MIT HAN LAB

Algorithm-System Co-Design for TinyML

Ligeng Zhu
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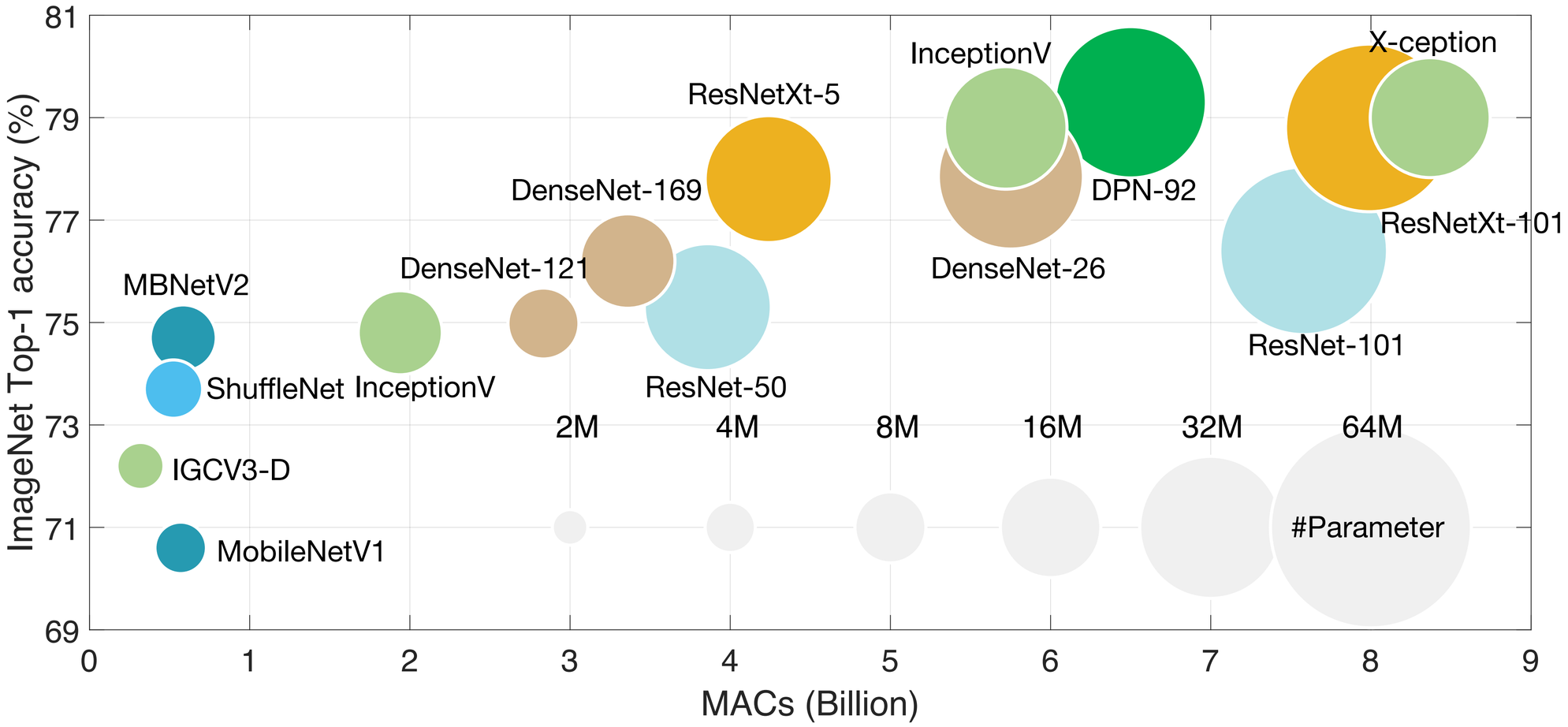
MIT

Brief Bio

- MIT EECS Ph.D. #3rd year, supervisor: Song Han
- Obtained B.Sc from Zhejiang University and Simon Fraser University in 2019.
- Research interests include efficient deep learning algorithms and systems.
- Enthusiastic about open source
    - Projects collects >7k stars / Contributed to pytorch, tvm, horovod, mmdetection
- Previous work integrated into PyTorch, AutoGluon, adapted by Sony, Intel, Amazon

Today's AI is growing tooooo BIG

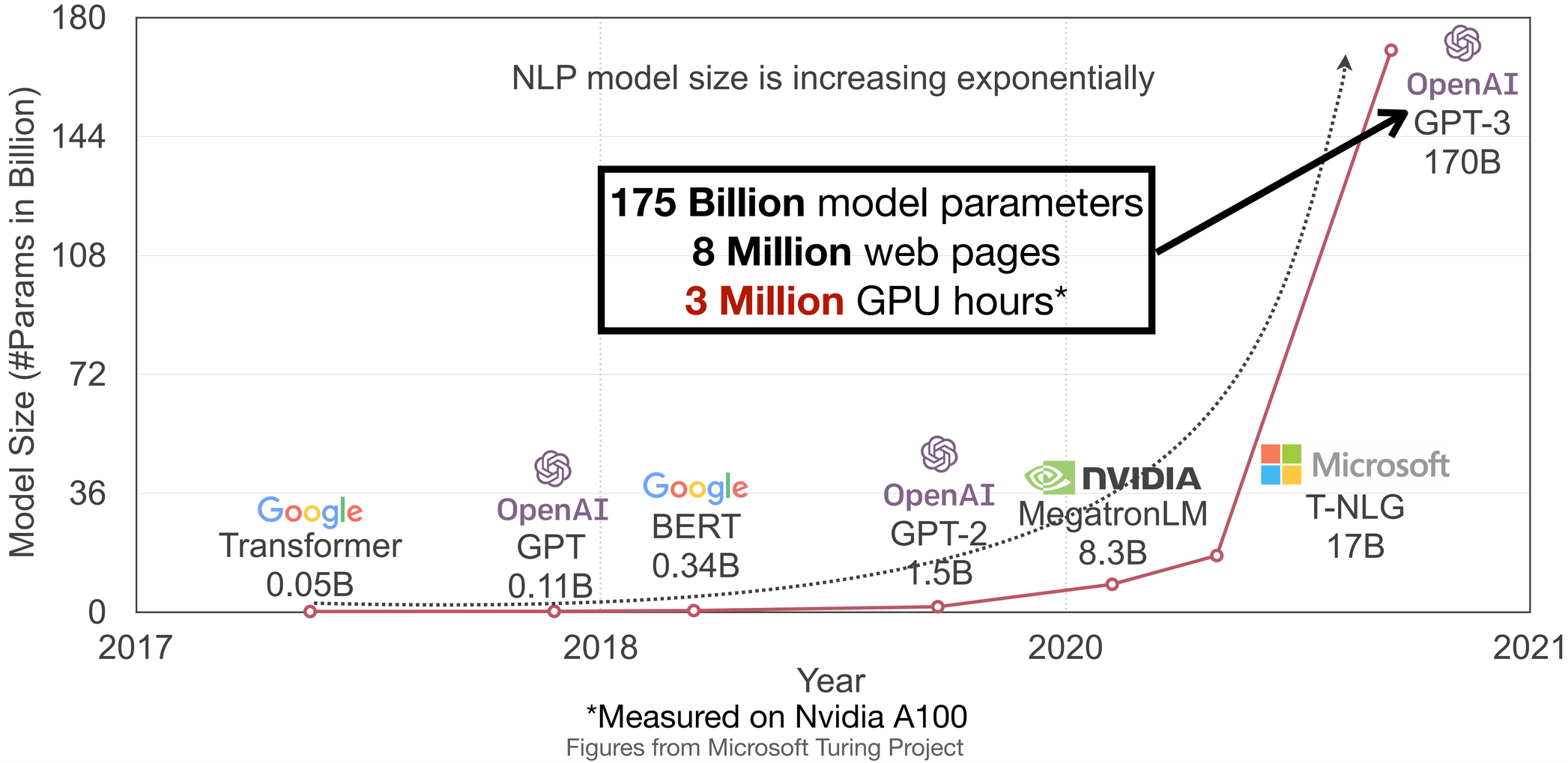
Better model always comes with higher computational cost (vision)



Figures from Once-for-all project page.

Today's AI is growing tooooo BIG

Better model always comes with higher computational cost (NLP)

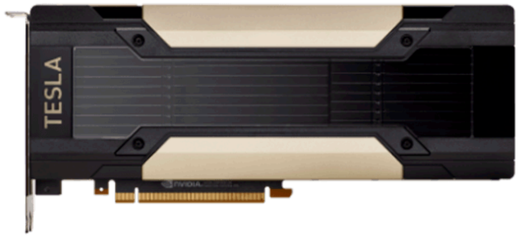


*Measured on Nvidia A100

Figures from Microsoft Turing Project

Deep Learning Going “Tiny”

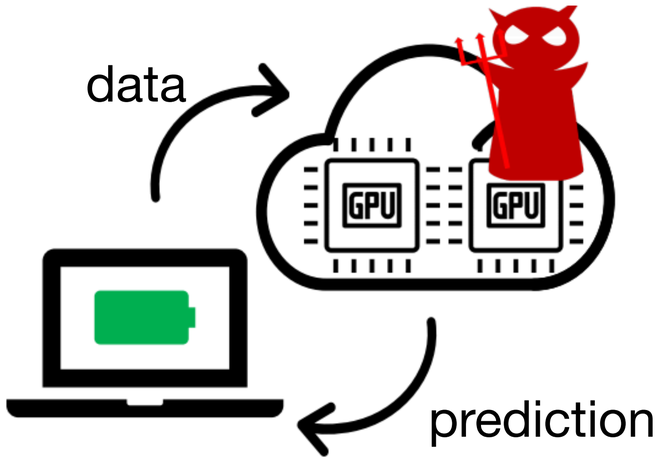
Cloud → Mobile → Tiny



Cloud AI

GPUs/TPUs

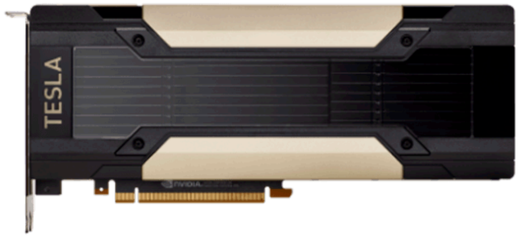
ResNet

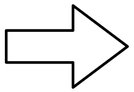


- Data uploaded to the cloud for inference/training

Deep Learning Going “Tiny”

