BNNs – Binary Neuronal Networks –

Making AI-Training Energy-efficient

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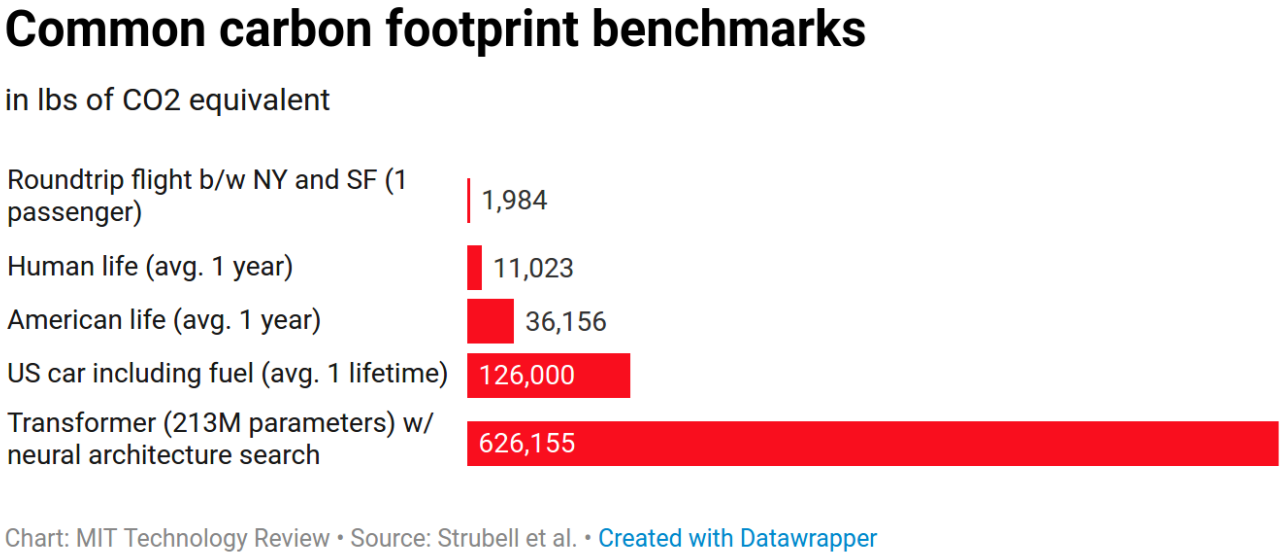
Deep Learning Models **Spend Lots of Energy**

An extreme example during training of very large CNNs:



Strubell, Emma, Ananya Ganesh, and Andrew McCallum. "Energy and Policy Considerations for Deep Learning in NLP." In the 57th Annual Meeting of the Association for Computational Linguistics (ACL). Florence, Italy. July 2019

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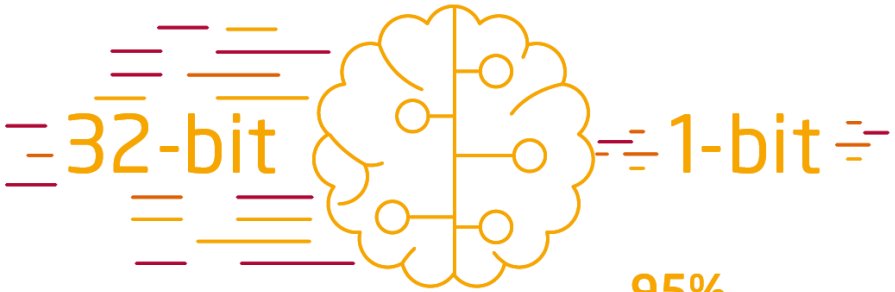
HPI clean-IT Initiative – Energy-efficient AI Training: Deep Learning with **Binary Neuronal Networks**

Binary neuronal networks – BNNs

- State of the art deep neuronal networks are trained and operate on 32-bit models
- Design and Training of deep neuronal networks on binary-level (1-bit) is possible



