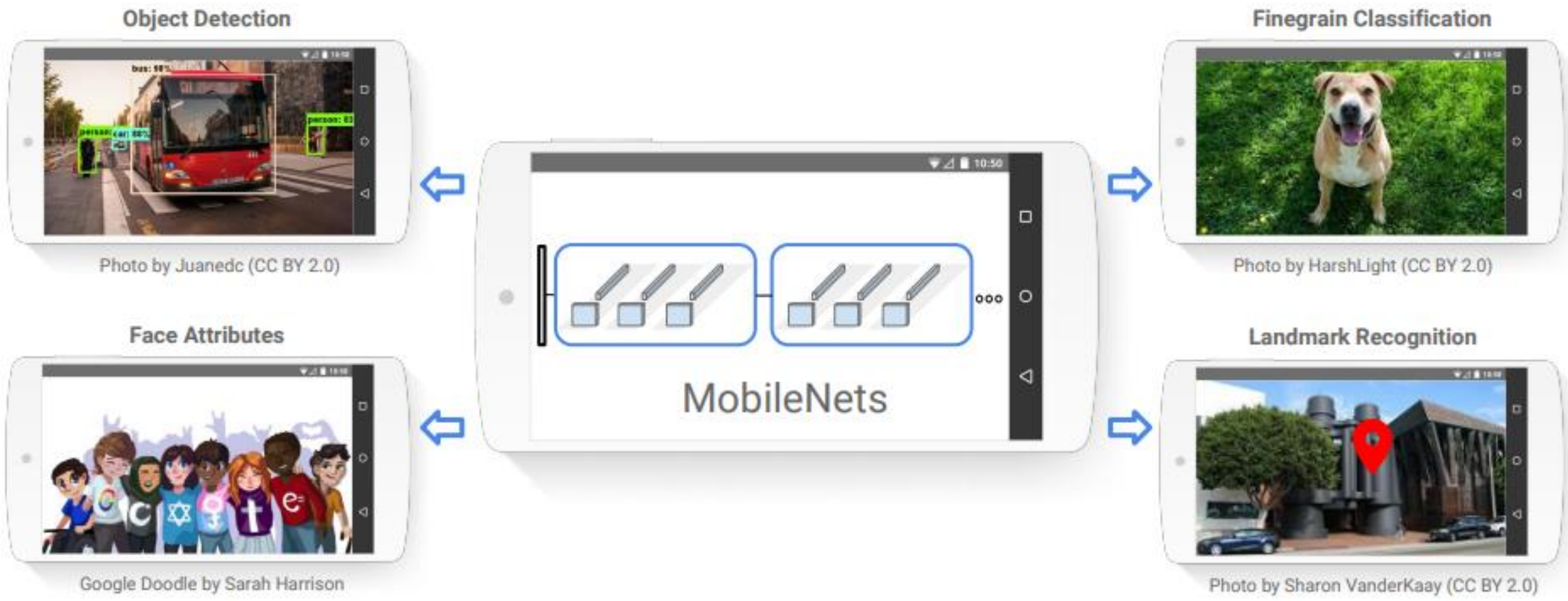
MobileNets: Efficient Convolutional Neural Networks for Mobile Vision Applications (CVPR 2017)

- **연구동기:**
  휴대폰이나 임베디드 시스템같은 저용량 메모리 환경에 딥러닝 적용을 위한 **모델 경량화** 필수.
  Depthwise Separable Convolution을 사용한 MobileNet 제안.
  Application 환경에 따른 적절한 설계를 위한 2개의 hyperparameter(width multiplier, resolution multiplier)
  -> latency, accuracy 균형 조절