Cloud → Mobile → Tiny





Cloud AI

GPUs/TPUs

ResNet

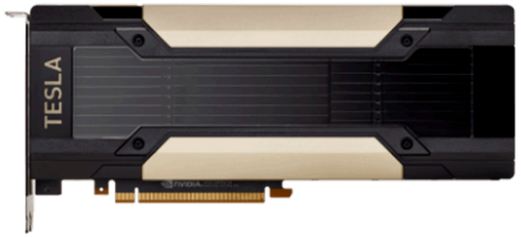
Mobile AI

Smartphones

MobileNet

Deep Learning Going “Tiny”

Cloud → Mobile → Tiny



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Cloud AI

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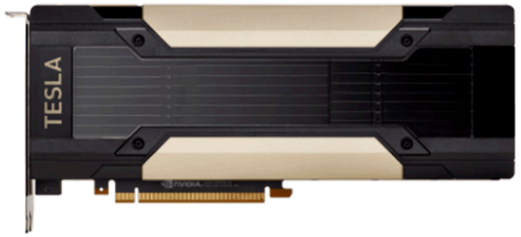
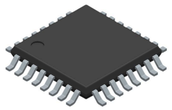




Cloud AI

GPUs/TPUs

ResNet

Mobile AI

Smartphones

MobileNet

Tiny AI

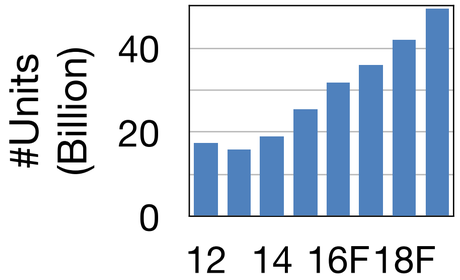
IoT/Microcontrollers

MCUNet

Deep Learning Going “Tiny”

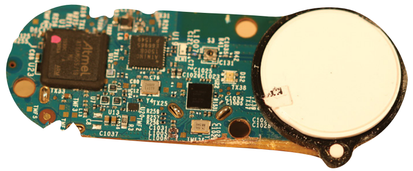
Squeezing deep learning into IoT devices

- Billions of IoT devices around the world based on **microcontrollers**
- **Low-cost**: low-income people can afford access. Democratize AI.
- **Low-power**: **green AI**, reduce carbon



Ubiquitous

Low-cost
($0.1 - $10)



Low-power
(mW)

Deep Learning Going “Tiny”

Squeezing deep learning into IoT devices

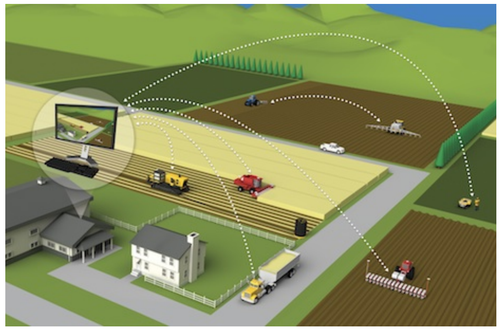
- Billions of IoT devices around the world based on **microcontrollers**
- **Low-cost**: low-income people can afford access. Democratize AI.
- **Low-power**: **green AI**, reduce carbon
- Various applications

Smart Home

Smart Manufacturing

Personalized Healthcare

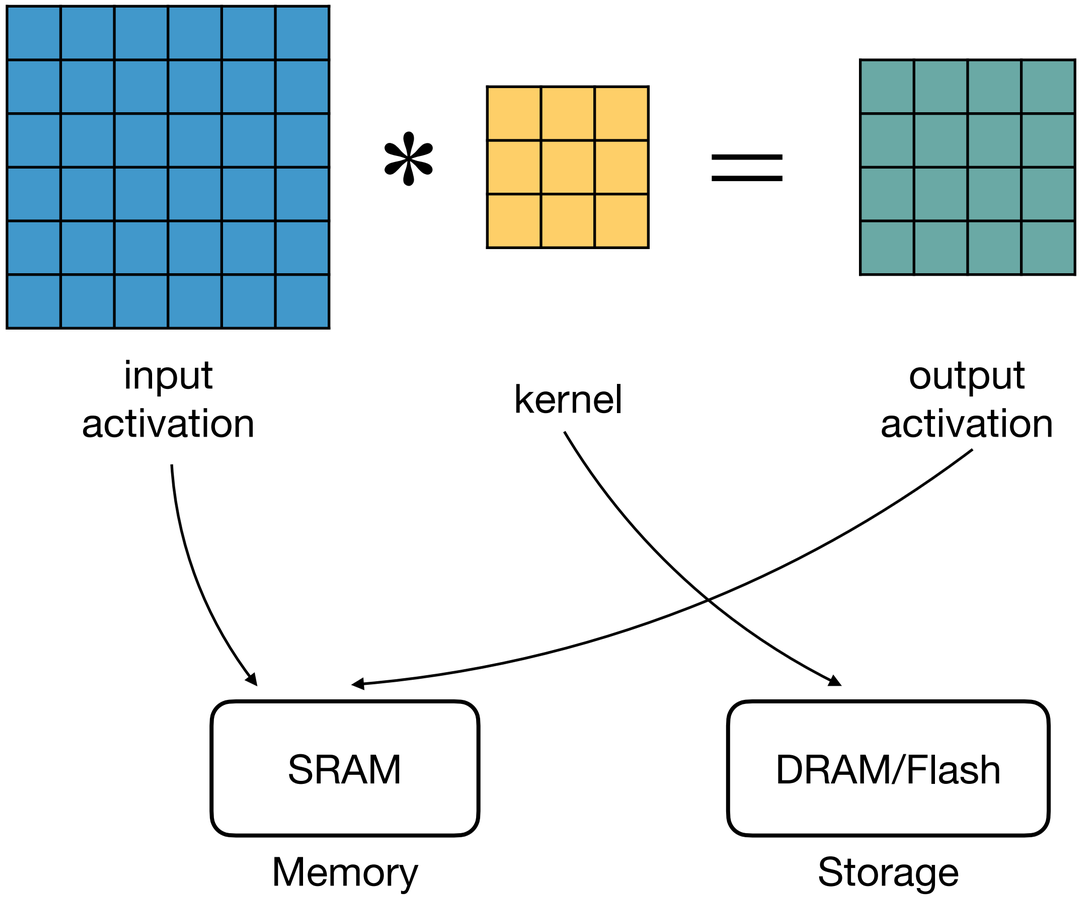
Precise Agriculture



TinyML is Challenging

Memory size is too small to hold DNNs

- Memory usage of a conv net



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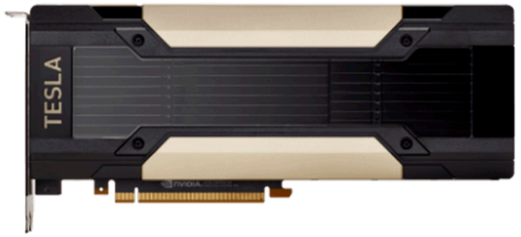

	Cloud AI	Mobile AI
Memory (Activation)	32GB	4GB
Storage (Weights)	~TB/PB	256GB

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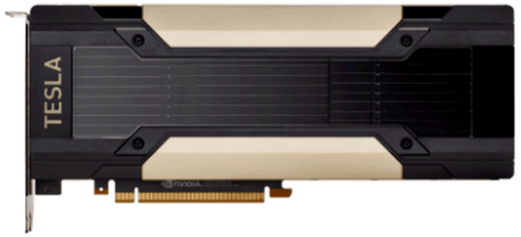

	Cloud AI	Mobile AI	Tiny AI
Memory (Activation)	32GB	4GB	320kB
Storage (Weights)	~TB/PB	256GB	1MB

TinyML is Challenging

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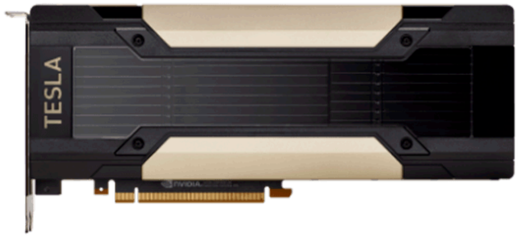

