1, pad 1	3x3 Conv Stride 1, pad 1

There is a correspondence between the coordinate system of the input and the coordinate system of the output



Projecting Points

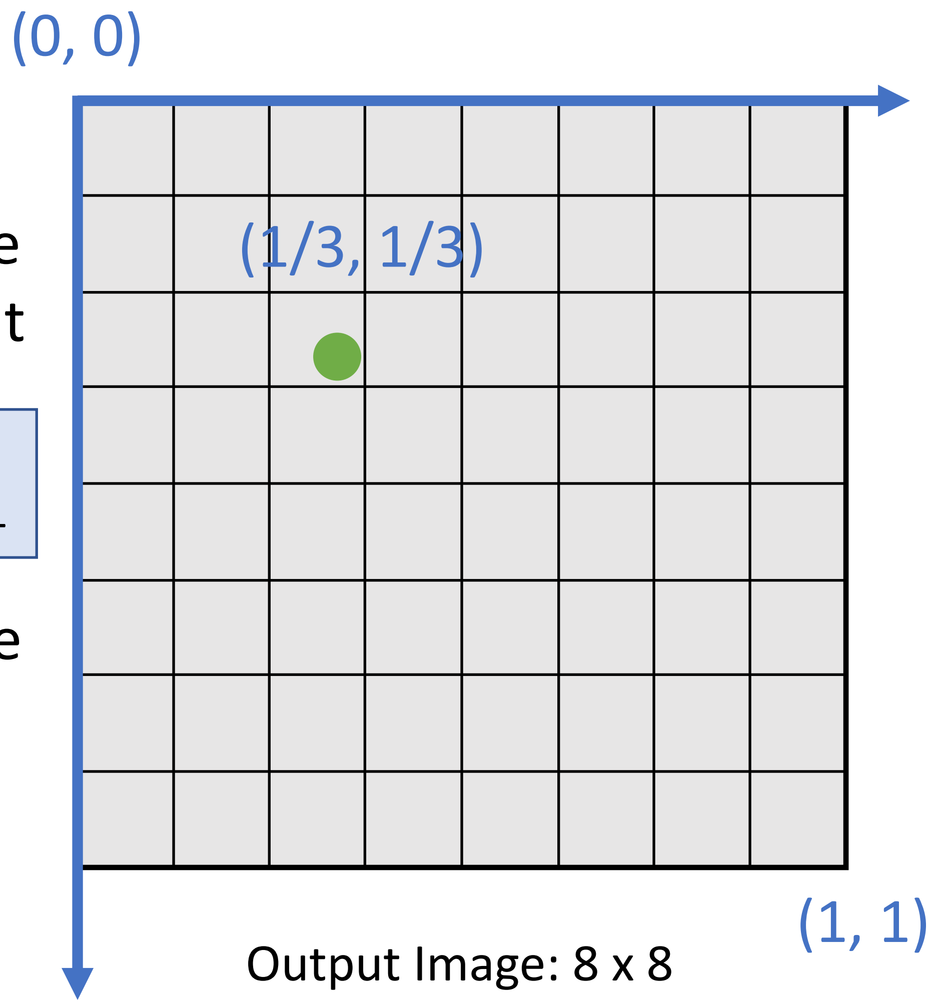


We can align arbitrary points between coordinate system of input and output

3x3 Conv
Stride 1, pad 1

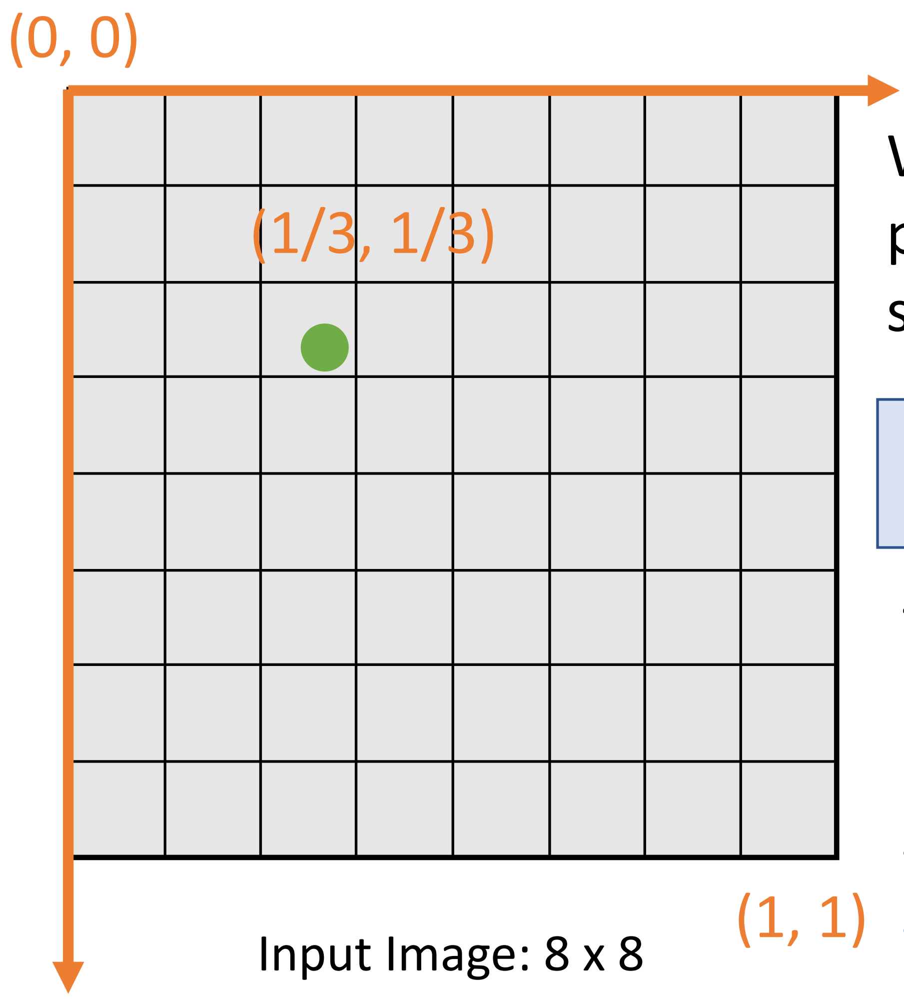
3x3 Conv
Stride 1, pad 1

There is a correspondence between the coordinate system of the input and the coordinate system of the output



Projecting Points

Same logic holds for more complicated CNNs, even if spatial resolution of input and output are different



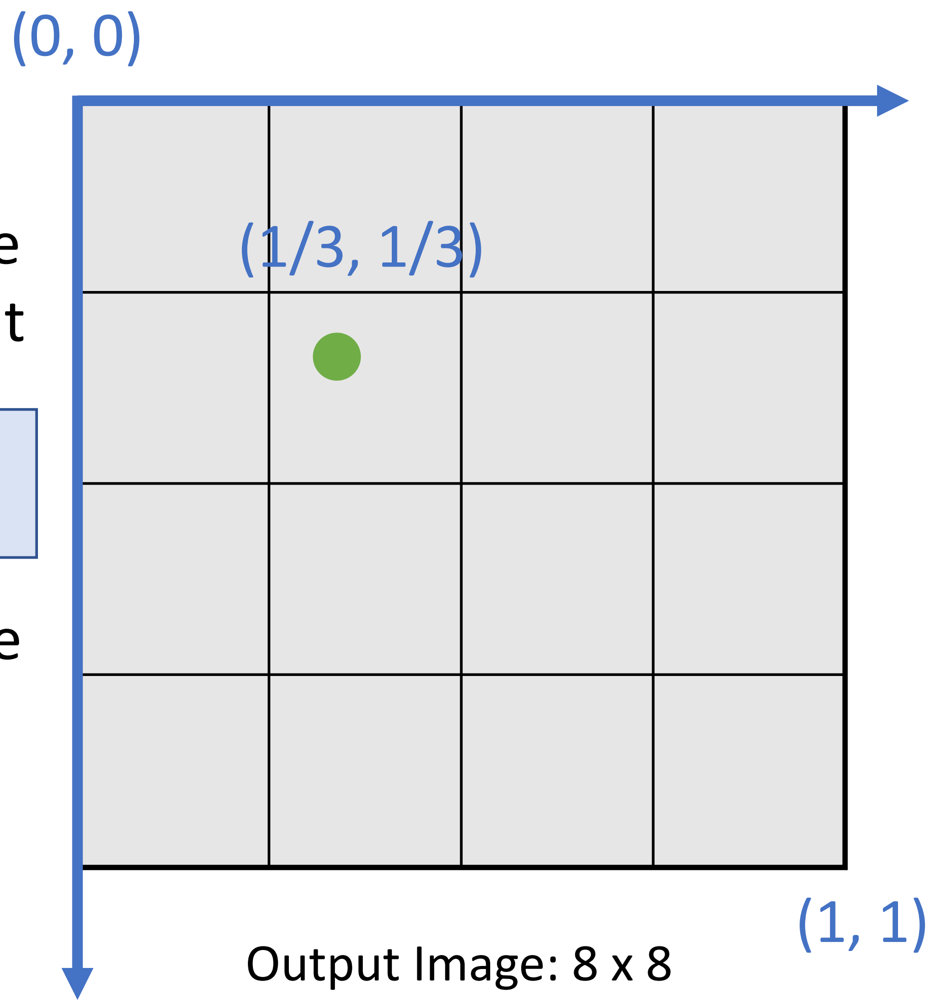
Input Image: 8 x 8

We can align arbitrary points between coordinate system of input and output

3x3 Conv
Stride 1, pad 1

2x2 MaxPool
Stride 2

There is a correspondence between the coordinate system of the input and the coordinate system of the output



Output Image: 8 x 8

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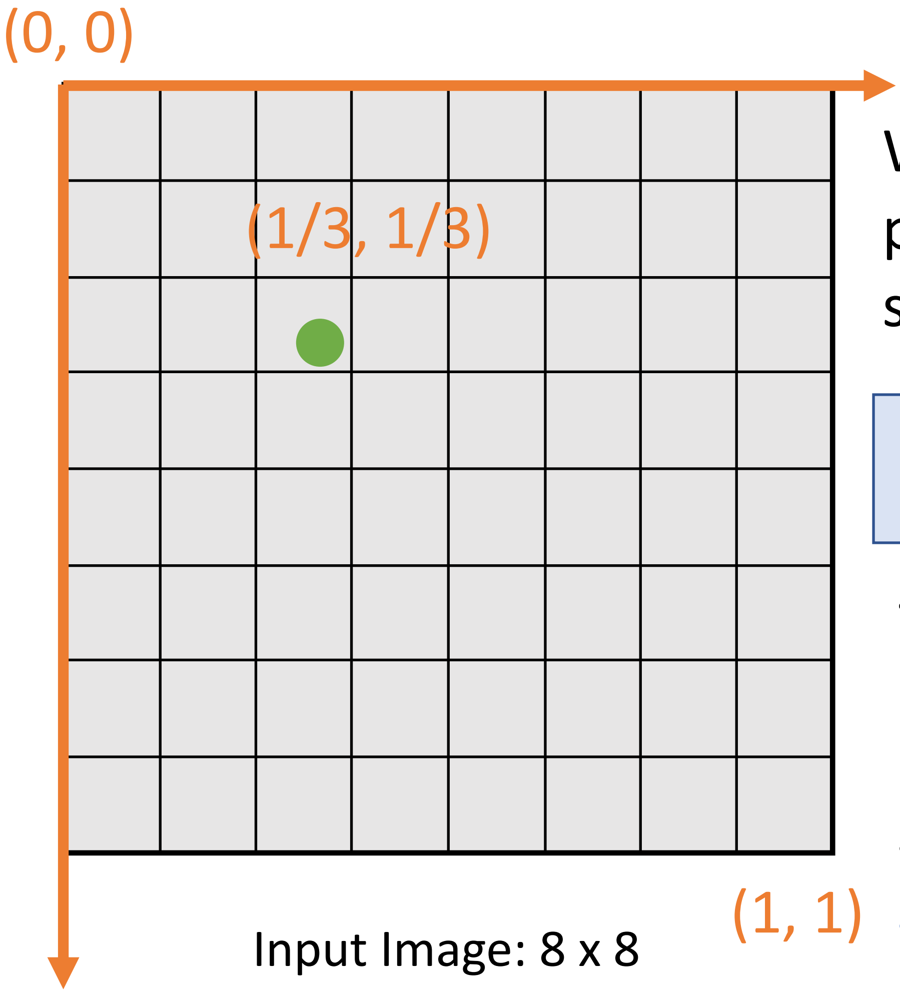


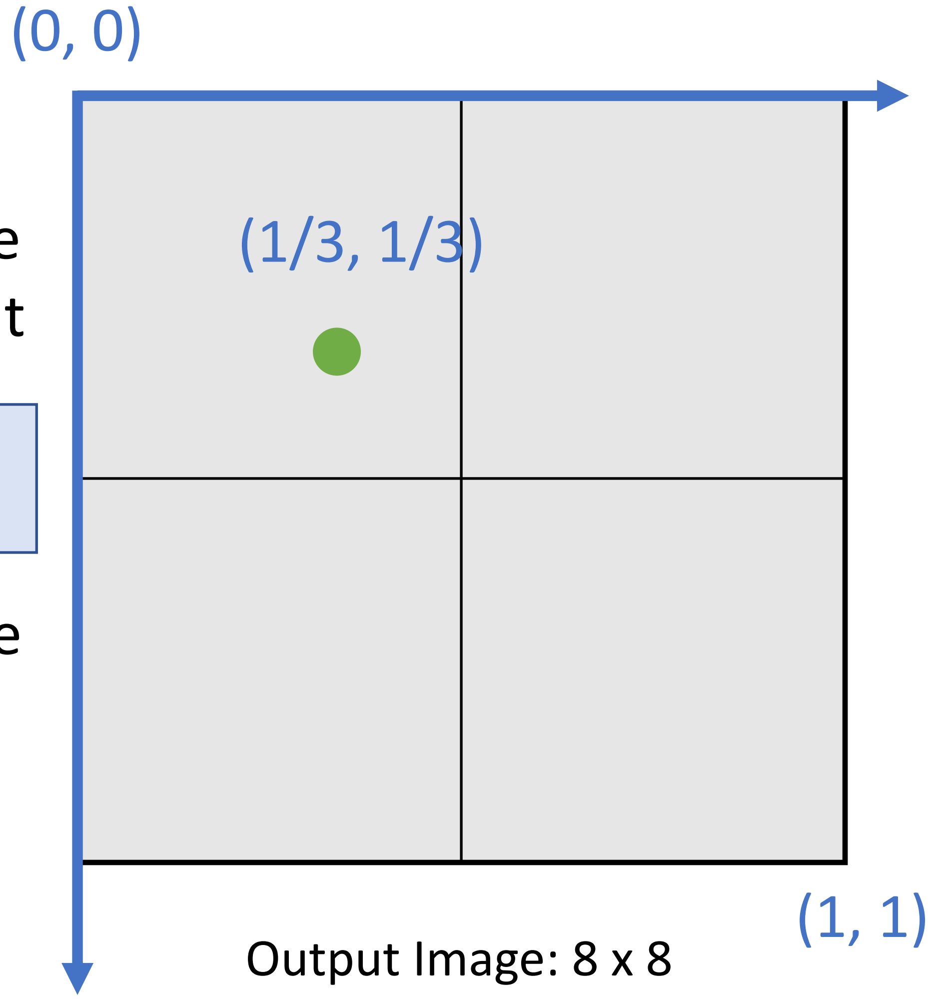
Input Image: 8 x 8

We can align arbitrary points between coordinate system of input and output

3x3 Conv
Stride 1, pad 1

4x4 MaxPool
Stride 4

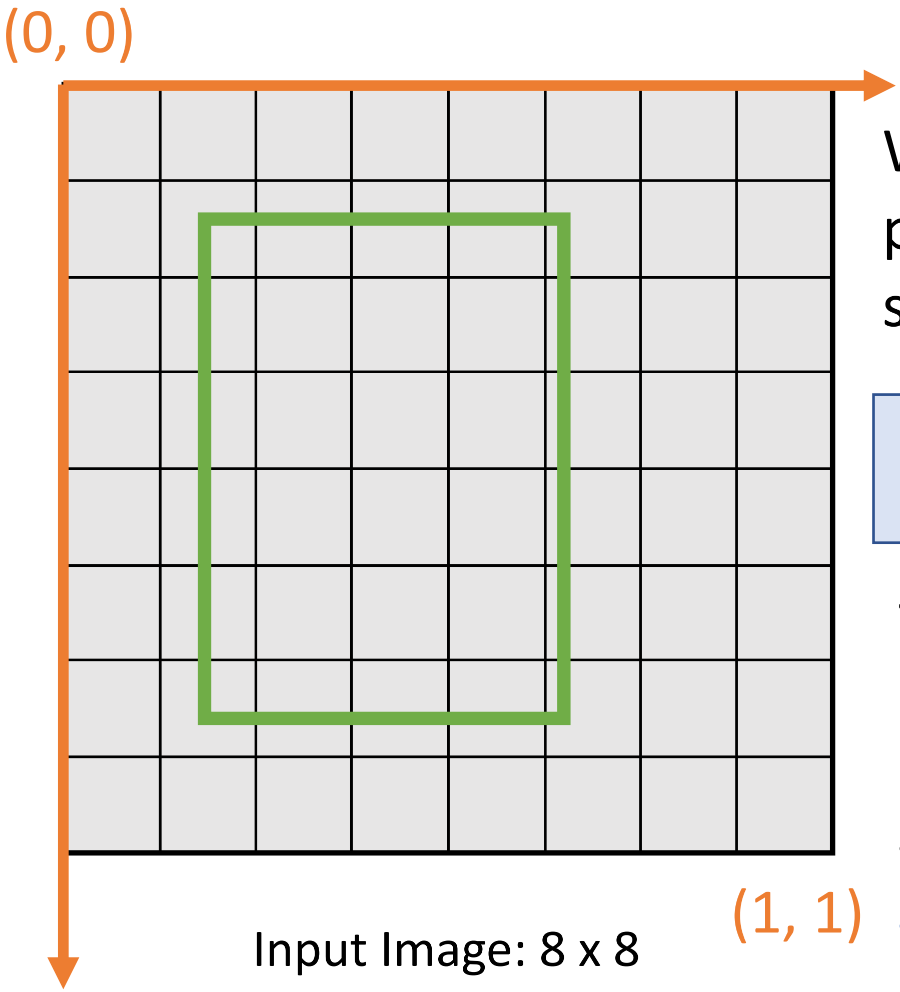
There is a correspondence between the coordinate system of the input and the coordinate system of the output



Output Image: 8 x 8

Projecting Boxes

We can use this idea to project **bounding boxes** between an input image and a feature map

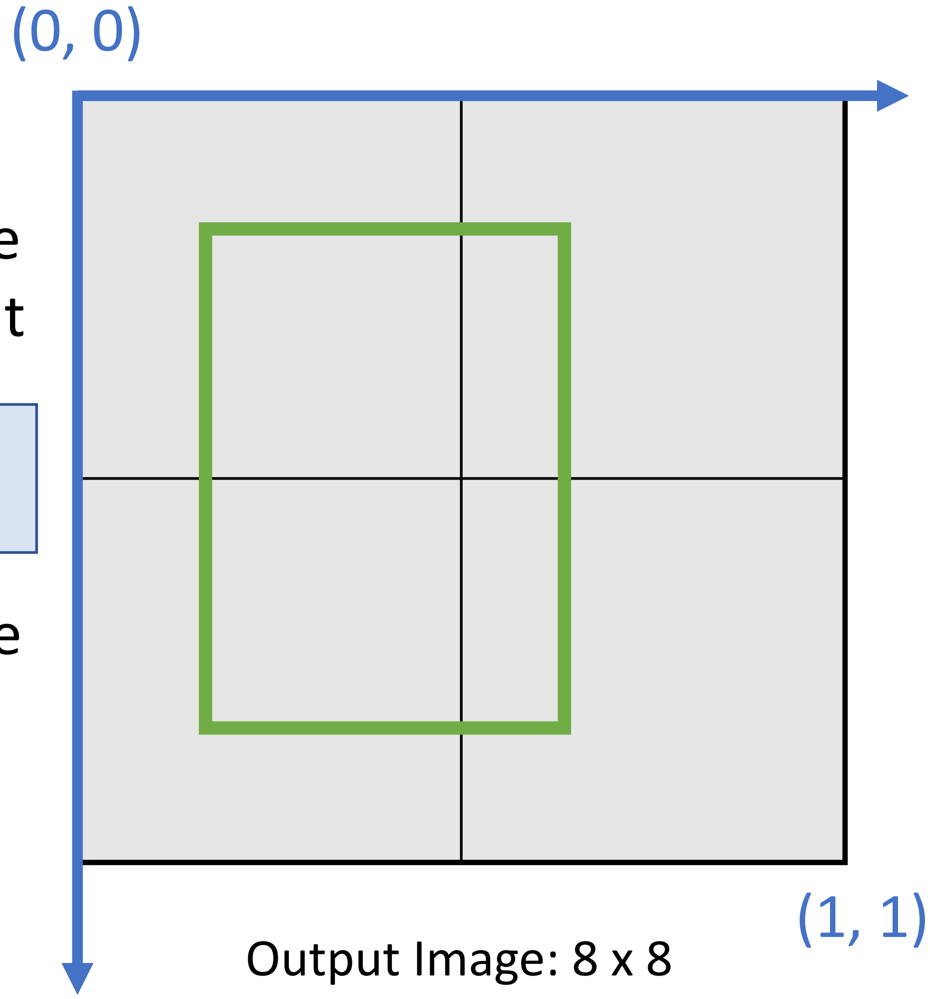


Input Image: 8 x 8

We can align arbitrary points between coordinate system of input and output

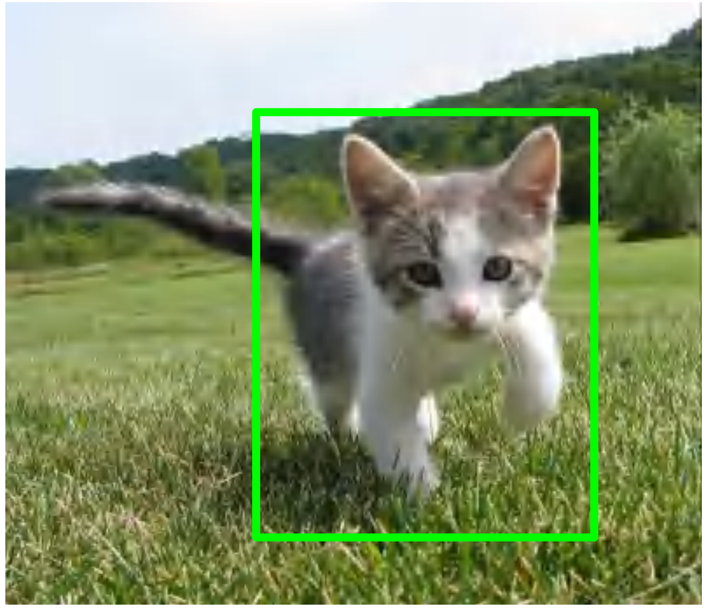
3x3 Conv Stride 1, pad 1	4x4 MaxPool Stride 4

There is a correspondence between the coordinate system of the input and the coordinate system of the output



Output Image: 8 x 8

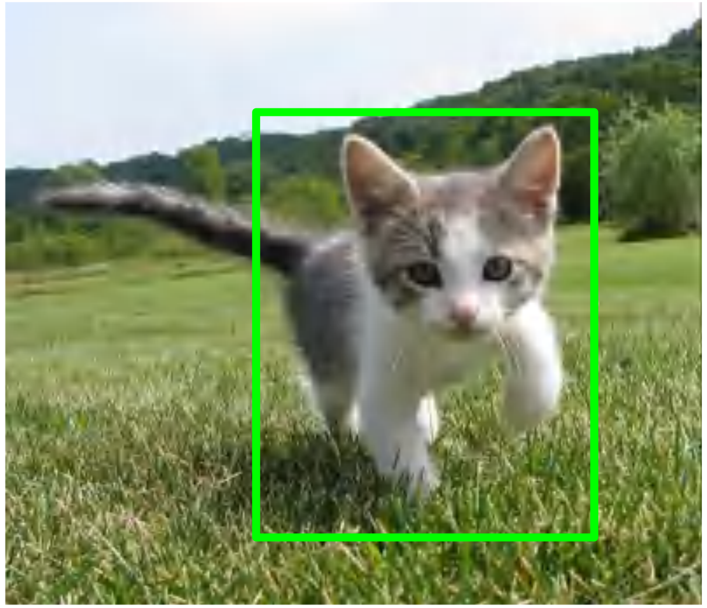
Cropping Features: RoI Pool



Input Image
(e.g. 3 x 640 x 480)

Girshick, “Fast R-CNN”, ICCV 2015.

Cropping Features: RoI Pool



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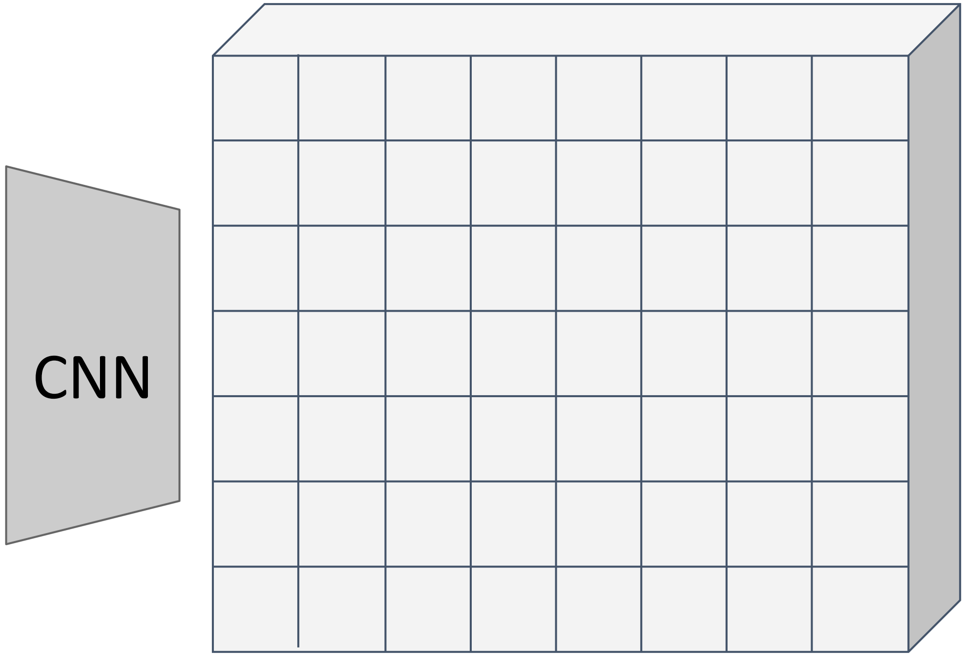
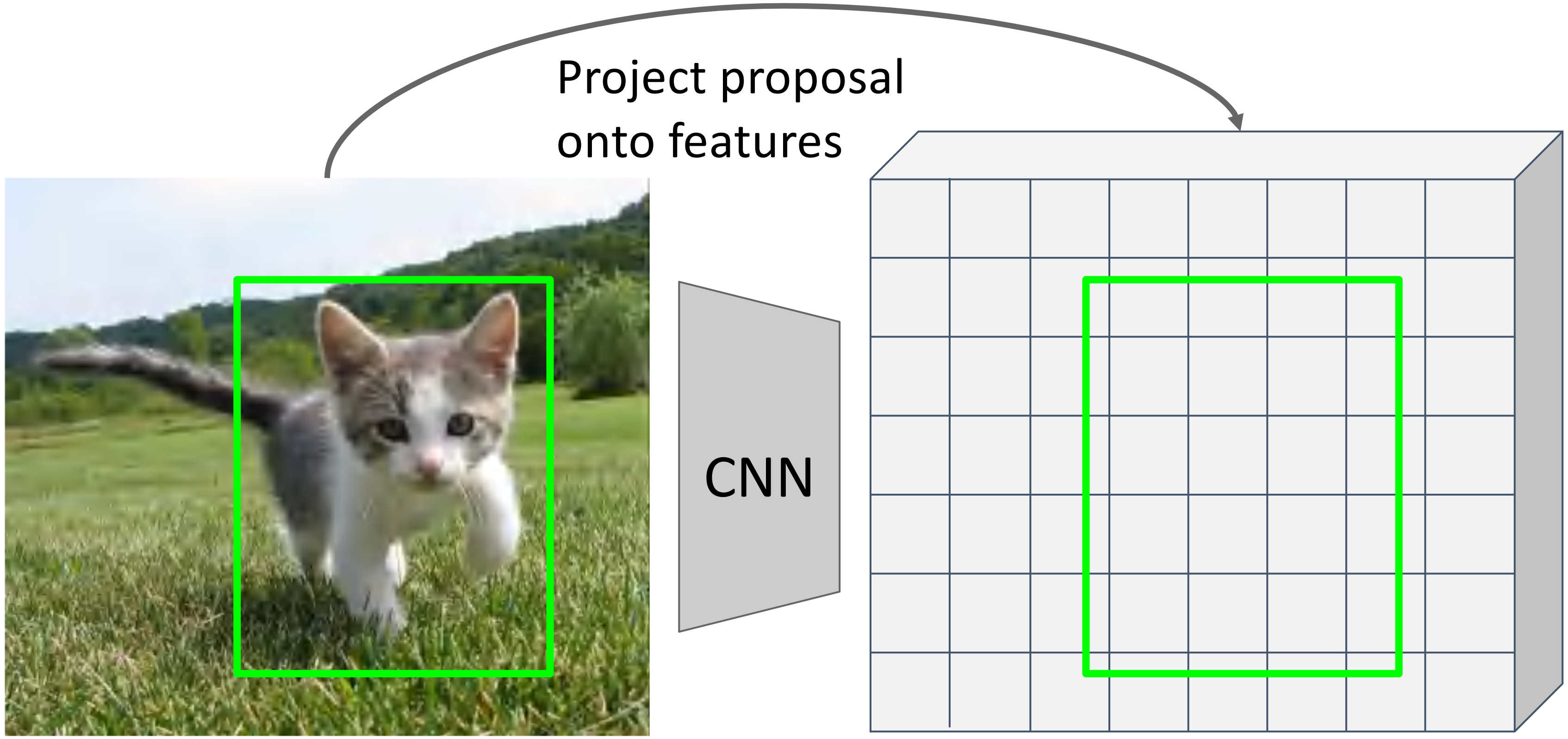


Image features
(e.g. 512 x 20 x 15)

Want features for the box of a fixed size (2x2 in this example, 7x7 or 14x14 in practice)

Girshick, "Fast R-CNN", ICCV 2015.

Cropping Features: RoI Pool



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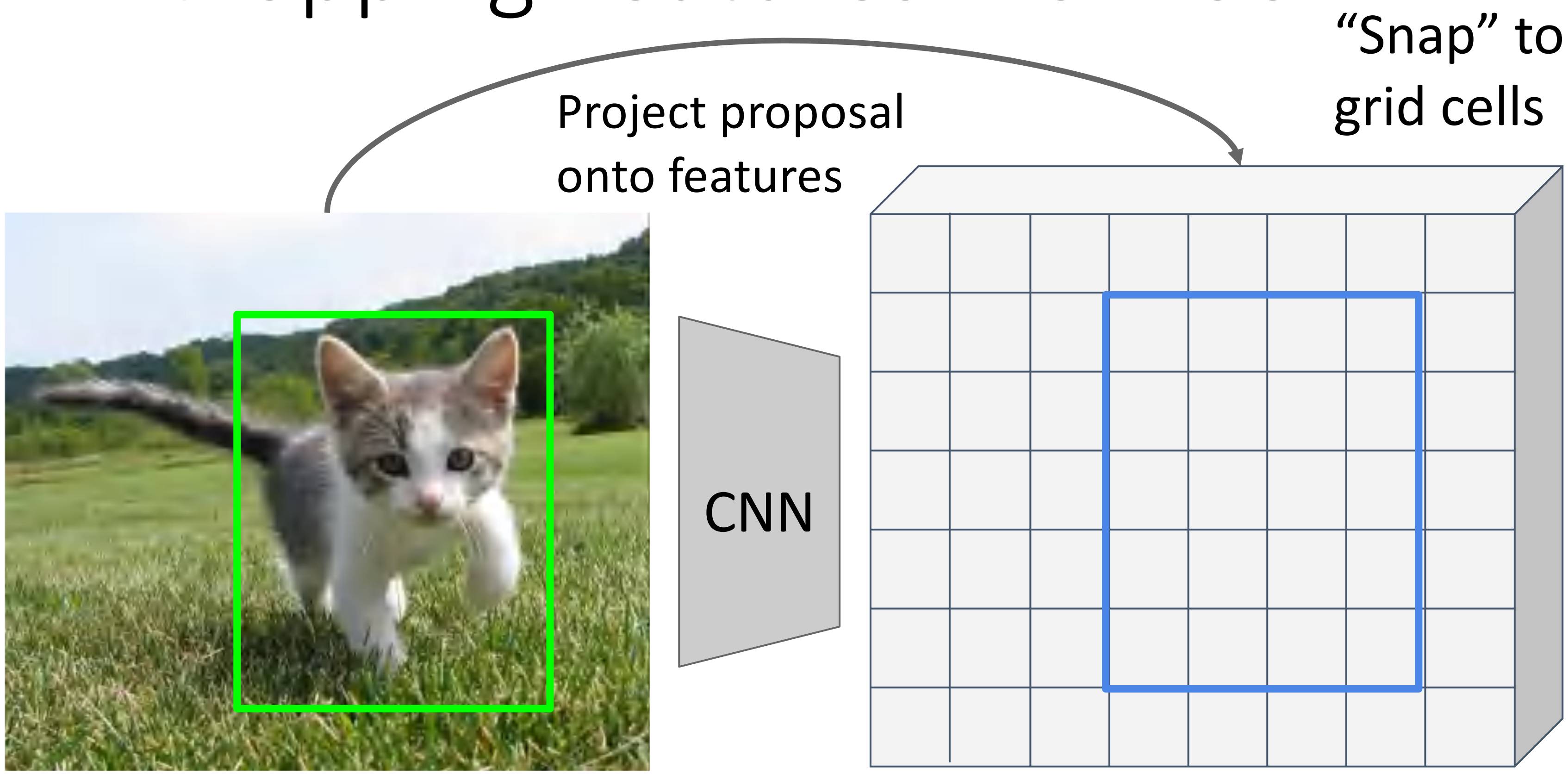

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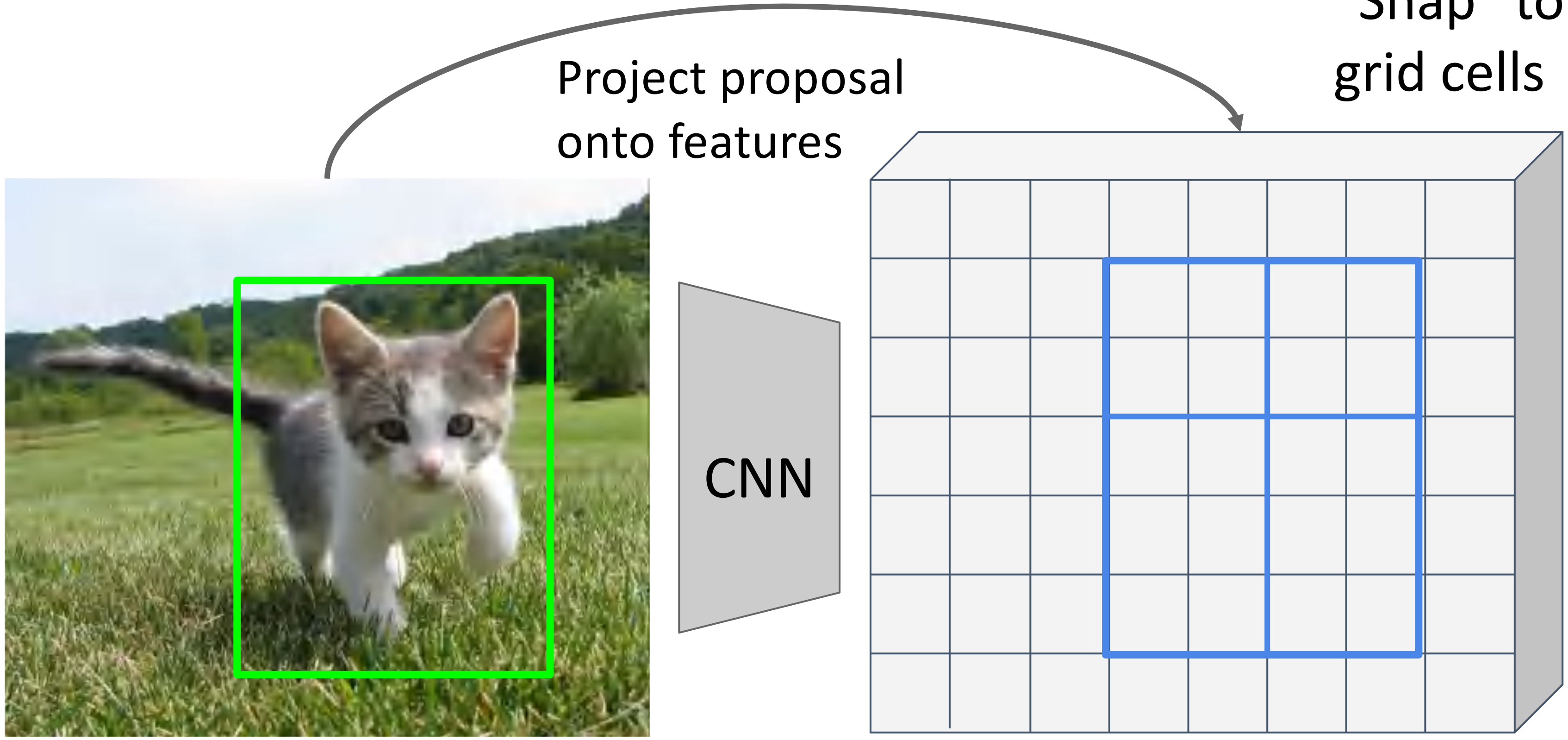
Girshick, "Fast R-CNN", ICCV 2015.