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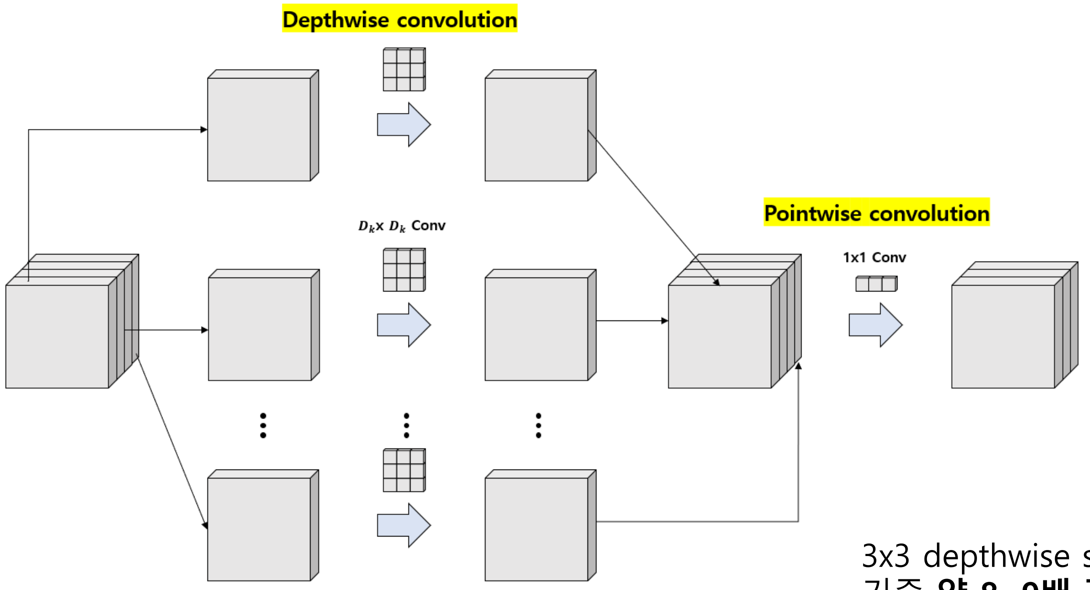
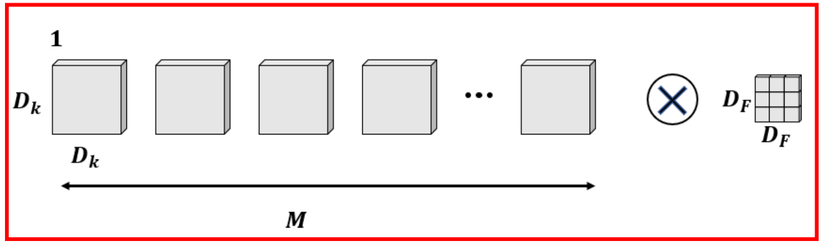
- **Method:**
  모델의 첫 번째 layer를 제외하고 모두 depthwise separable convolution으로 변경해 적용.
  Depthwise convolution + **Pointwise convolution** => 연산량↓ + 모델 크기↓

Depthwise Separable Convolution

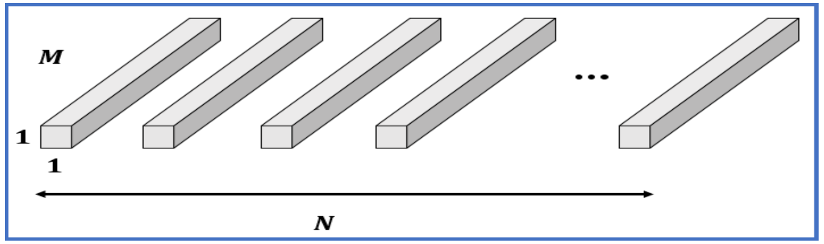


3x3 depthwise separable conv
기준 **약 8~9배 적은 연산량**

Depthwise Convolution ($D_K \cdot D_K \cdot M \cdot D_F \cdot D_F$)



Pointwise Convolution ($M \cdot N \cdot D_F \cdot D_F$)



Computational cost

Depthwise Separable Convolution

General Convolution

$$\frac{\boxed{M \cdot N \cdot D_F \cdot D_F + D_K \cdot D_K \cdot M \cdot D_F \cdot D_F}}{\boxed{D_K \cdot D_K \cdot M \cdot N \cdot D_F \cdot D_F}} = \frac{1}{N} + \frac{1}{D_K^2}$$