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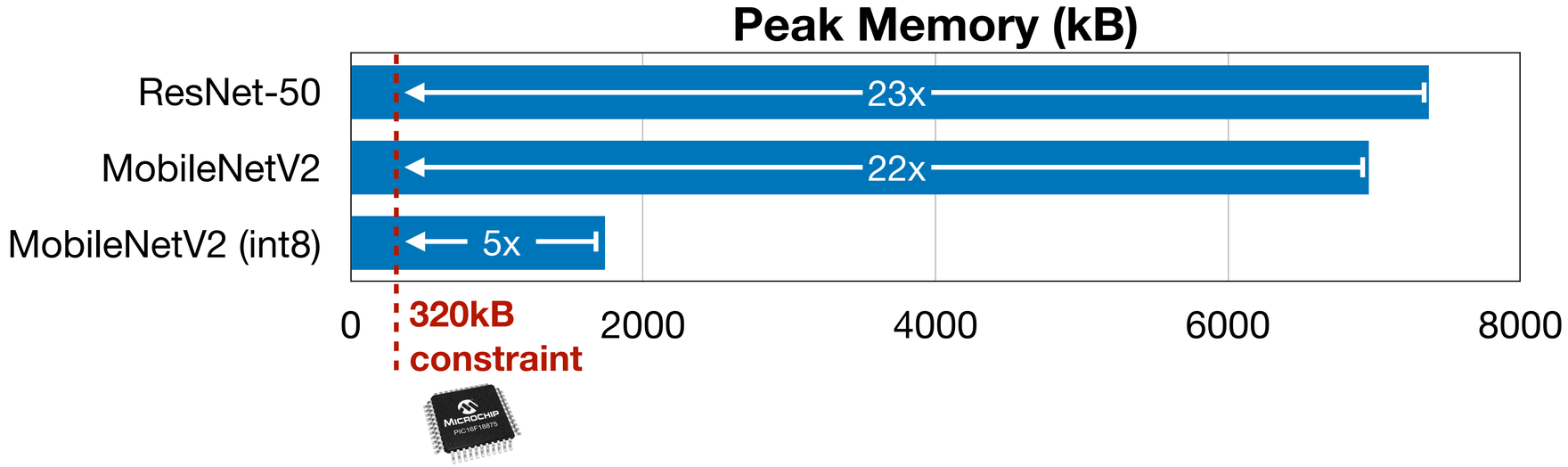
13,000x smaller