Cropping Features: RoI Pool



"Snap" to grid cells

Divide into 2x2 grid of (roughly) equal subregions

Input Image
(e.g. 3 x 640 x 480)

Image features
(e.g. 512 x 20 x 15)

Want features for the box of a fixed size (2x2 in this example, 7x7 or 14x14 in practice)

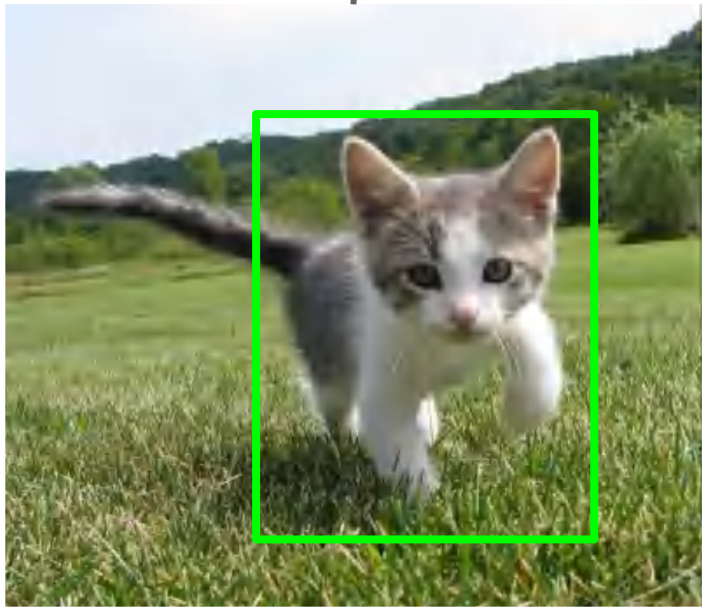
Girshick, "Fast R-CNN", ICCV 2015.

Cropping Features: RoI Pool

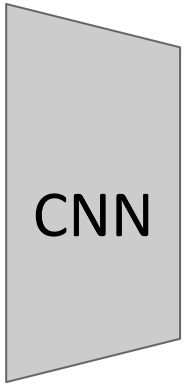
Project proposal onto features

"Snap" to grid cells

Divide into 2x2 grid of (roughly) equal subregions



Input Image
(e.g. 3 x 640 x 480)



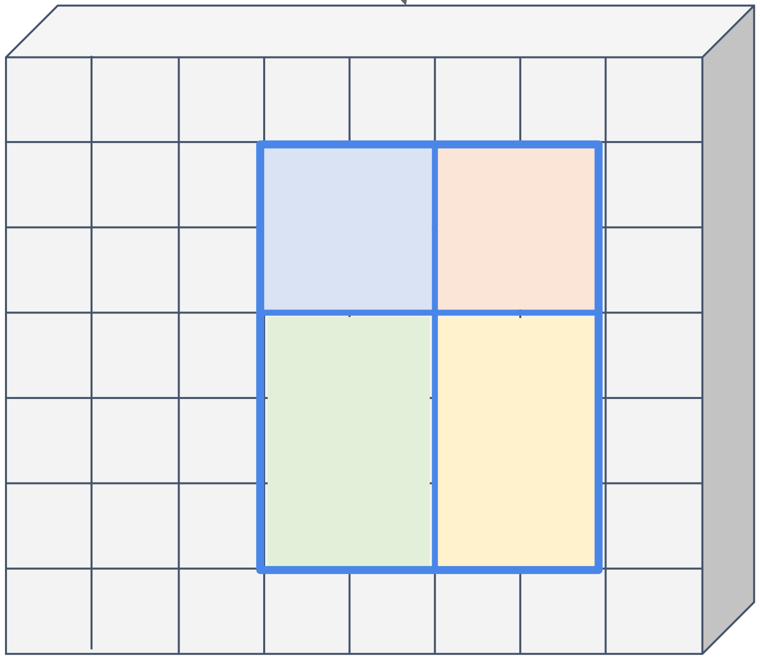
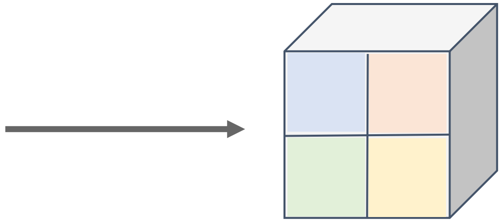


Image features
(e.g. 512 x 20 x 15)

Max-pool within each subregion

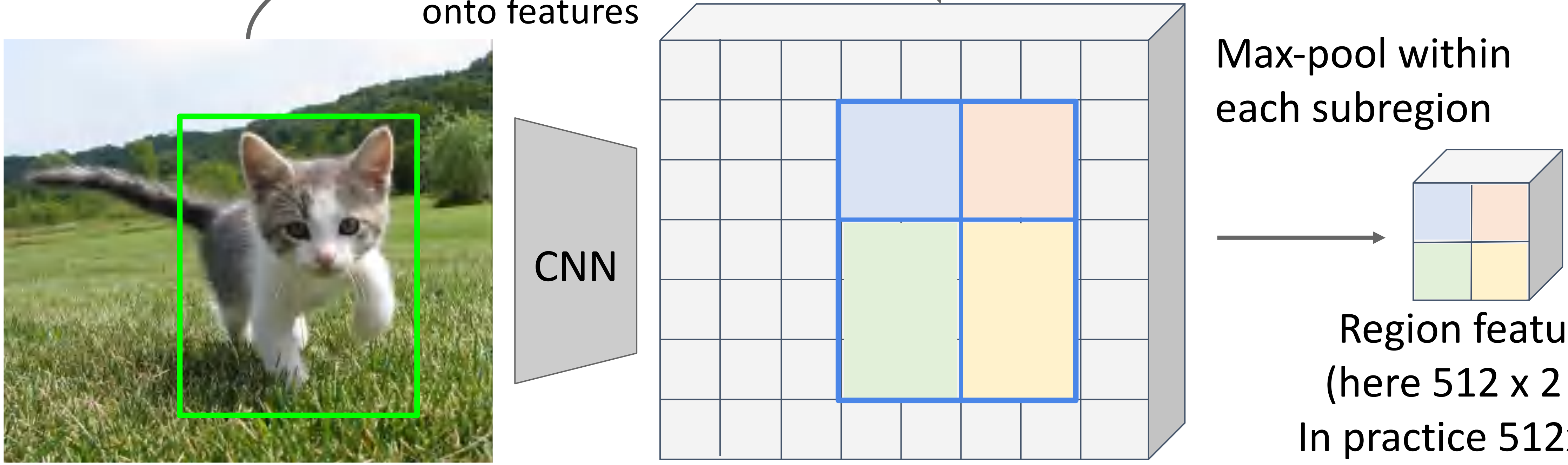


Region features
(here 512 x 2 x 2;
In practice 512x7x7)

Region features always the same size even if input regions have different sizes!

Girshick, "Fast R-CNN", ICCV 2015.

Cropping Features: RoI Pool



Project proposal onto features

"Snap" to grid cells

Divide into 2x2 grid of (roughly) equal subregions

Max-pool within each subregion

Input Image
(e.g. 3 x 640 x 480)

Image features
(e.g. 512 x 20 x 15)

Region features
(here 512 x 2 x 2;
In practice 512x7x7)

Region features always the same size even if input regions have different sizes!

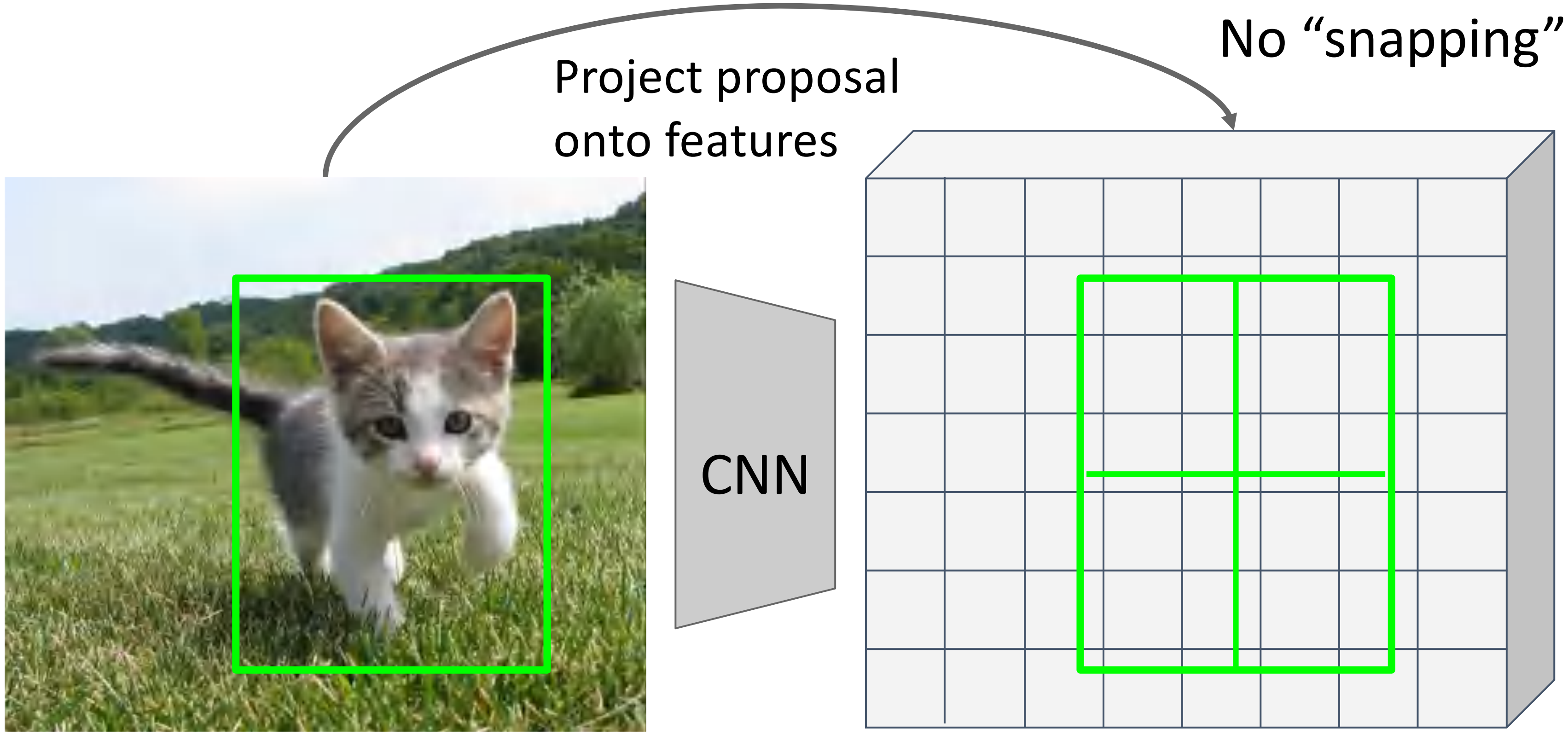
Problem: Slight misalignment due to snapping; different-sized subregions is weird

Girshick, "Fast R-CNN", ICCV 2015.

Cropping Features: RoI Align

Divide into equal-sized subregions
(may not be aligned to grid!)

No “snapping”!



Input Image
(e.g. 3 x 640 x 480)

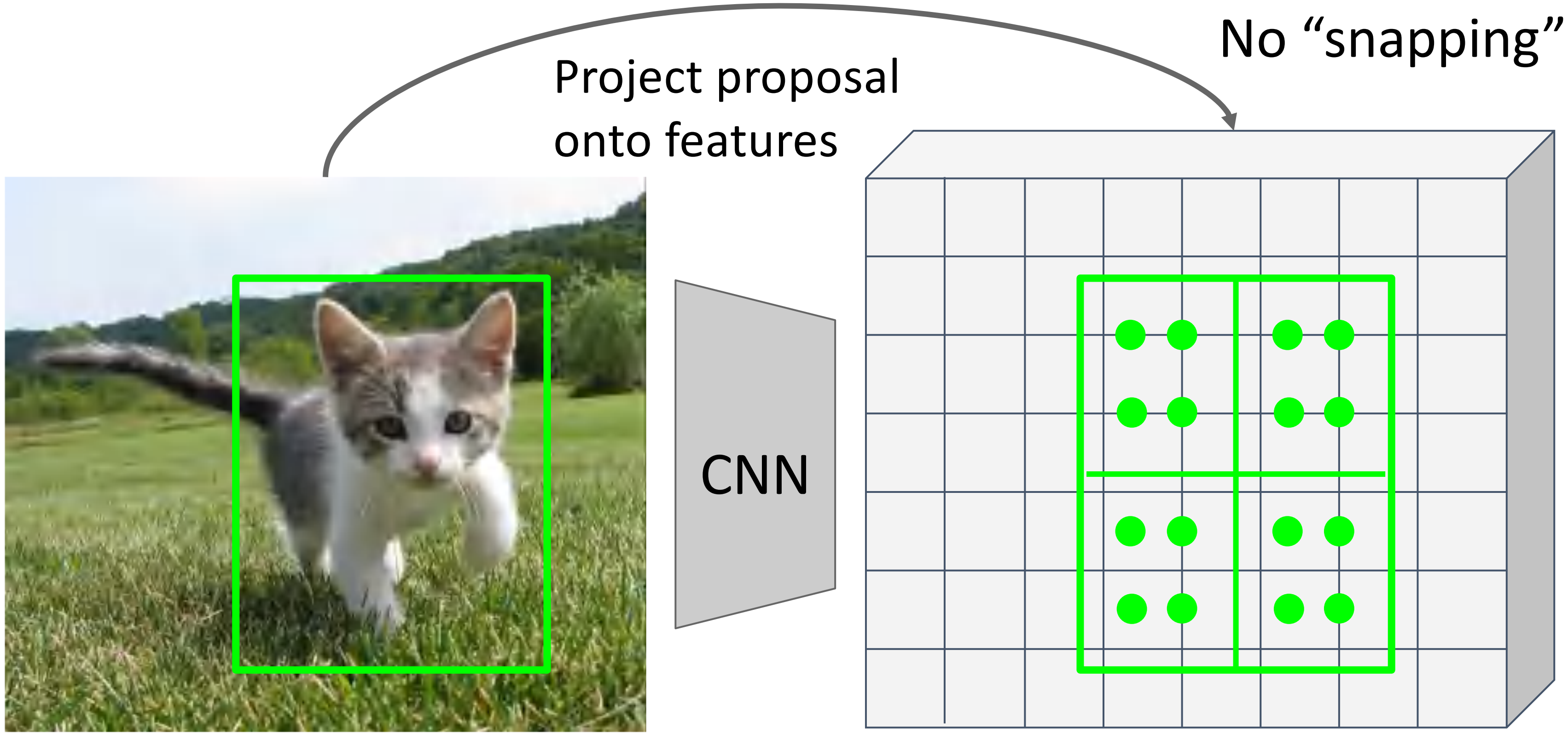
Image features
(e.g. 512 x 20 x 15)

Want features for the
box of a fixed size
(2x2 in this example,
7x7 or 14x14 in practice)

He et al, “Mask R-CNN”, ICCV 2017.

Cropping Features: RoI Align

Divide into equal-sized subregions (may not be aligned to grid!)



Input Image (e.g. 3 x 640 x 480)

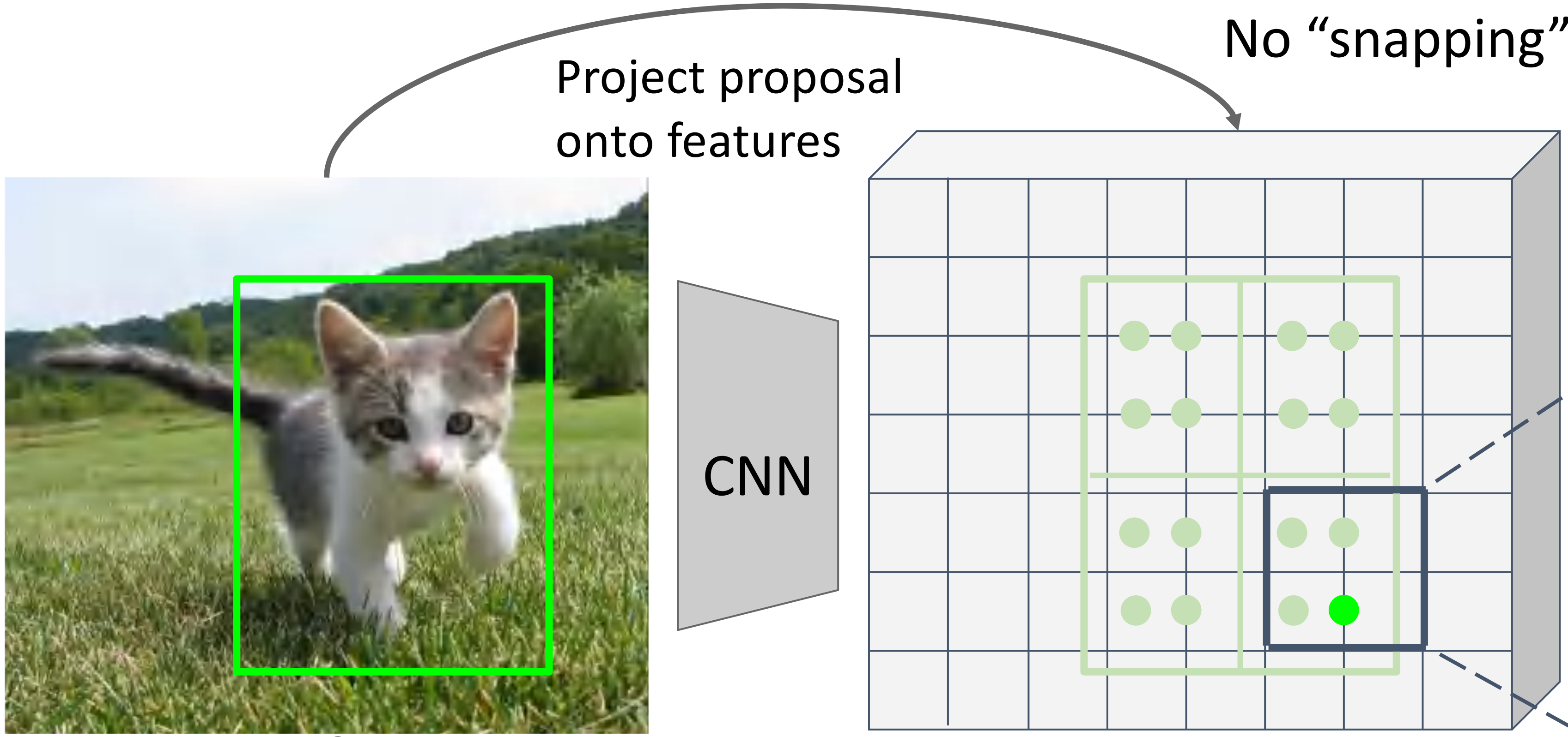
Image features (e.g. 512 x 20 x 15)

Sample features at regularly-spaced points in each subregion using **bilinear interpolation**

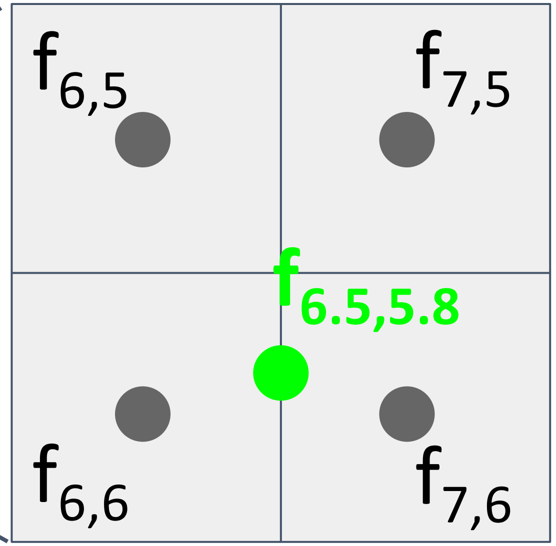
He et al, "Mask R-CNN", ICCV 2017

Cropping Features: RoI Align

Divide into equal-sized subregions (may not be aligned to grid!)



Sample features at regularly-spaced points in each subregion using **bilinear interpolation**



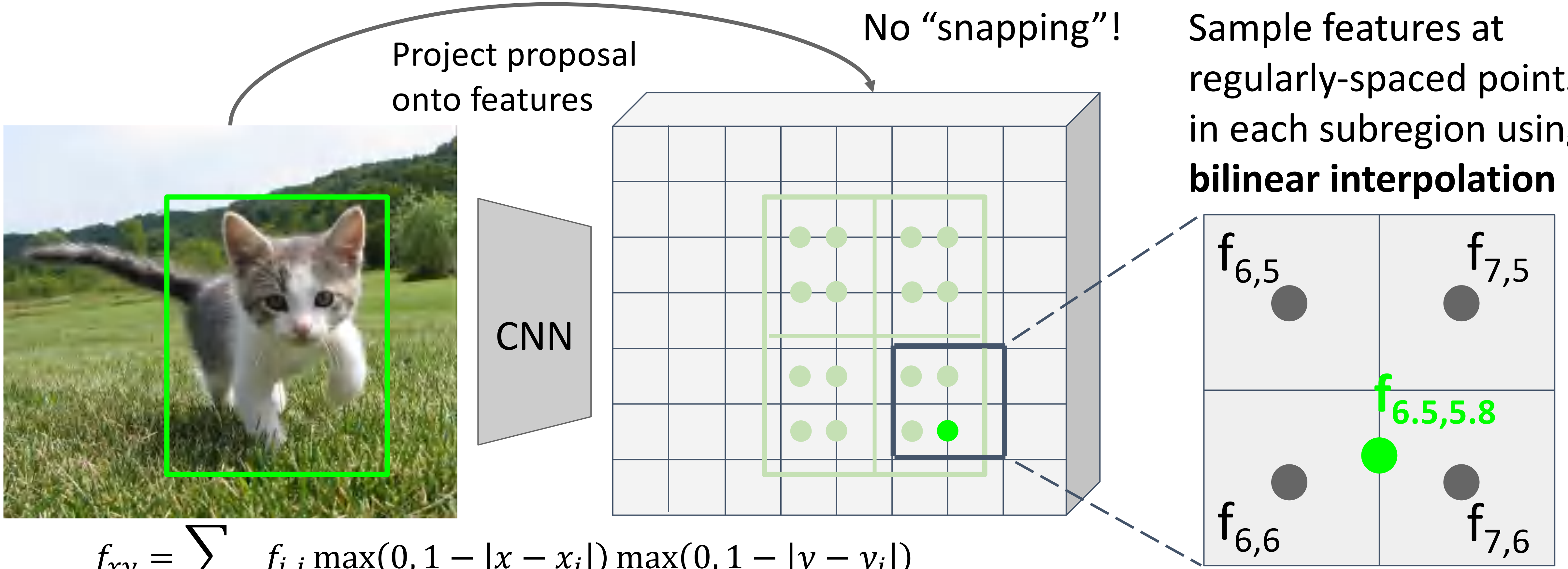
$$f_{xy} = \sum_{i,j=1}^{2} f_{i,j} \max(0, 1 - |x - x_i|) \max(0, 1 - |y - y_j|)$$

Feature f_{xy} for point (x, y) is a linear combination of features at its four neighboring grid cells:

Cropping Features: RoI Align

Divide into equal-sized subregions (may not be aligned to grid!)

Sample features at regularly-spaced points in each subregion using **bilinear interpolation**

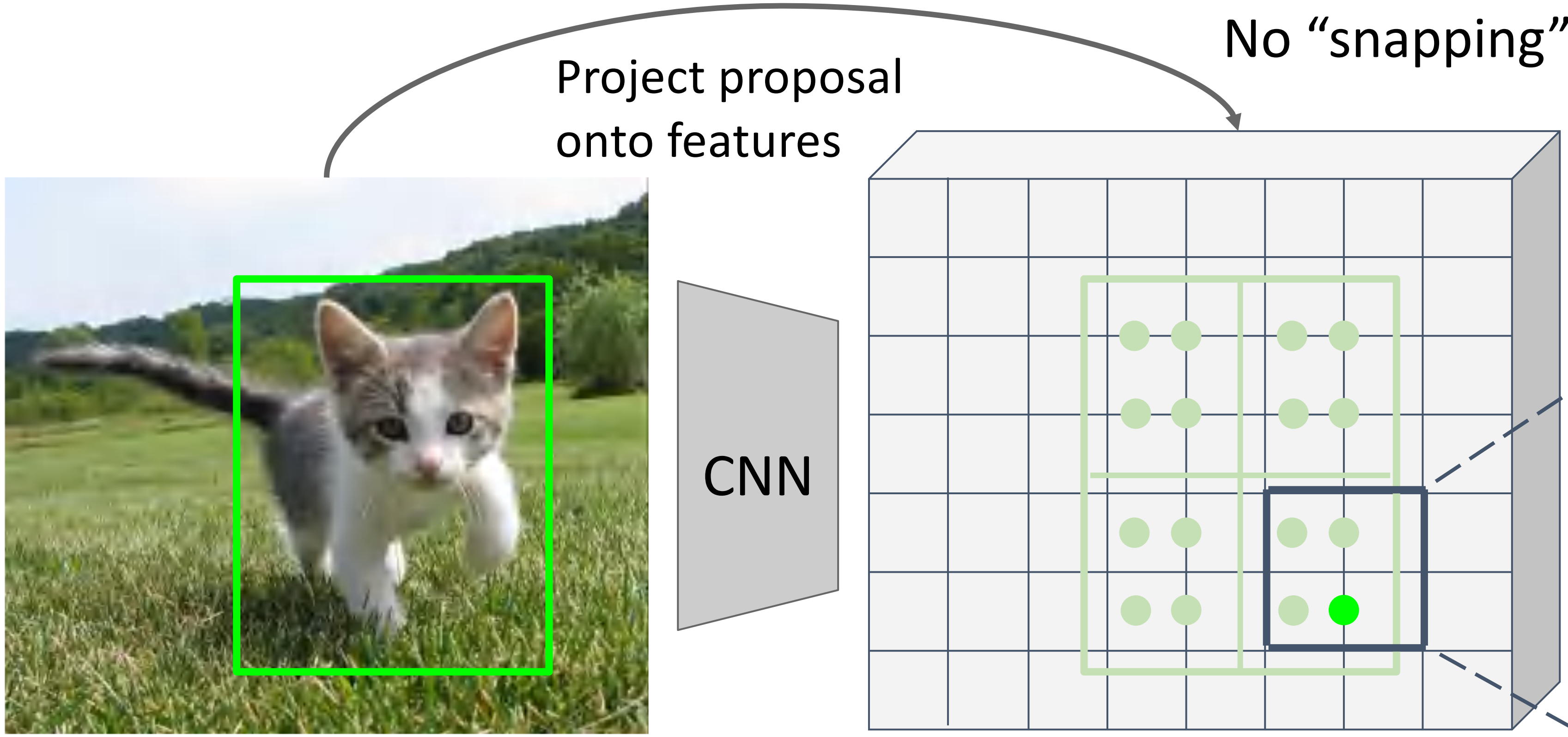


$$f_{xy} = \sum_{i,j} f_{i,j} \max(0, 1 - |x - x_i|) \max(0, 1 - |y - y_i|)$$

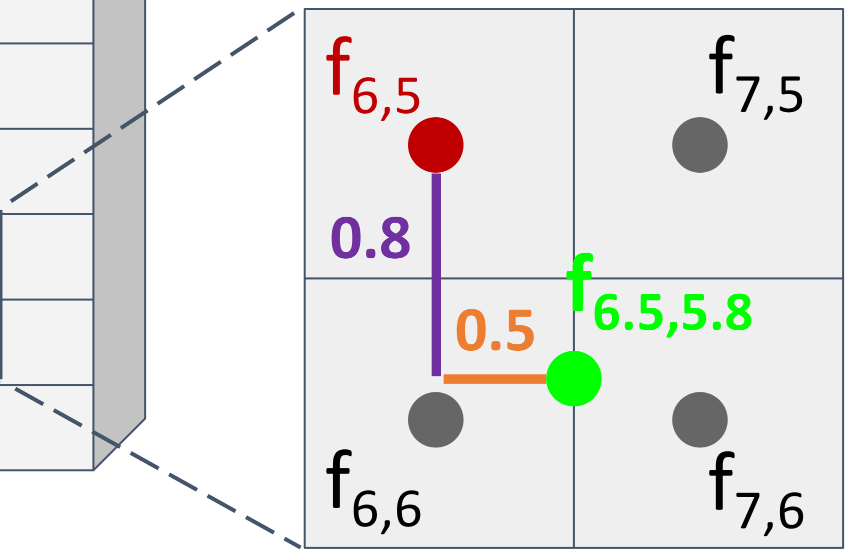
$$f_{6.5,5.8} = (f_{6,5} * 0.5 * 0.2) + (f_{7,5} * 0.5 * 0.2) + (f_{6,6} * 0.5 * 0.8) + (f_{7,6} * 0.5 * 0.8)$$

Feature f_{xy} for point (x, y) is a linear combination of features at its four neighboring grid cells:

Cropping Features: RoI Align



Sample features at regularly-spaced points in each subregion using **bilinear interpolation**

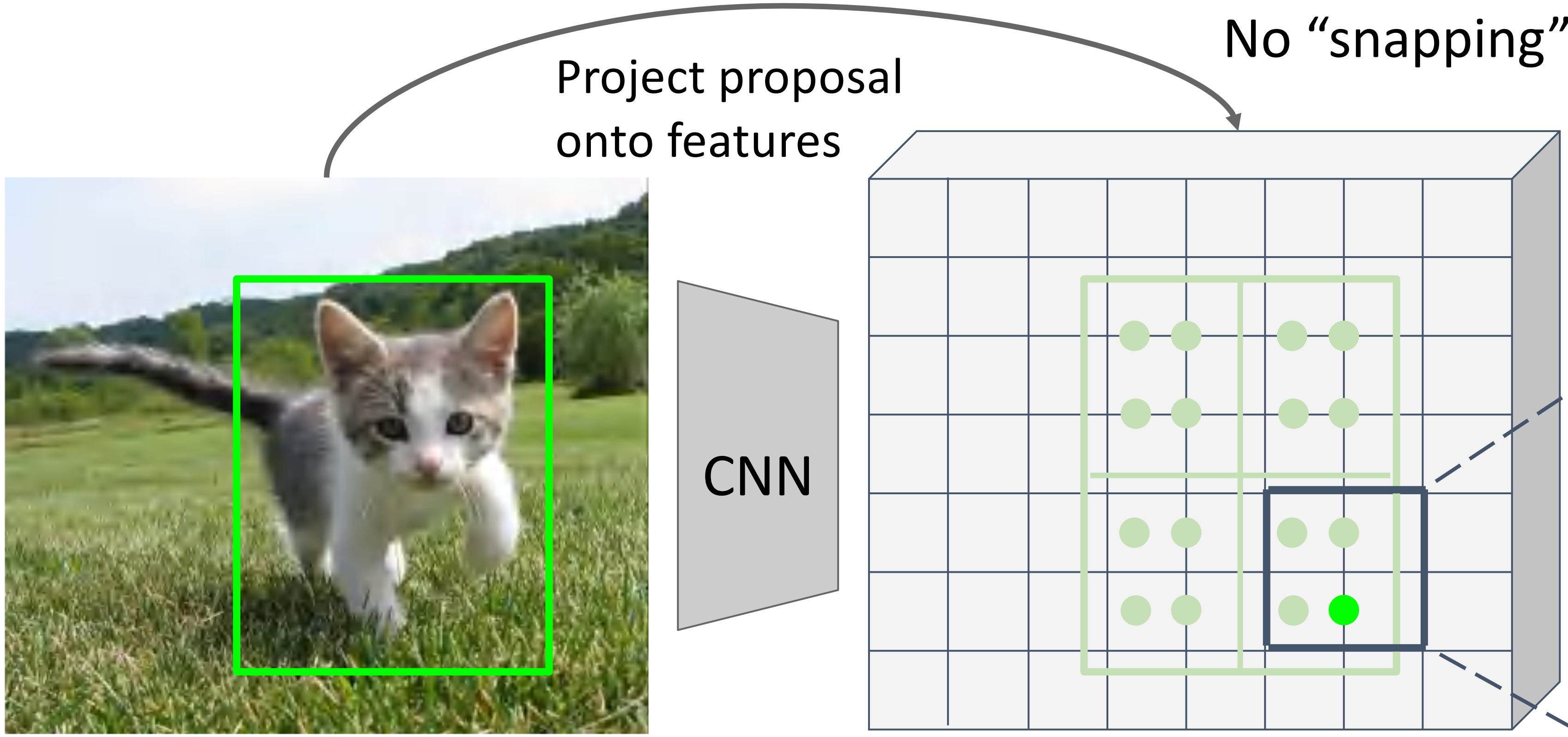


$$f_{xy} = \sum_{i,j} f_{i,j} \max(0, 1 - |x - x_i|) \max(0, 1 - |y - y_i|)$$

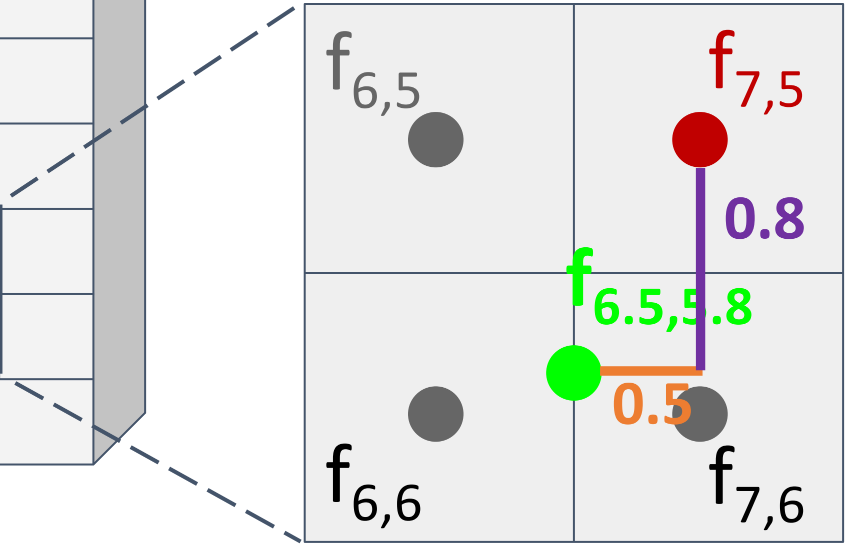
$$f_{6.5,5.8} = (f_{6,5} * \mathbf{0.5} * \mathbf{0.2}) + (f_{7,5} * 0.5 * 0.2)$$
$$+ (f_{6,6} * 0.5 * 0.8) + (f_{7,6} * 0.5 * 0.8)$$

Feature f_{xy} for point (x, y) is a linear combination of features at its four neighboring grid cells:

Cropping Features: RoI Align



Sample features at regularly-spaced points in each subregion using **bilinear interpolation**