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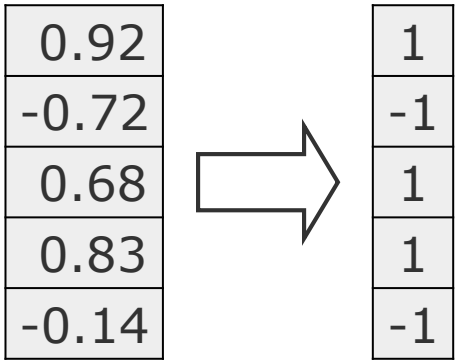
Low-bit Neural Networks

- The extreme case **Binary Neuronal Networks** only use +1 and -1 for weights and inputs instead of 32-bit floating point numbers



- Up to 32x model compression and 58x speedup during inference[1]
- **More than 1000x energy saving on dedicated hardware[2]**

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[1] Rastegari, Mohammad, et al. "Xnor-net: Imagenet Classification using Binary Convolutional Neural Networks." European conference on computer vision. Springer, Cham, 2016.

[2] Mishra, Asit, et al. "WRPN: Wide Reduced-Precision Networks." International Conference on Learning Representations. 2018.

Challenges of **Low-bit Networks**

- Loss of accuracy compared to 32-bit networks
  - for example, directly binarizing a network trained on ImageNet, leads to a loss in accuracy of about 10% [1]
- We belief that we can shrink that gap

The goal of our ongoing research work:

- To achieve the same accuracy with binary networks as with "traditional" CNN

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[1] Joseph Bethge, Haojin Yang, Marvin Bornstein, Christoph Meinel. "BinaryDenseNet: Developing an Architecture for Binary Neural Networks." Proceedings of the IEEE International Conference on Computer Vision Workshops. 2019.

Future Potential of **Low-bit Networks**

If the gap between 32-bit CNNS and BNNs is closed:

- We can deploy dedicated hardware on servers and achieve huge energy savings
- Networks can run on mobile and embedded devices without a loss of accuracy

https://commons.wikimedia.org/wiki/File:Raspberry_Pi_3_B%2B_(39906369025).png

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Our Research Insights on **Binary Neuronal Networks**

- The clipping threshold t_{clip} should be considered a hyperparameter and values between 1.2 and 1.3 leads to better results than the value of 1 that was used in most previous work [1]
- A scaling of channels after a binary convolution according to Rastegari et al. [2] can be absorbed by BatchNorm layers [3]
- A tighter approximation of the sign function does not necessarily achieve better results [4]

[1] Bethge, Joseph, Haojin Yang, and Christoph Meinel. "Training accurate binary neural networks from scratch." 2019 IEEE International Conference on Image Processing (ICIP). IEEE, 2019.

[2] Rastegari, Mohammad, et al. "Xnor-net: Imagenet classification using binary convolutional neural networks." European conference on computer vision. Springer, Cham, 2016.

[3Joseph Bethge, Haojin Yang, Marvin Bornstein, Christoph Meinel. "BinaryDenseNet: Developing an Architecture for Binary Neural Networks." Proceedings of the IEEE International Conference on Computer Vision Workshops. 2019.

[4] Bethge, Joseph, Bethge, Joseph, Christian Bartz, Haojin Yang, Ying Chen, Christoph Meinel. "Training competitive binary neural networks from scratch." arXiv preprint arXiv:1812.01965 (2018).