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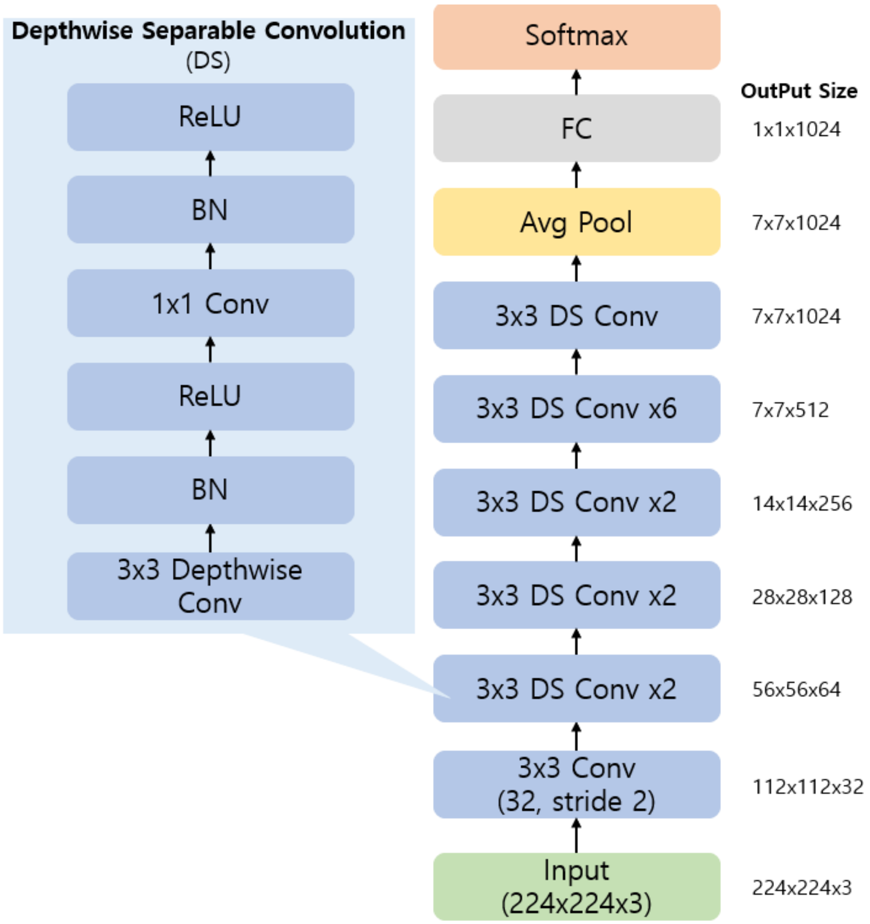
MobileNet Architecture

Table 1. MobileNet Body Architecture

Type / Stride	Filter Shape	Input Size
Conv / s2	$3 \times 3 \times 3 \times 32$	$224 \times 224 \times 3$
Conv dw / s1	$3 \times 3 \times 32$ dw	$112 \times 112 \times 32$
Conv / s1	$1 \times 1 \times 32 \times 64$	$112 \times 112 \times 32$
Conv dw / s2	$3 \times 3 \times 64$ dw	$112 \times 112 \times 64$
Conv / s1	$1 \times 1 \times 64 \times 128$	$56 \times 56 \times 64$
Conv dw / s1	$3 \times 3 \times 128$ dw	$56 \times 56 \times 128$
Conv / s1	$1 \times 1 \times 128 \times 128$	$56 \times 56 \times 128$
Conv dw / s2	$3 \times 3 \times 128$ dw	$56 \times 56 \times 128$
Conv / s1	$1 \times 1 \times 128 \times 256$	$28 \times 28 \times 128$
Conv dw / s1	$3 \times 3 \times 256$ dw	$28 \times 28 \times 256$
Conv / s1	$1 \times 1 \times 256 \times 256$	$28 \times 28 \times 256$
Conv dw / s2	$3 \times 3 \times 256$ dw	$28 \times 28 \times 256$
Conv / s1	$1 \times 1 \times 256 \times 512$	$14 \times 14 \times 256$
$5\times$ Conv dw / s1	$3 \times 3 \times 512$ dw	$14 \times 14 \times 512$
$5\times$ Conv / s1	$1 \times 1 \times 512 \times 512$	$14 \times 14 \times 512$
Conv dw / s2	$3 \times 3 \times 512$ dw	$14 \times 14 \times 512$
Conv / s1	$1 \times 1 \times 512 \times 1024$	$7 \times 7 \times 512$
Conv dw / s2	$3 \times 3 \times 1024$ dw	$7 \times 7 \times 1024$
Conv / s1	$1 \times 1 \times 1024 \times 1024$	$7 \times 7 \times 1024$
Avg Pool / s1	Pool 7×7	$7 \times 7 \times 1024$
FC / s1	1024×1000	$1 \times 1 \times 1024$
Softmax / s1	Classifier	$1 \times 1 \times 1000$



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- **Method:** 2개의 hyperparameter (width multiplier, resolution multiplier) -> **latency, accuracy** 균형 조절

Width Multiplier (α) : Thinner Models
네트워크를 균일하게 **얇게** 만든다.