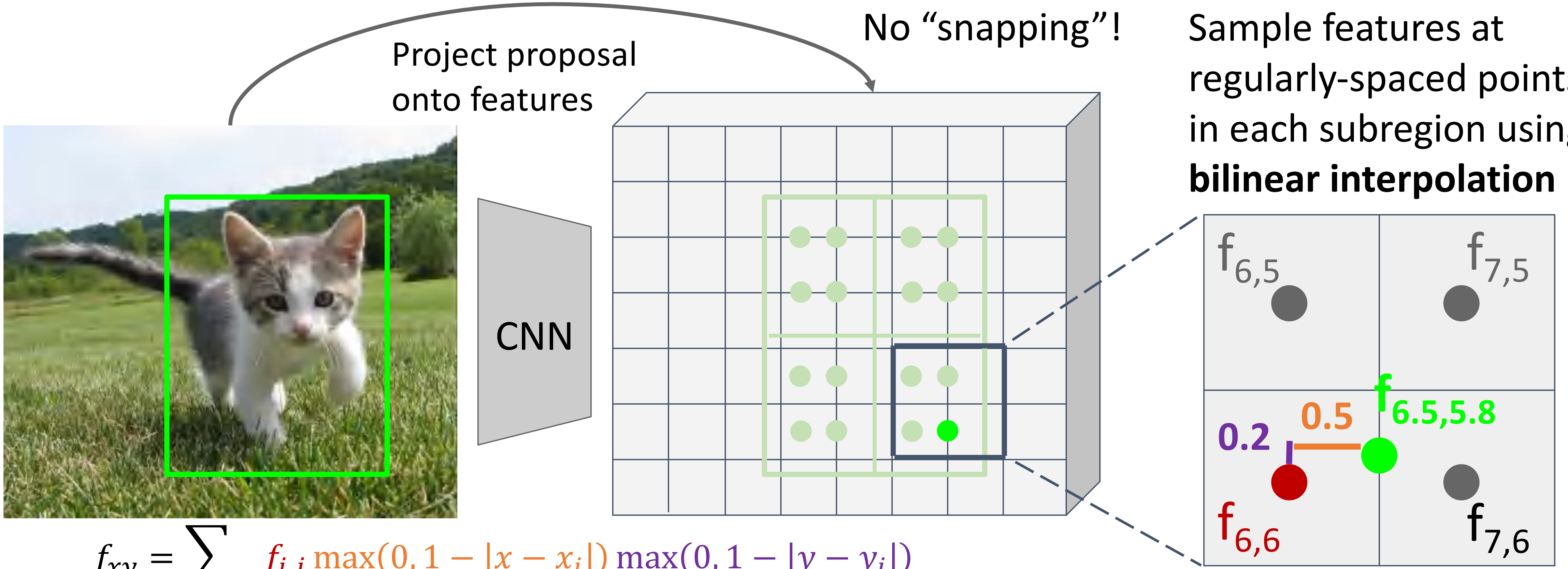


$$f_{xy} = \sum_{i,j} f_{i,j} \max(0, 1 - |x - x_i|) \max(0, 1 - |y - y_i|)$$

$$f_{6.5,5.8} = (f_{6,5} * 0.5 * 0.2) + (f_{7,5} * \mathbf{0.5} * \mathbf{0.2}) + (f_{6,6} * 0.5 * 0.8) + (f_{7,6} * 0.5 * 0.8)$$

Feature f_{xy} for point (x, y) is a linear combination of features at its four neighboring grid cells:

Cropping Features: RoI Align



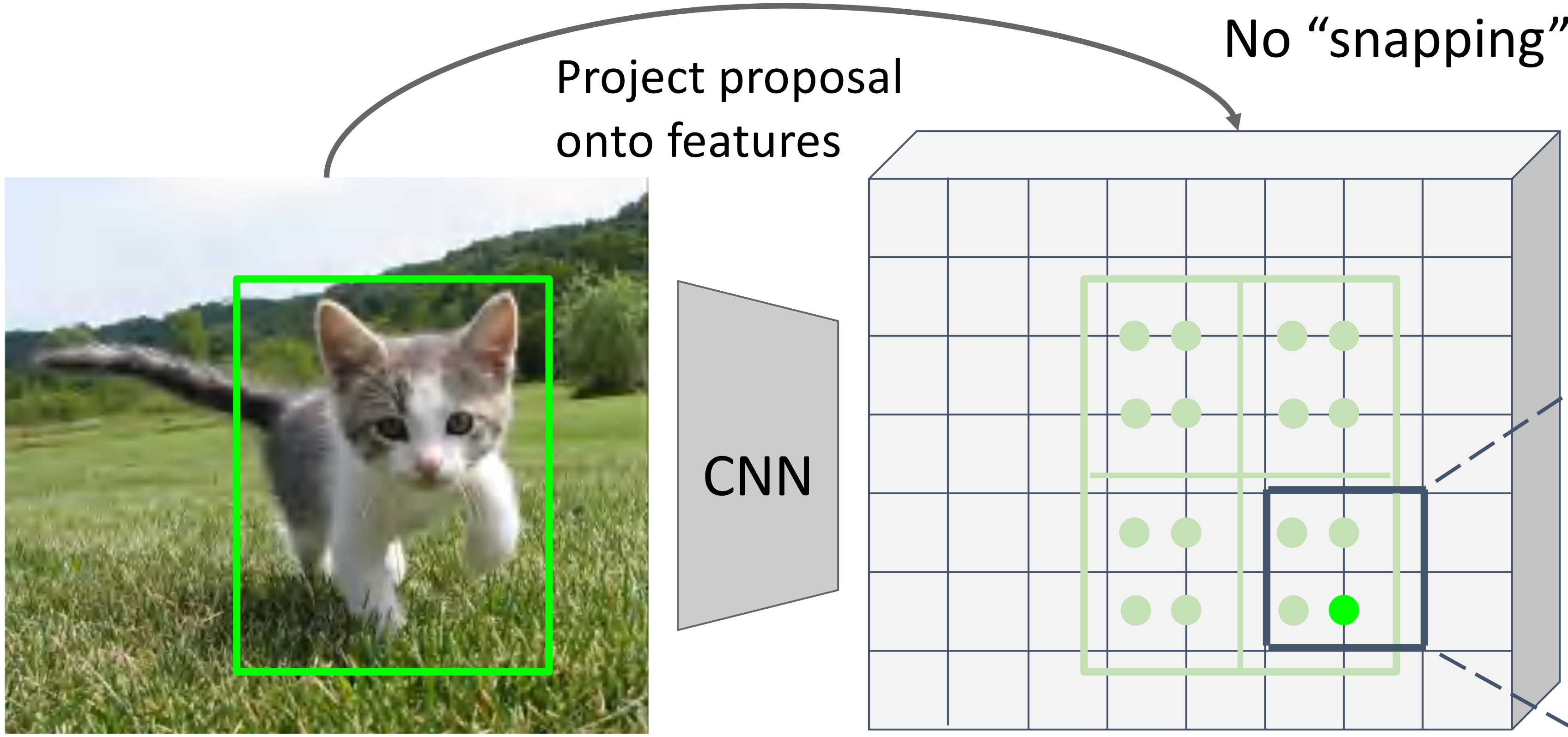
Sample features at regularly-spaced points in each subregion using **bilinear interpolation**

Feature f_{xy} for point (x, y) is a linear combination of features at its four neighboring grid cells:

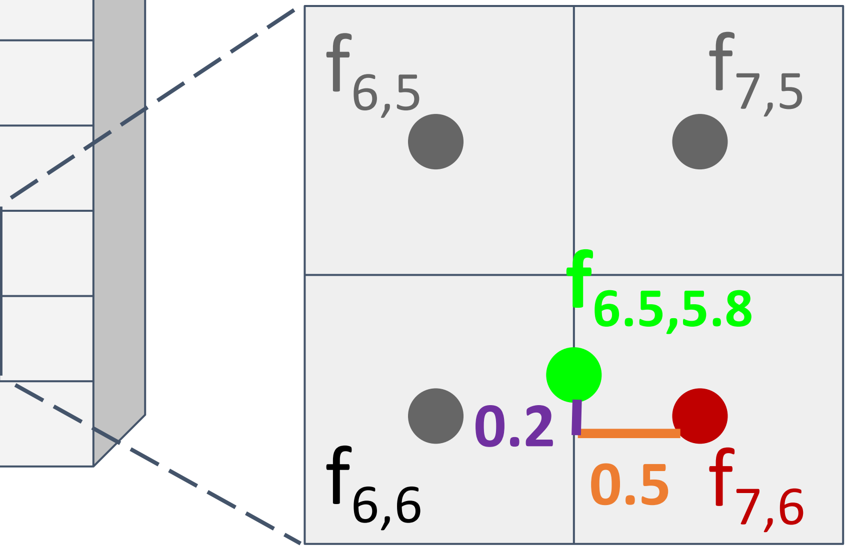
$$f_{xy} = \sum_{i,j} f_{i,j} \max(0, 1 - |x - x_i|) \max(0, 1 - |y - y_i|)$$

$$f_{6.5,5.8} = (f_{6,5} * 0.5 * 0.2) + (f_{7,5} * 0.5 * 0.2) + (f_{6,6} * \mathbf{0.5} * \mathbf{0.8}) + (f_{7,6} * 0.5 * 0.8)$$

Cropping Features: RoI Align



Sample features at regularly-spaced points in each subregion using **bilinear interpolation**

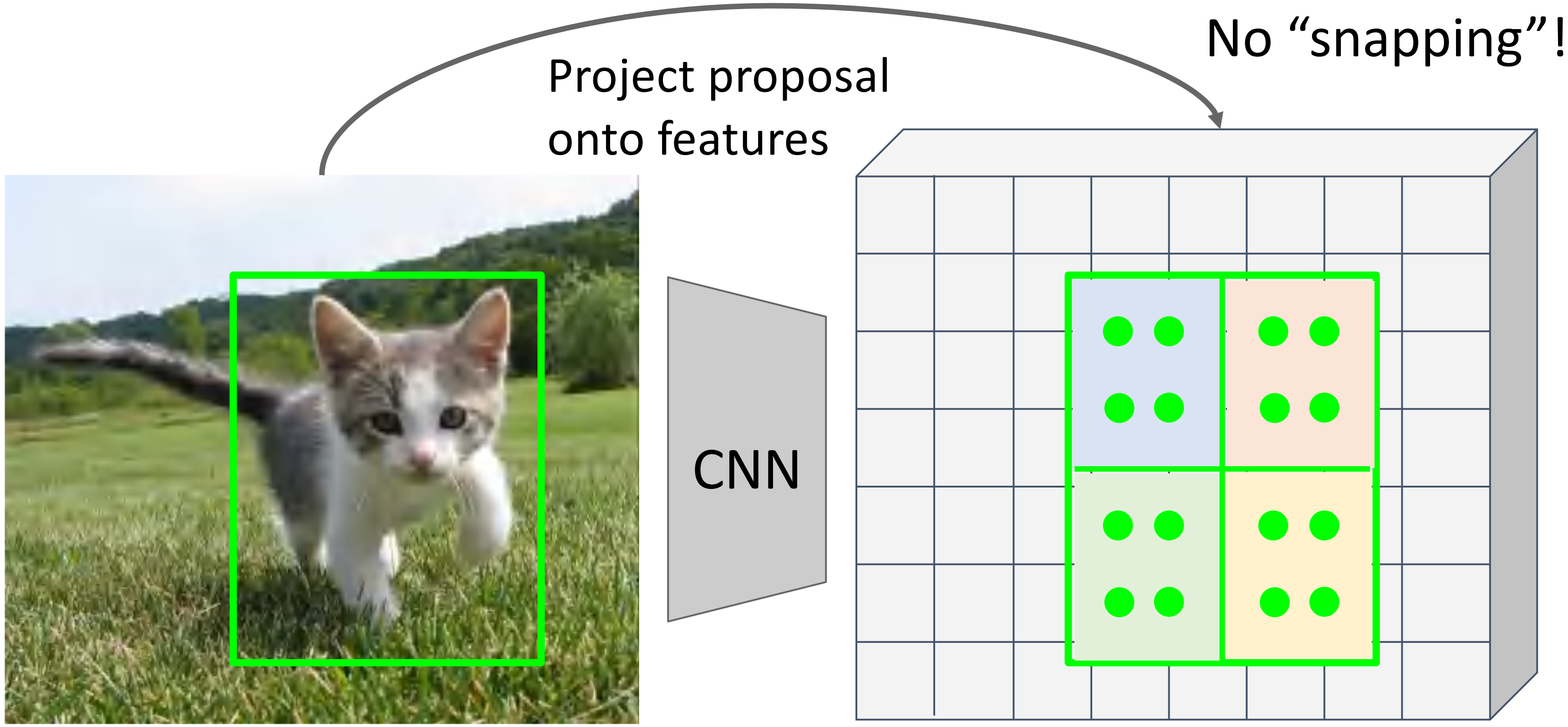


$$f_{xy} = \sum_{i,j} f_{i,j} \max(0, 1 - |x - x_i|) \max(0, 1 - |y - y_i|)$$

$$f_{6.5,5.8} = (f_{6,5} * 0.5 * 0.2) + (f_{7,5} * 0.5 * 0.2) + (f_{6,6} * 0.5 * 0.8) + (f_{7,6} * 0.5 * 0.8)$$

Feature f_{xy} for point (x, y) is a linear combination of features at its four neighboring grid cells:

Cropping Features: RoI Align

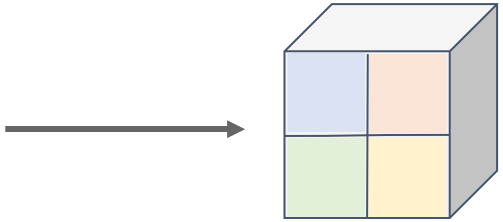


Input Image
(e.g. 3 x 640 x 480)

Image features
(e.g. 512 x 20 x 15)

Sample features at regularly-spaced points in each subregion using **bilinear interpolation**

After sampling, max-pool in each subregion

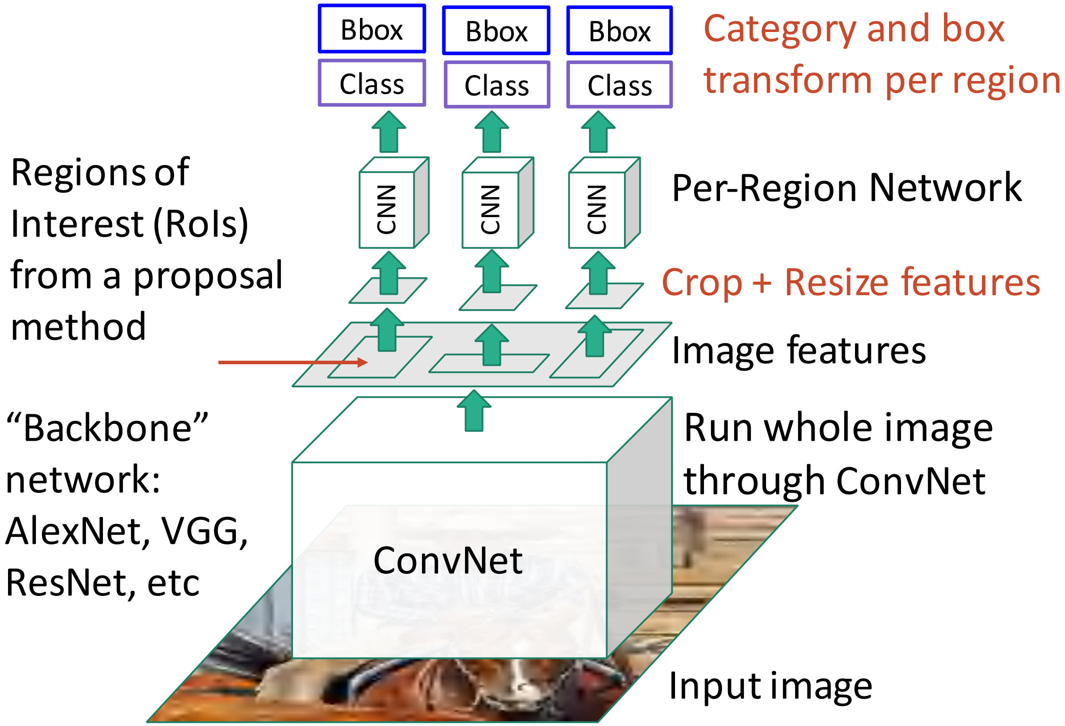


Region features
(here 512 x 2 x 2;
In practice e.g 512 x 7 x 7)

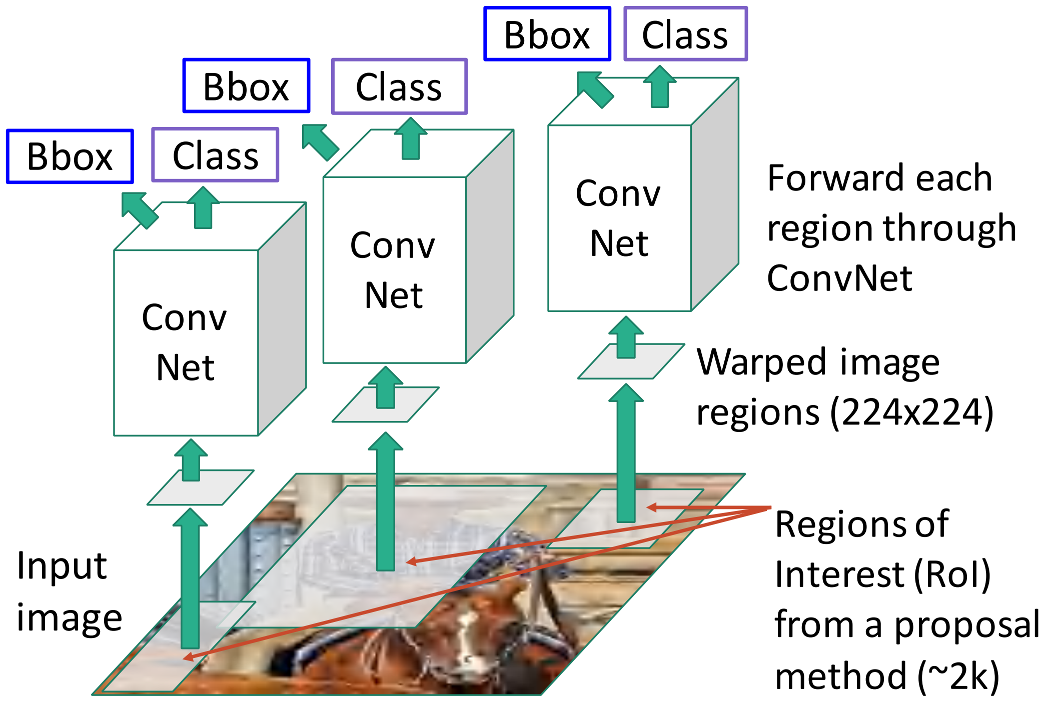
He et al, "Mask R-CNN", ICCV 2017

Fast R-CNN vs “Slow” R-CNN

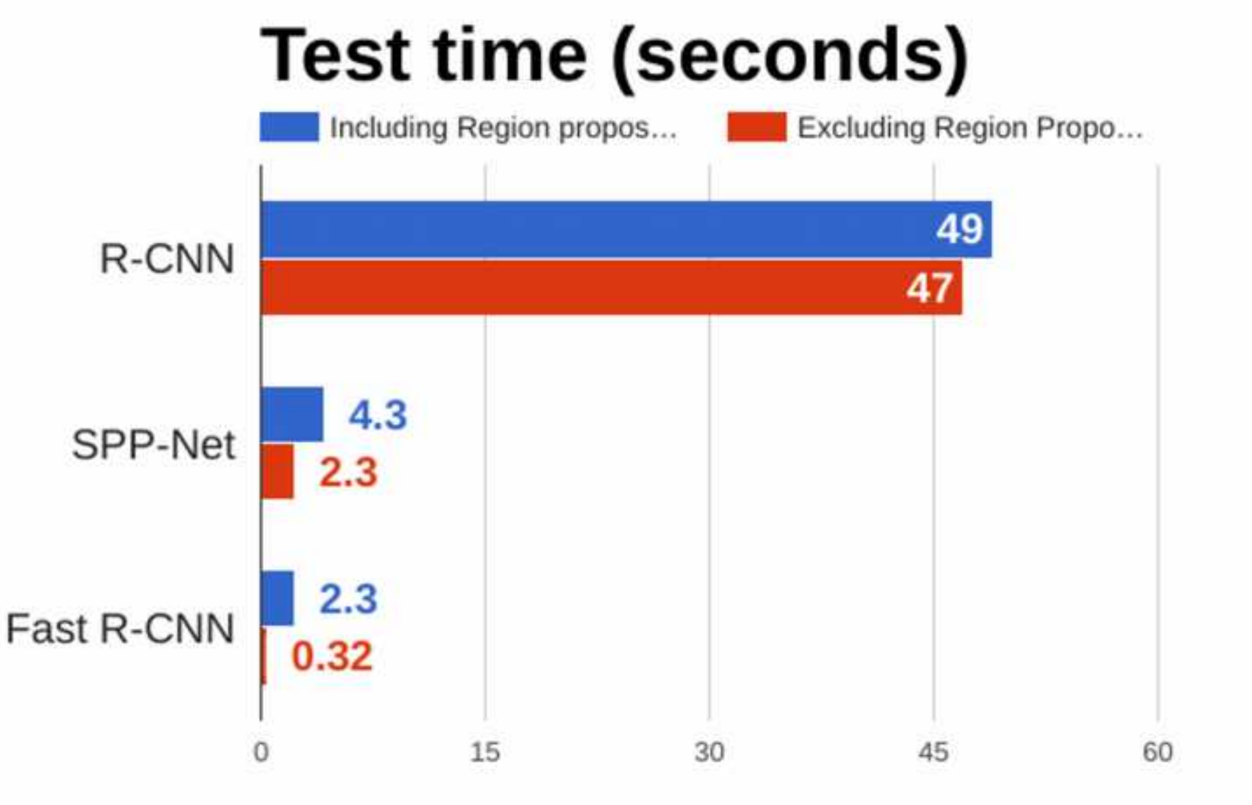
Fast R-CNN: Apply differentiable cropping to shared image features



“Slow” R-CNN: Apply differentiable cropping to shared image features

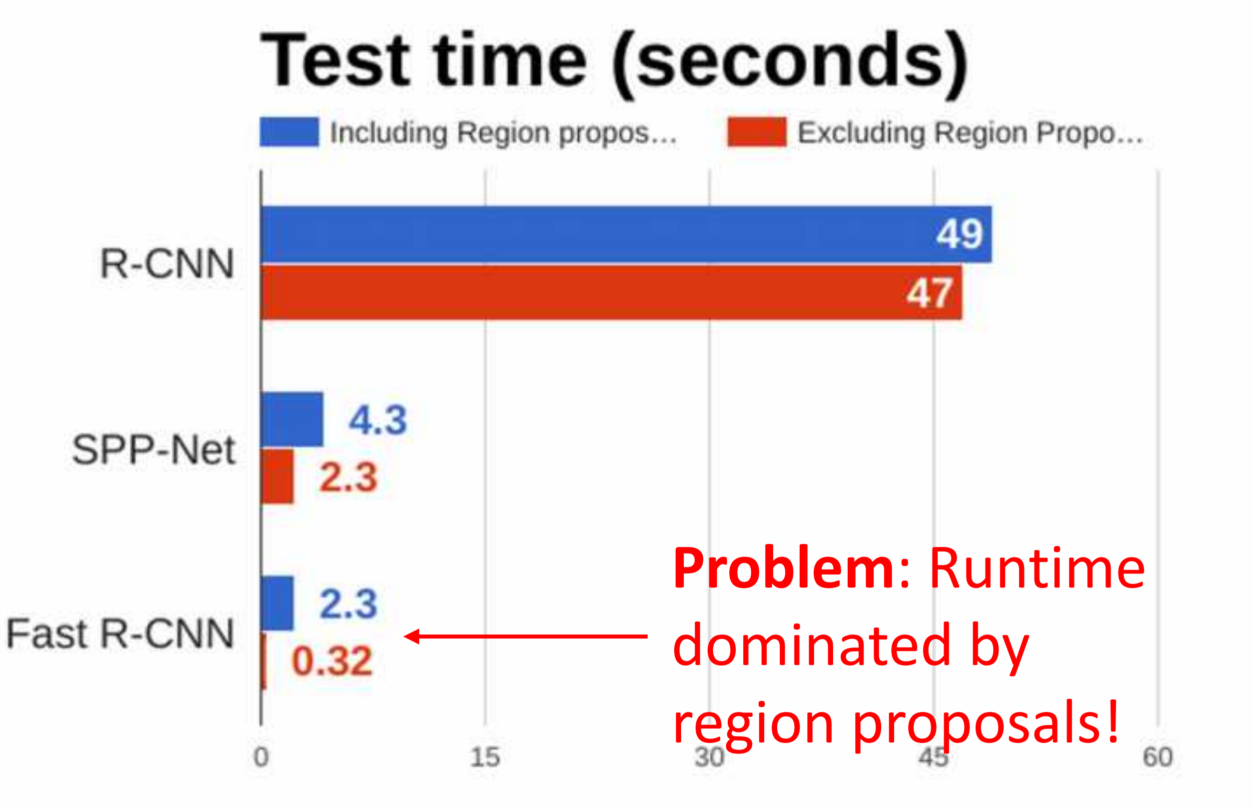


Fast R-CNN vs “Slow” R-CNN



Girshick et al, “Rich feature hierarchies for accurate object detection and semantic segmentation”, CVPR 2014.
He et al, “Spatial pyramid pooling in deep convolutional networks for visual recognition”, ECCV 2014
Girshick, “Fast R-CNN”, ICCV 2015

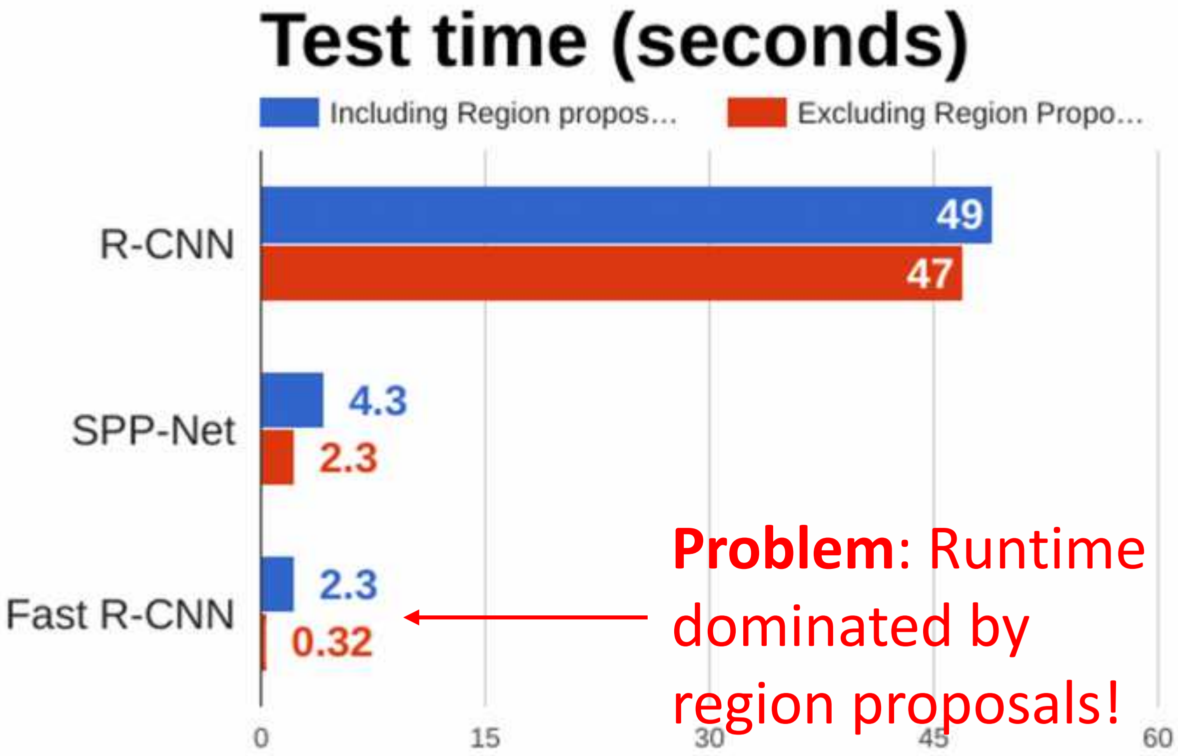
Fast R-CNN vs “Slow” R-CNN



Problem: Runtime dominated by region proposals!

Girshick et al, “Rich feature hierarchies for accurate object detection and semantic segmentation”, CVPR 2014.
He et al, “Spatial pyramid pooling in deep convolutional networks for visual recognition”, ECCV 2014
Girshick, “Fast R-CNN”, ICCV 2015

Fast R-CNN vs "Slow" R-CNN



Problem: Runtime dominated by region proposals!

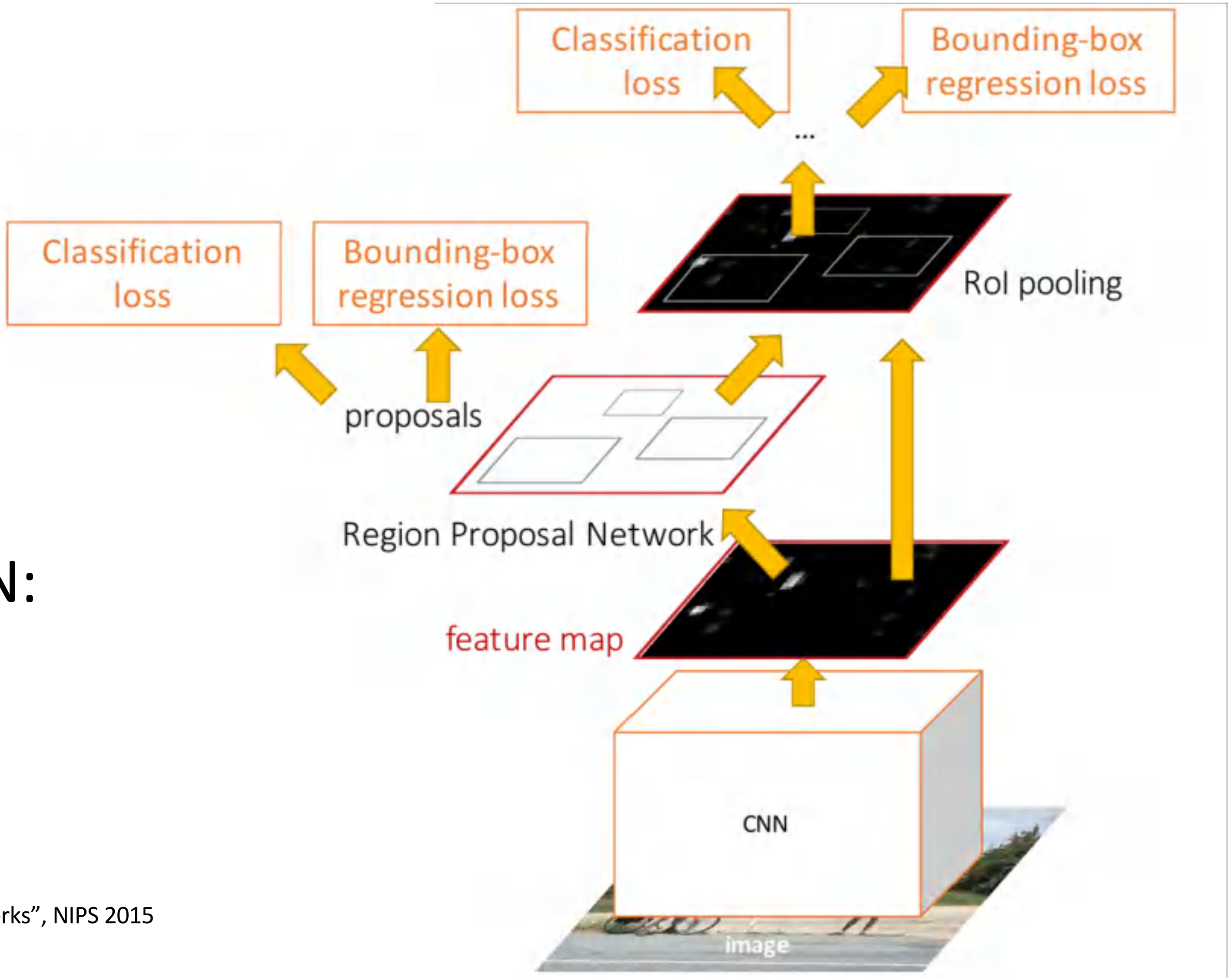
Recall: Region proposals computed by heuristic "Selective Search" algorithm on CPU -- let's learn them with a CNN instead!