100,000x smaller

Today's CNNs are Too Big for TinyML

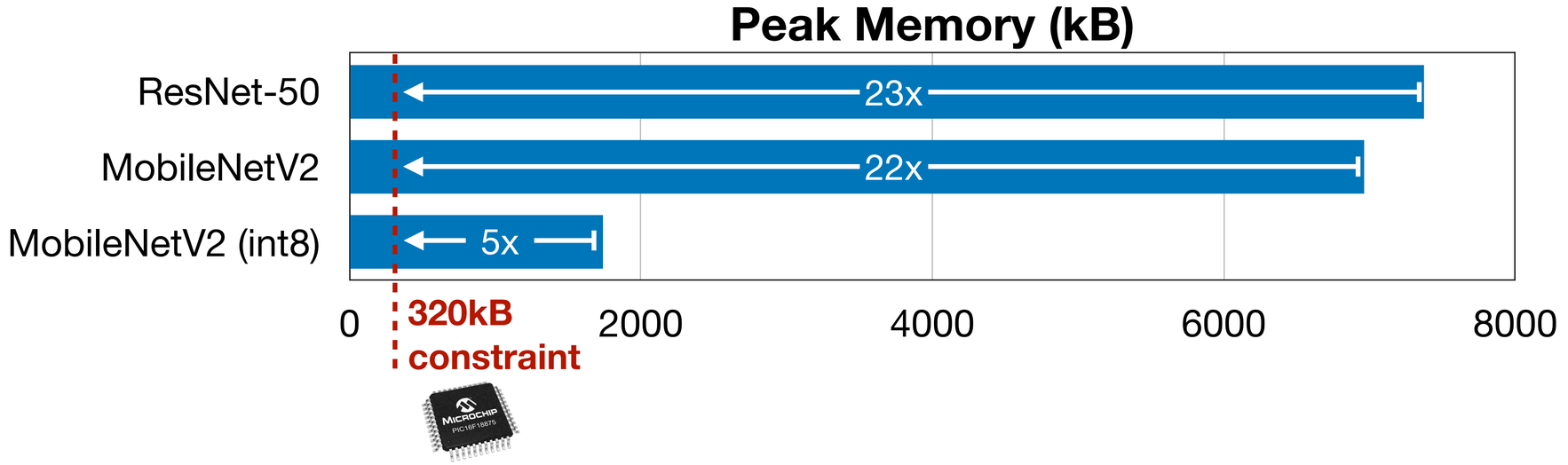
Cloud/Mobile CNNs cannot fit tinyML



Toy applications

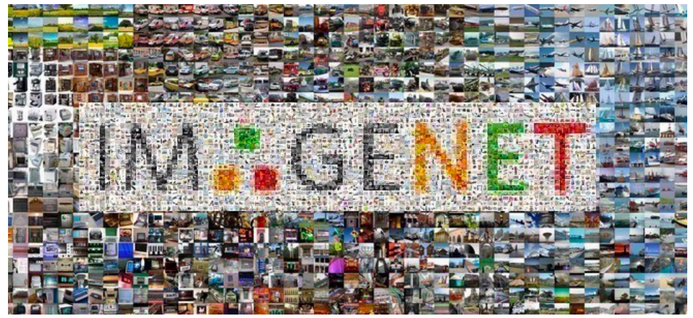
Today's CNNs are Too Big for TinyML

Cloud/Mobile CNNs cannot fit tinyML



Toy applications

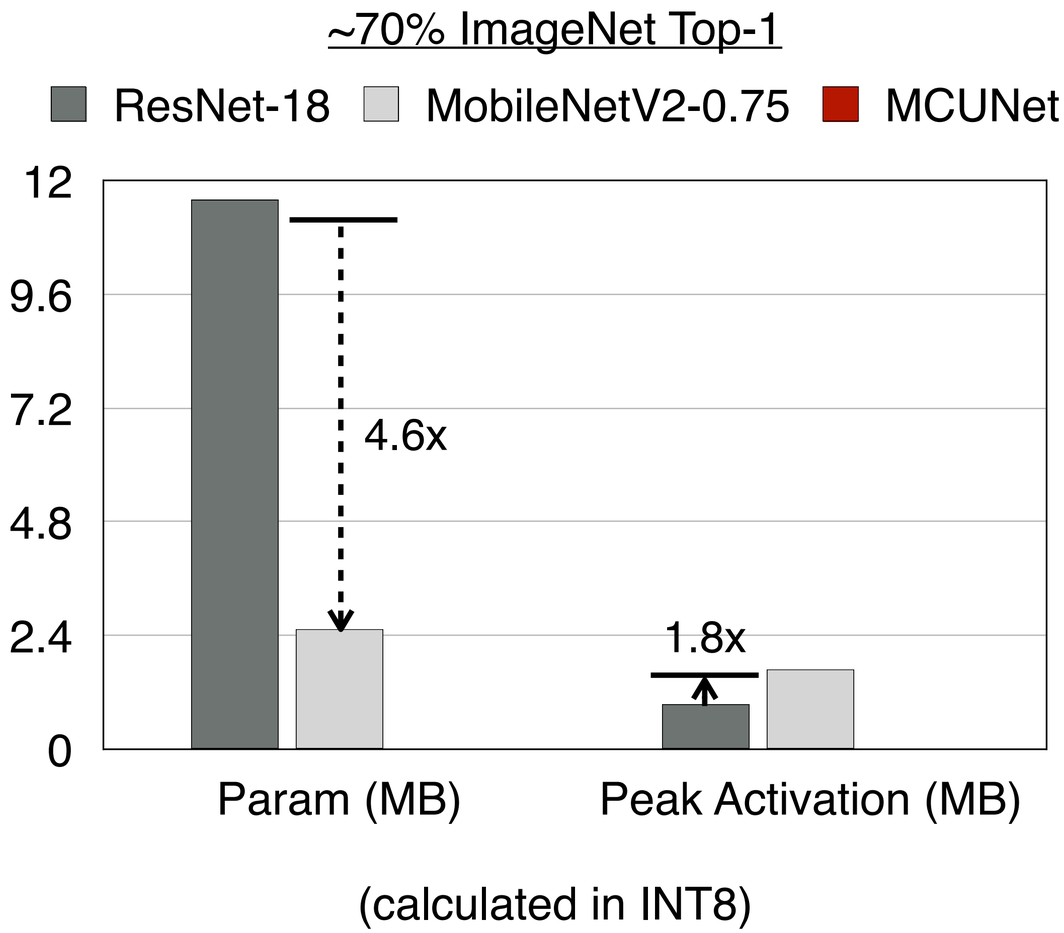
TinyML



Real-life applications

TinyML is Challenging

We need to reduce both weight and activation



TinyML is Challenging

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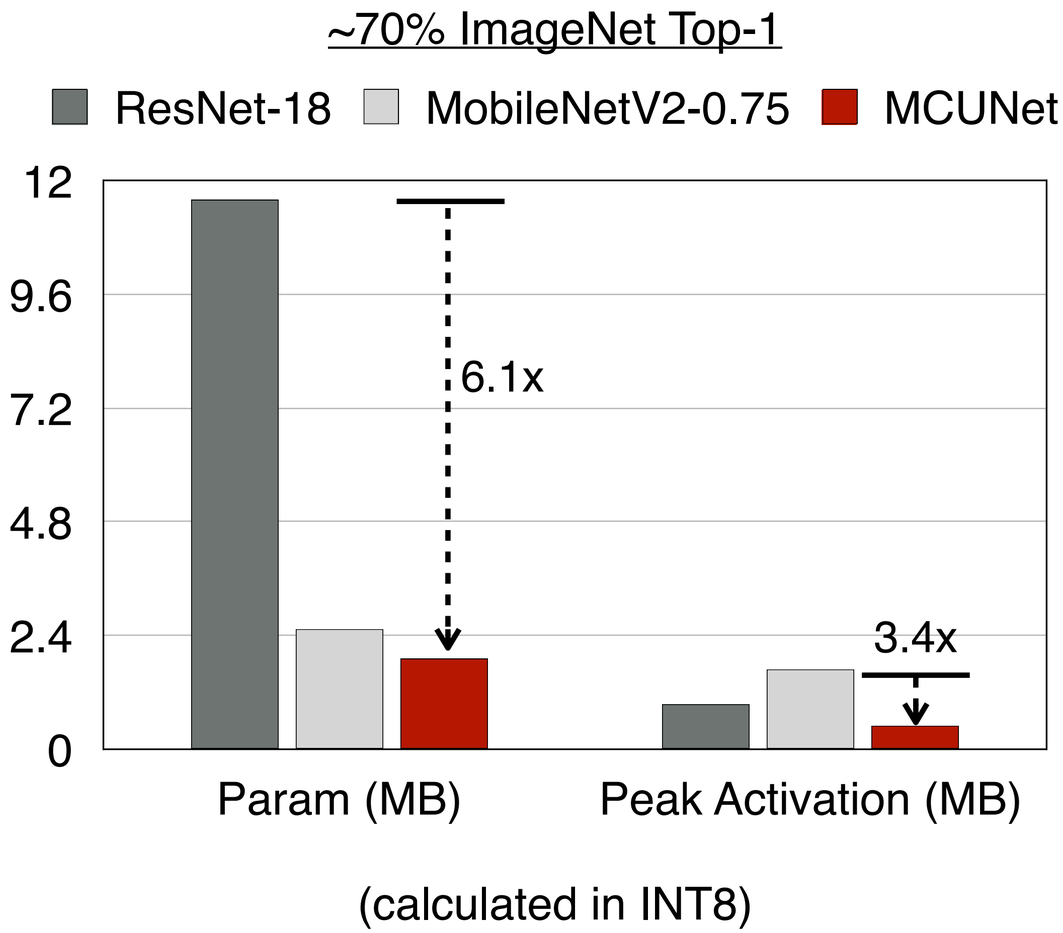
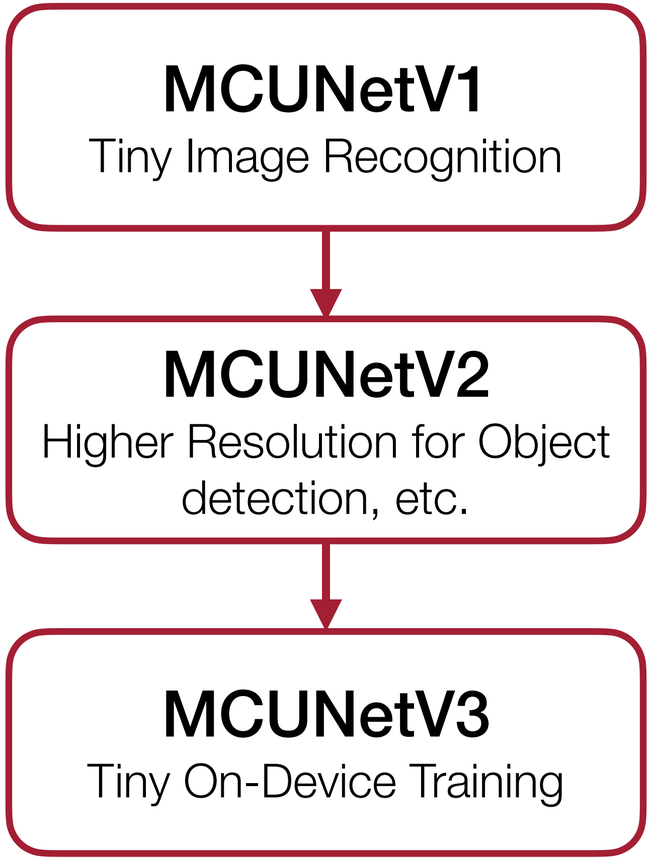
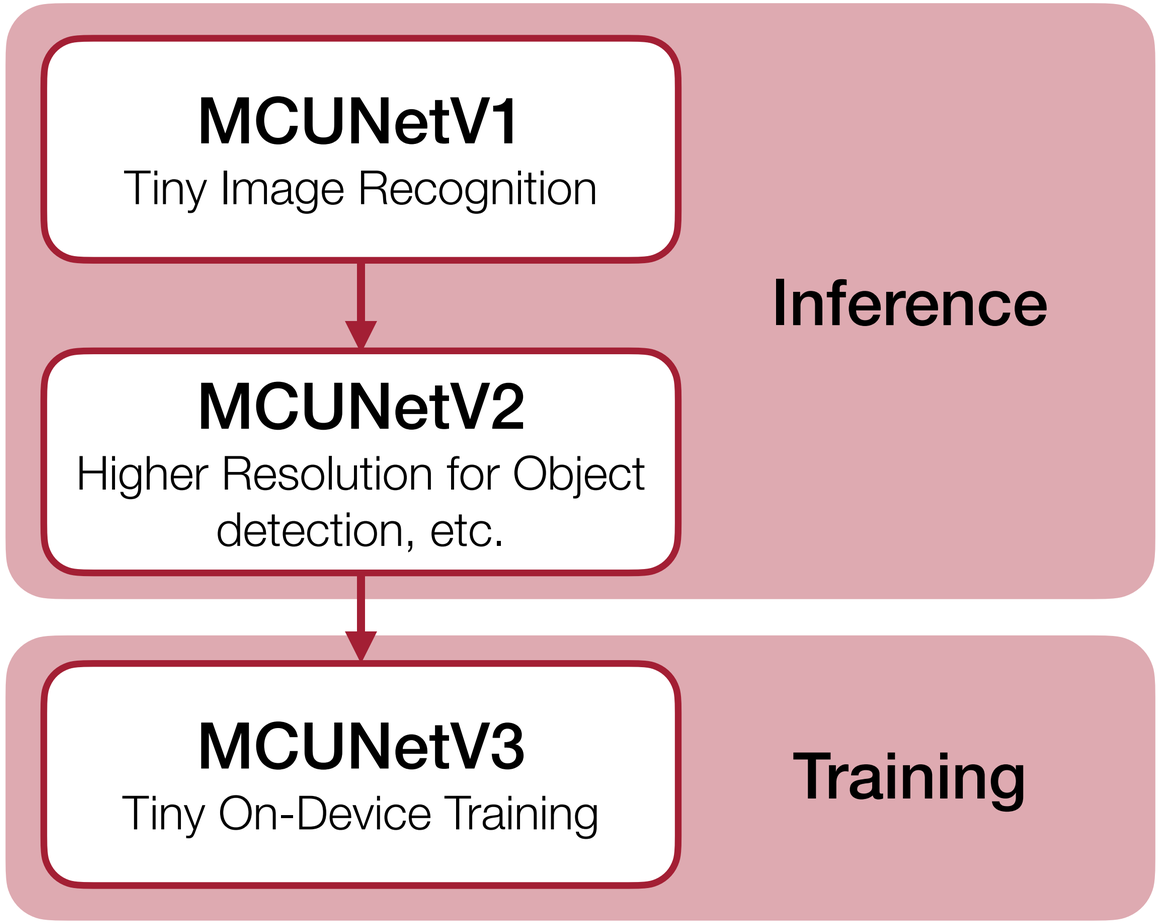


Overview



MCUNet: Tiny Deep Learning on IoT Devices [Lin *et al.*, NeurIPS 2020]
MCUNetV2: Memory-Efficient Patch-based Inference for Tiny Deep Learning [Lin *et al.*, NeurIPS 2021]
On-Device Training Under 256KB Memory [Lin *et al.*, NeurIPS 2022]

Overview



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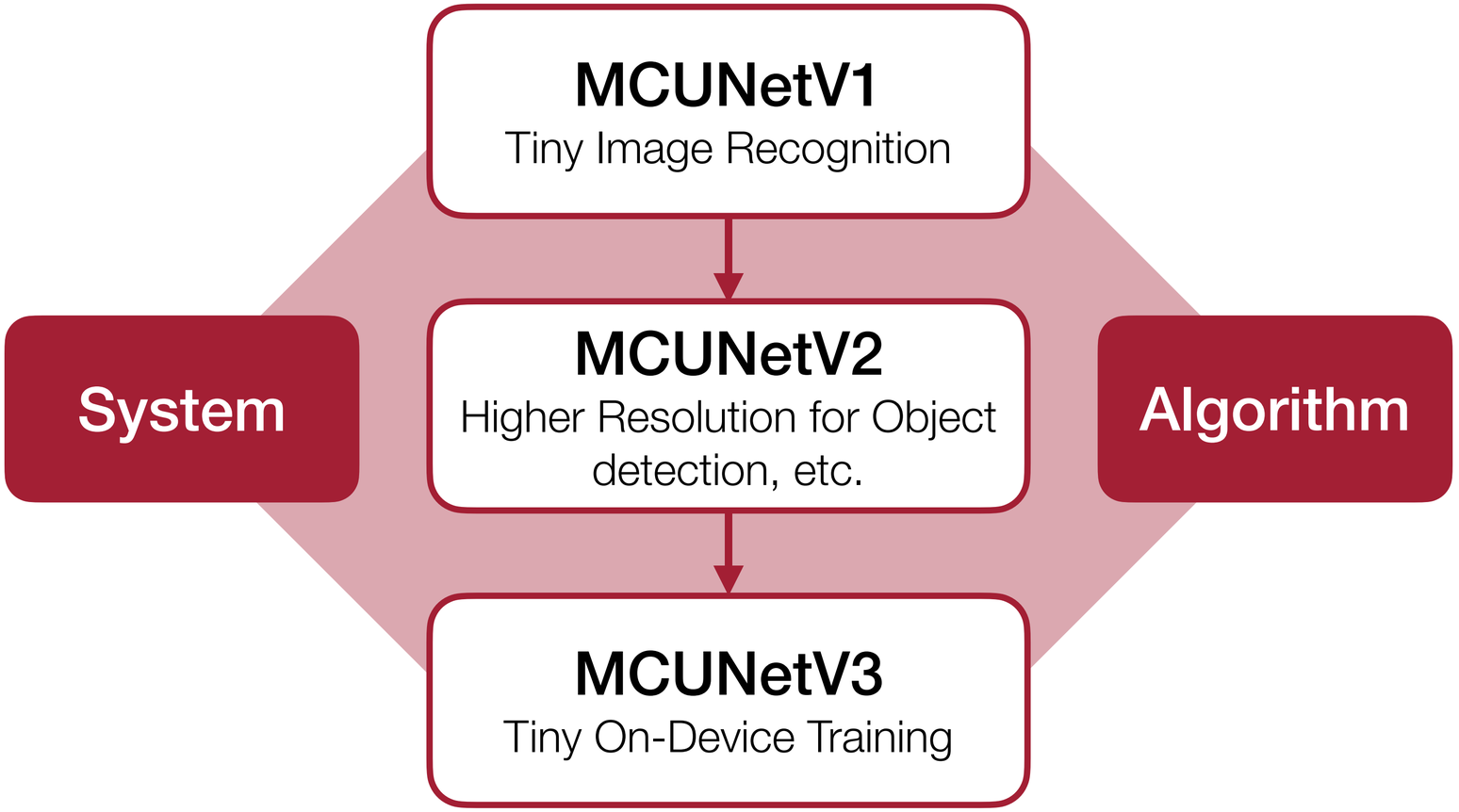
Overview