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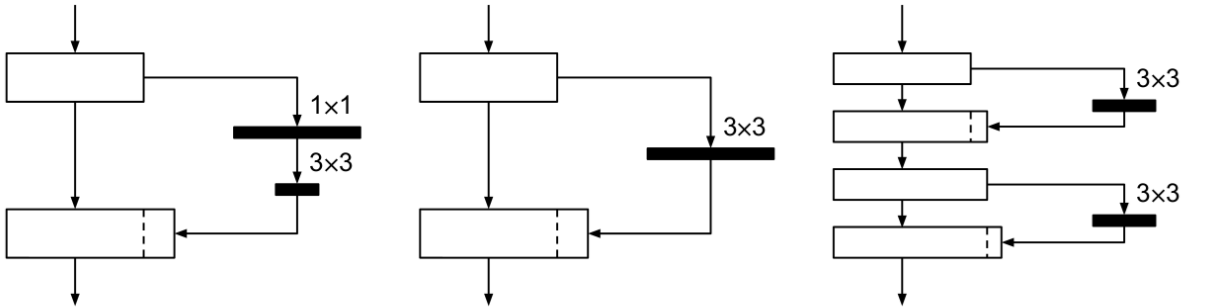
Our BNN Models: **BinaryDenseNet**

BinaryDenseNet: a DenseNet adapted for Binary Networks

- Replace bottlenecks
- Add shortcuts



(a) DenseNet (bottleneck)

(b) DenseNet (no bottleneck)

(c) BinaryDenseNet (our suggestion)

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[3] Joseph Bethge, Haojin Yang, Marvin Bornstein, Christoph Meinel. "BinaryDenseNet: Developing an Architecture for Binary Neural Networks." Proceedings of the IEEE International Conference on Computer Vision Workshops. 2019.

Our BNN Models: **BinaryDenseNet**

Model size	Method	Top-1/Top-5 accuracy
∼4.0MB	XNOR-ResNet18 [25]	51.2%/73.2%
	TBN-ResNet18 [30]	55.6%/74.2%
	Bi-Real-ResNet18 [24]	56.4%/79.5%
	BinaryResNetE18	58.1%/80.6%
	BinaryDenseNet28	**60.7%/82.4%**
∼5.1MB	TBN-ResNet34 [30]	58.2%/81.0%
	Bi-Real-ResNet34 [24]	62.2%/83.9%
	BinaryDenseNet37	62.5%/83.9%
	*BinaryDenseNet37-dilated**	**63.7%/84.7%**
7.4MB	*BinaryDenseNet45*	63.7%/84.8%
46.8MB	Full-precision ResNet18	69.3%/89.2%
249MB	Full-precision AlexNet	56.6%/80.2%

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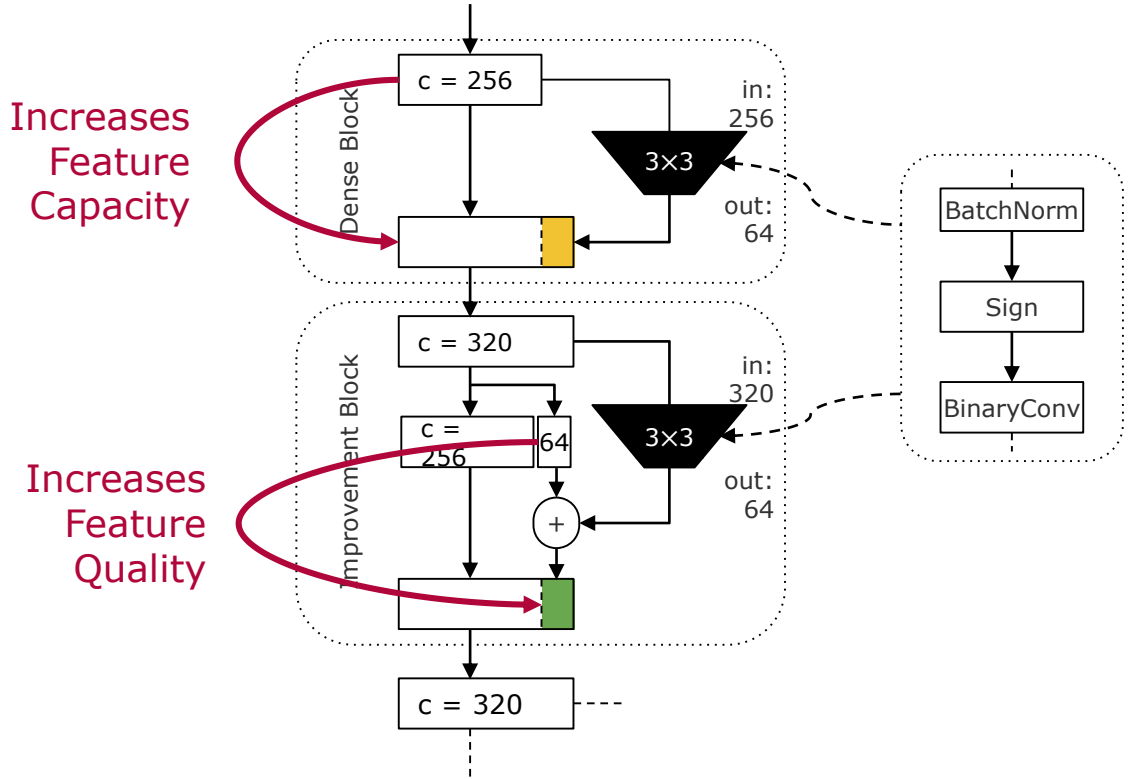
Our BNN Models: **MeliusNet**