Girshick et al, "Rich feature hierarchies for accurate object detection and semantic segmentation", CVPR 2014.
He et al, "Spatial pyramid pooling in deep convolutional networks for visual recognition", ECCV 2014
Girshick, "Fast R-CNN", ICCV 2015

Fast<u>er</u> R-CNN: Learnable Region Proposals

Insert **Region Proposal Network (RPN)** to predict proposals from features

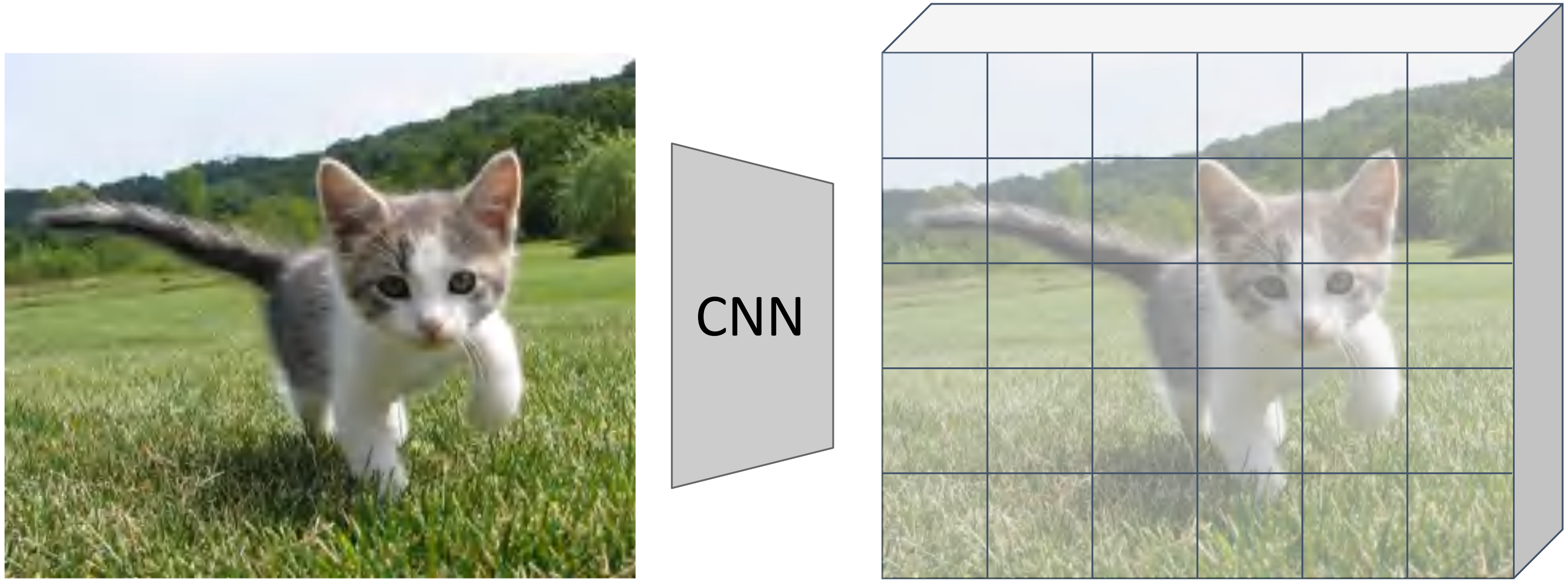
Otherwise same as Fast R-CNN: Crop features for each proposal, classify each one



Ren et al, "Faster R-CNN: Towards Real-Time Object Detection with Region Proposal Networks", NIPS 2015

Region Proposal Network (RPN)

Run backbone CNN to get features aligned to input image



Input Image
(e.g. 3 x 640 x 480)

Image features
(e.g. 512 x 5 x 6)

Ren et al, “Faster R-CNN: Towards Real-Time Object Detection with Region Proposal Networks”, NIPS 2015

Region Proposal Network (RPN)

Run backbone CNN to get features aligned to input image

Each feature corresponds to a point in the input

Input Image
(e.g. 3 x 640 x 480)

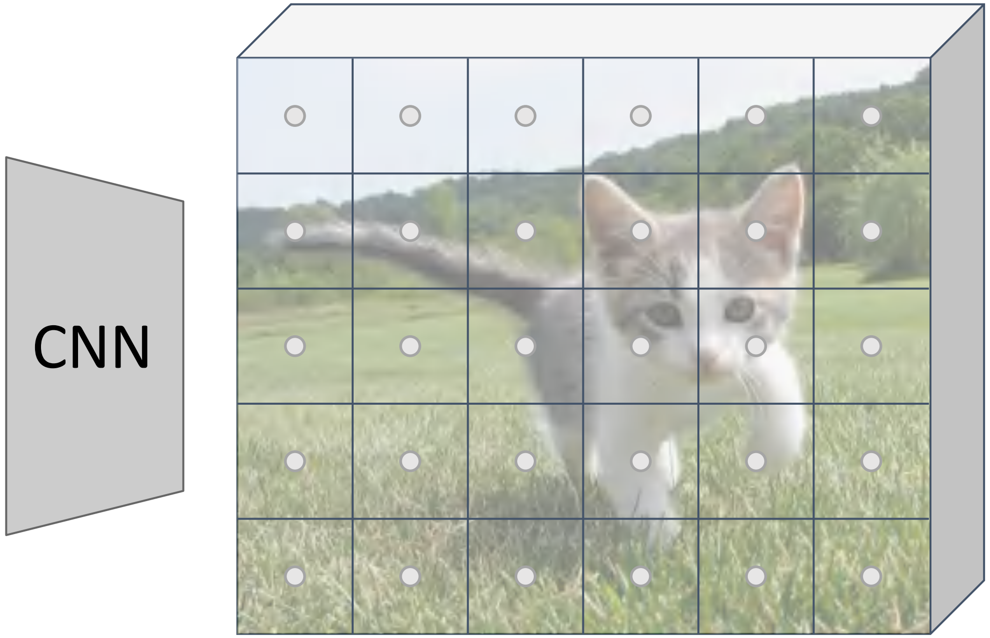


Image features
(e.g. 512 x 5 x 6)

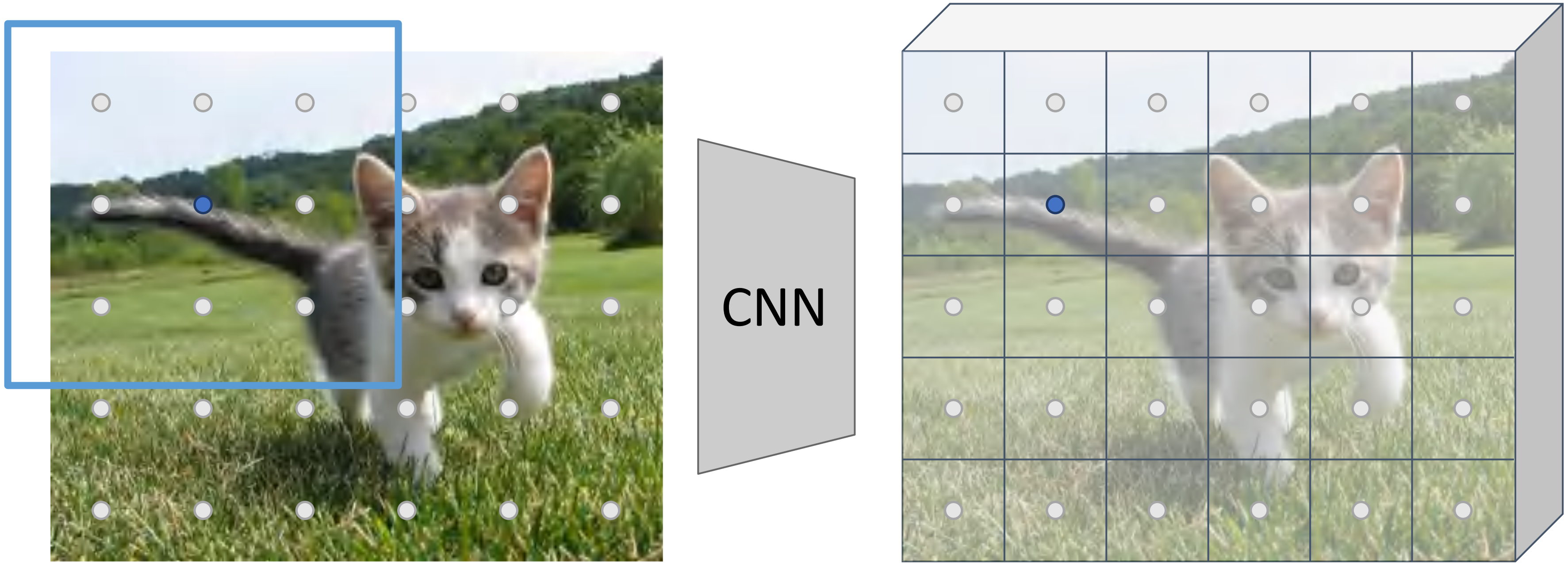
Ren et al, "Faster R-CNN: Towards Real-Time Object Detection with Region Proposal Networks", NIPS 2015

Region Proposal Network (RPN)

Imagine an **anchor box** of fixed size at each point in the feature map

Run backbone CNN to get features aligned to input image

Each feature corresponds to a point in the input



Input Image
(e.g. 3 x 640 x 480)

Image features
(e.g. 512 x 5 x 6)

Ren et al, “Faster R-CNN: Towards Real-Time Object Detection with Region Proposal Networks”, NIPS 2015

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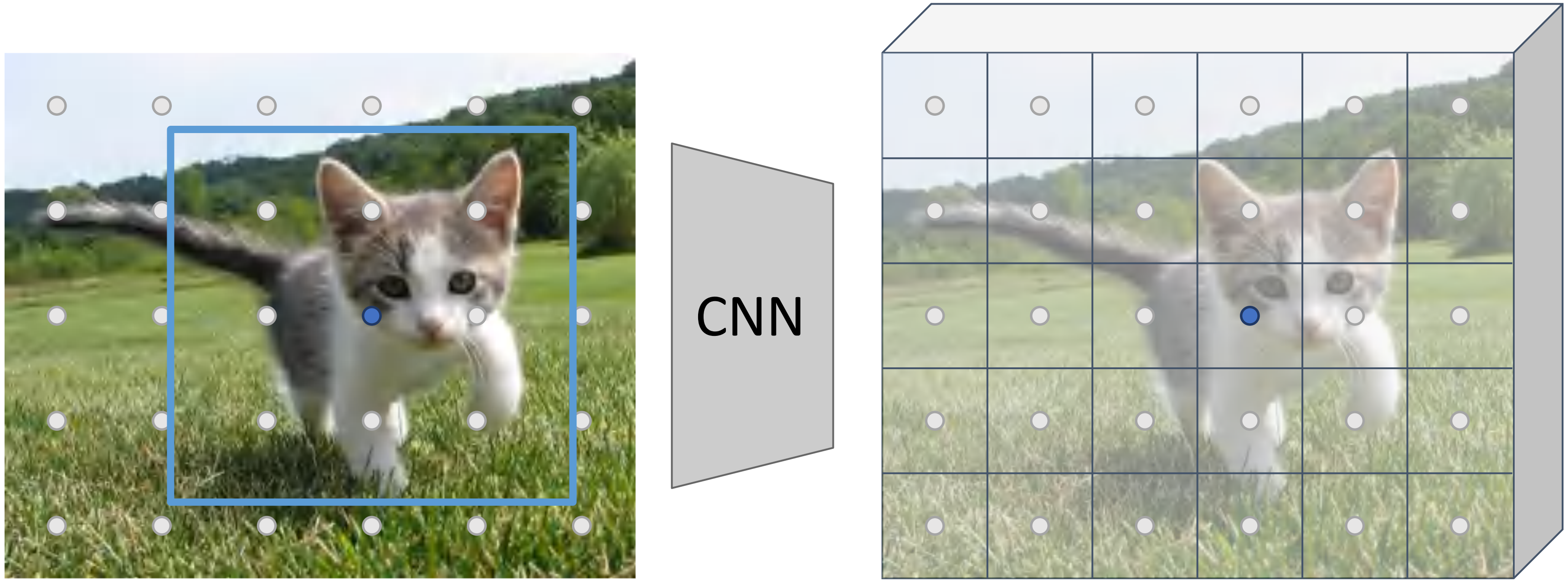

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Image features
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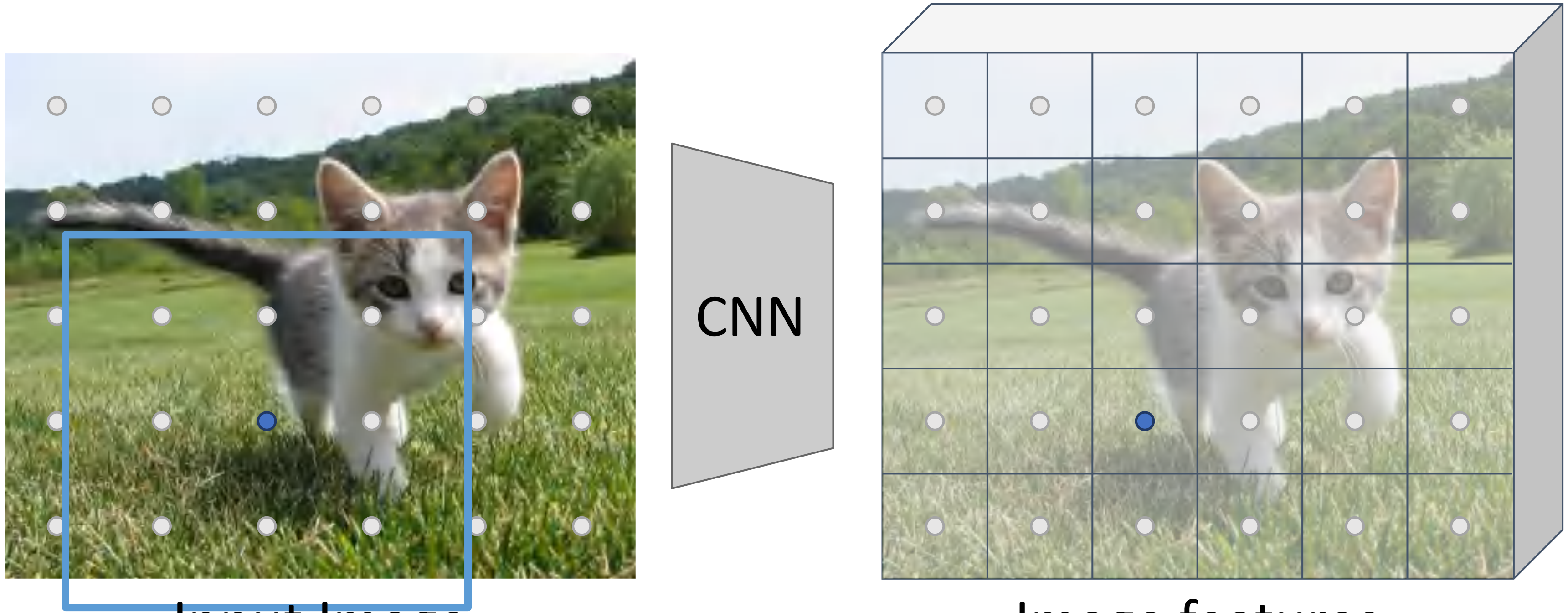

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Image features
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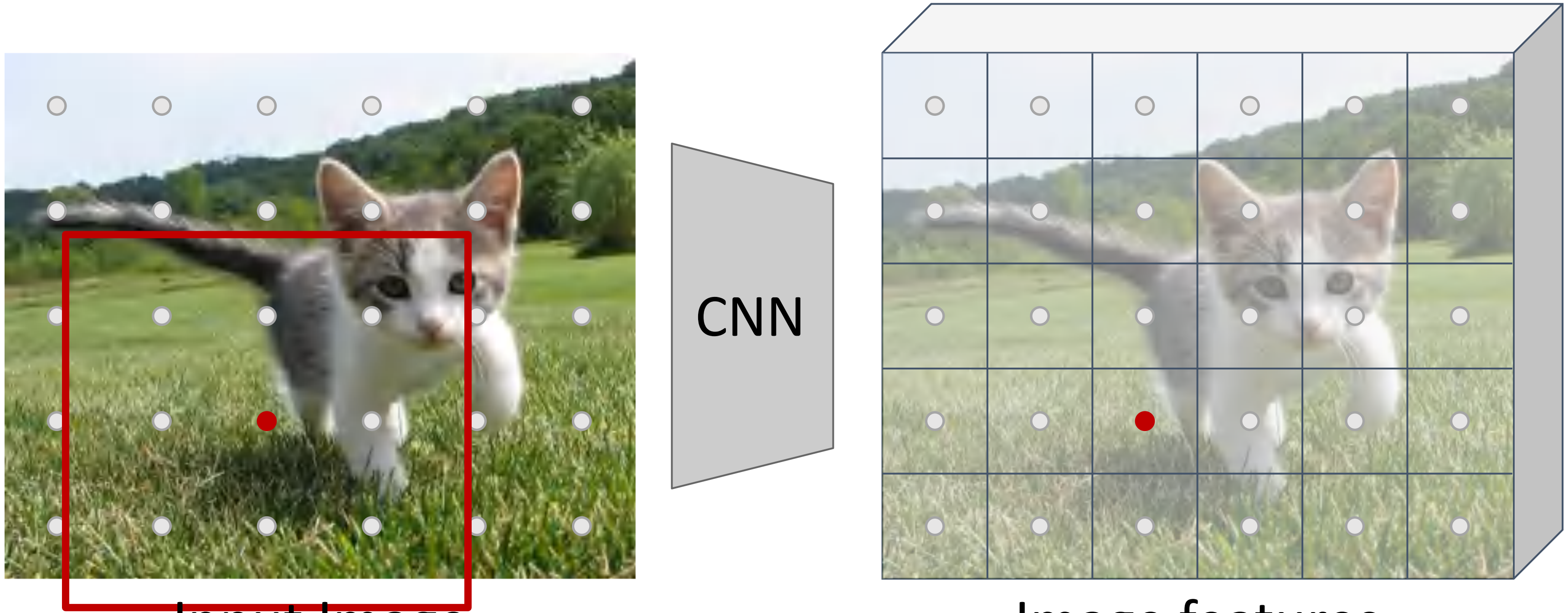
Region Proposal Network (RPN)

Imagine an **anchor box** of fixed size at each point in the feature map

Run backbone CNN to get features aligned to input image

Each feature corresponds to a point in the input



Input Image (e.g. 3 x 640 x 480)

Image features (e.g. 512 x 5 x 6)

Classify each anchor as positive (object) or negative (no object)

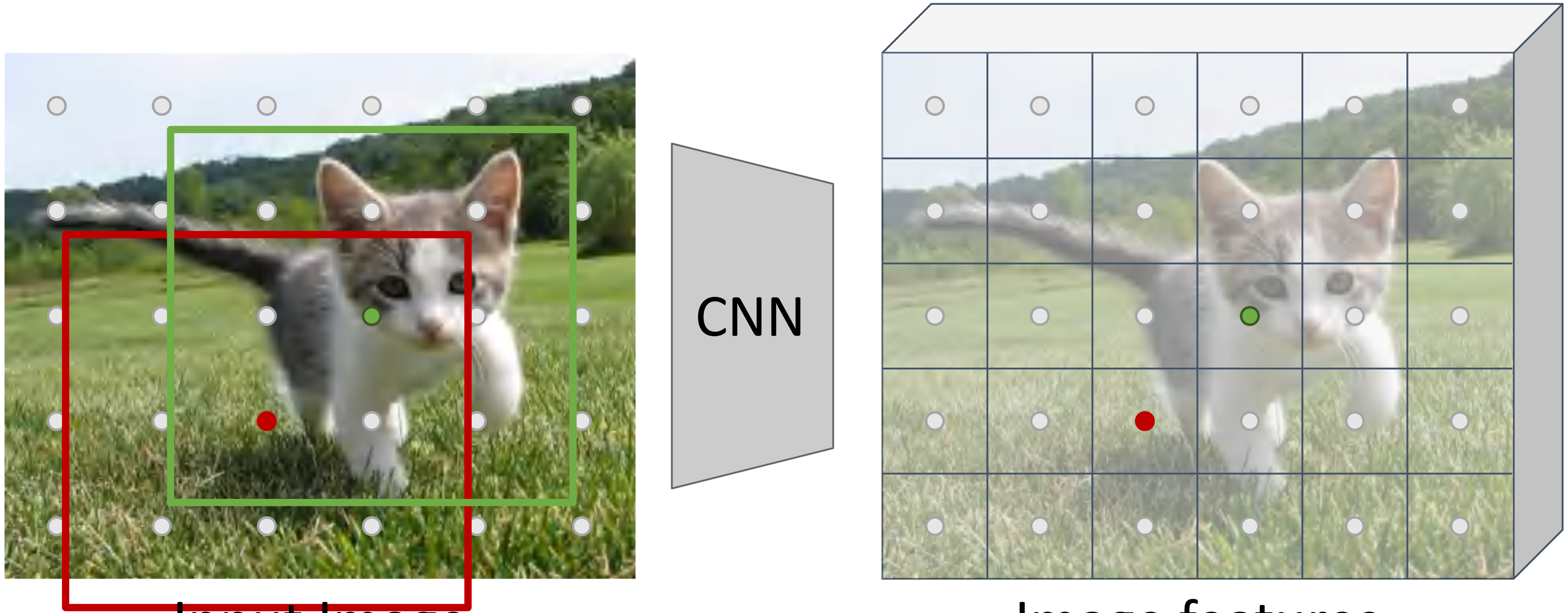
Ren et al, “Faster R-CNN: Towards Real-Time Object Detection with Region Proposal Networks”, NIPS 2015

Region Proposal Network (RPN)

Imagine an **anchor box** of fixed size at each point in the feature map

Run backbone CNN to get features aligned to input image

Each feature corresponds to a point in the input



Input Image
(e.g. 3 x 640 x 480)

Image features
(e.g. 512 x 5 x 6)

Classify each anchor as positive (object) or negative (no object)

Ren et al, "Faster R-CNN: Towards Real-Time Object Detection with Region Proposal Networks", NIPS 2015

Region Proposal Network (RPN)

Imagine an **anchor box** of fixed size at each point in the feature map

Run backbone CNN to get features aligned to input image

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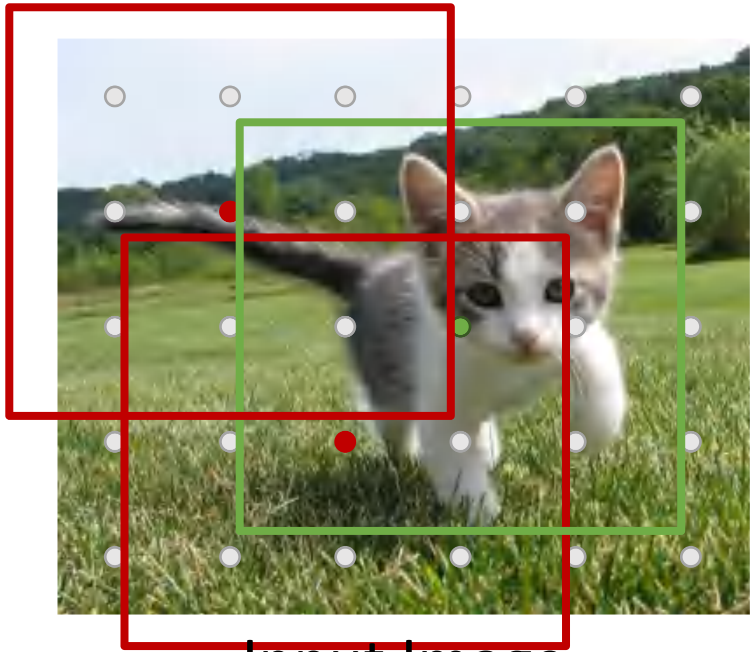

Input Image
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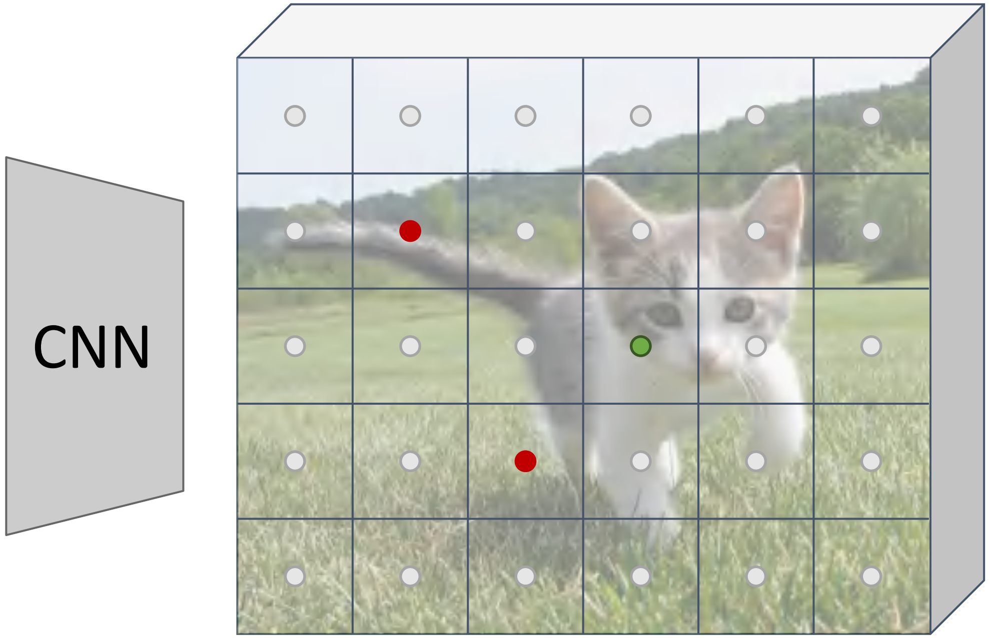


Image features
(e.g. 512 x 5 x 6)

Classify each anchor as positive (object) or negative (no object)

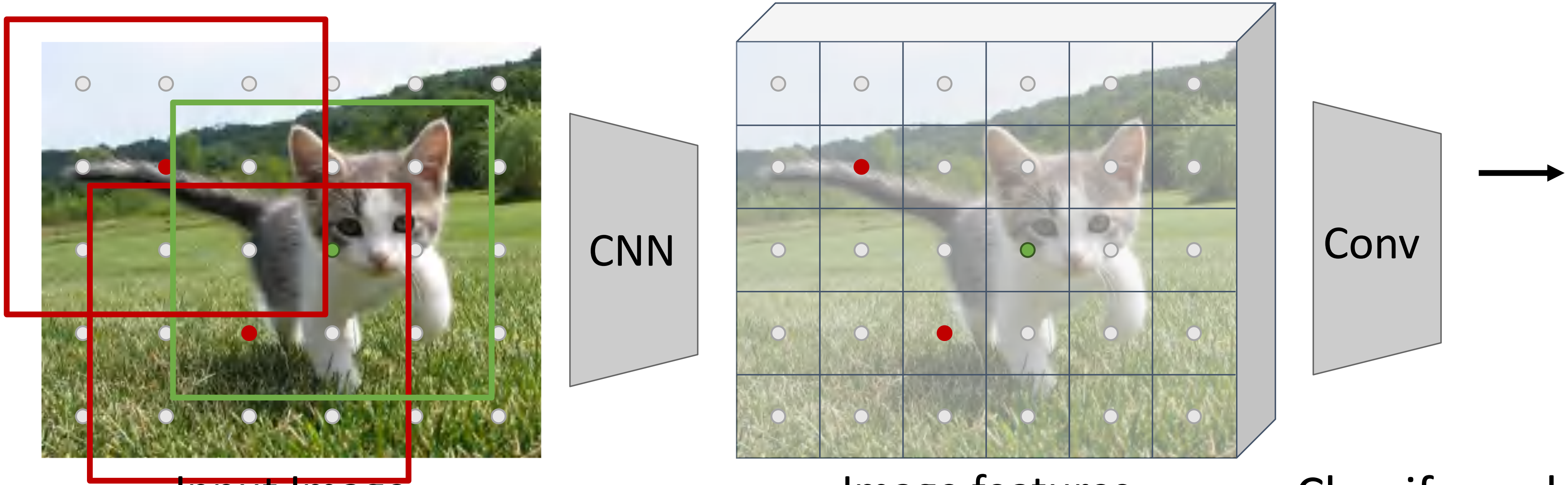
Ren et al, “Faster R-CNN: Towards Real-Time Object Detection with Region Proposal Networks”, NIPS 2015

Region Proposal Network (RPN)

Predict object vs not object scores for all anchors with a conv layer (512 input filters, 2 output filters)

Run backbone CNN to get features aligned to input image

Each feature corresponds to a point in the input



Anchor is object?
2 x 5 x 6

Input Image
(e.g. 3 x 640 x 480)

Image features
(e.g. 512 x 5 x 6)

Classify each anchor as positive (object) or negative (no object)

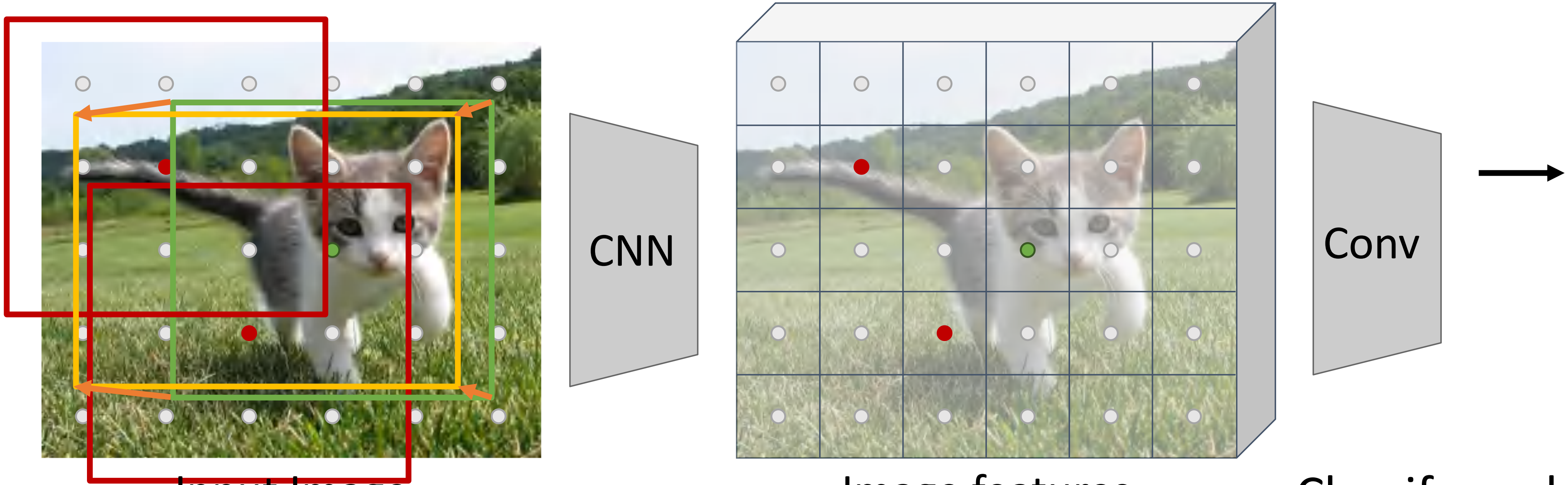
Ren et al, “Faster R-CNN: Towards Real-Time Object Detection with Region Proposal Networks”, NIPS 2015

Region Proposal Network (RPN)

For positive anchors, also predict a transform that converting the anchor to the GT box (like R-CNN)

Run backbone CNN to get features aligned to input image

Each feature corresponds to a point in the input



Input Image
(e.g. 3 x 640 x 480)

Image features
(e.g. 512 x 5 x 6)

Classify each anchor as positive (object) or negative (no object)

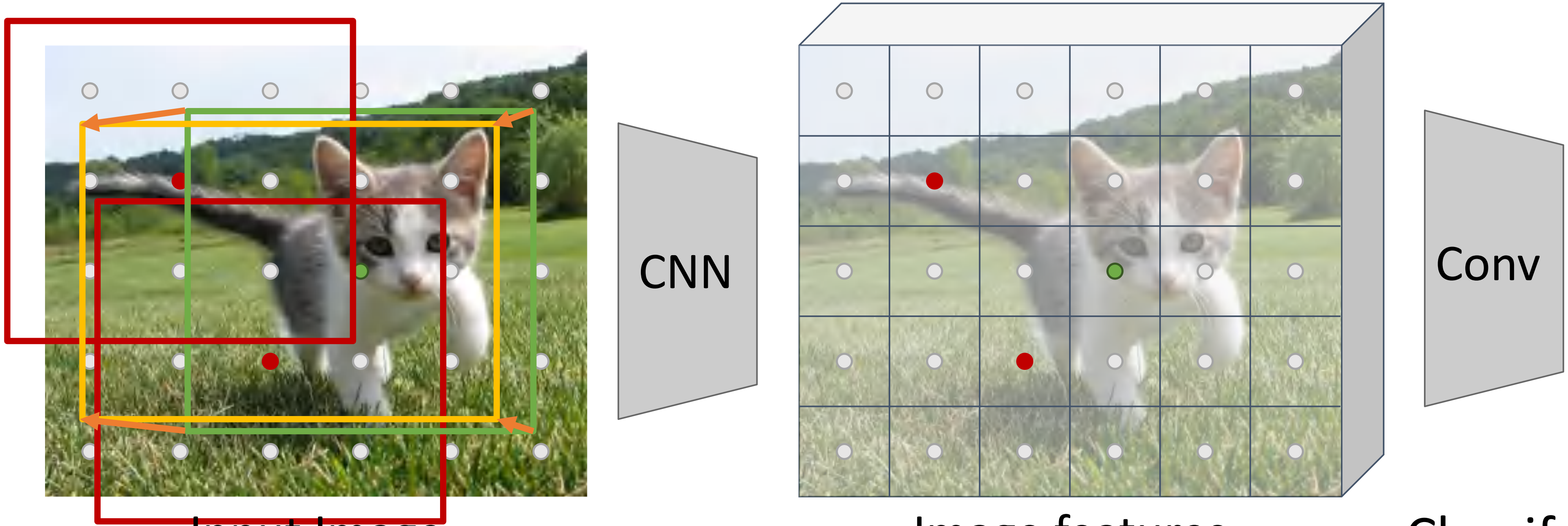
Ren et al, “Faster R-CNN: Towards Real-Time Object Detection with Region Proposal Networks”, NIPS 2015

Region Proposal Network (RPN)

For positive anchors, also predict a transform that converting the anchor to the GT box (like R-CNN)
Predict transforms with conv

Run backbone CNN to get features aligned to input image

Each feature corresponds to a point in the input



Anchor is object?
2 x 5 x 6

Anchor transforms
4 x 5 x 6

Input Image
(e.g. 3 x 640 x 480)

Image features
(e.g. 512 x 5 x 6)

Classify each anchor as positive (object) or negative (no object)

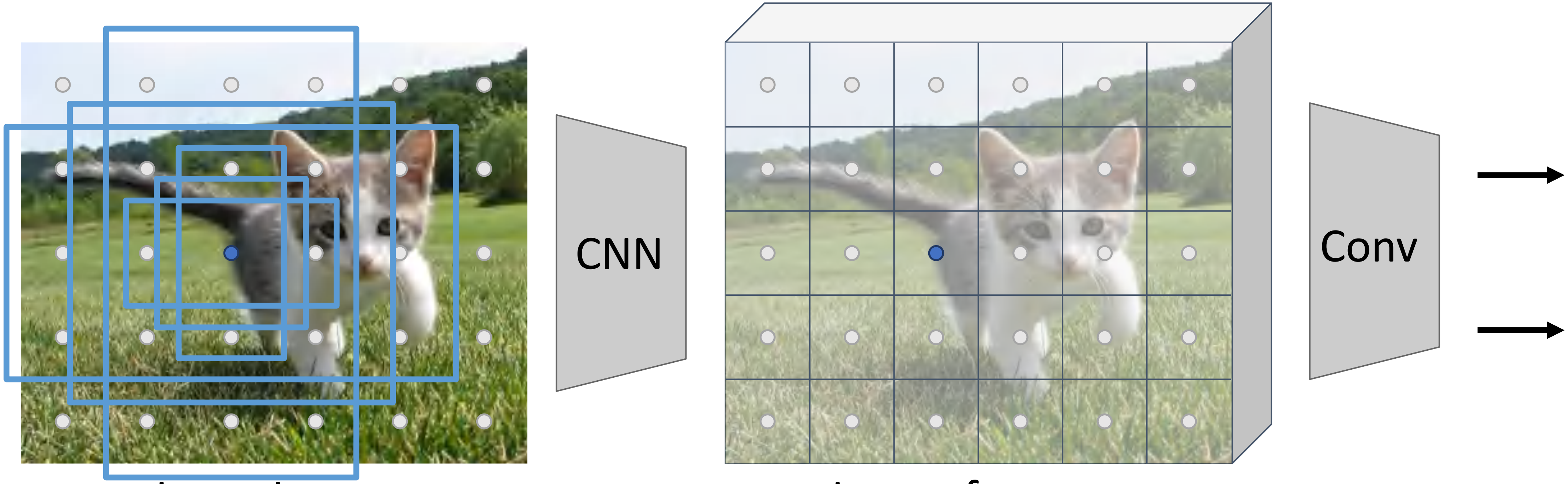
Ren et al, “Faster R-CNN: Towards Real-Time Object Detection with Region Proposal Networks”, NIPS 2015

Region Proposal Network (RPN)

In practice: Rather than using one anchor per point, instead consider K different anchors with different size and scale (here K = 6)

Run backbone CNN to get features aligned to input image

Each feature corresponds to a point in the input



Anchor is object?
2K x 5 x 6

Anchor transforms
4K x 5 x 6

Input Image
(e.g. 3 x 640 x 480)

Image features
(e.g. 512 x 5 x 6)

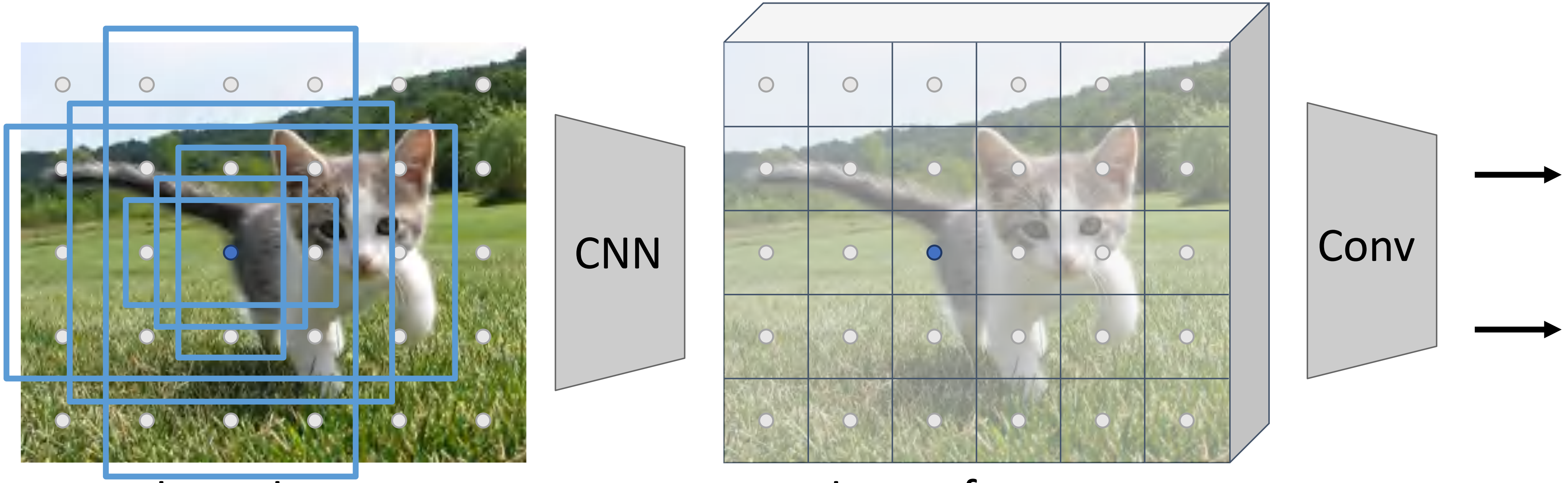
Ren et al, "Faster R-CNN: Towards Real-Time Object Detection with Region Proposal Networks", NIPS 2015

Region Proposal Network (RPN)

In practice: Rather than using one anchor per point, instead consider K different anchors with different size and scale (here K = 6)

Run backbone CNN to get features aligned to input image

Each feature corresponds to a point in the input



Anchor is object?
2K x 5 x 6

Anchor transforms
4K x 5 x 6

Input Image
(e.g. 3 x 640 x 480)

Image features
(e.g. 512 x 5 x 6)

During training, supervised positive / negative anchors and box transforms like R-CNN

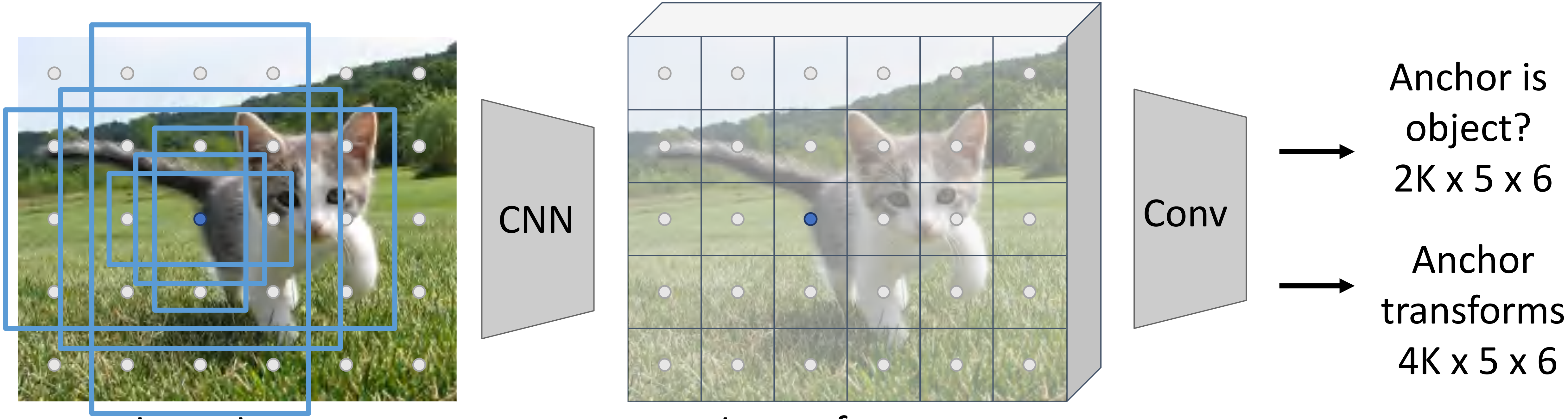
Ren et al, "Faster R-CNN: Towards Real-Time Object Detection with Region Proposal Networks", NIPS 2015

Region Proposal Network (RPN)

In practice: Rather than using one anchor per point, instead consider K different anchors with different size and scale (here K = 6)

Run backbone CNN to get features aligned to input image

Each feature corresponds to a point in the input



Input Image
(e.g. 3 x 640 x 480)

Image features
(e.g. 512 x 5 x 6)

Positive anchors: >= 0.7 IoU with some GT box (plus highest IoU to each GT)

Ren et al, "Faster R-CNN: Towards Real-Time Object Detection with Region Proposal Networks", NIPS 2015

Region Proposal Network (RPN)

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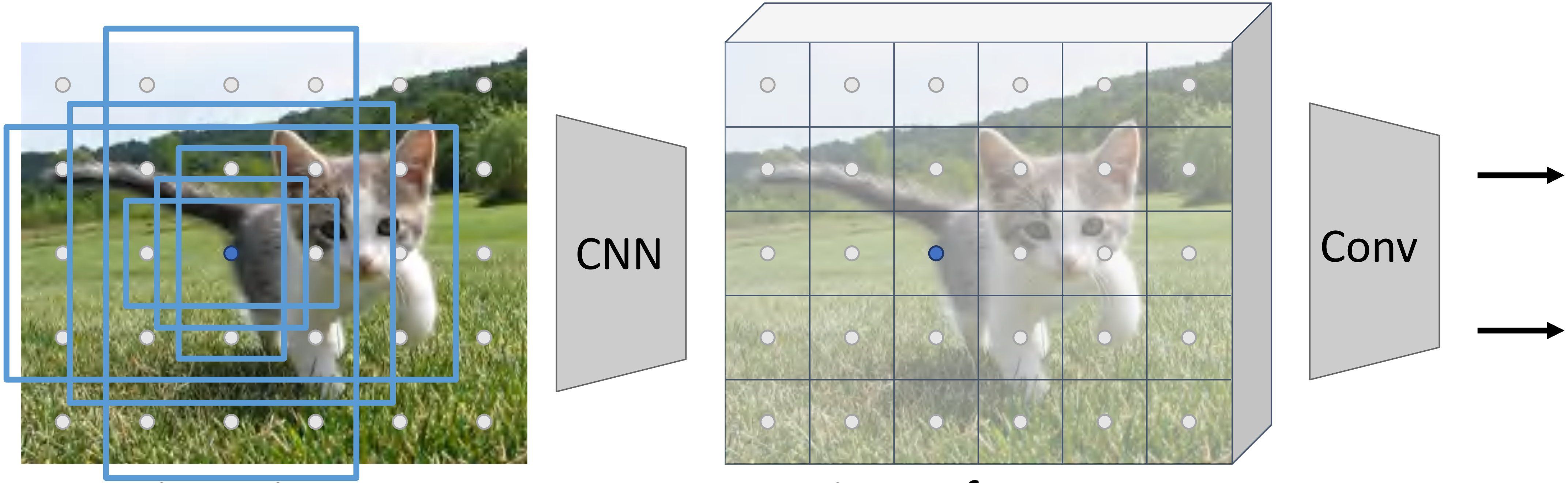

Anchor is object?
2K x 5 x 6

Anchor transforms
4K x 5 x 6

Input Image
(e.g. 3 x 640 x 480)

Image features
(e.g. 512 x 5 x 6)

Negative anchors: < 0.3 IoU with all GT boxes. Don't supervised transforms for negative boxes.