Co-design



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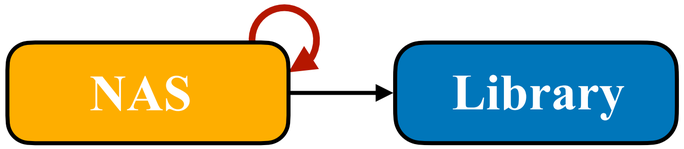
Tiny Inference

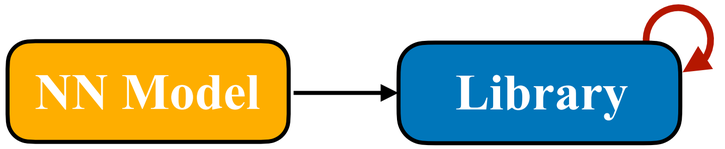
- **MCUNetV1**
- **MCUNetV2**

MCUNet: Tiny Deep Learning on IoT Devices [Lin *et al.*, NeurIPS 2020]

MCUNet: System-Algorithm Co-design



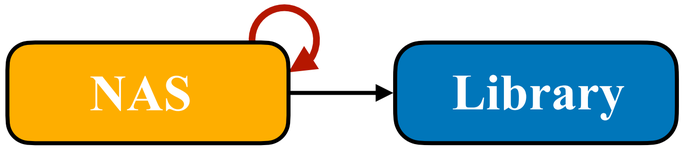
(a) Search NN model on an existing library
e.g., *ProxylessNAS, MnasNet*



(b) Tune deep learning library given a NN model
e.g., *TVM*

TVM: An Automated End-to-End Optimizing Compiler for Deep Learning [Chen *et al.*, OSDI 2018]

MCUNet: System-Algorithm Co-design



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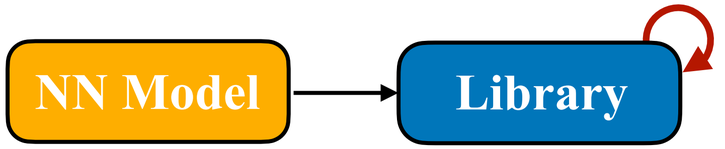

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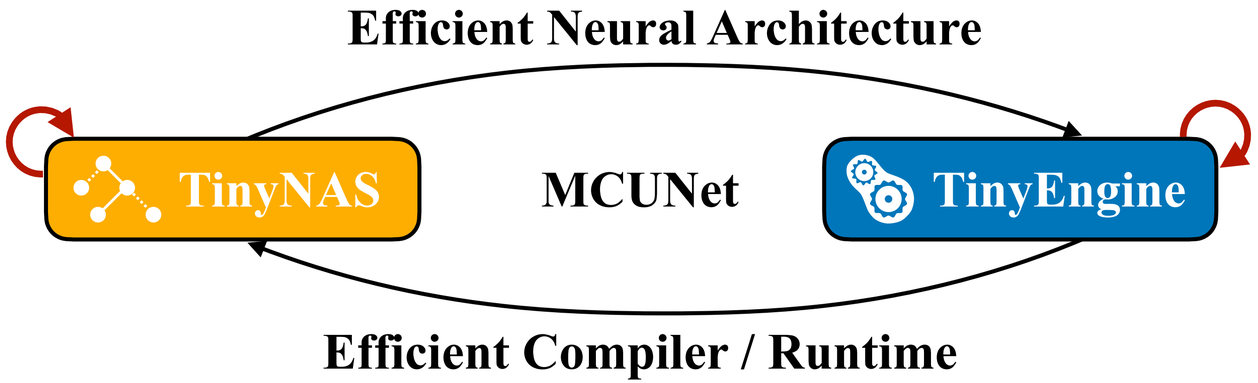
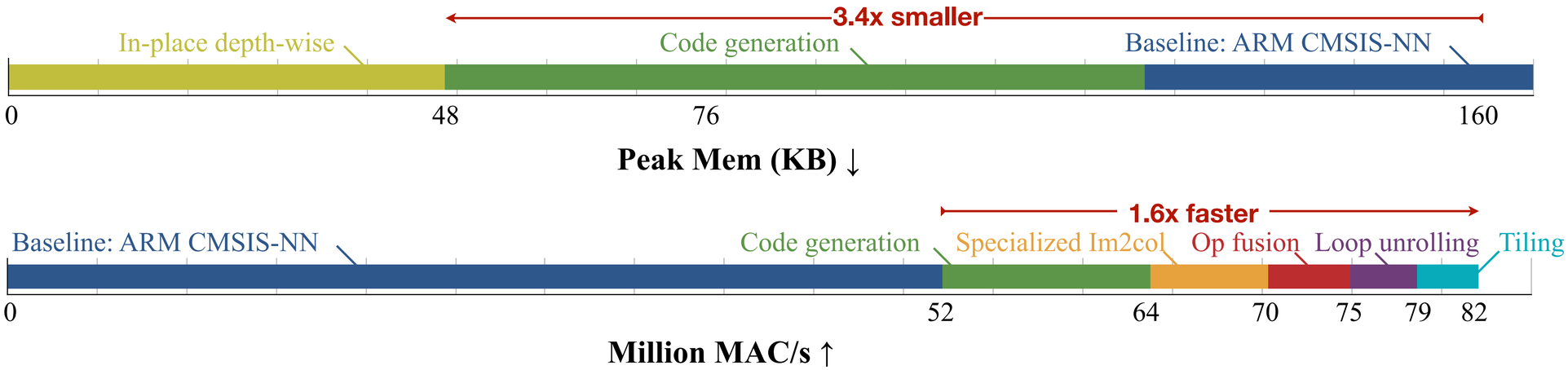


(c) *MCUNet*: system-algorithm co-design

TinyEngine: A Memory-Efficient Inference Library



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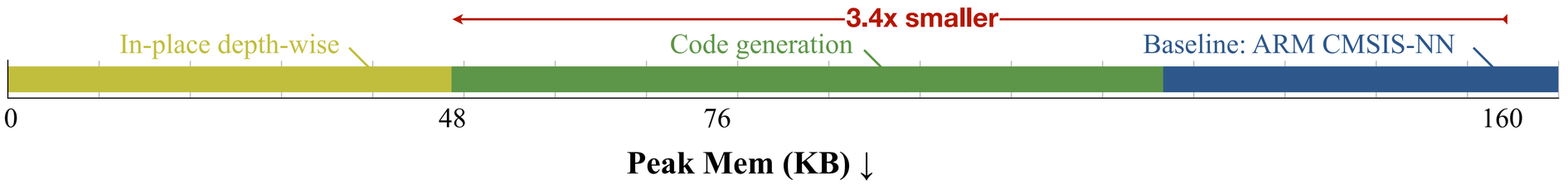
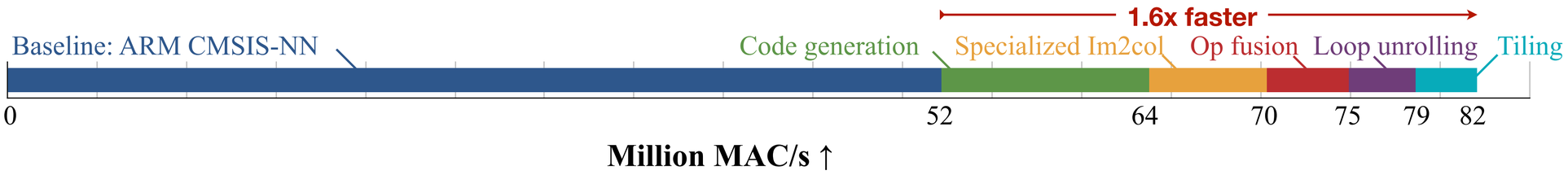
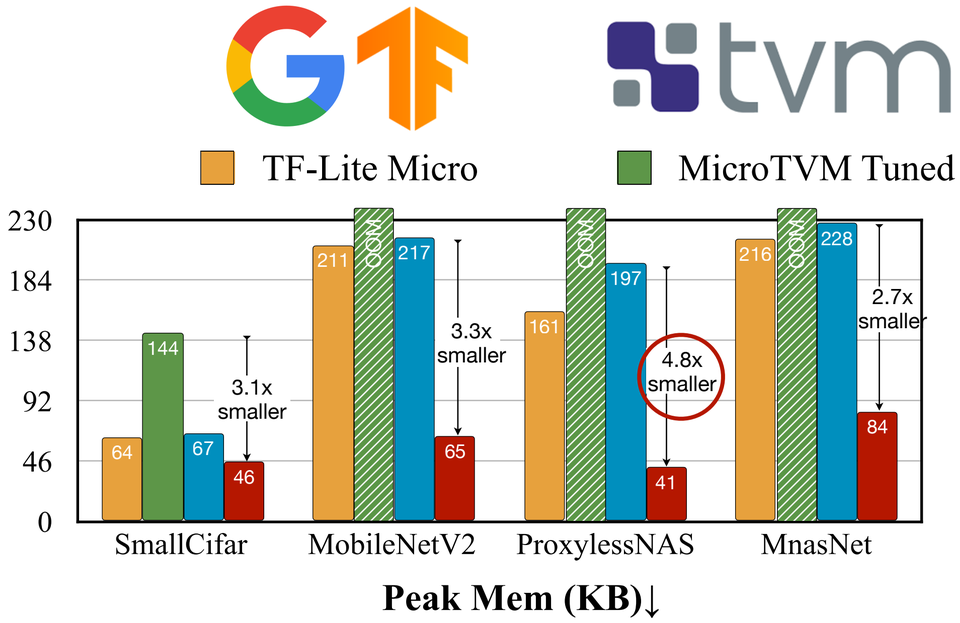
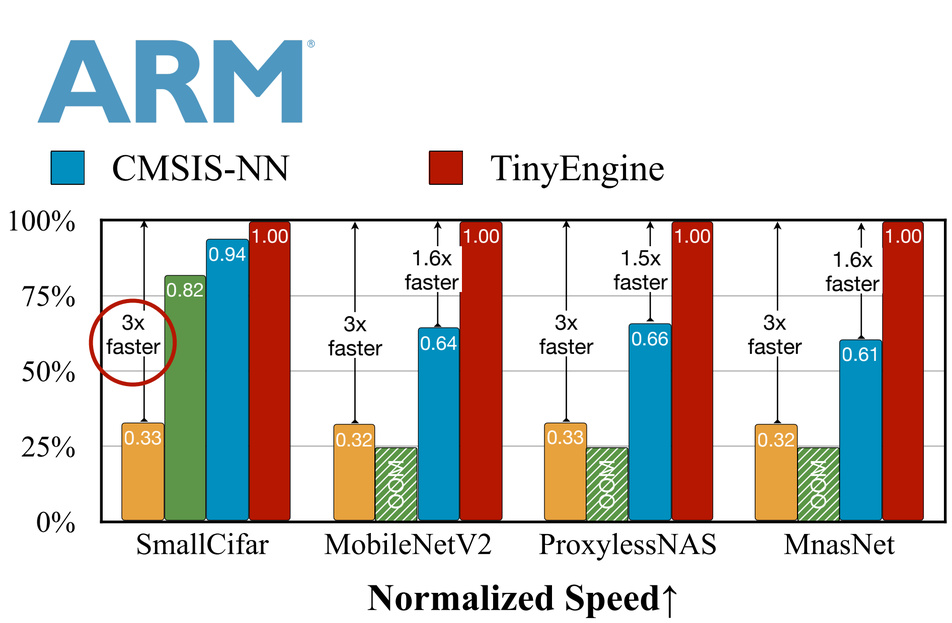