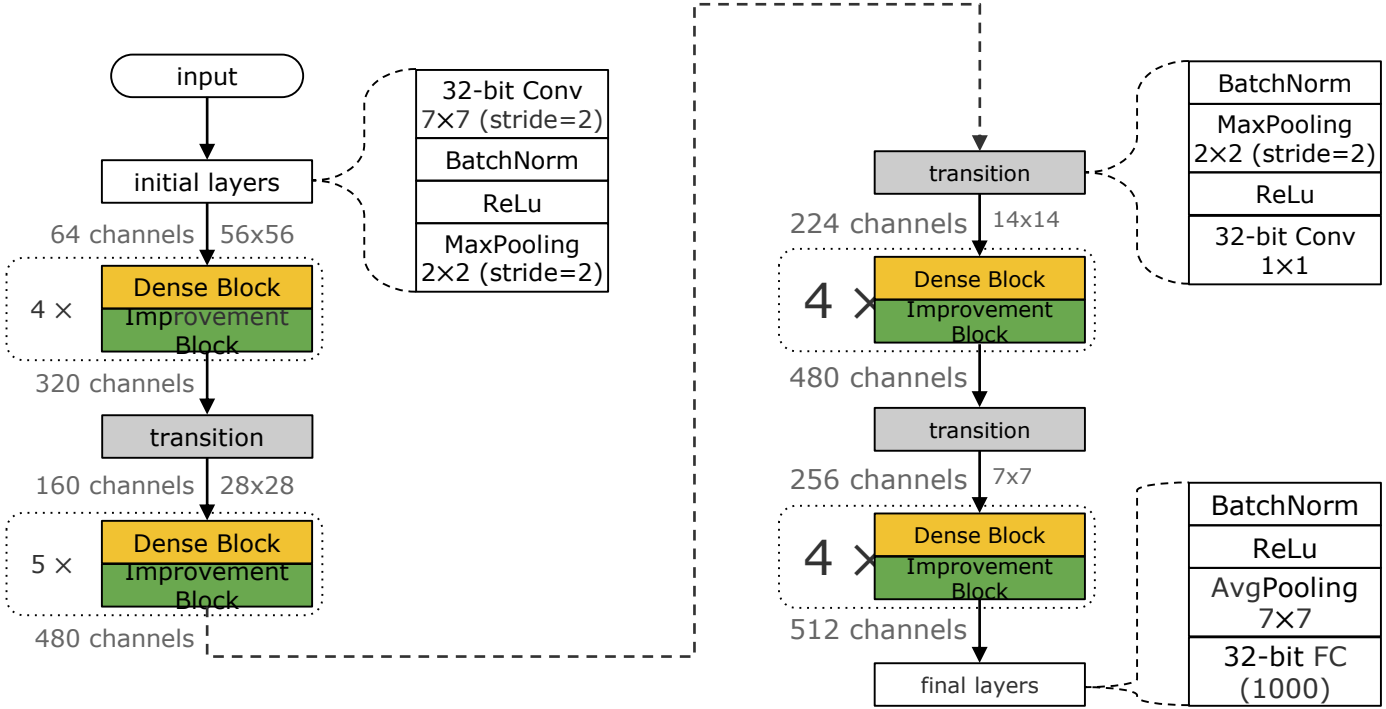
- Using 1 bit for weights and inputs leads to lower quality and capacity
- Number of possible values for **weights** is reduced from 2^{32} to 2
  - → leads to quantization error
  - → lower feature **quality**
- Value range of **inputs** is similarly reduced
  - → fine granular differences can no longer exist, only -1 and +1
  - → lower feature **capacity**
- Idea: solve both challenges through a specific architecture design