Ren et al, "Faster R-CNN: Towards Real-Time Object Detection with Region Proposal Networks", NIPS 2015

Region Proposal Network (RPN)

In practice: Rather than using one anchor per point, instead consider K different anchors with different size and scale (here K = 6)

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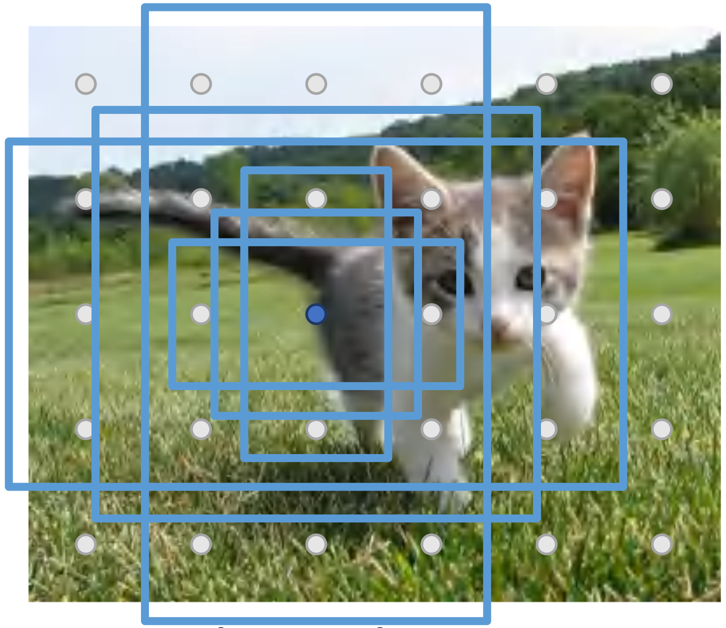

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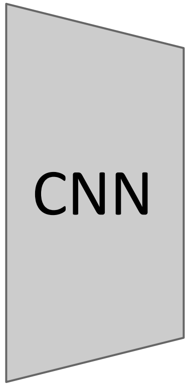

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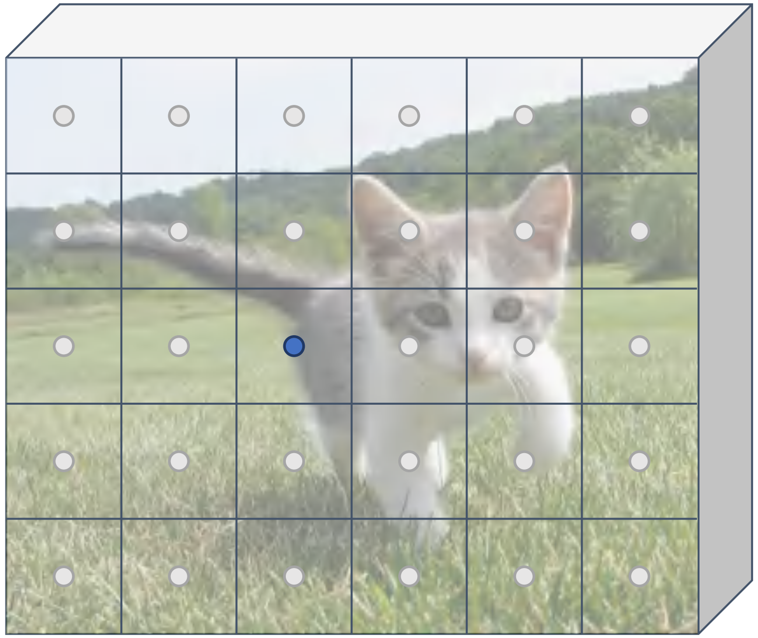
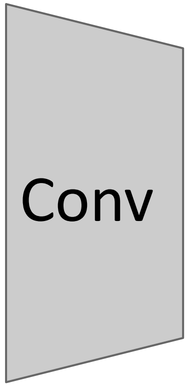


Image features
(e.g. 512 x 5 x 6)



→ Anchor is object?
2K x 5 x 6

→ Anchor transforms
4K x 5 x 6

Neutral anchors: between 0.3 and 0.7 IoU with all GT boxes; ignored during training

Ren et al, “Faster R-CNN: Towards Real-Time Object Detection with Region Proposal Networks”, NIPS 2015

Region Proposal Network (RPN)

In practice: Rather than using one anchor per point, instead consider K different anchors with different size and scale (here K = 6)

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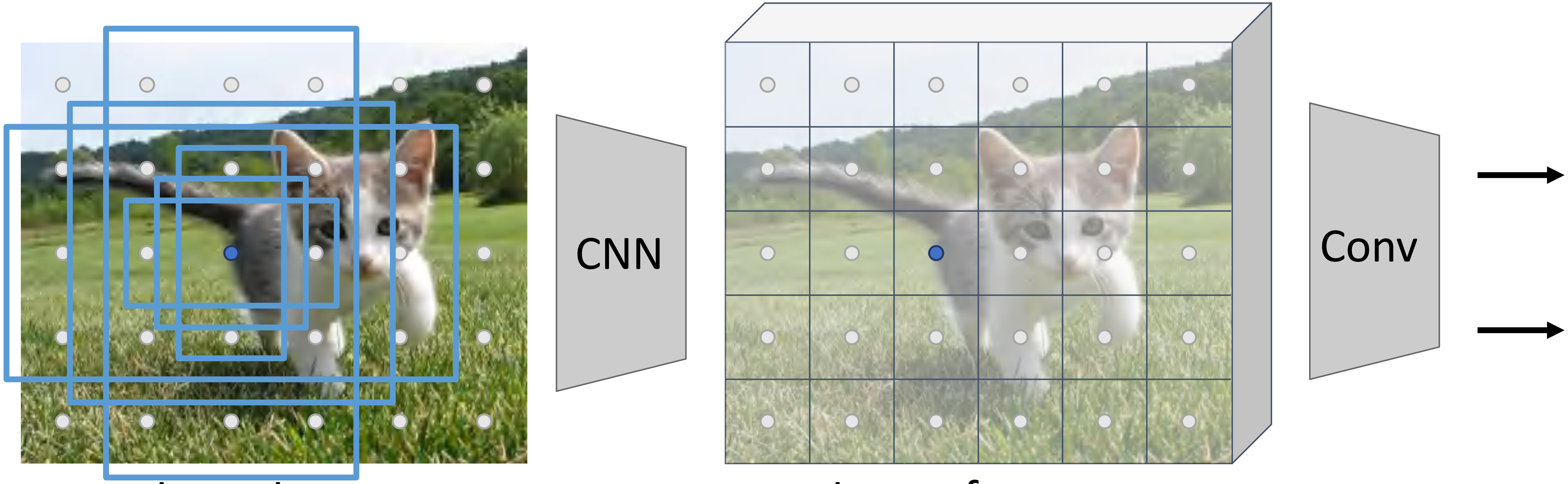


Input Image
(e.g. 3 x 640 x 480)

Image features
(e.g. 512 x 5 x 6)

Anchor is object?
2K x 5 x 6

Anchor transforms
4K x 5 x 6

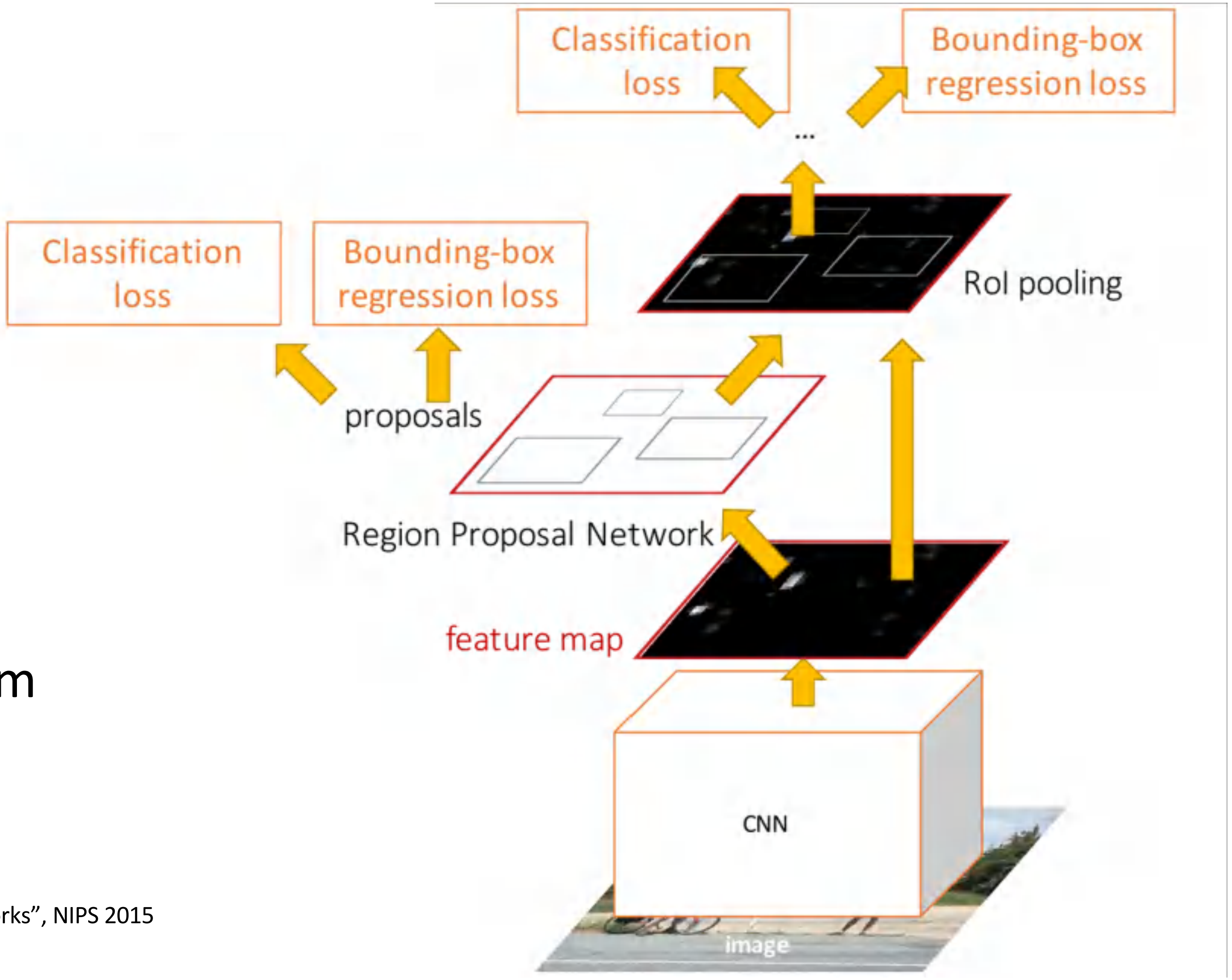
At test-time, sort all K*5*6 boxes by their positive score, take top 300 as our region proposals

Ren et al, “Faster R-CNN: Towards Real-Time Object Detection with Region Proposal Networks”, NIPS 2015

Faster R-CNN: Learnable Region Proposals

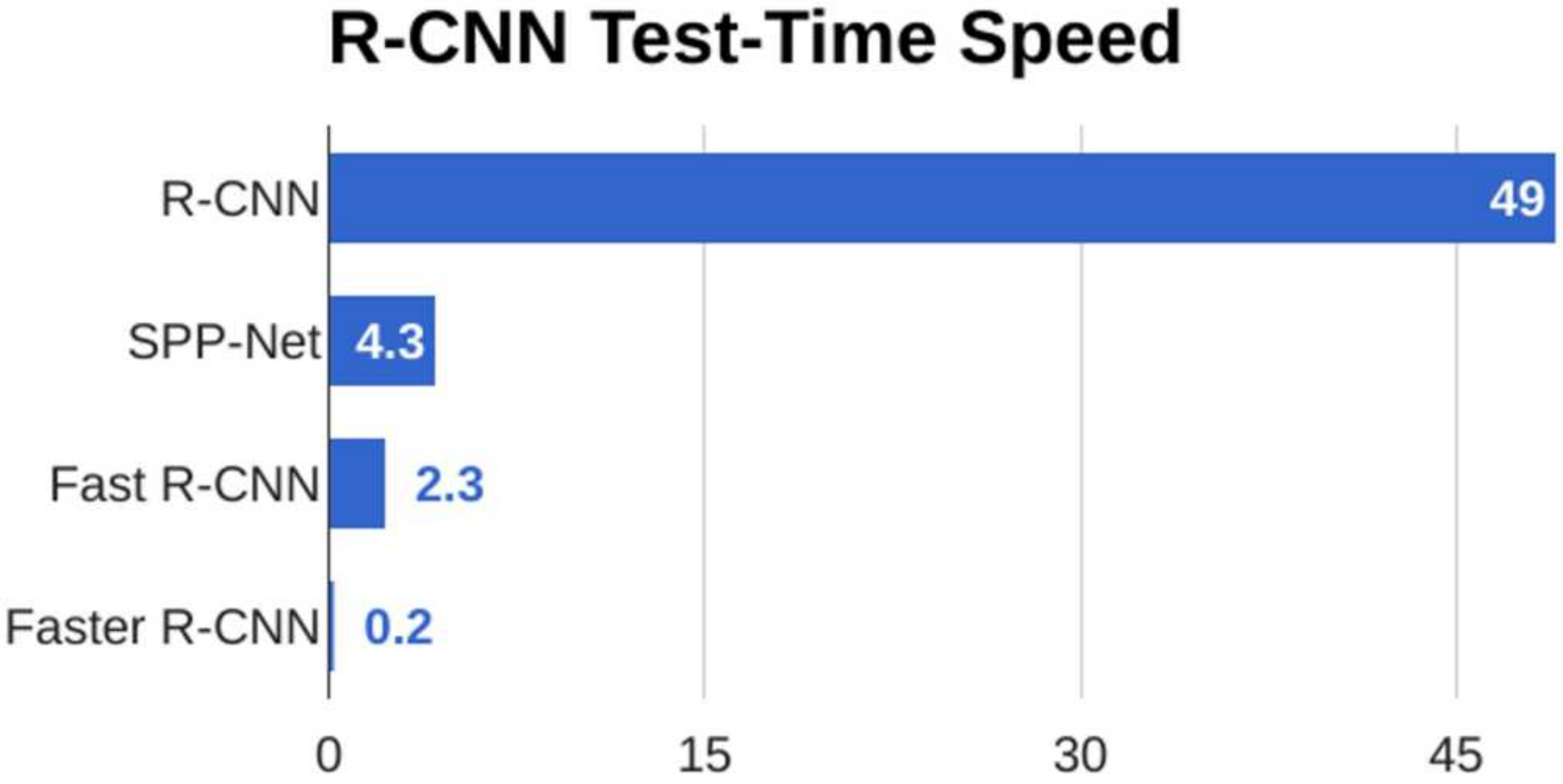
Jointly train with 4 losses:

1. **RPN classification**: anchor box is object / not an object
2. **RPN regression**: predict transform from anchor box to proposal box
3. **Object classification**: classify proposals as background / object class
4. **Object regression**: predict transform from proposal box to object box



Ren et al, "Faster R-CNN: Towards Real-Time Object Detection with Region Proposal Networks", NIPS 2015

Faster R-CNN: Learnable Region Proposals

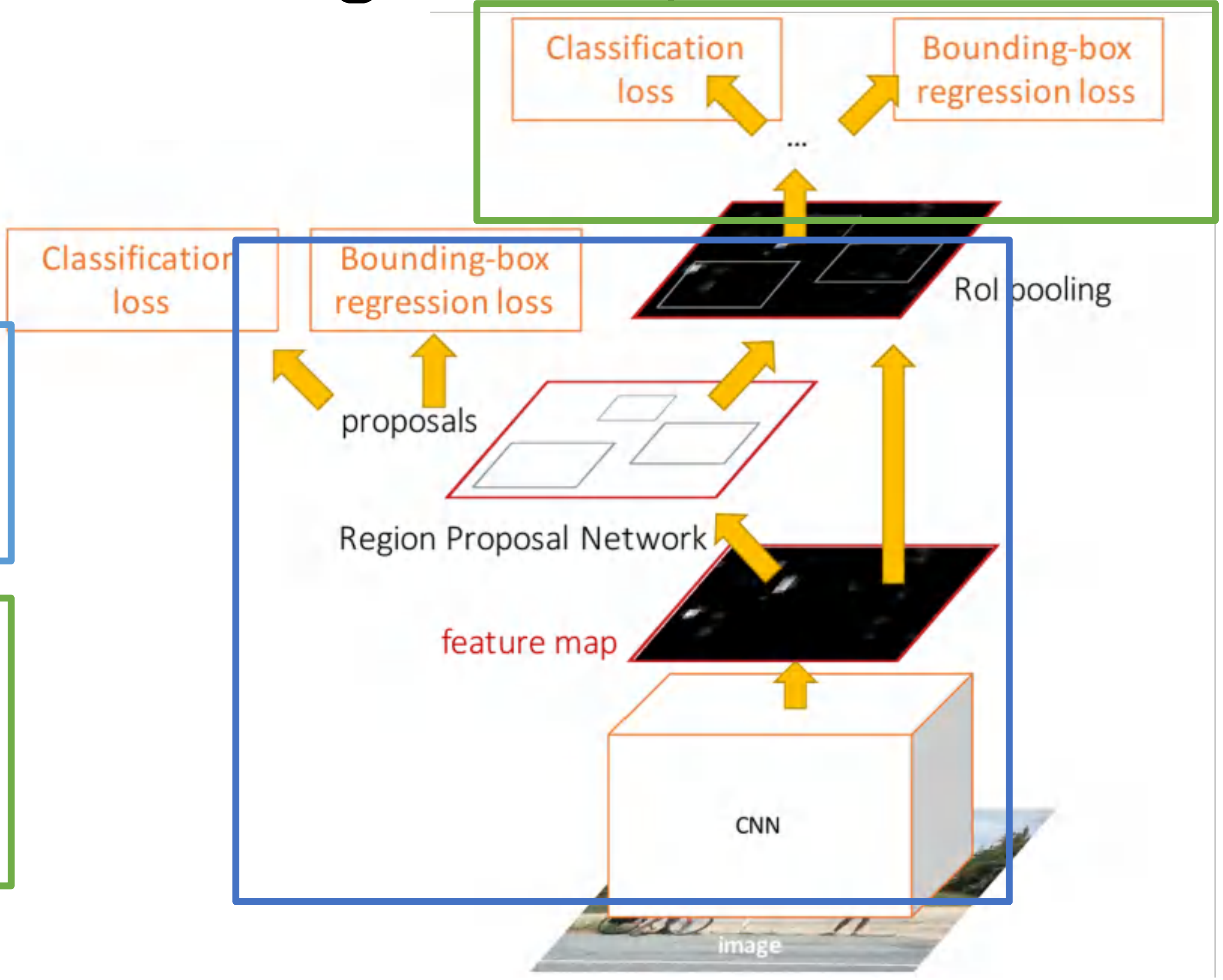


Faster R-CNN: Learnable Region Proposals

Faster R-CNN is a
Two-stage object detector

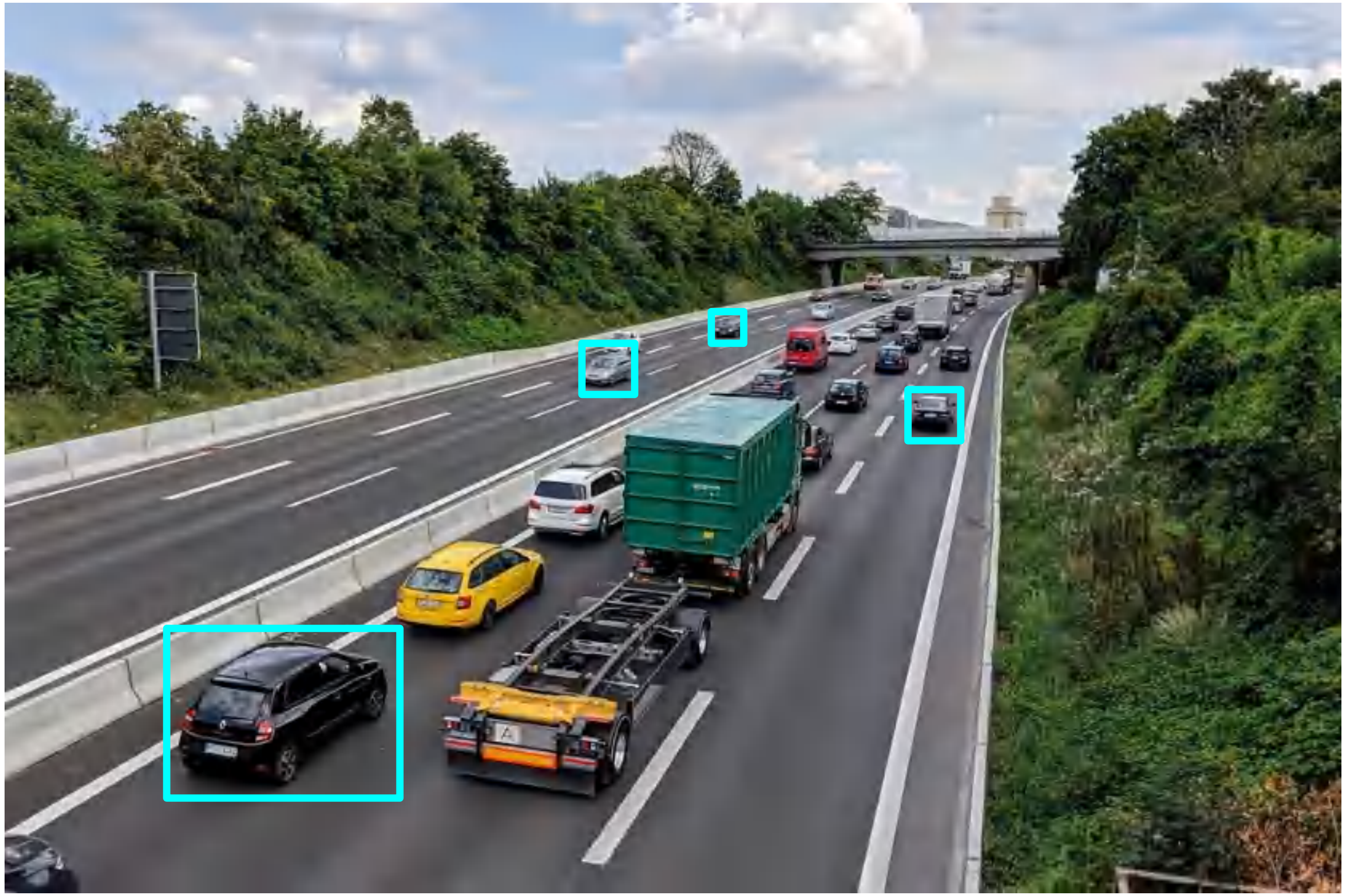
First stage: Run once per image
- Backbone network
- Region proposal network

Second stage: Run once per region
- Crop features: RoI pool / align
- Predict object class
- Prediction bbox offset



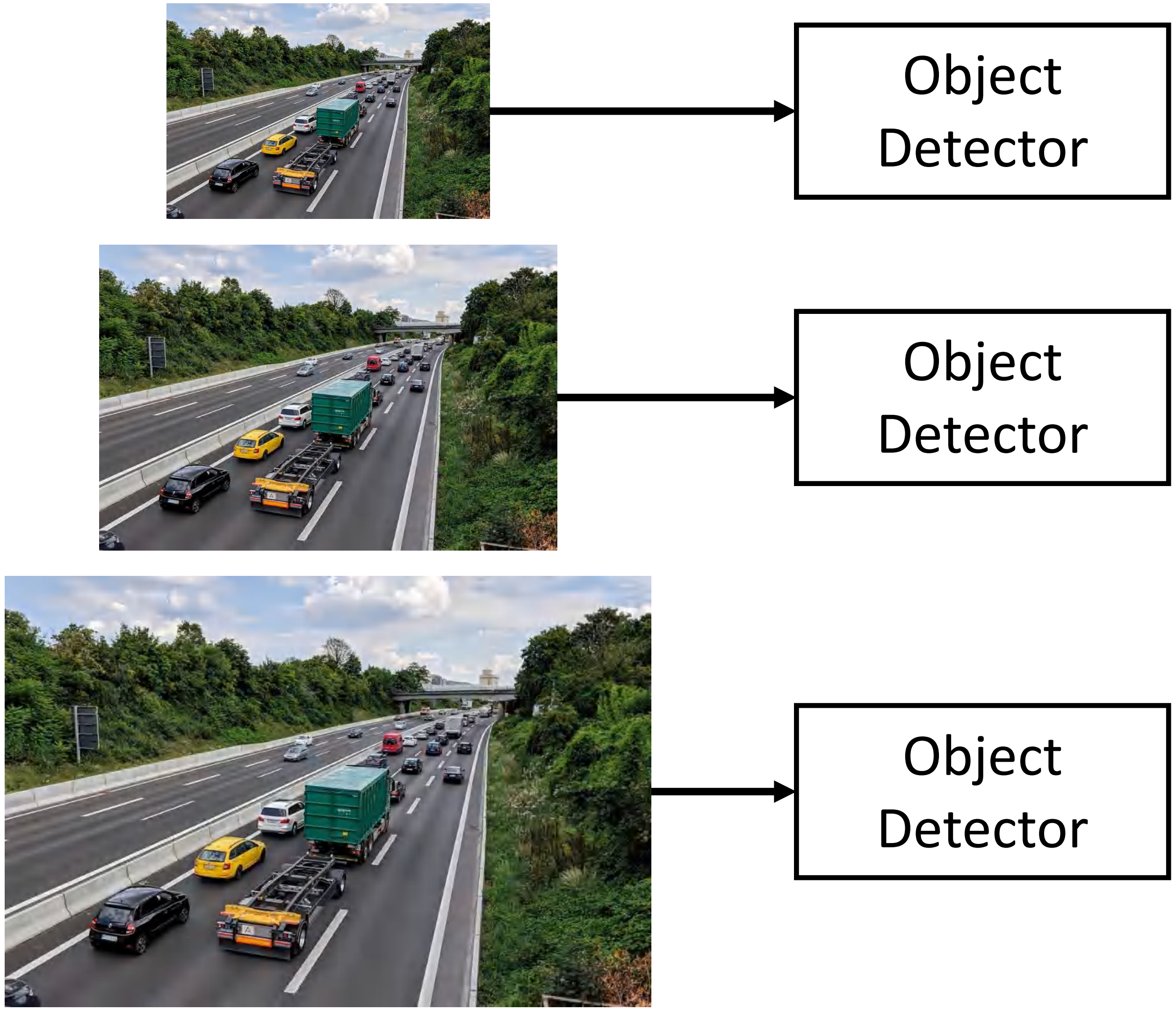
Dealing with Scale

We need to detect objects of many different scales.
How to improve *scale invariance* of the detector?



Dealing with Scale: Image Pyramid

Classic idea: build an *image pyramid* by resizing the image to different scales, then process each image scale independently.

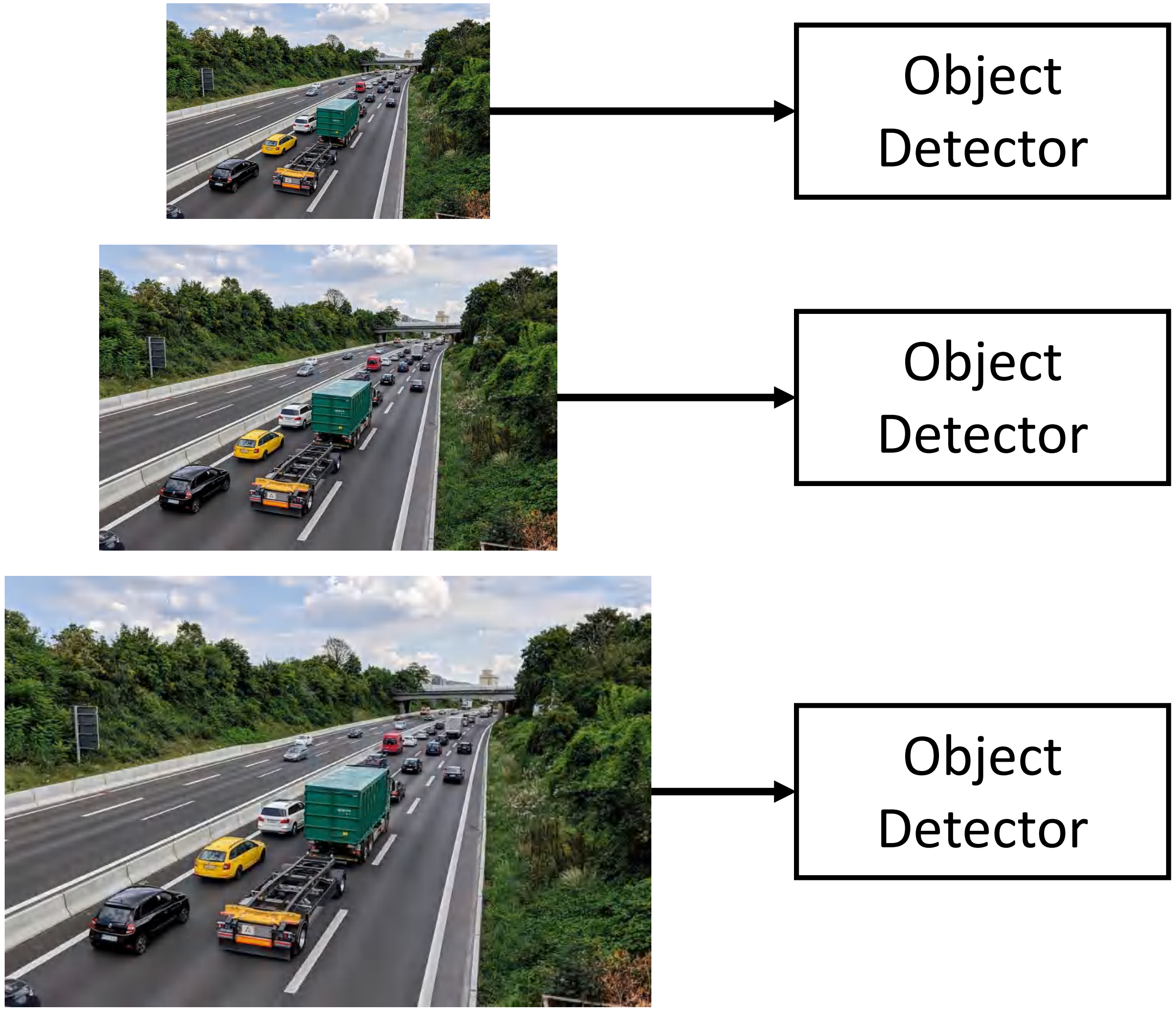


Lin et al, “Feature Pyramid Networks for Object Detection”, ICCV 2017

Dealing with Scale: Image Pyramid

Classic idea: build an *image pyramid* by resizing the image to different scales, then process each image scale independently.