Computational cost using Width Multiplier (α)
$$\alpha M \cdot \alpha N \cdot D_F \cdot D_F + D_K \cdot D_K \cdot \alpha M \cdot D_F \cdot D_F$$
$\alpha \in (0, 1)$, α = (1, 0.75, 0.5, 0.25)

Table 6. MobileNet Width Multiplier

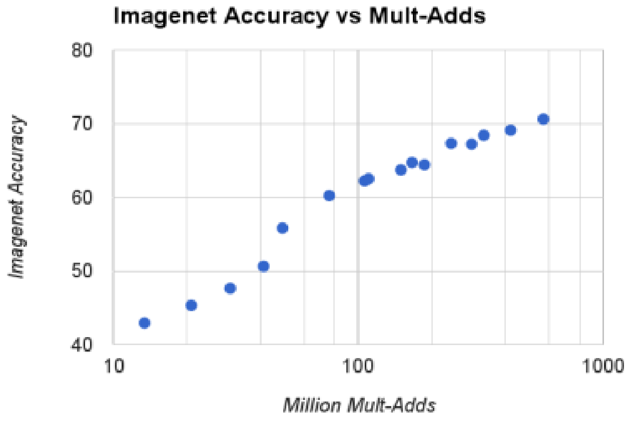
Width Multiplier	ImageNet Accuracy	Million Mult-Adds	Million Parameters
1.0 MobileNet-224	70.6%	569	4.2
0.75 MobileNet-224	68.4%	325	2.6
0.5 MobileNet-224	63.7%	149	1.3
0.25 MobileNet-224	50.6%	41	0.5

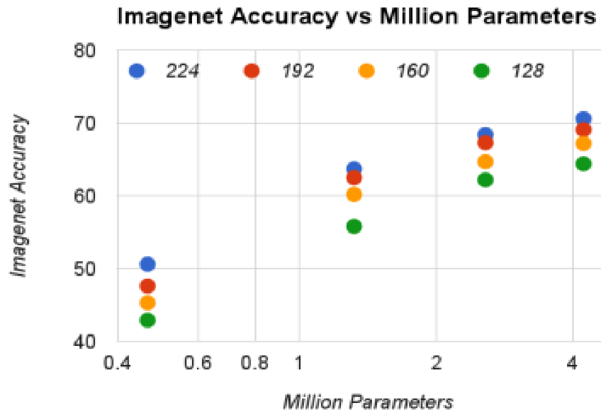
Resolution Multiplier (ρ) : Reduced Representation
신경망의 **계산비용 감소**.

Computational cost using Resolution Multiplier (ρ)
$$\alpha M \cdot \alpha N \cdot \rho D_F \cdot \rho D_F + D_K \cdot D_K \cdot \alpha M \cdot \rho D_F \cdot \rho D_F$$
$\rho \in (0, 1)$, ρ = (224, 192, 160, 128)

Table 7. MobileNet Resolution

Resolution	ImageNet Accuracy	Million Mult-Adds	Million Parameters
1.0 MobileNet-224	70.6%	569	4.2
1.0 MobileNet-192	69.1%	418	4.2
1.0 MobileNet-160	67.2%	290	4.2
1.0 MobileNet-128	64.4%	186	4.2





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- **Experiment:**
  Depthwise separable conv를 사용한 MobileNet이 Fully convolutional MobileNet보다 더 적은 parameter를 나타내면서 합리적인 정확도를 보인다.
  기존의 VGG-16보다 더 적은 parameter 로 비슷한 정확도를 보인다.
  기존의 very small network (squeezeNet, AlexNet) 보다 더 좋은 성능을 보인다.
  이 외에도 다양한 task에서 성공적인 모델 경량화.

Table 4. Depthwise Separable vs Full Convolution MobileNet

Model	ImageNet Accuracy	Million Mult-Adds	Million Parameters
Conv MobileNet	71.7%	4866	29.3
MobileNet	70.6%	569	4.2

Better Performance

Table 5. Narrow vs Shallow MobileNet

Model	ImageNet Accuracy	Million Mult-Adds	Million Parameters
0.75 MobileNet	68.4%	325	2.6
Shallow MobileNet	65.3%	307	2.9

Better Performance

Table 8. MobileNet Comparison to Popular Models

Model	ImageNet Accuracy	Million Mult-Adds	Million Parameters
1.0 MobileNet-224	70.6%	569	4.2
GoogleNet	69.8%	1550	6.8
VGG 16	71.5%	15300	138

Table 9. Smaller MobileNet Comparison to Popular Models

Model	ImageNet Accuracy	Million Mult-Adds	Million Parameters
0.50 MobileNet-160	60.2%	76	1.32
Squeezenet	57.5%	1700	1.25
AlexNet	57.2%	720	60

Table 10. MobileNet for Stanford Dogs

Model	Top-1 Accuracy	Million Mult-Adds	Million Parameters
Inception V3 [18]	84%	5000	23.2
1.0 MobileNet-224	83.3%	569	3.3
0.75 MobileNet-224	81.9%	325	1.9
1.0 MobileNet-192	81.9%	418	3.3
0.75 MobileNet-192	80.5%	239	1.9