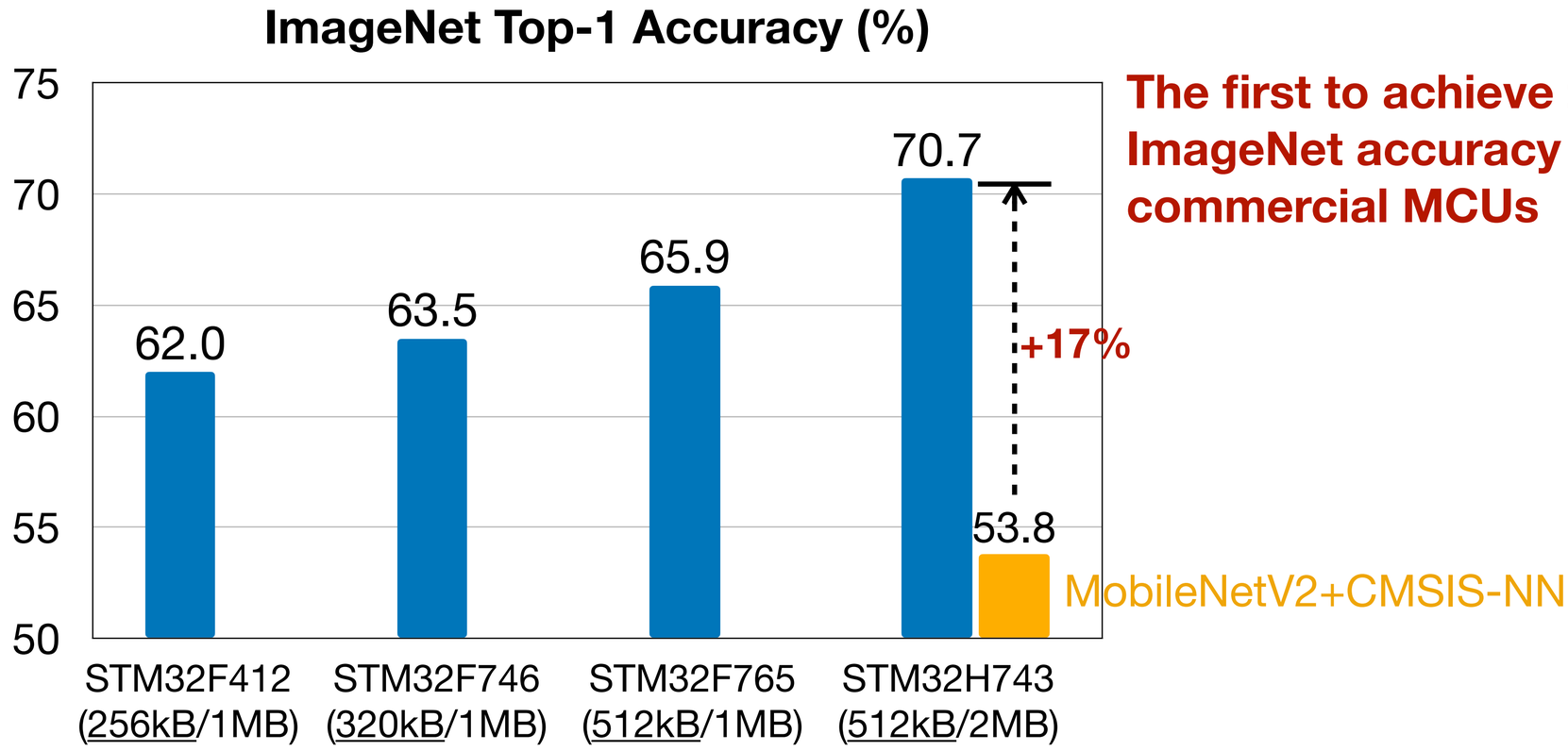


Tiny Image Classification

ImageNet-level image classification

- With techniques like MCUNet, we are able to achieve ImageNet-level image classification performance on microcontrollers (**int4** quantization)

70% milestone:
ResNet
MobileNetV2
MCUNet



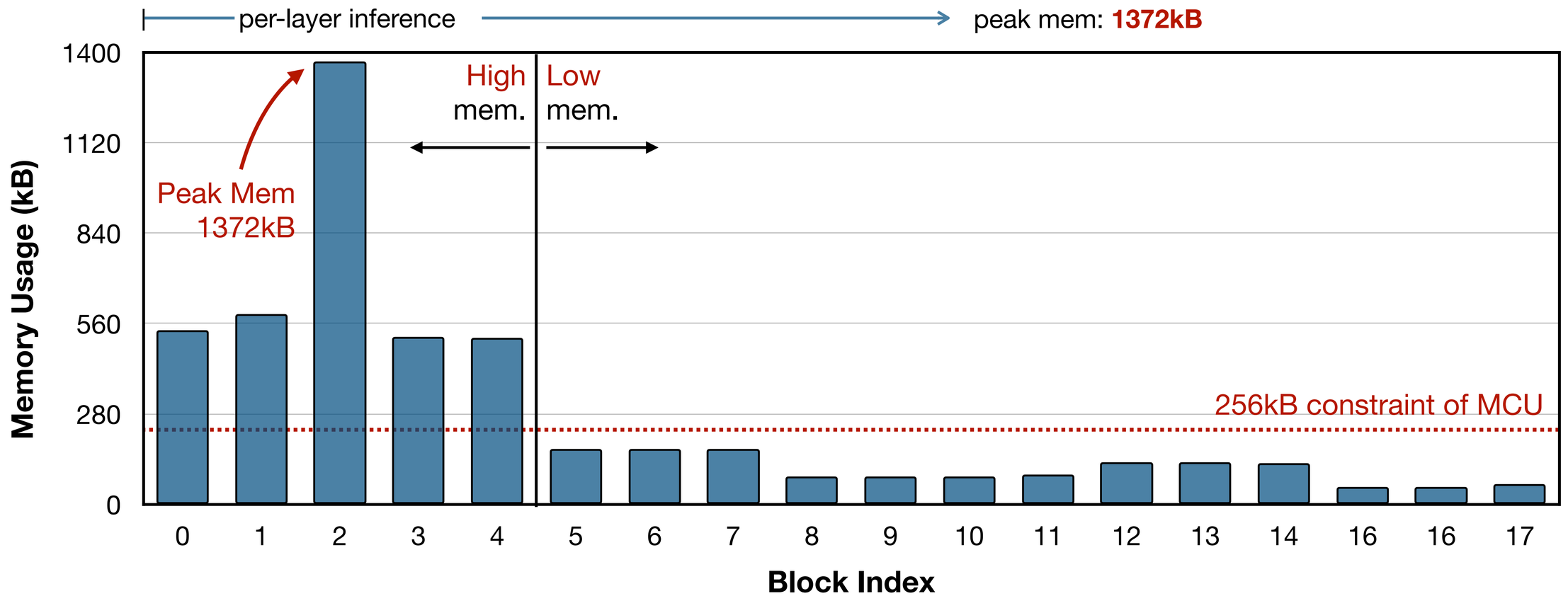
The first to achieve >70% ImageNet accuracy on commercial MCUs

MCUNet: Tiny Deep Learning on IoT Devices [Lin *et al.*, NeurIPS 2019]