Problem: Expensive! Don't share any computation between scales



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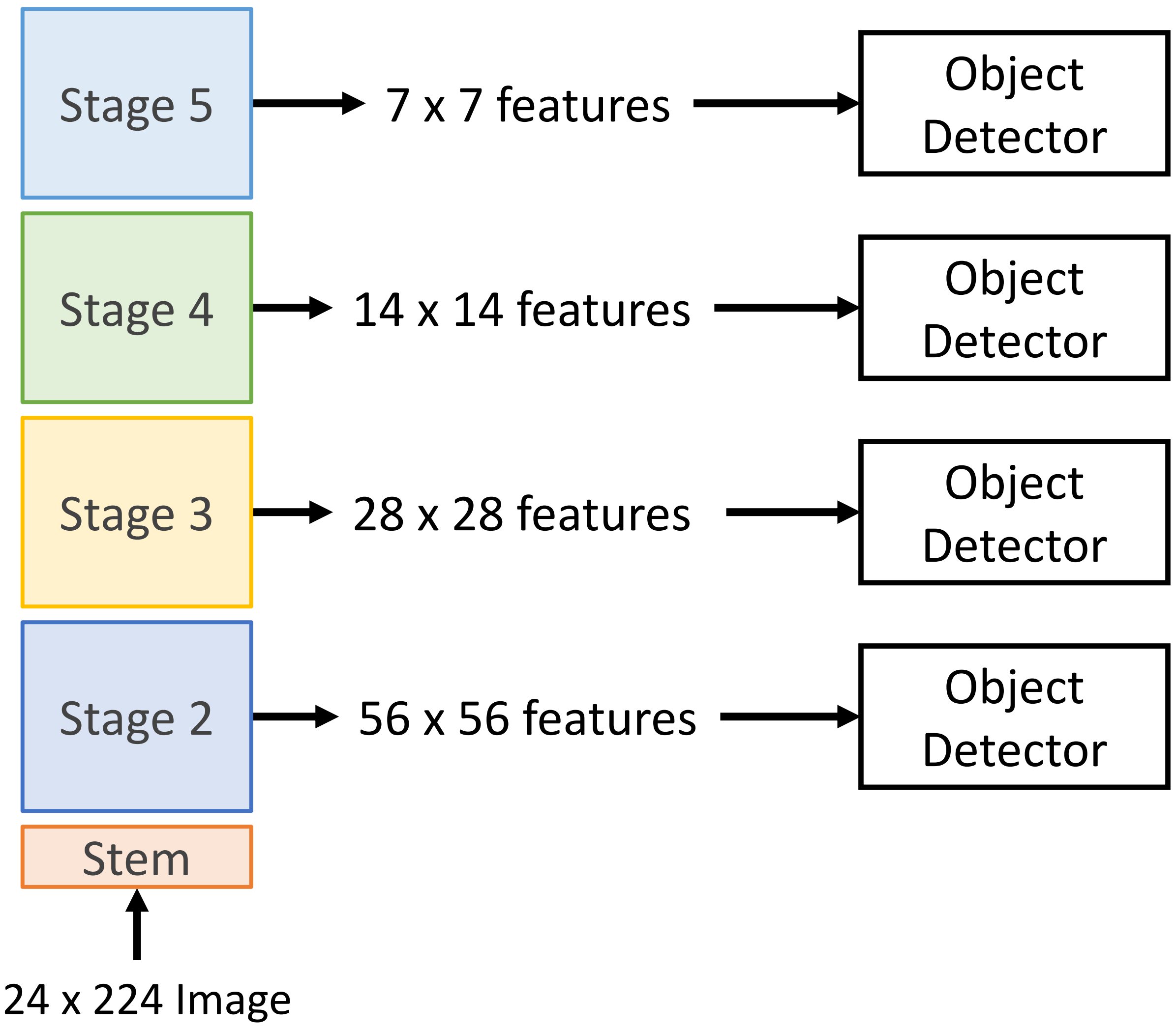
Dealing with Scale: Multiscale Features

CNNs have multiple *stages* that operate at different resolutions. Attach an independent detector to the features at each level

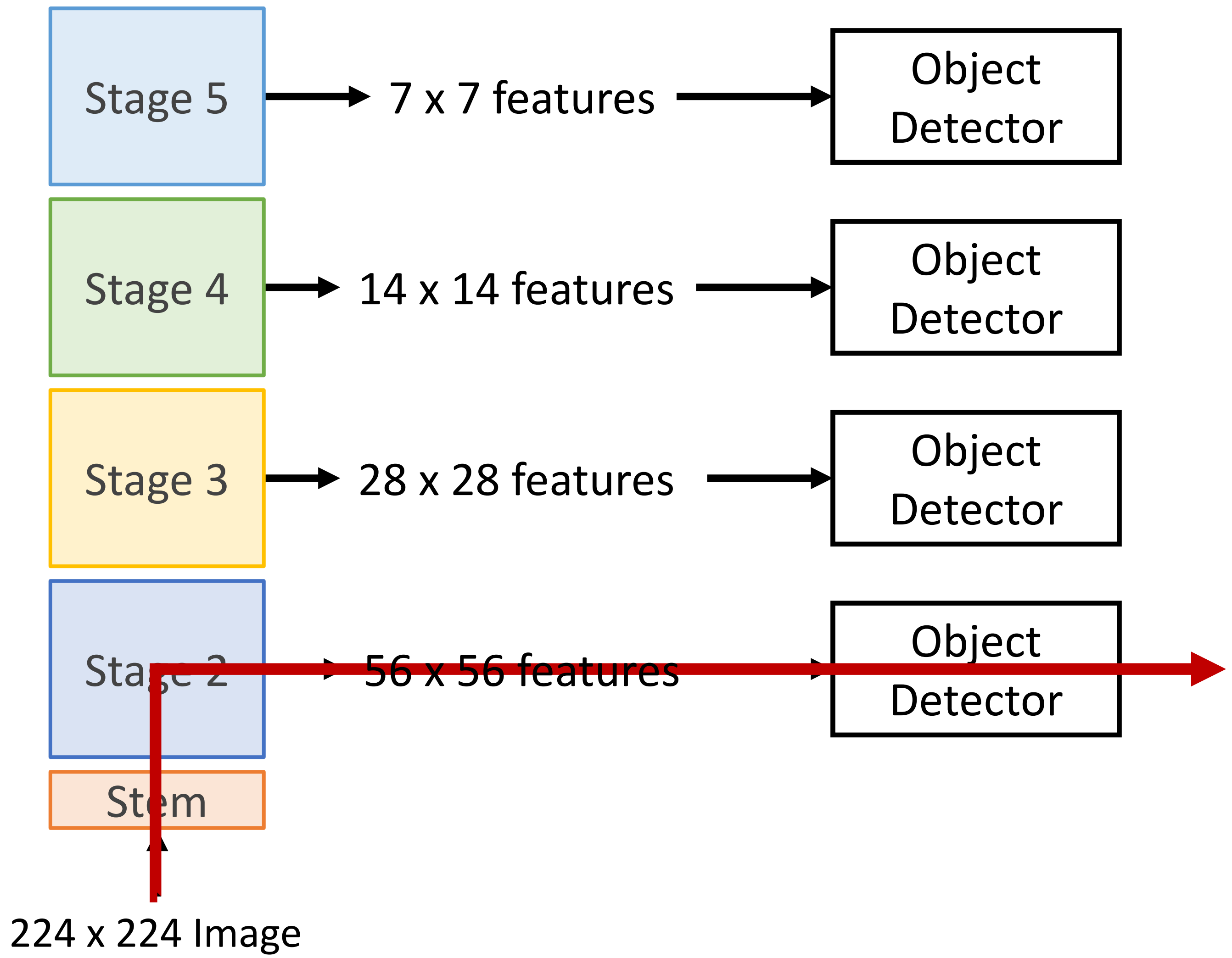


Lin et al, "Feature Pyramid Networks for Object Detection", ICCV 2017

Dealing with Scale: Multiscale Features

CNNs have multiple *stages* that operate at different resolutions. Attach an independent detector to the features at each level

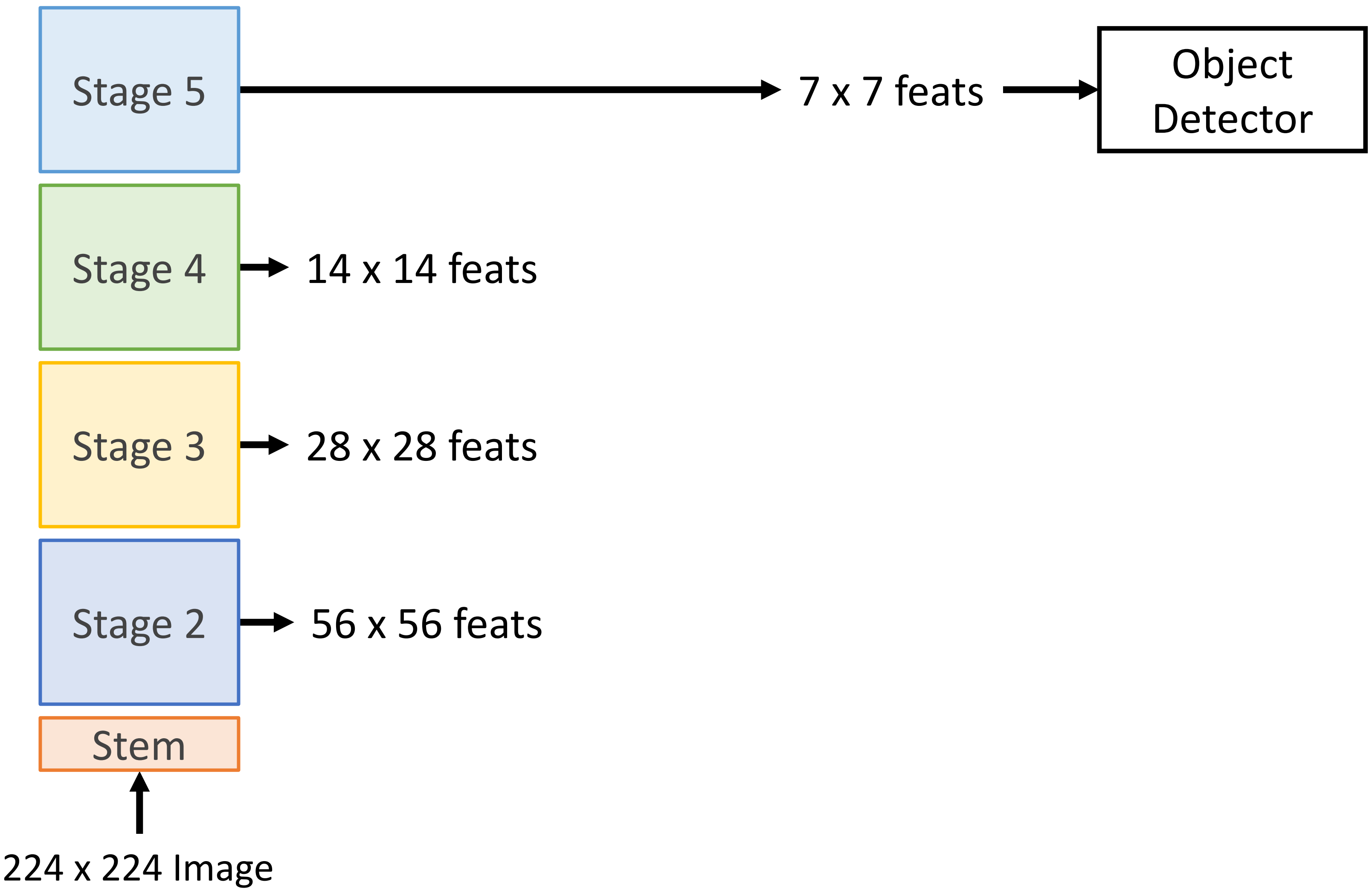
Problem: detector on early features doesn't make use of the entire backbone; doesn't get access to high-level features



Lin et al, "Feature Pyramid Networks for Object Detection", ICCV 2017

Dealing with Scale: Feature Pyramid Network

Add *top down connections* that feed information from high level features back down to lower level features



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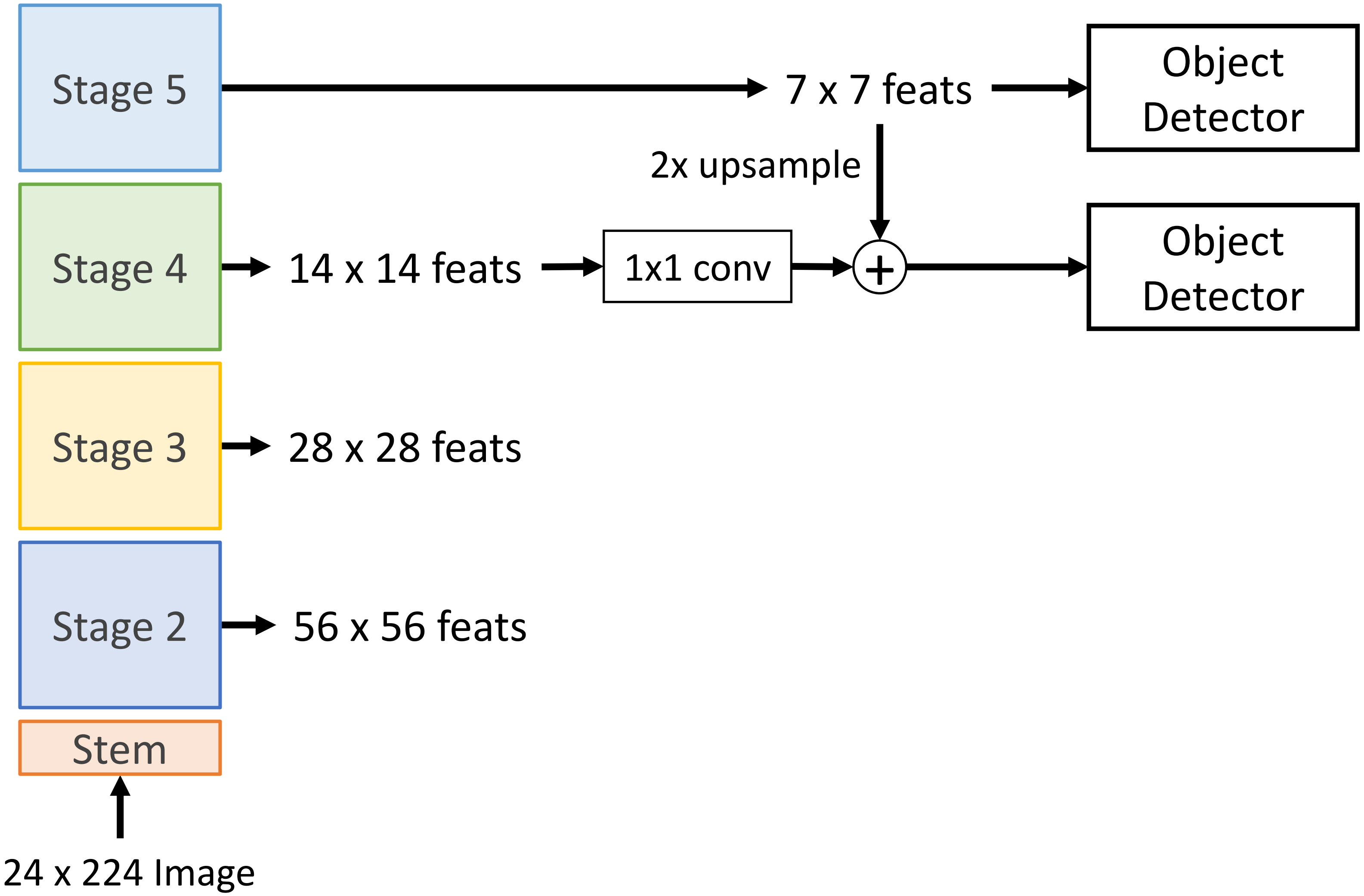

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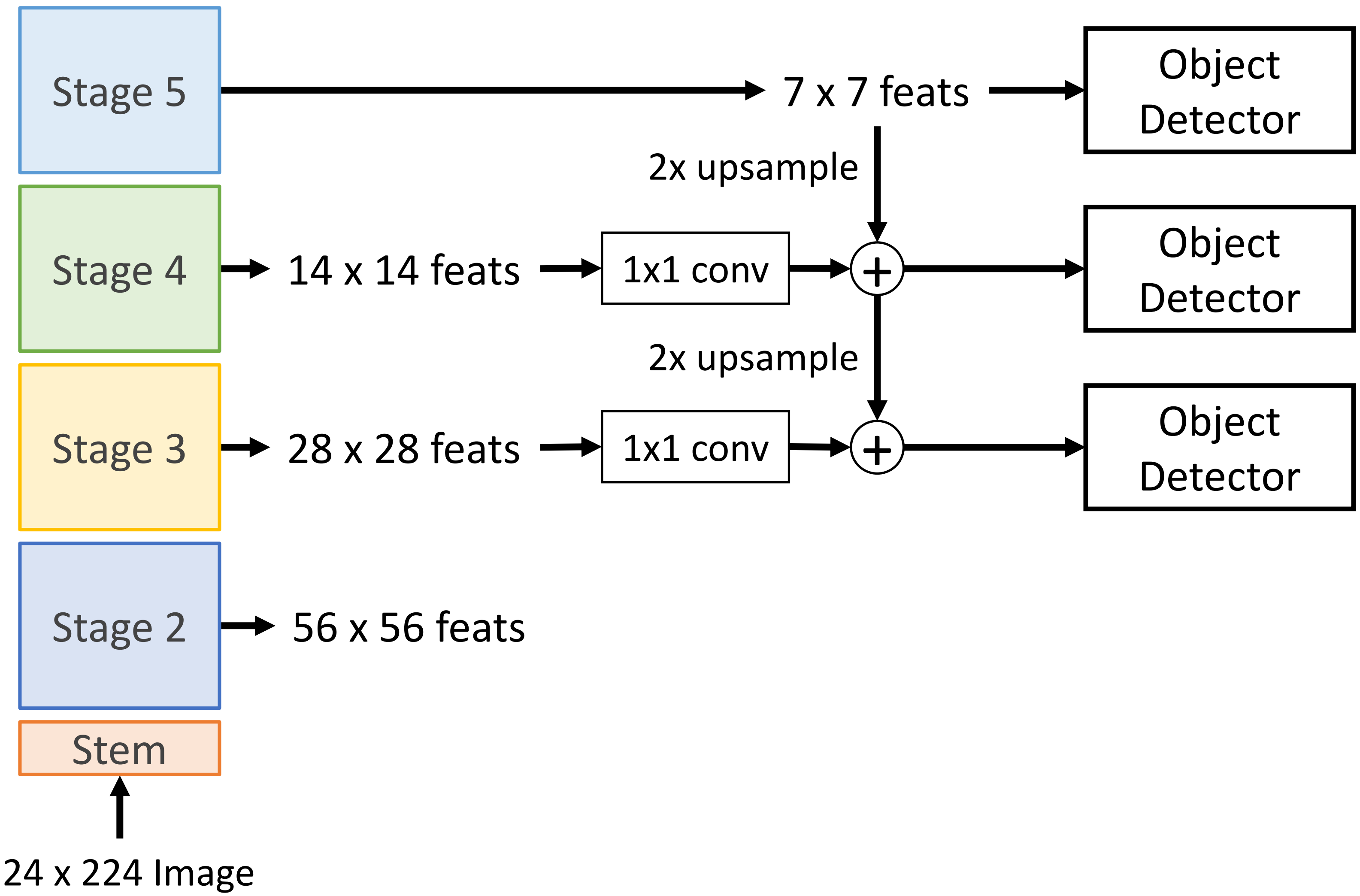

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Dealing with Scale: Feature Pyramid Network

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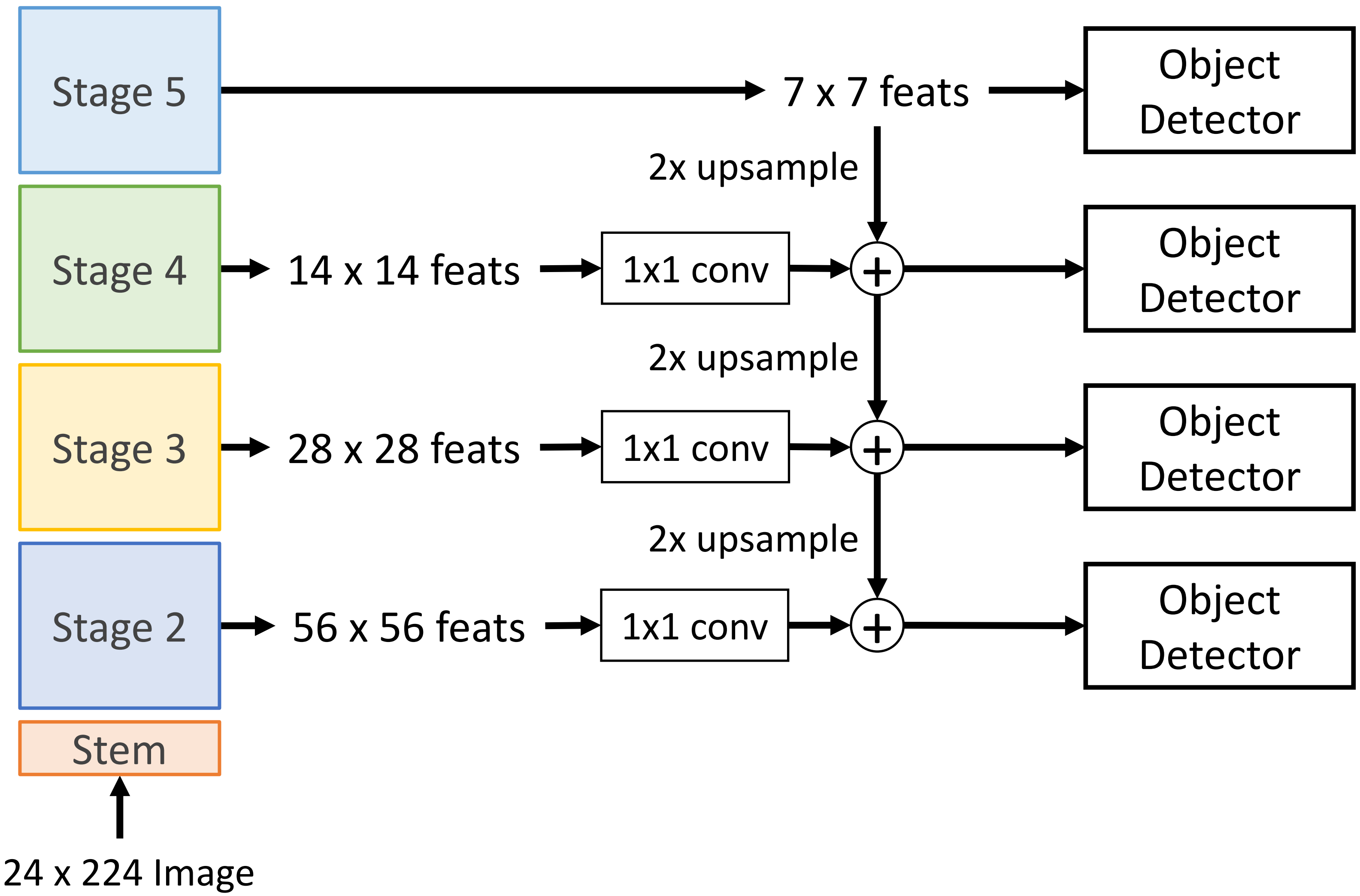
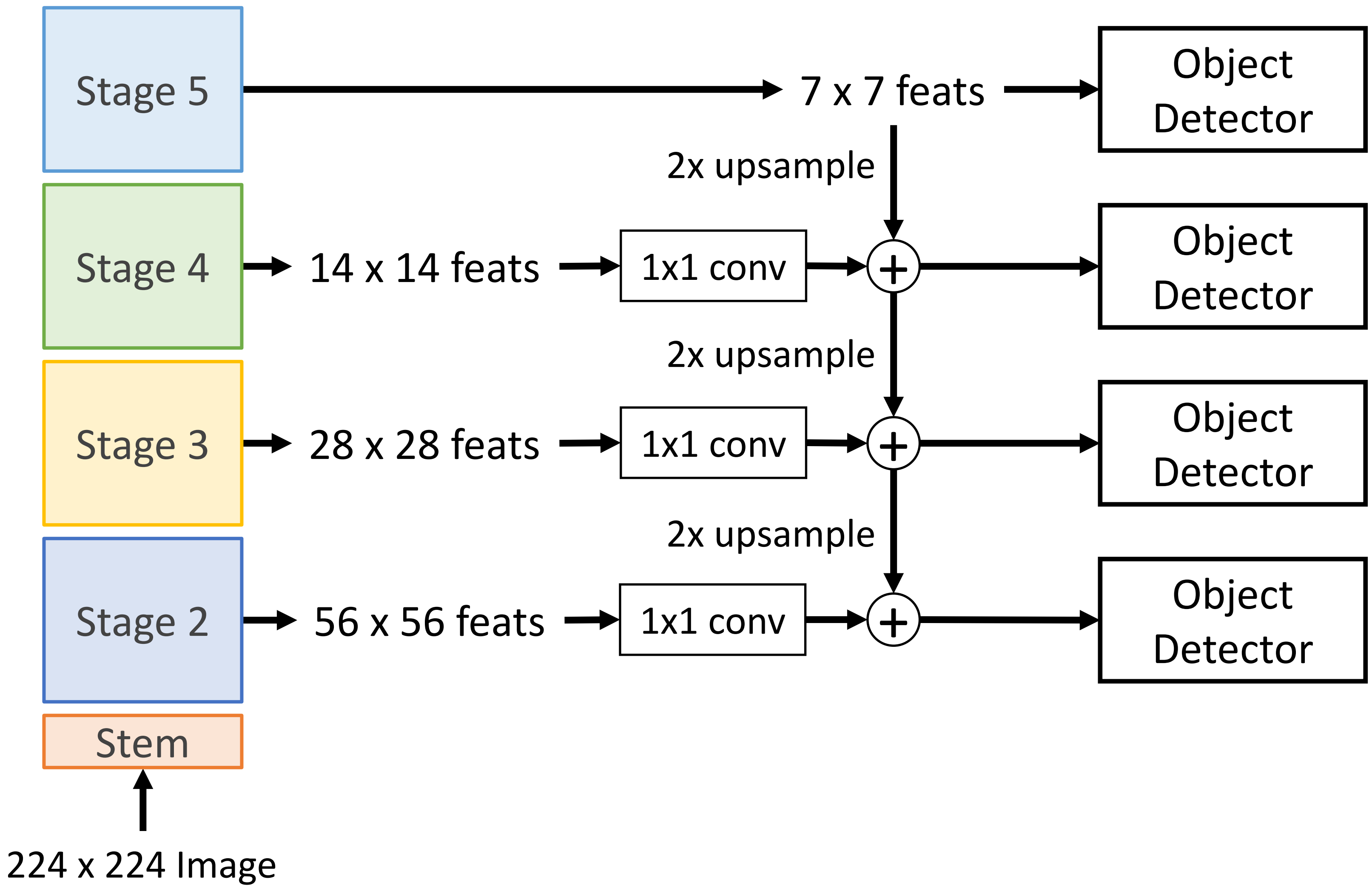


Lin et al, "Feature Pyramid Networks for Object Detection", ICCV 2017

Dealing with Scale: Feature Pyramid Network

Add *top down connections* that feed information from high level features back down to lower level features

Efficient multiscale features where all levels benefit from the whole backbone! Widely used in practice



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Dealing with Scale: Feature Pyramid Network

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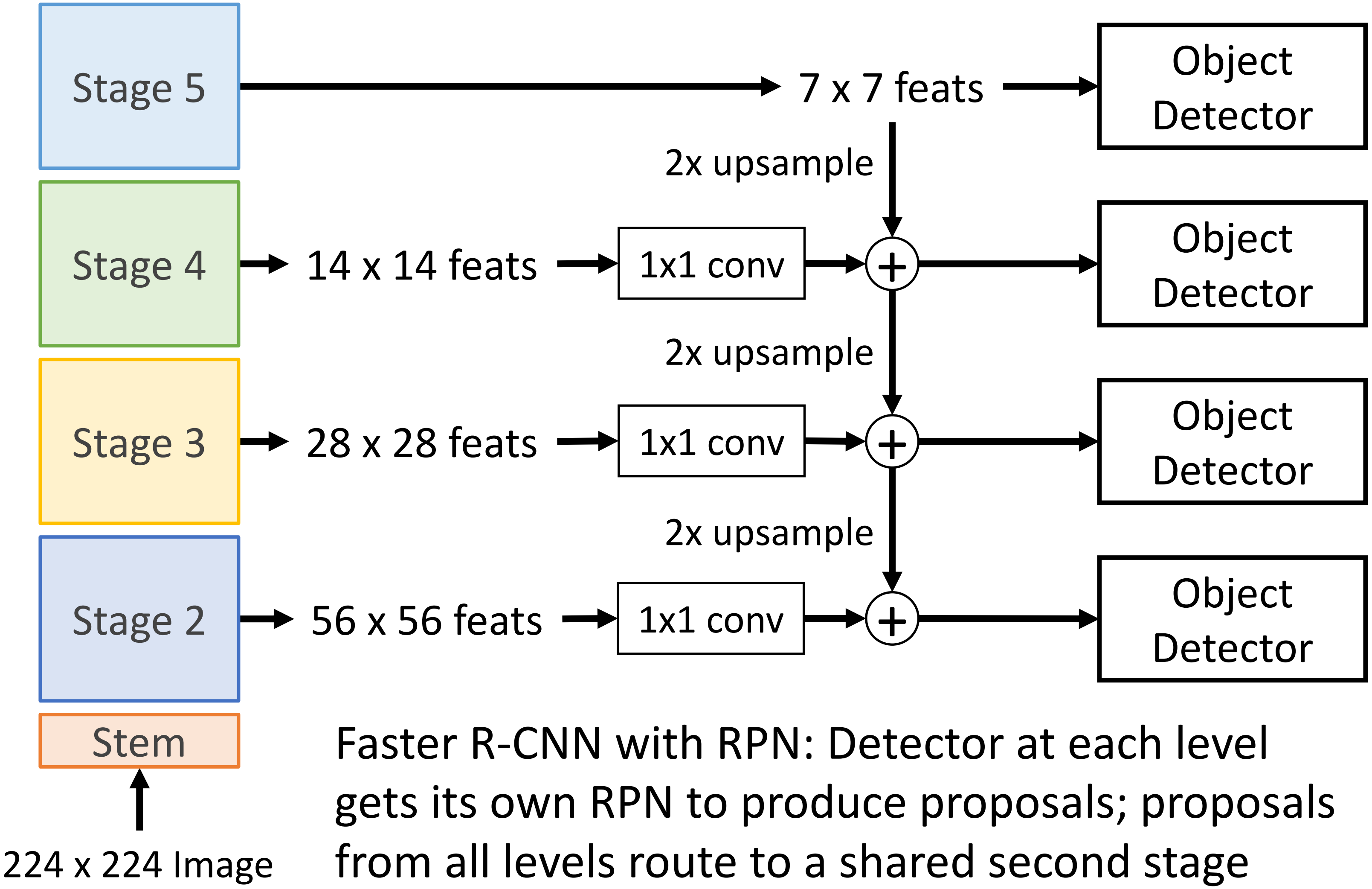


Faster R-CNN with RPN: Detector at each level gets its own RPN to produce proposals; proposals from all levels route to a shared second stage

Lin et al, "Feature Pyramid Networks for Object Detection", ICCV 2017

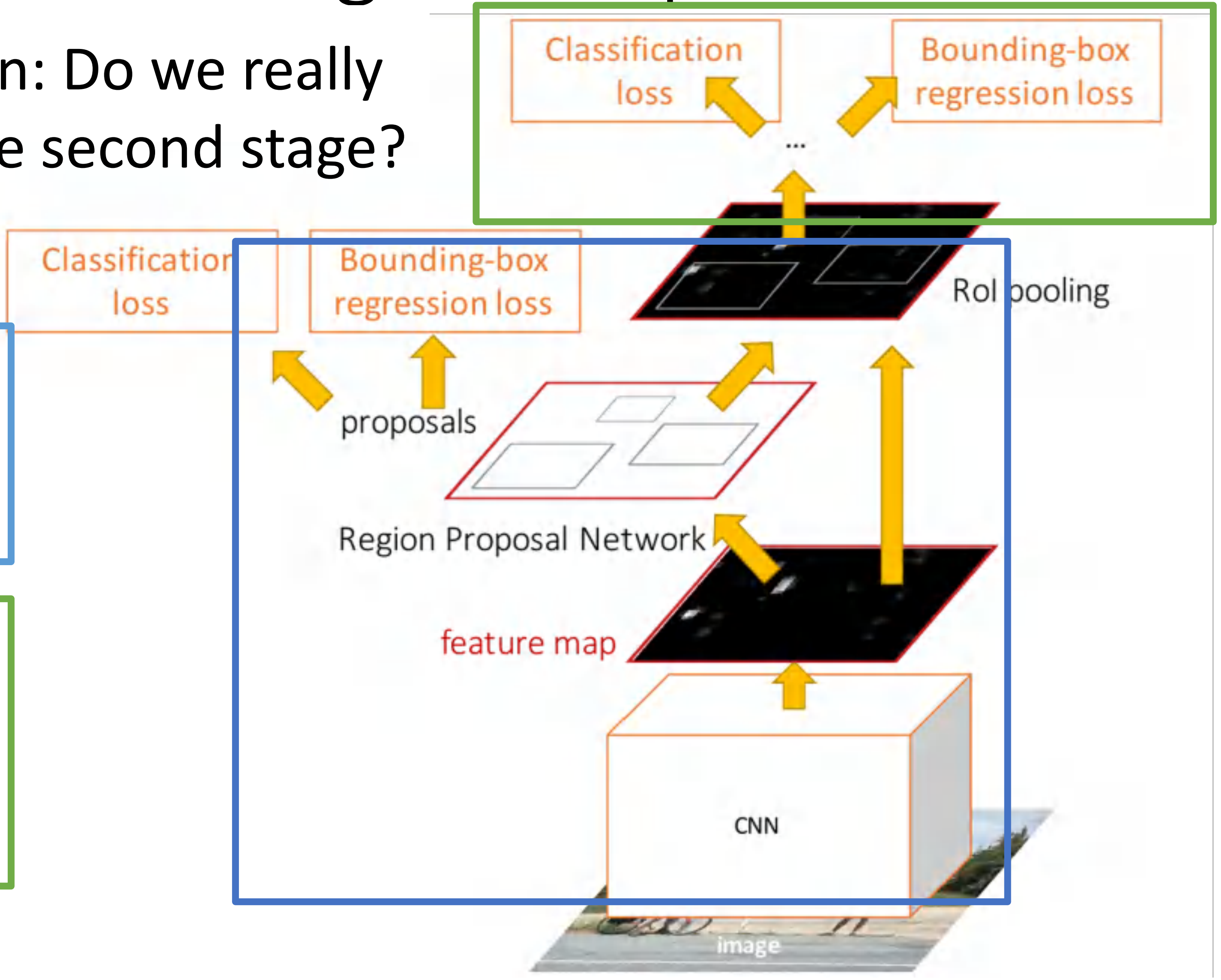
Faster R-CNN: Learnable Region Proposals

Question: Do we really need the second stage?