Our BNN Models: **MeliusNet**



Bethge, Joseph, Bethge, Joseph, Christian Bartz, Haojin Yang, Ying Chen, Christoph Meinel. "MeliusNet: Can Binary Neural Networks Achieve MobileNet-level Accuracy?." To appear in WACV 2021.

Our BNN Models: MeliusNet



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Our BNN Models: **MeliusNet**

Method	Bitwidth (W/A)	ImageNet (≈18 layers)			ImageNet (≈34 layers)		
		Top-1 Acc.	Model Size	OPs ($\cdot 10^8$)	Top-1 Acc.	Model Size	OPs ($\cdot 10^8$)
BWN[35]	1/32	60.8	4MB	18.1	-	-	-
TTQ[47]	2/32	**66.6**	5.3MB	18.1	-	-	-
HWGQ[7]	1/2	59.6	4MB	∼2.4	64.3	5.1MB	∼3.4
LQ-Net[44]	1/2	62.6	4MB	∼2.4	**66.6**	5.1MB	∼3.4
SYQ[11]	1/2	55.4	4MB	∼2.4	-	-	-
DoReFa[46]	2/2	62.6	5.3MB	∼2.4	-	-	-
Ensemble[48]	(1/1)×6	61.0	-	-	-	-	-
Circulant-CNN[29]	(1/1)×4	61.4	-	-	-	-	-
ABC-Net[28]	(1/1)×5	65.0	8.7MB	7.8	-	-	-
GroupNet[28]	(1/1)×5	**67.0**	9.2MB	2.68	**70.5**	15.3MB	4.13
BNN[22]	1/1	42.2		1.57	-		-
XNOR-Net[35]	1/1	51.2		1.59	-		-
Bi-RealNet[31]	1/1	56.4		1.63	62.2		1.93
XNOR-Net++[6]	1/1	57.1		1.59	-		-
Bi-RealNet (our baseline)	1/1	60.6	∼4MB	1.14	63.7	∼5.1MB	1.43
BinaryDenseNet[5]	1/1	60.7		2.58	62.5		2.71
Strong Baseline[32]	1/1	60.9		1.82	-		-
BinaryDenseNet (our baseline)	1/1	62.6		2.09	64.2		2.20
MeliusNetA,B (ours)	1/1	**63.4**		1.62	**65.7**		1.96
32-bit baseline (ResNet)	32/32	69.3	46.8MB	18.1	73.3	87.2MB	36.6

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BMXNet 2
Open Source Framework for Binary Neuronal Networks

- BMXNet 2 is based on mxnet [1]
- Contains reproducible models and demos to provide a strong basis for research and industry
- Can be used to find new network architectures, test new ideas, ...

https://github.com/hpi-xnor/BMXNet-v2

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[1] https://mxnet.incubator.apache.org/

BMXNet 2
Showcases and Demo Applications

- Android demo app:
  https://github.com/hpi-xnor/android-image-classification
  - ImageNet classification based on a ResNetE
- Human Pose detection demo for a Raspberry Pi

https://github.com/hpi-xnor/BMXNet-v2

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Thank You for Your Interest!

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