MCUNetV2: Patch-based Inference

1. Saving Memory with Patch-based Inference

- Memory saving for MobileNetV2

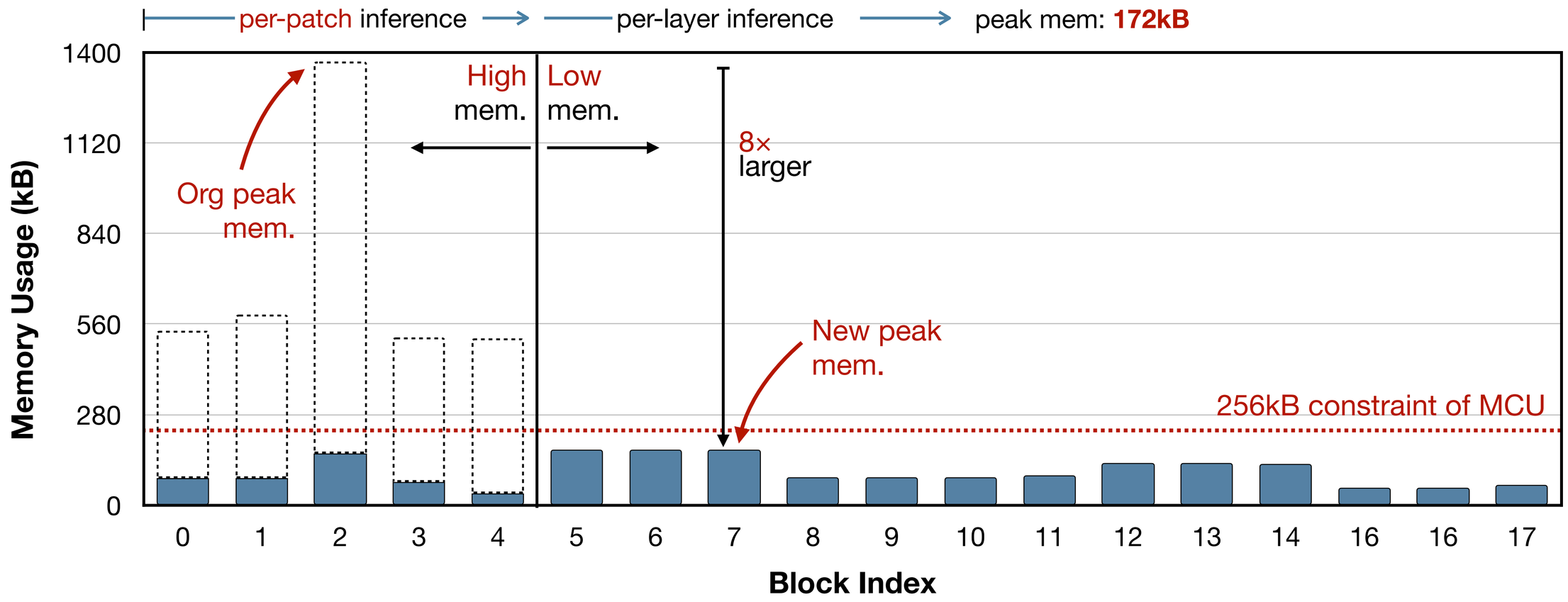


MCUNetV2: Memory-Efficient Patch-based Inference for Tiny Deep Learning [Lin *et al.*, NeurIPS 2021]

MCUNetV2: Patch-based Inference

1. Saving Memory with Patch-based Inference

- Memory saving for MobileNetV2

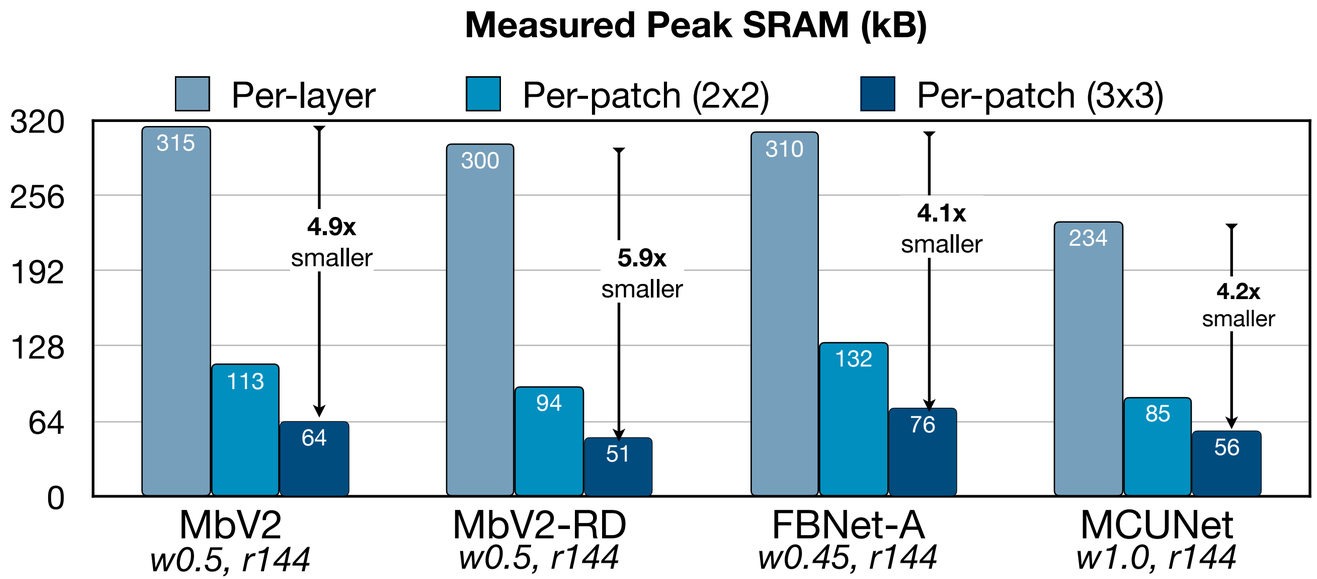


MCUNetV2: Memory-Efficient Patch-based Inference for Tiny Deep Learning [Lin *et al.*, NeurIPS 2021]

MCUNetV2: Patch-based Inference

1. Saving Memory with Patch-based Inference

- Memory saving for other models
  - Baseline: TinyEngine. Measured on STM32F746

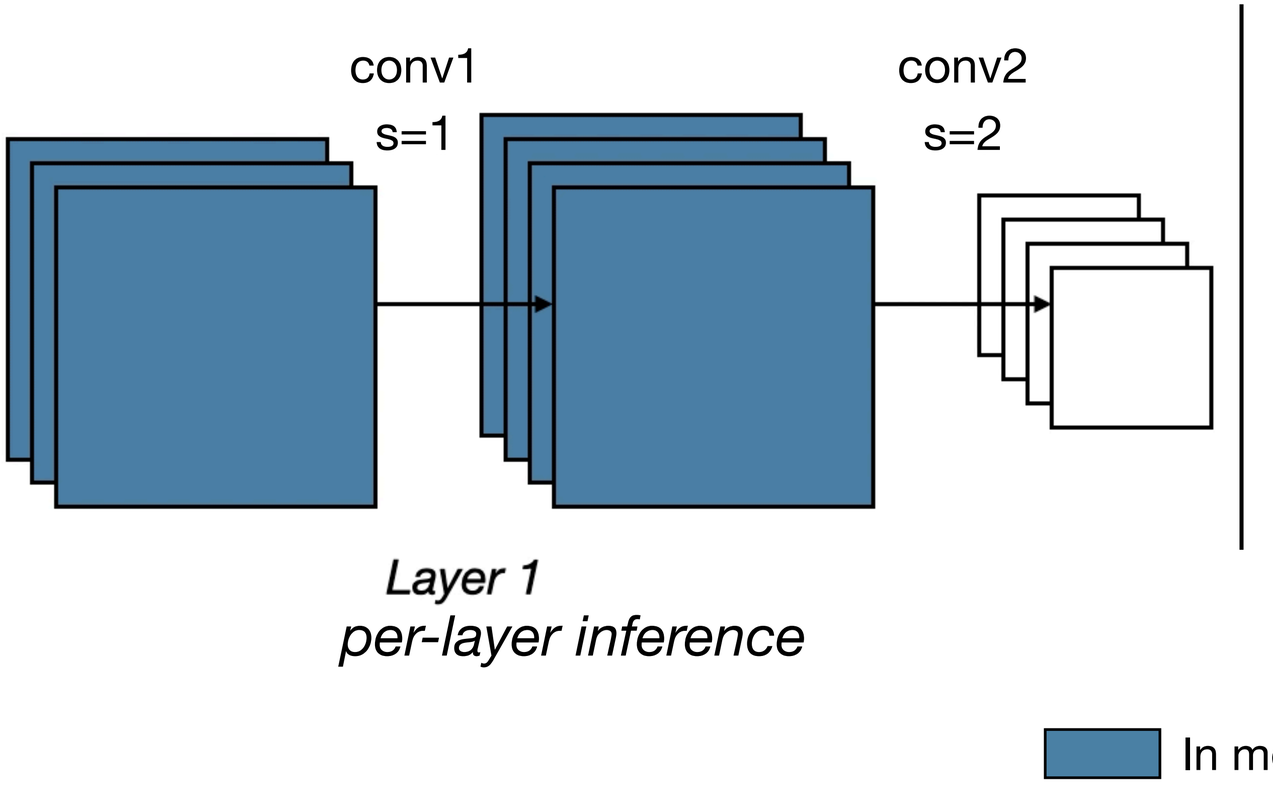


MCUNetV2: Memory-Efficient Patch-based Inference for Tiny Deep Learning [Lin *et al.*, NeurIPS 2021]

MCUNetV2: Patch-based Inference

1. Saving Memory with Patch-based Inference

- Break the memory bottleneck with patch-based inference
  - a practical 2-layer example