Faster R-CNN is a
Two-stage object detector

First stage: Run once per image
- Backbone network
- Region proposal network

Second stage: Run once per region
- Crop features: RoI pool / align
- Predict object class
- Prediction bbox offset

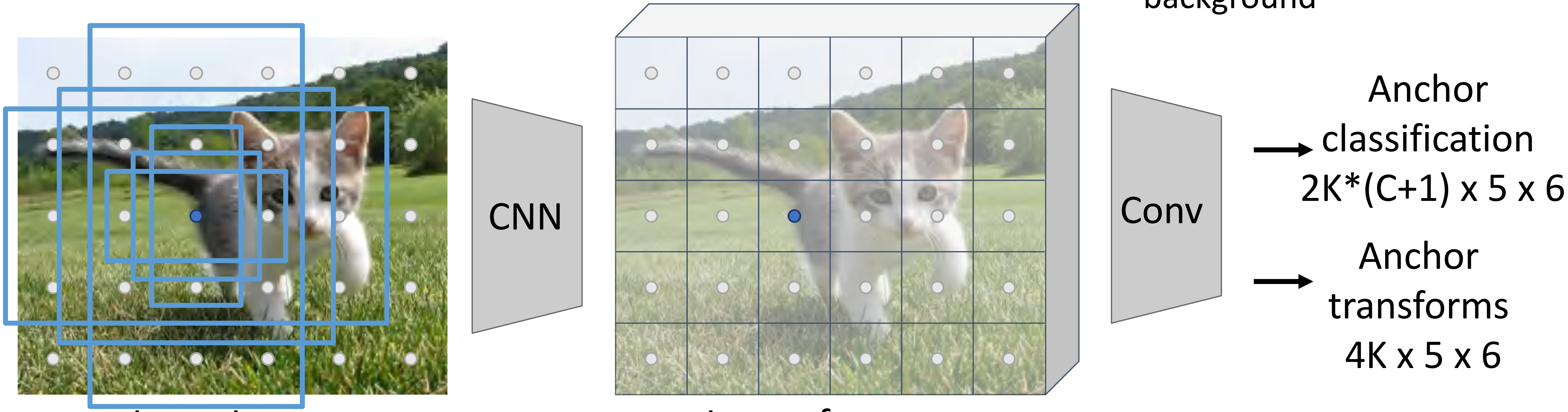


Single-Stage Detectors: RetinaNet

Similar to RPN – but rather than classify anchors as object/no object, directly predict object category (among C categories) or background

Run backbone CNN to get features aligned to input image

Each feature corresponds to a point in the input



Input Image
(e.g. 3 x 640 x 480)

Image features
(e.g. 512 x 5 x 6)

Lin et al, "Focal Loss for Dense Object Detection", ICCV 2017

Single-Stage Detectors: RetinaNet

Problem: class imbalance – many more background anchors vs non-background

Run backbone CNN to get features aligned to input image

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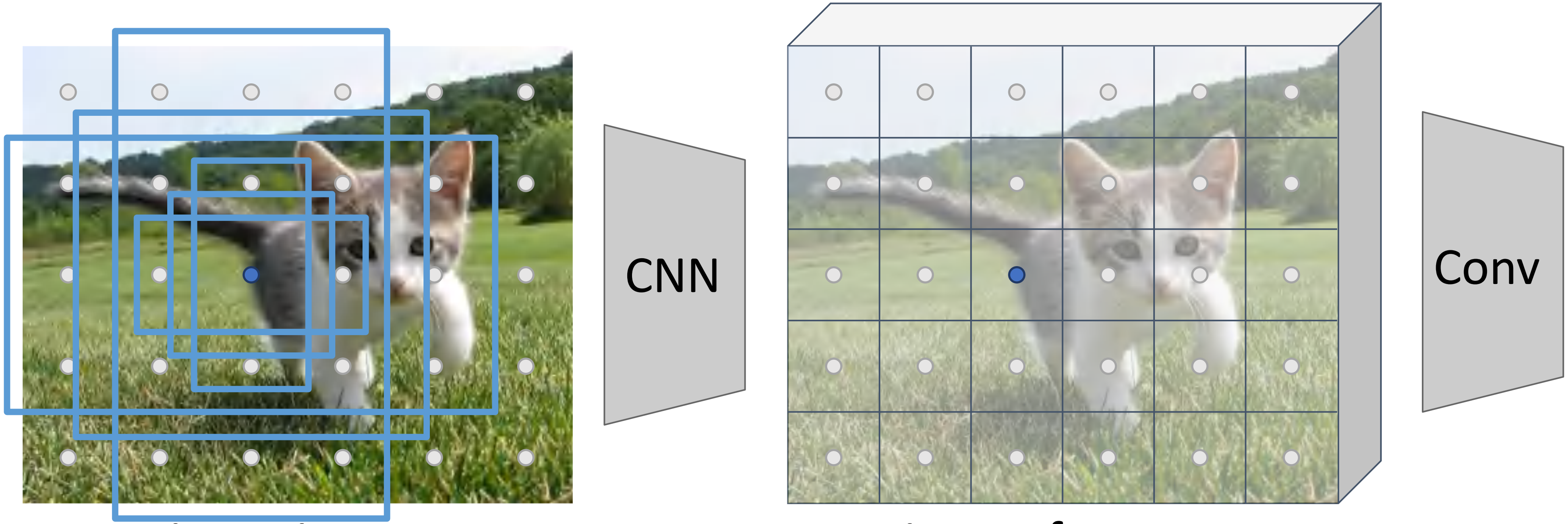


Input Image
(e.g. 3 x 640 x 480)

Image features
(e.g. 512 x 5 x 6)

Anchor classification
2K*(C+1) x 5 x 6

Anchor transforms
4K x 5 x 6

Lin et al, "Focal Loss for Dense Object Detection", ICCV 2017

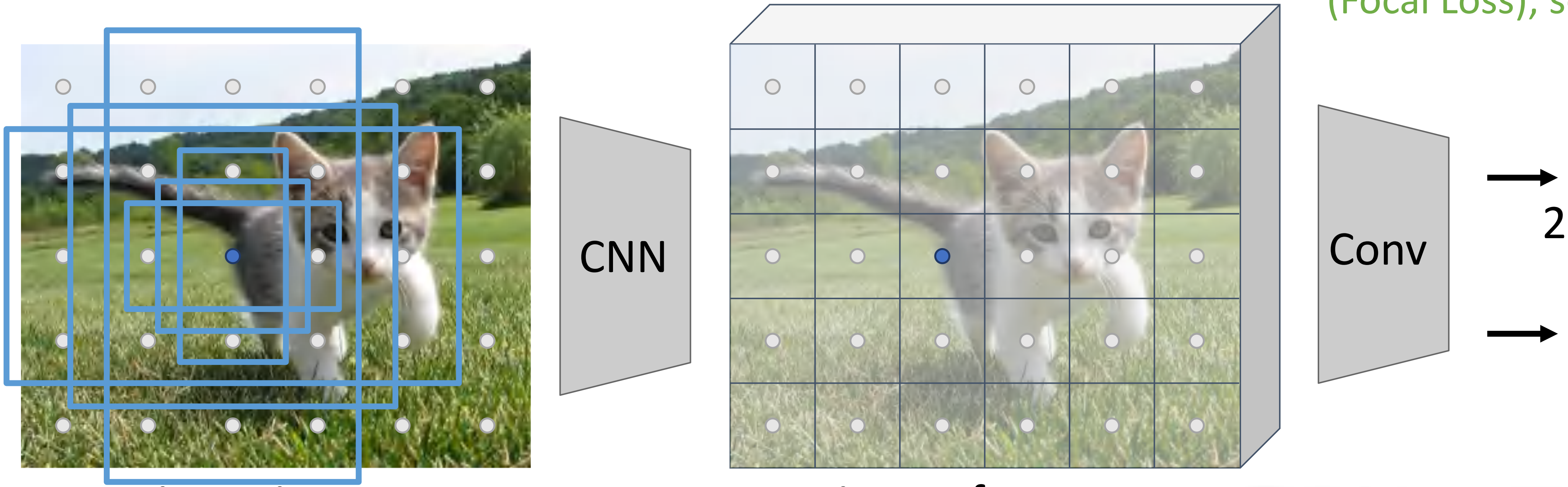
Single-Stage Detectors: RetinaNet

Problem: class imbalance – many more background anchors vs non-background

Solution: new loss function (Focal Loss); see paper

Run backbone CNN to get features aligned to input image

Each feature corresponds to a point in the input



Anchor classification
2K*(C+1) x 5 x 6

Anchor transforms
4K x 5 x 6

Input Image
(e.g. 3 x 640 x 480)

Image features
(e.g. 512 x 5 x 6)

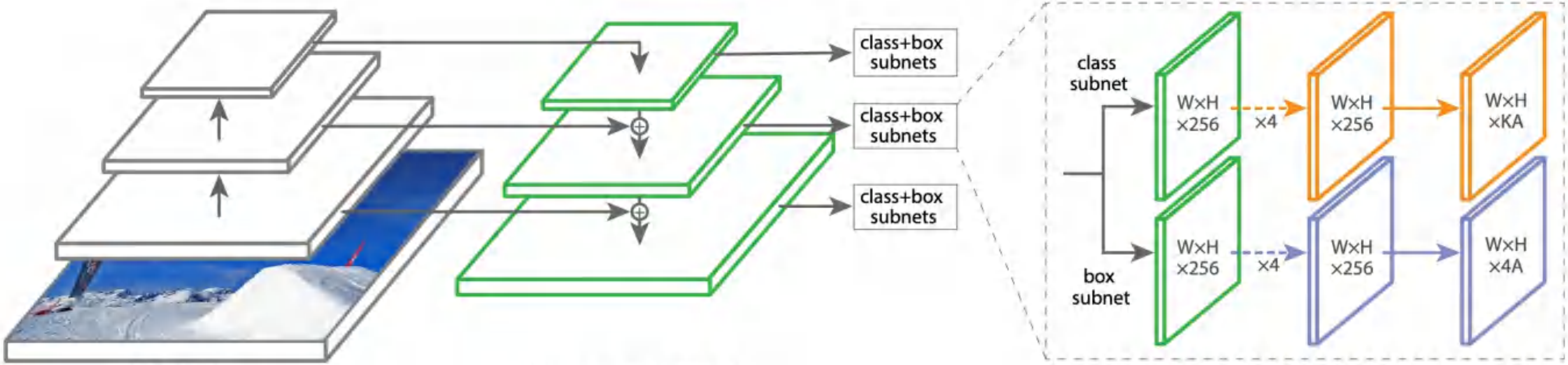
$$\mathrm{CE}(p_t) = -\log(p_t)$$

$$\mathrm{FL}(p_t) = -(1-p_t)^{\gamma}\log(p_t)$$

Lin et al, "Focal Loss for Dense Object Detection", ICCV 2017

Single-Stage Detectors: RetinaNet

In practice, RetinaNet also uses Feature Pyramid Network to handle multiscale



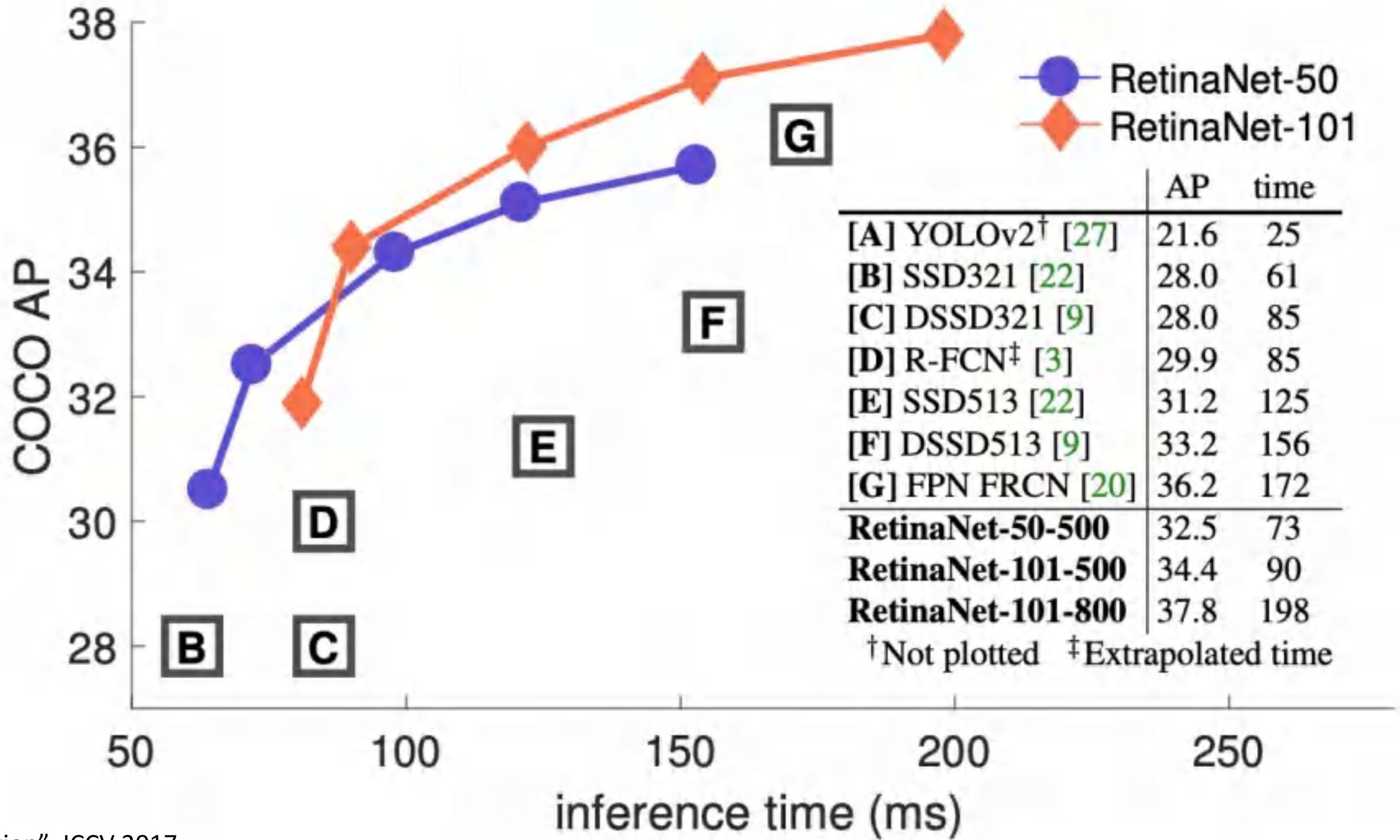
(a) ResNet (b) feature pyramid net (c) class subnet (top) (d) box subnet (bottom)

Lin et al, “Focal Loss for Dense Object Detection”, ICCV 2017

Figure credit: Lin et al, ICCV 2017

Single-Stage Detectors: RetinaNet

Single-Stage detectors can be much faster than two-stage detectors



Lin et al, "Focal Loss for Dense Object Detection", ICCV 2017

Figure credit: Lin et al, ICCV 2017

Single-Stage Detectors: RetinaNet

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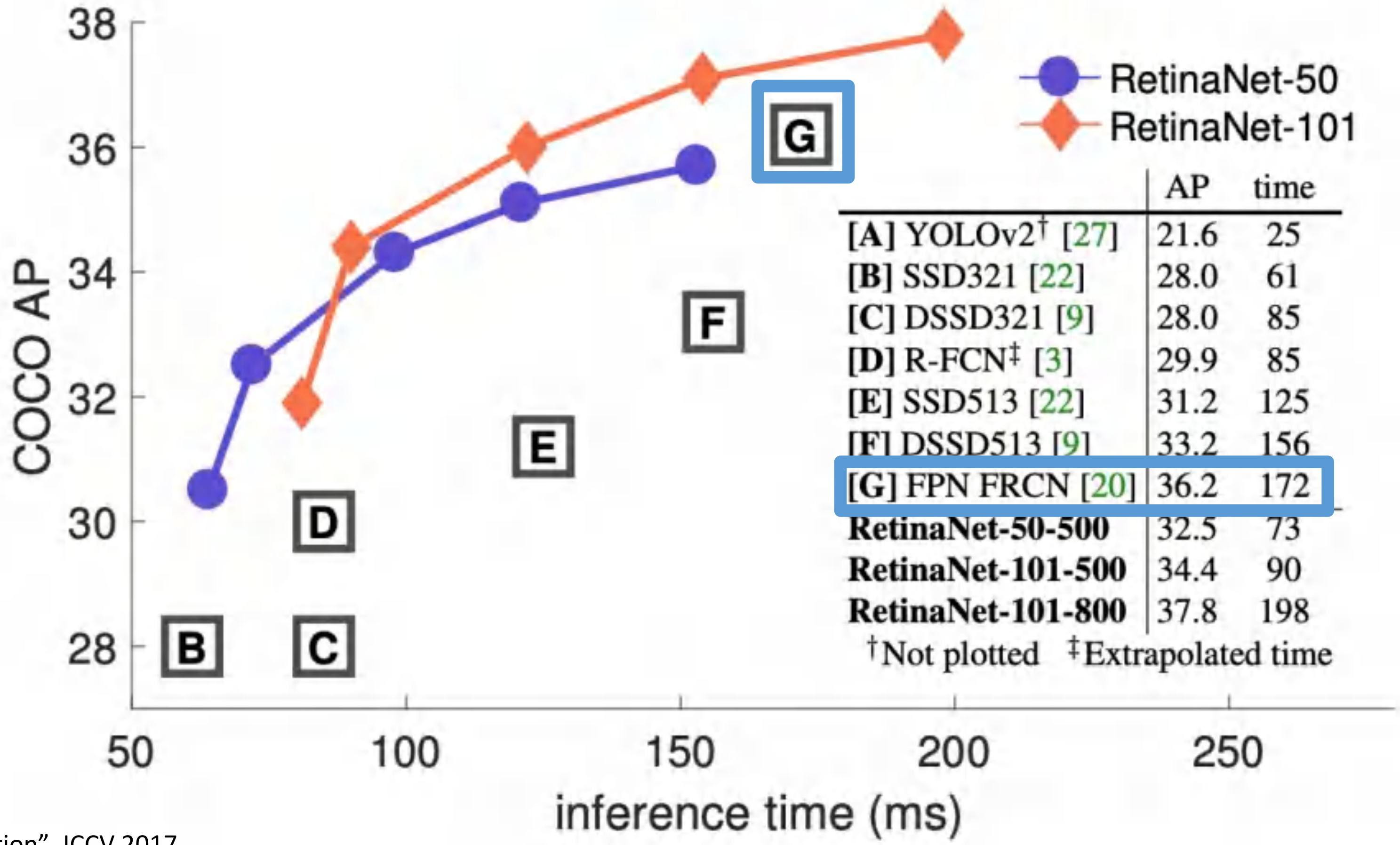

	AP	time
[A] YOLOv2† [27]	21.6	25
[B] SSD321 [22]	28.0	61
[C] DSSD321 [9]	28.0	85
[D] R-FCN‡ [3]	29.9	85
[E] SSD513 [22]	31.2	125
[F] DSSD513 [9]	33.2	156
[G] FPN FRCN [20]	36.2	172
RetinaNet-50-500	32.5	73
RetinaNet-101-500	34.4	90
RetinaNet-101-800	37.8	198

†Not plotted ‡Extrapolated time

Faster R-CNN with Feature Pyramid Network

Lin et al, "Focal Loss for Dense Object Detection", ICCV 2017

Figure credit: Lin et al, ICCV 2017

"Anchor-free" detector

Single-Stage Detectors: FCOS

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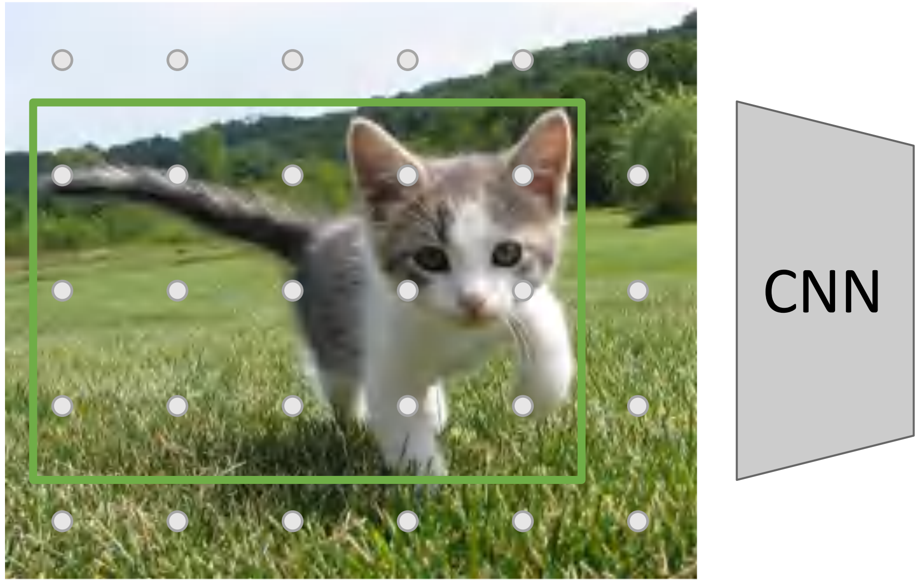
Each feature corresponds to a point in the input



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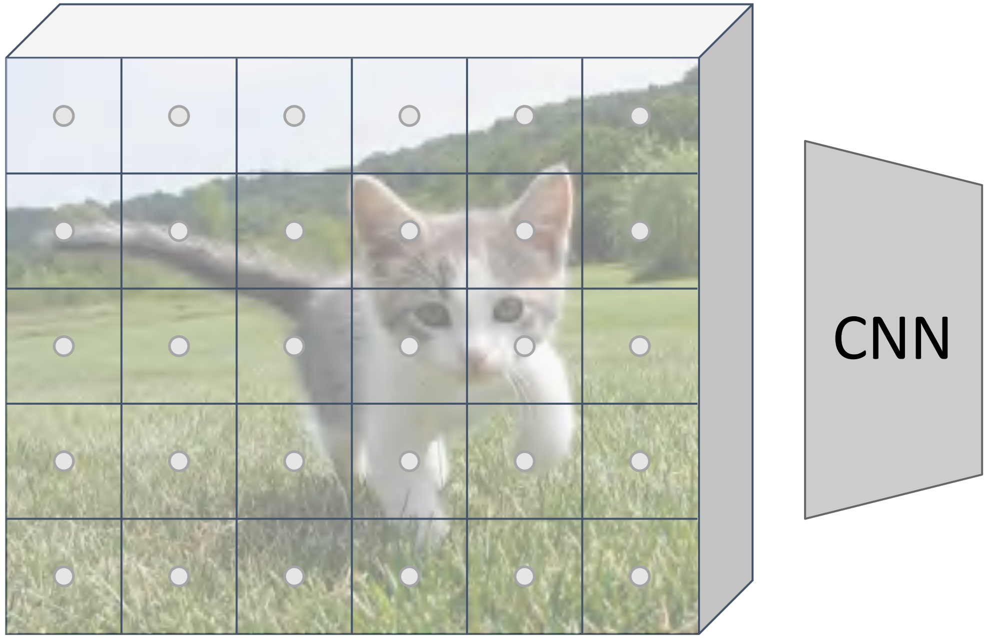


Image features
(e.g. 512 x 5 x 6)

Tian et al, "FCOS: Fully Convolutional One-Stage Object Detection", ICCV 2019

Single-Stage Detectors: FCOS

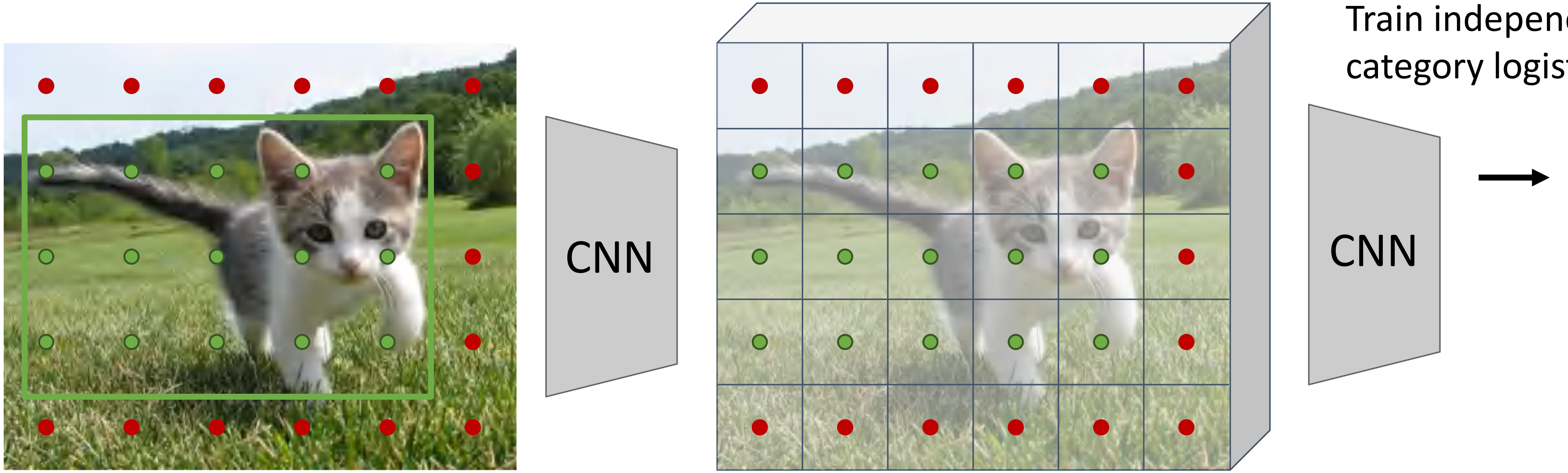
"Anchor-free" detector

Classify points as positive if they fall into a GT box, or negative if they don't

Train independent per-category logistic regressors

Run backbone CNN to get features aligned to input image

Each feature corresponds to a point in the input



Class scores
C x 5 x 6

Input Image
(e.g. 3 x 640 x 480)

Image features
(e.g. 512 x 5 x 6)

Tian et al, "FCOS: Fully Convolutional One-Stage Object Detection", ICCV 2019

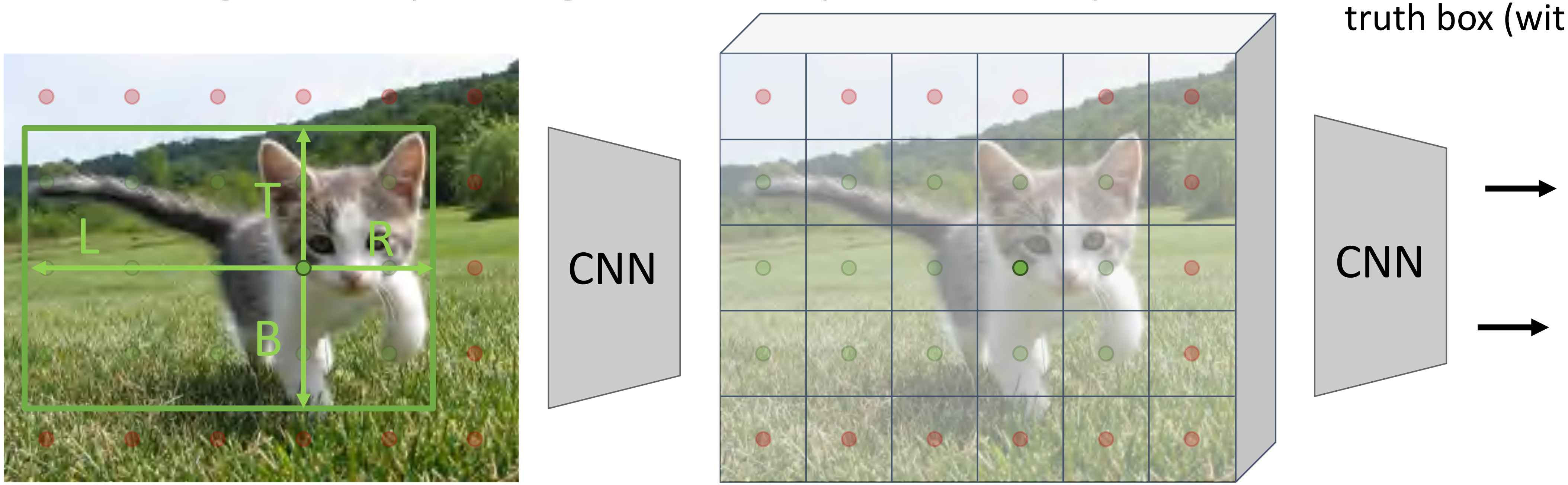
Single-Stage Detectors: FCOS

"Anchor-free" detector

Run backbone CNN to get features aligned to input image

Each feature corresponds to a point in the input

For positive points, also regress distance to left, right, top, and bottom of ground-truth box (with L2 loss)



Class scores
C x 5 x 6

Box edges
4 x 5 x 6

Input Image
(e.g. 3 x 640 x 480)

Image features
(e.g. 512 x 5 x 6)

Tian et al, "FCOS: Fully Convolutional One-Stage Object Detection", ICCV 2019

Single-Stage Detectors: FCOS

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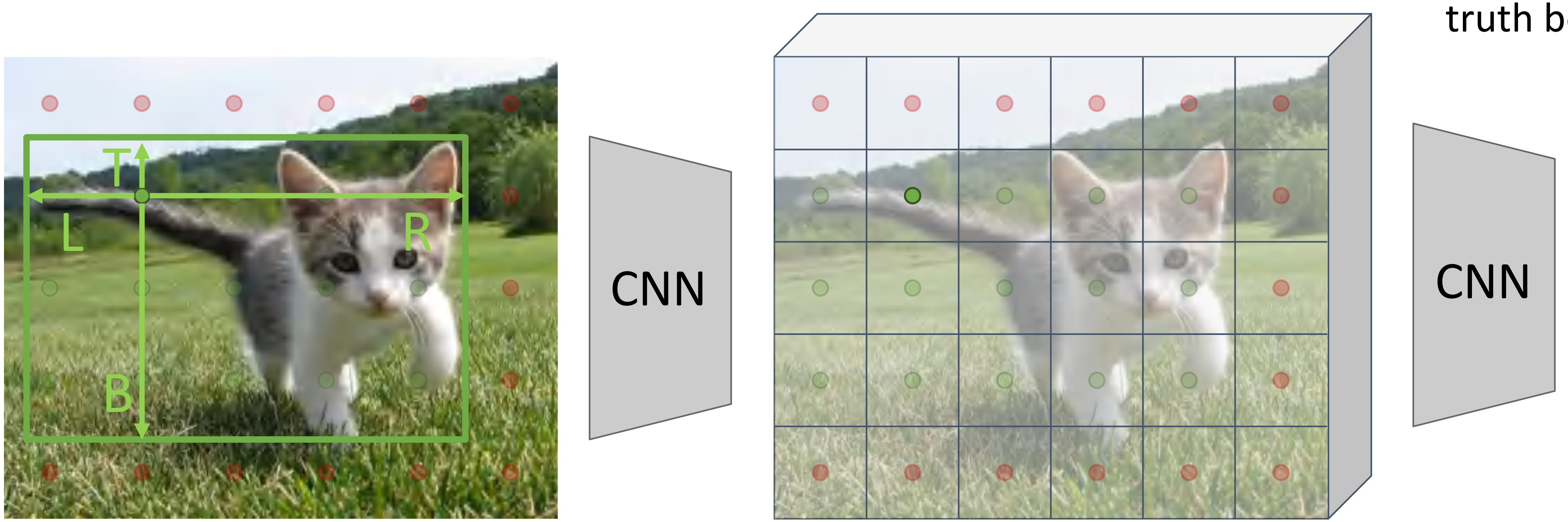

Class scores
C x 5 x 6

Box edges
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Input Image
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Tian et al, "FCOS: Fully Convolutional One-Stage Object Detection", ICCV 2019

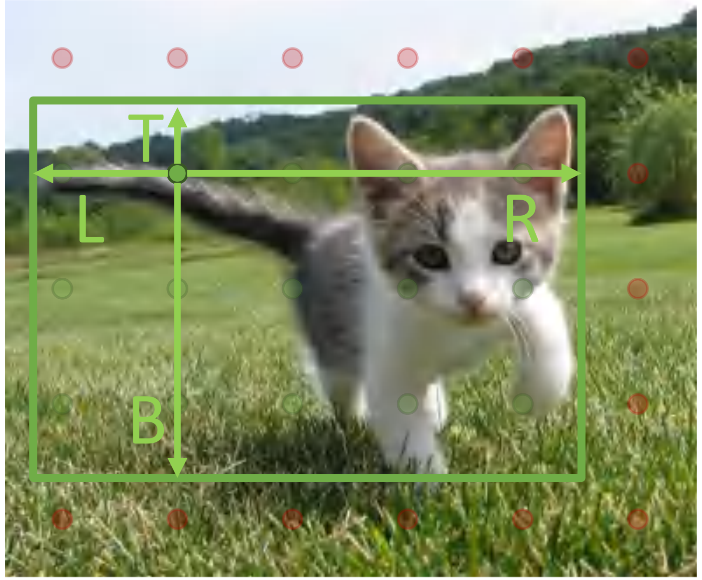
Single-Stage Detectors: FCOS

"Anchor-free" detector

Run backbone CNN to get features aligned to input image

Each feature corresponds to a point in the input

Finally, predict "centerness" for all positive points (using logistic regression loss)



Input Image
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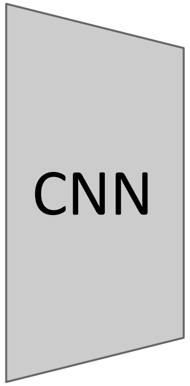


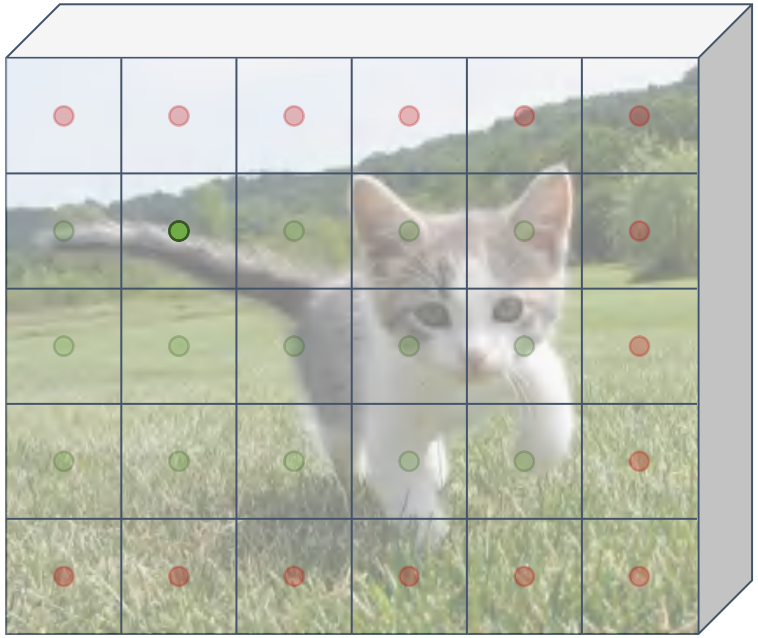
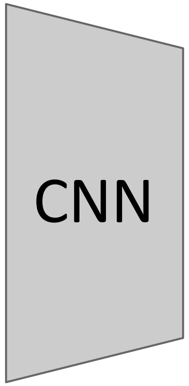


Image features
(e.g. 512 x 5 x 6)



Class scores
C x 5 x 6

Box edges
4 x 5 x 6

Centerness
1 x 5 x 6

$$centerness = \sqrt{\frac{\min(L,R)}{\max(L,R)} \cdot \frac{\min(T,B)}{\max(T,B)}}$$

Ranges from 1 at box center to 0 at box edge

Tian et al, "FCOS: Fully Convolutional One-Stage Object Detection", ICCV 2019

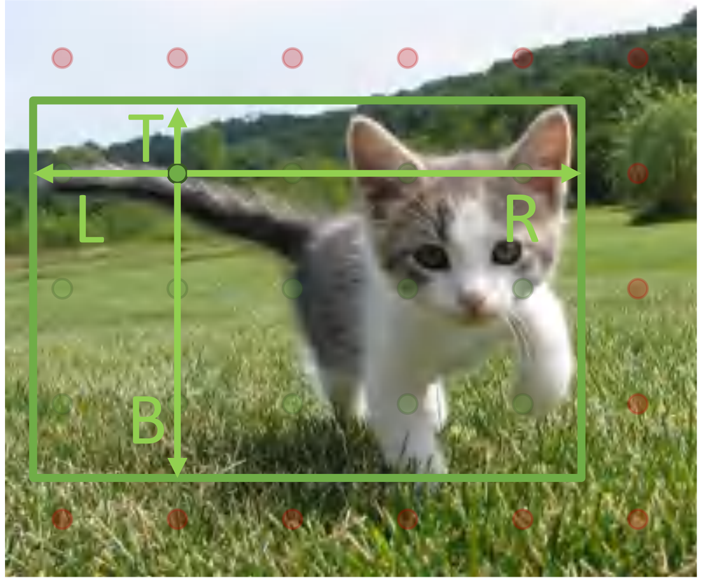
Single-Stage Detectors: FCOS

"Anchor-free" detector

Test-time: predicted "confidence" for the box from each point is product of its class score and centerness

Run backbone CNN to get features aligned to input image

Each feature corresponds to a point in the input



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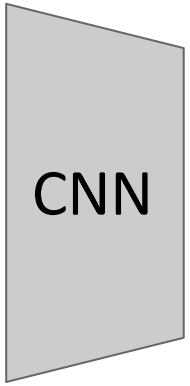

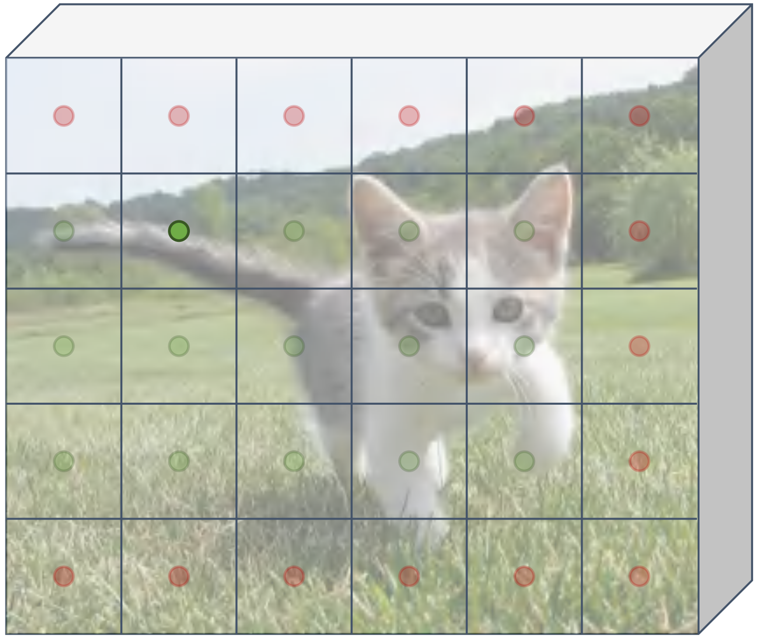

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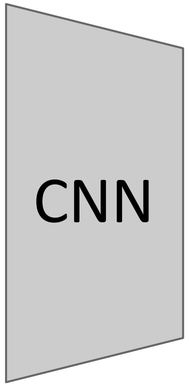


→ Class scores
C x 5 x 6

→ Box edges
4 x 5 x 6

→ Centerness
1 x 5 x 6

$$centerness = \sqrt{\frac{\min(L,R)}{\max(L,R)} \cdot \frac{\min(T,B)}{\max(T,B)}}$$

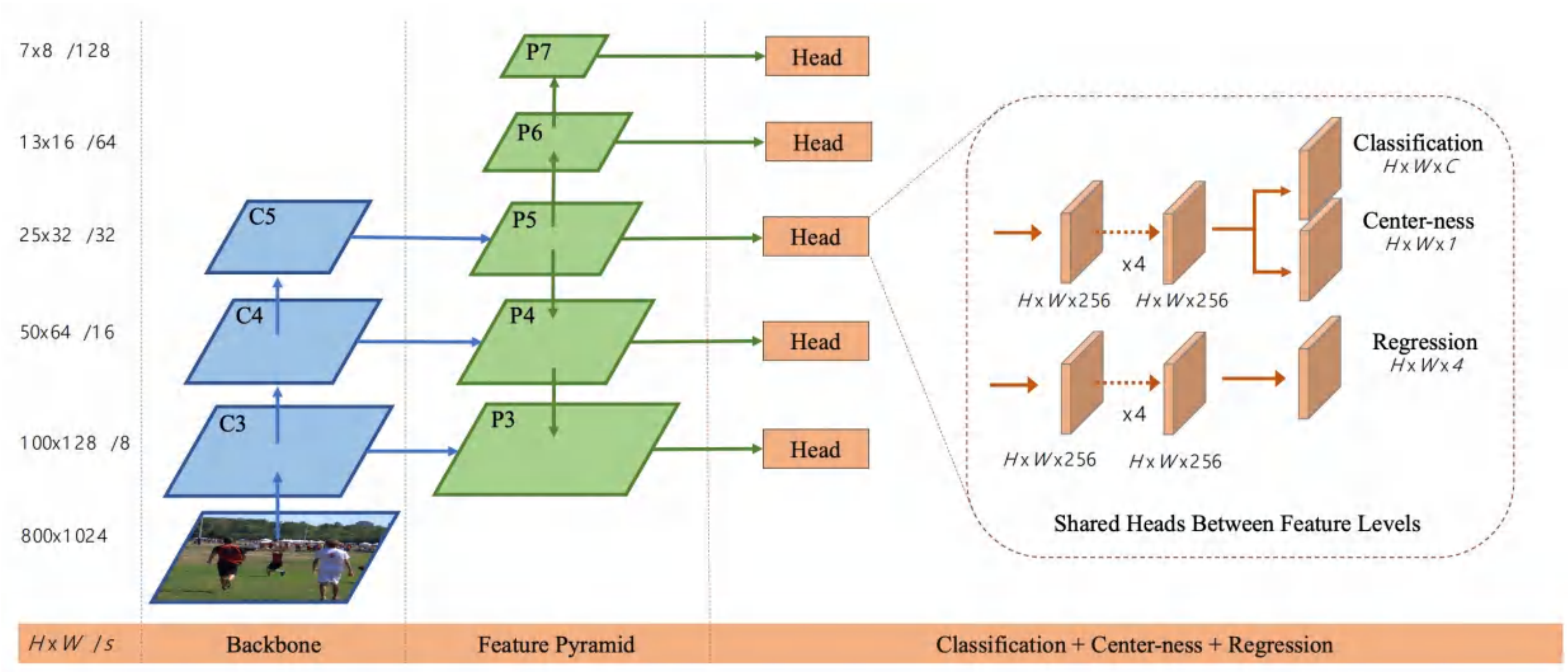
Ranges from 1 at box center to 0 at box edge

Tian et al, "FCOS: Fully Convolutional One-Stage Object Detection", ICCV 2019

Single-Stage Detectors: FCOS

"Anchor-free" detector

FCOS also uses a Feature Pyramid Network with heads shared across stages

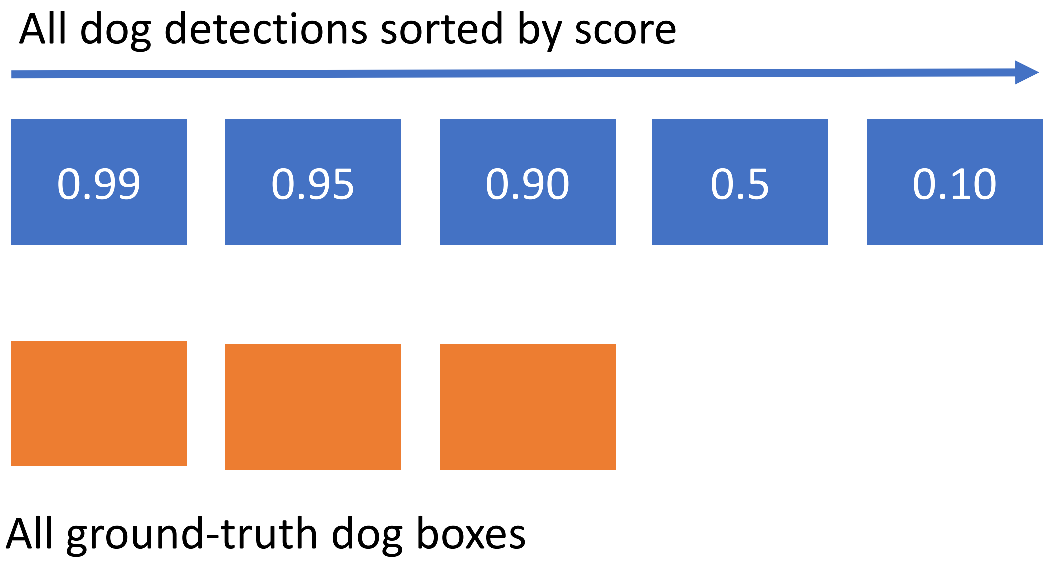


Tian et al, "FCOS: Fully Convolutional One-Stage Object Detection", ICCV 2019

Evaluating Object Detectors: Mean Average Precision (mAP)

1. Run object detector on all test images (with NMS)
2. For each category, compute Average Precision (AP) = area under Precision vs Recall Curve

Evaluating Object Detectors: Mean Average Precision (mAP)



1. Run object detector on all test images (with NMS)
2. For each category, compute Average Precision (AP) = area under Precision vs Recall Curve
    1. For each detection (highest score to lowest score)

Evaluating Object Detectors: Mean Average Precision (mAP)

1. Run object detector on all test images (with NMS)
2. For each category, compute Average Precision (AP) = area under Precision vs Recall Curve
   1. For each detection (highest score to lowest score)
      1. If it matches some GT box with IoU > 0.5, mark it as positive and eliminate the GT
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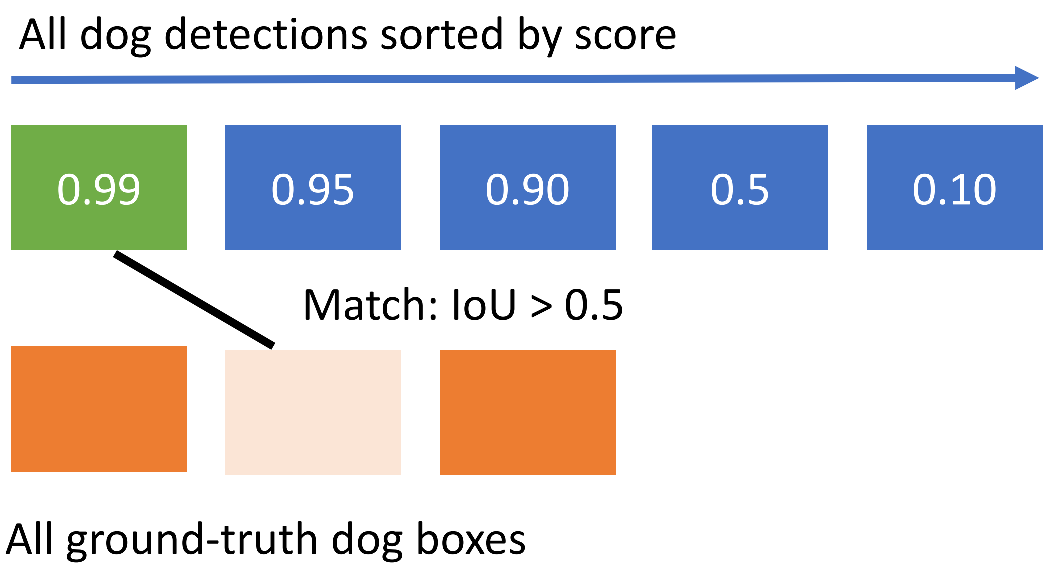

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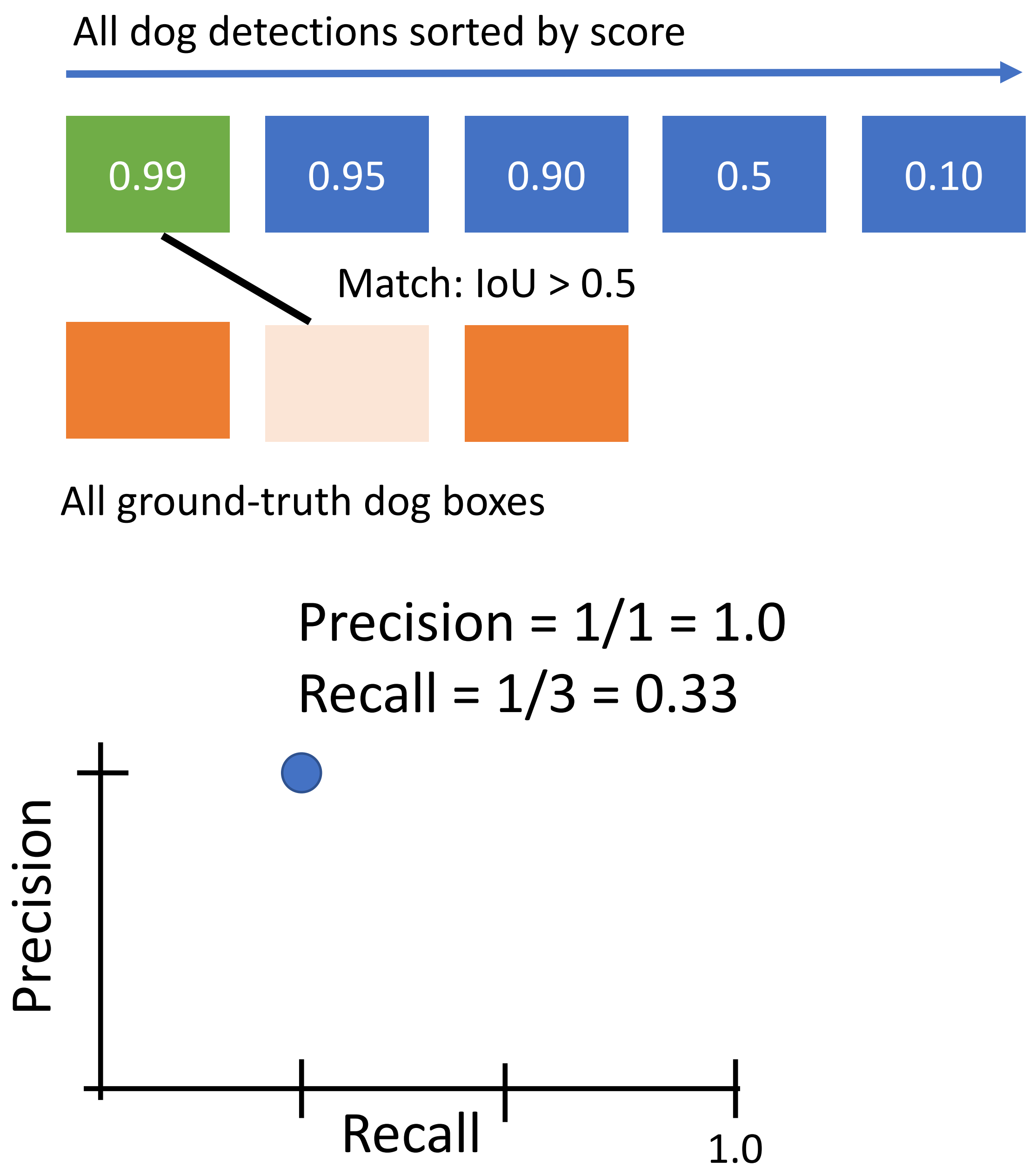
        3. Plot a point on PR Curve



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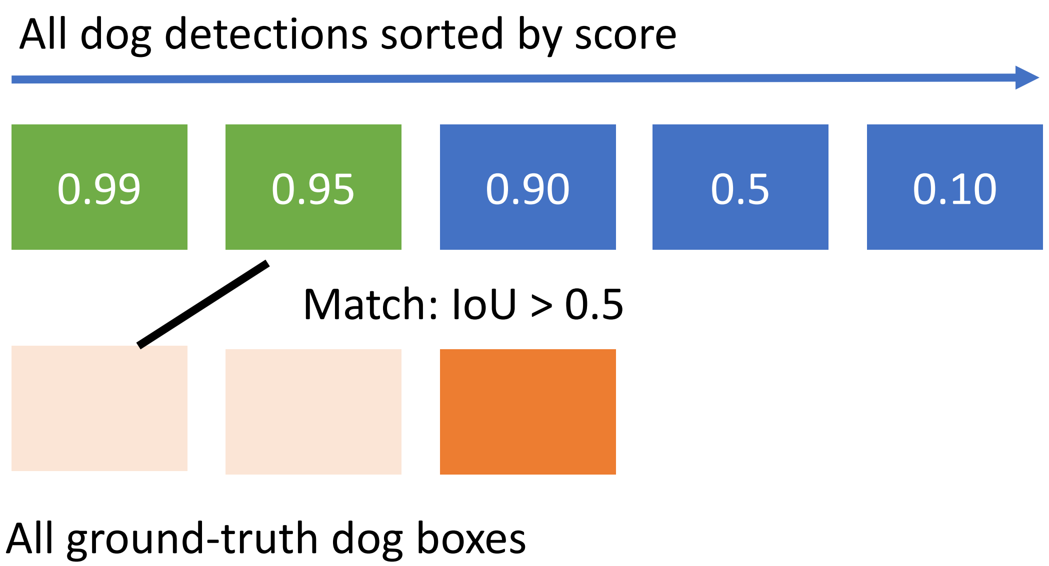
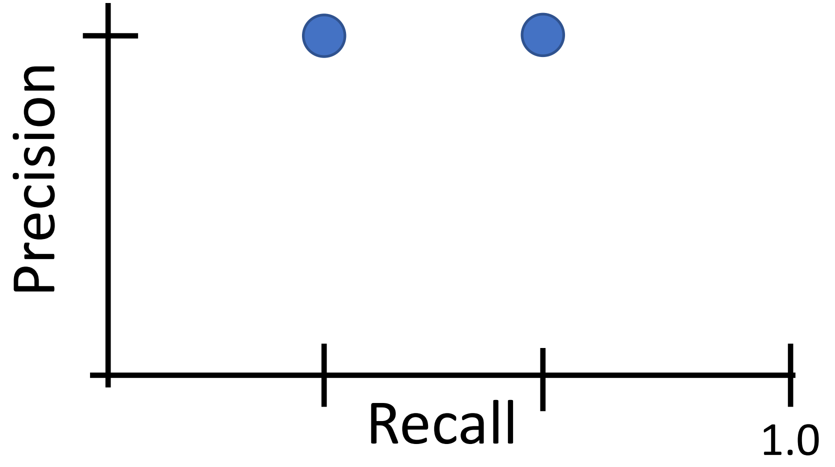


Precision = 2/2 = 1.0
Recall = 2/3 = 0.67



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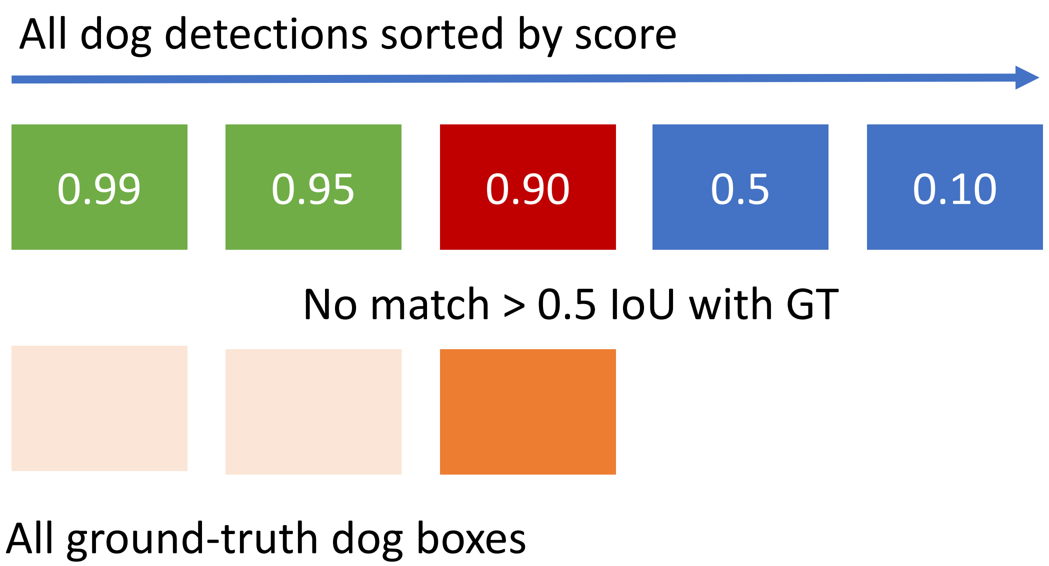
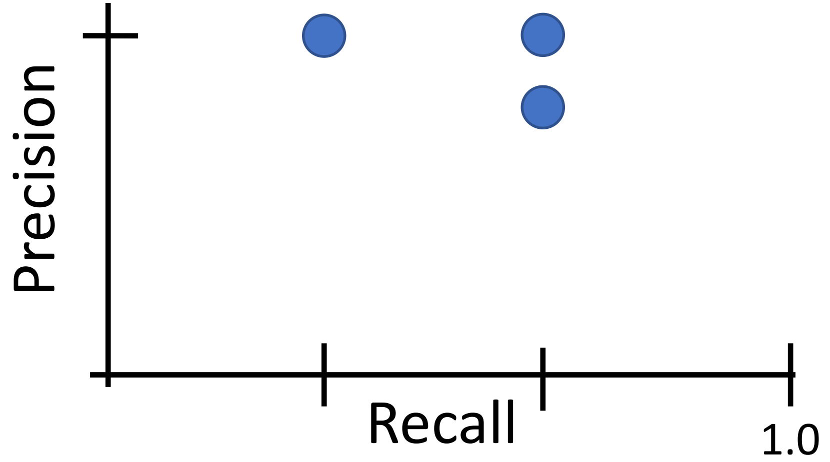


Precision = 2/3 = 0.67
Recall = 2/3 = 0.67



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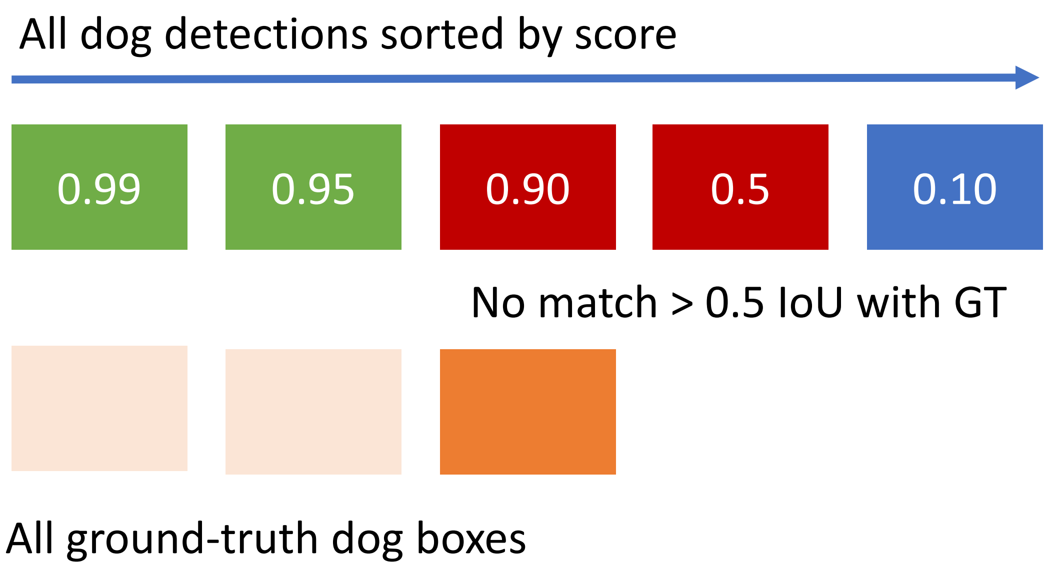
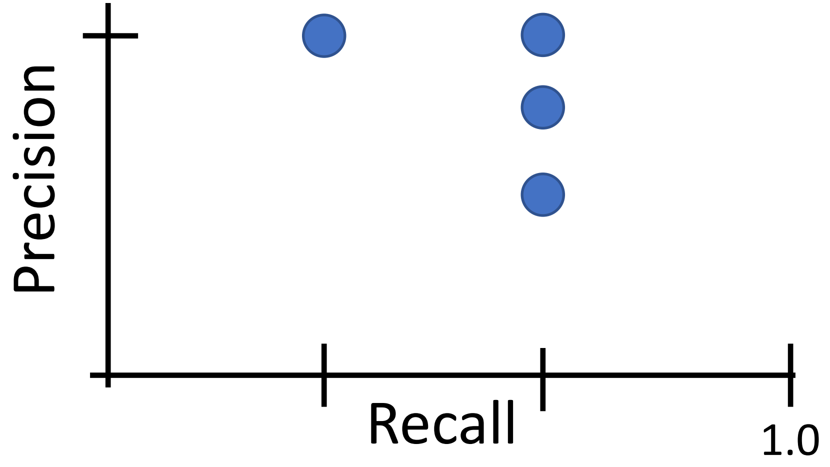


Precision = 2/4 = 0.5
Recall = 2/3 = 0.67



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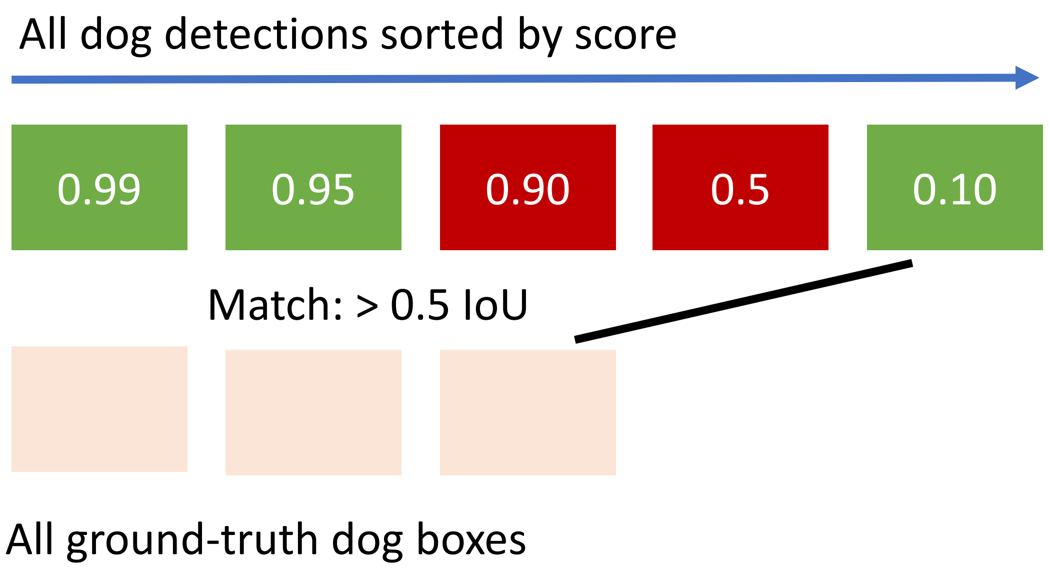
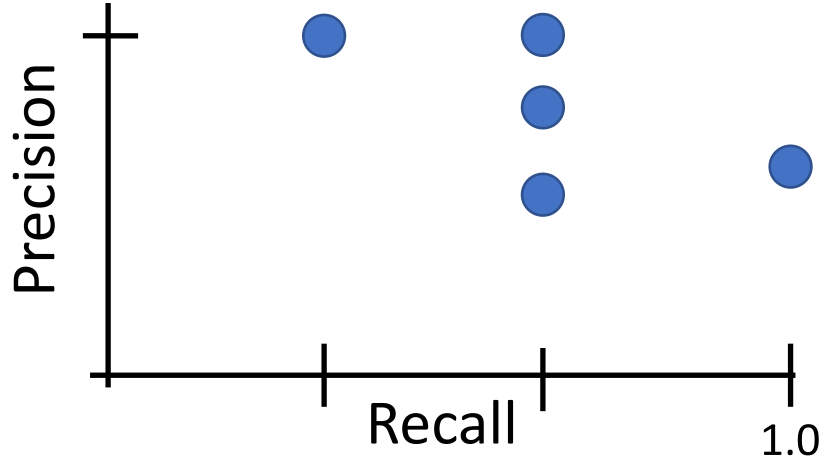


Precision = 3/5 = 0.6

Recall = 3/3 = 1.0



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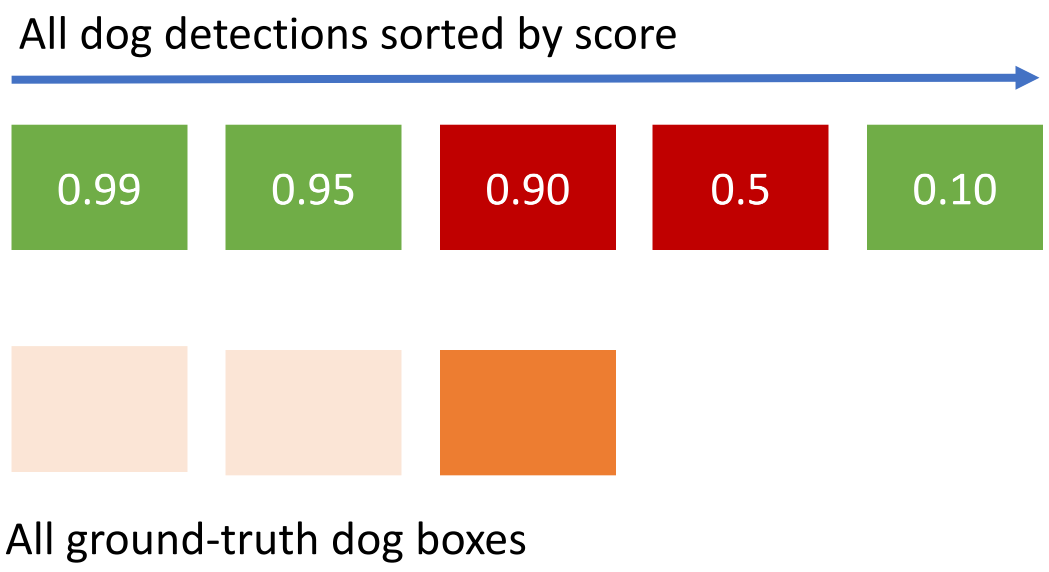
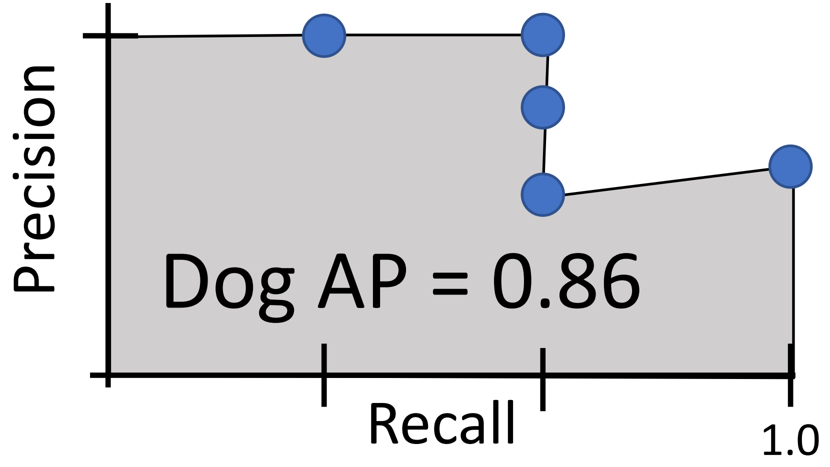
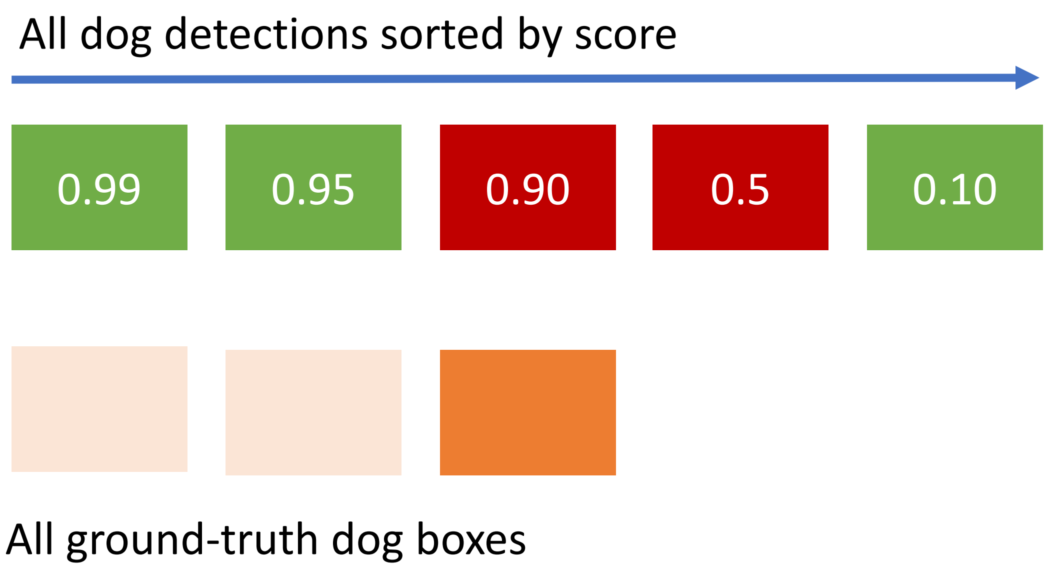
      3. Plot a point on PR Curve
   2. Average Precision (AP) = area under PR curve





Evaluating Object Detectors: Mean Average Precision (mAP)



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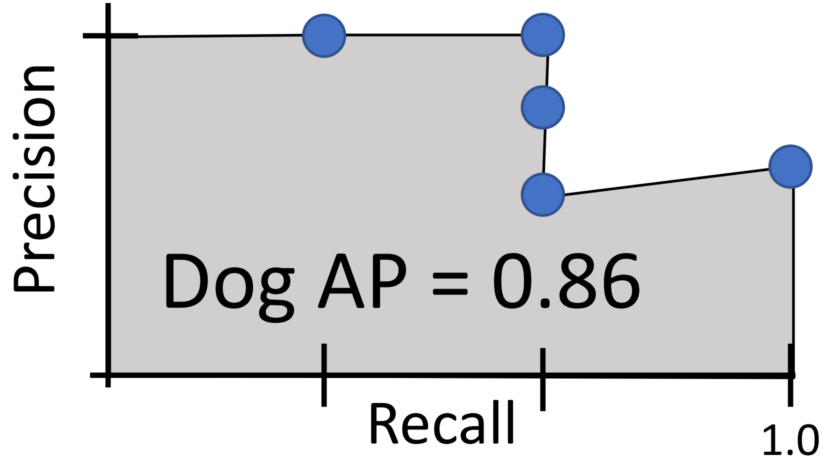
        3. Plot a point on PR Curve
    2. Average Precision (AP) = area under PR curve

How to get AP = 1.0: Hit all GT boxes with IoU > 0.5, and have no "false positive" detections ranked above any "true positives"



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   1. For each detection (highest score to lowest score)
      1. If it matches some GT box with IoU > 0.5, mark it as positive and eliminate the GT
      2. Otherwise mark it as negative
      3. Plot a point on PR Curve
   2. Average Precision (AP) = area under PR curve
3. Mean Average Precision (mAP) = average of AP for each category

Car AP = 0.65

Cat AP = 0.80

Dog AP = 0.86

mAP@0.5 = 0.77

Evaluating Object Detectors: Mean Average Precision (mAP)

1. Run object detector on all test images (with NMS)
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   1. For each detection (highest score to lowest score)
      1. If it matches some GT box with IoU > 0.5, mark it as positive and eliminate the GT
      2. Otherwise mark it as negative
      3. Plot a point on PR Curve
   2. Average Precision (AP) = area under PR curve
3. Mean Average Precision (mAP) = average of AP for each category
4. For "COCO mAP": Compute mAP@thresh for each IoU threshold (0.5, 0.55, 0.6, …, 0.95) and take average

mAP@0.5 = 0.77

mAP@0.55 = 0.71

mAP@0.60 = 0.65

…

mAP@0.95 = 0.2

COCO mAP = 0.4

Summary: Beyond Image Classification

Classification

CAT

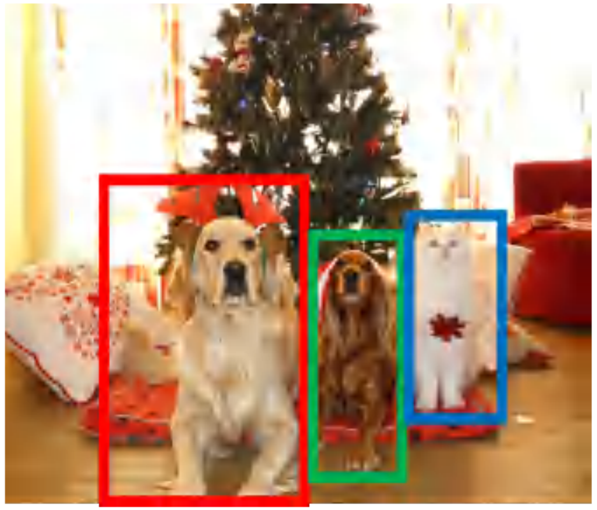
No spatial extent

Semantic Segmentation

GRASS, CAT, TREE, SKY

No objects, just pixels

Object Detection



DOG, DOG, CAT

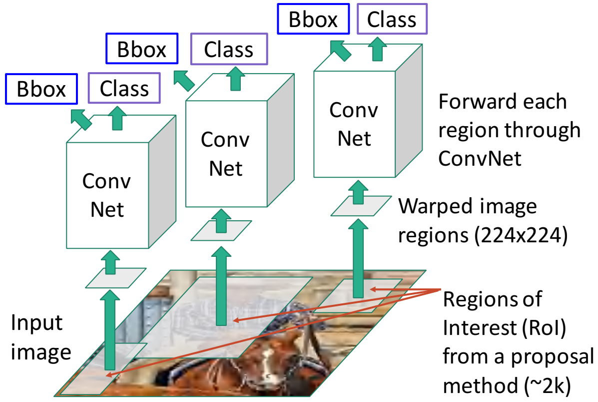
Instance Segmentation

DOG, DOG, CAT

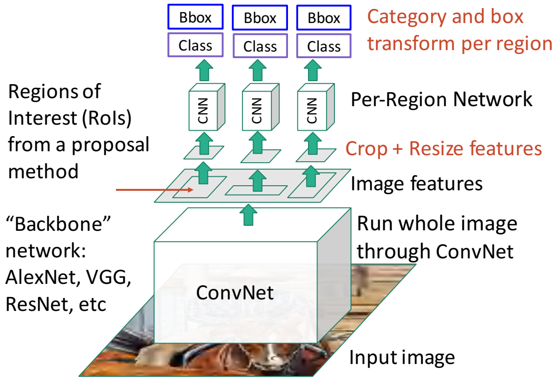
Multiple Objects

Summary

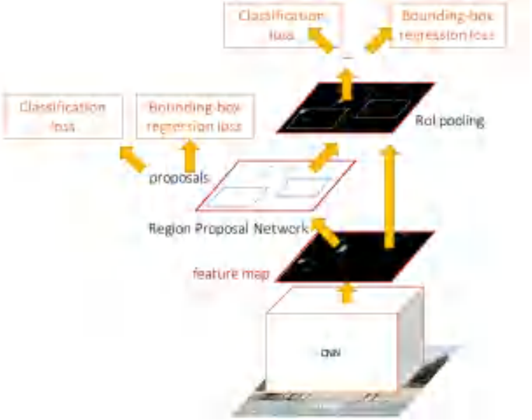
"Slow" R-CNN: Run CNN independently for each region



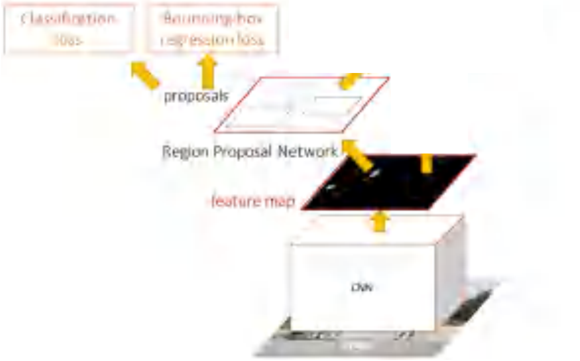
Fast R-CNN: Apply differentiable cropping to shared image features



Faster R-CNN: Compute proposals with CNN



Single-Stage: Fully convolutional detector



With anchors: RetinaNet
Anchor-Free: FCOS

Next time:
Image and Instance Segmentation