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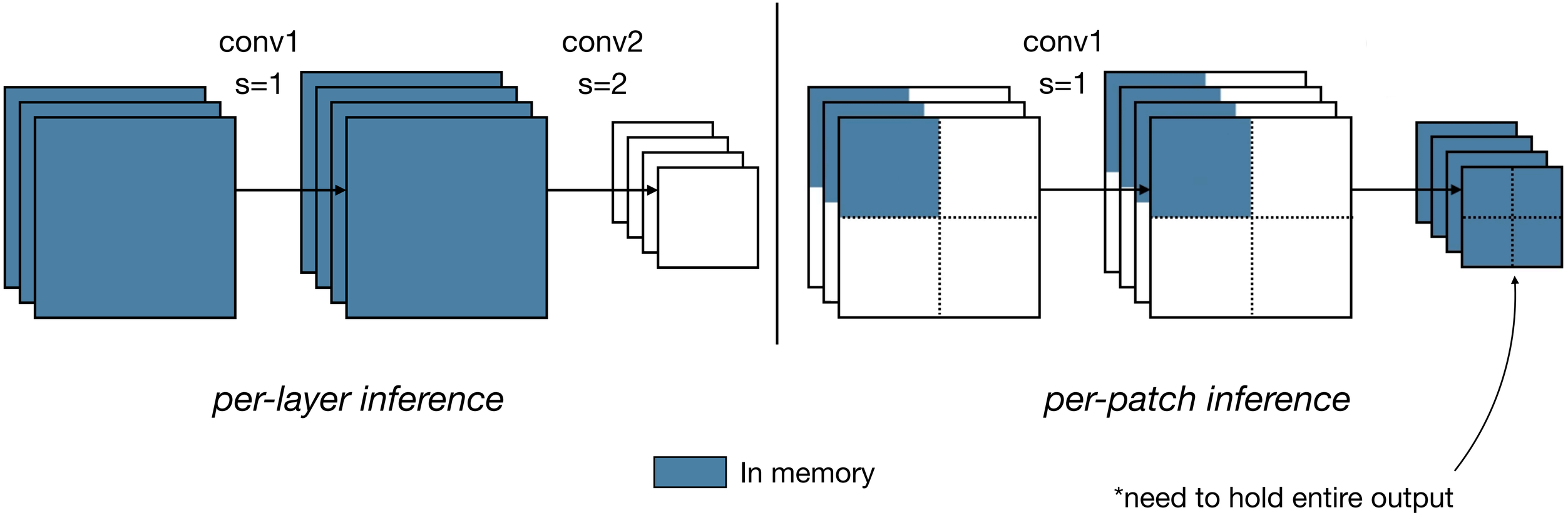
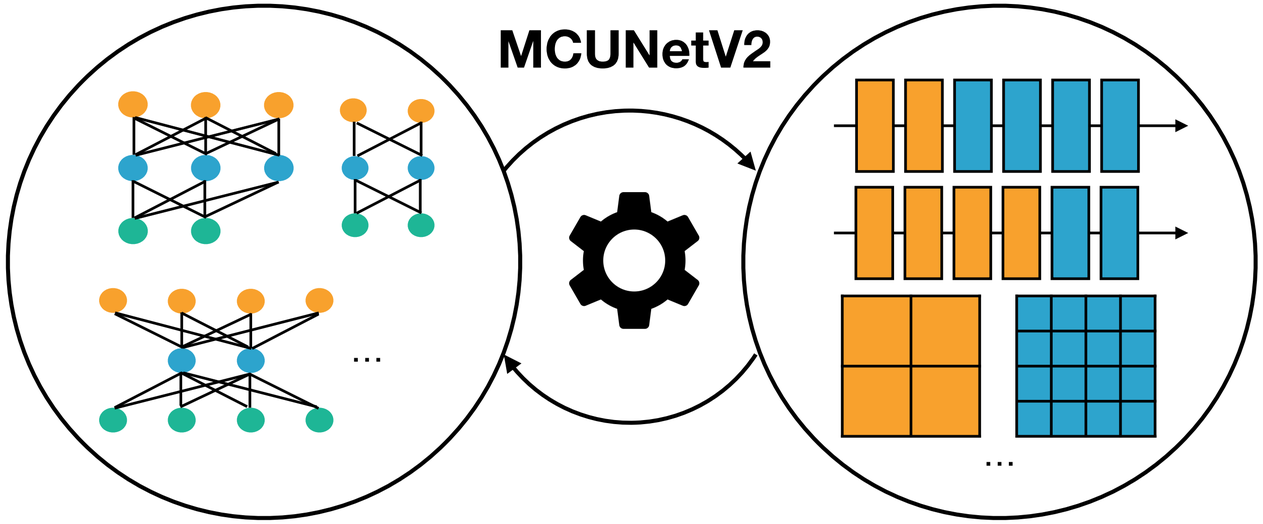


MCUNetV2: Memory-Efficient Patch-based Inference for Tiny Deep Learning [Lin *et al.*, NeurIPS 2021]

MCUNetV2: Patch-based Inference

2. Joint Automated Search for Optimization



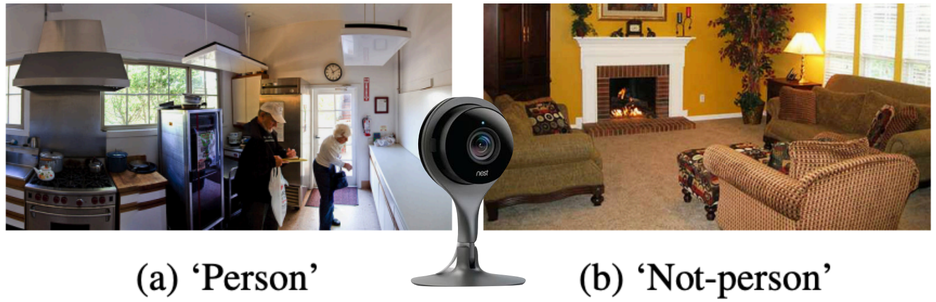
Neural architecture
#layers
#channels
kernel size
…

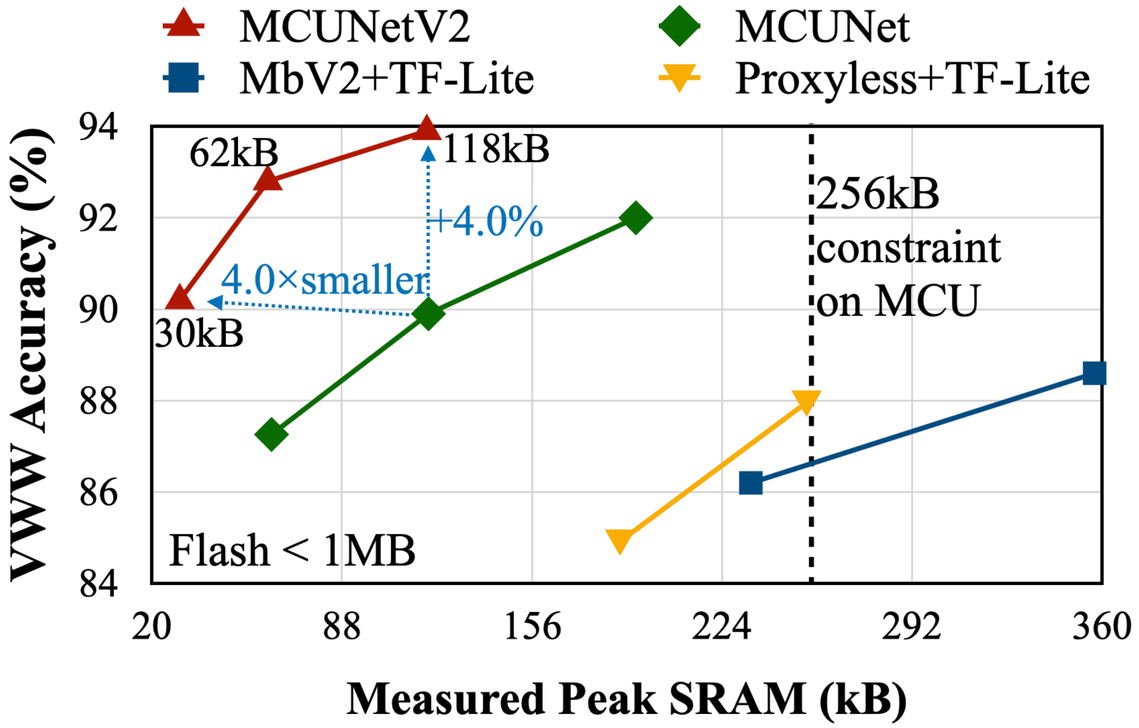
Inference scheduling
#patches
#layers for patch-based
other knobs from TinyEngine
…

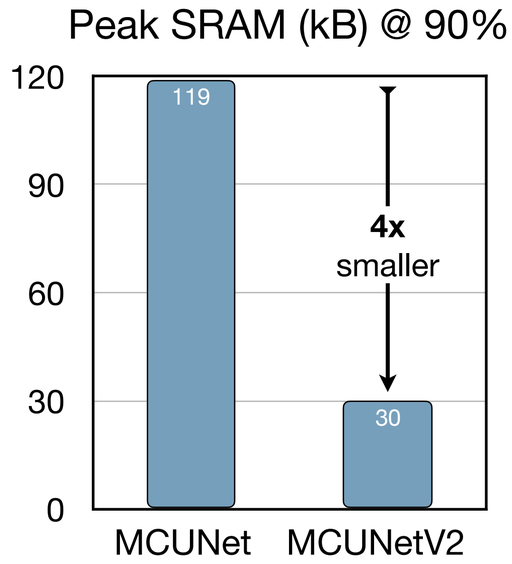
MCUNetV2: Patch-based Inference

Visual Wake Words under 32KB memory

- Higher accuracy, 4x lower SRAM



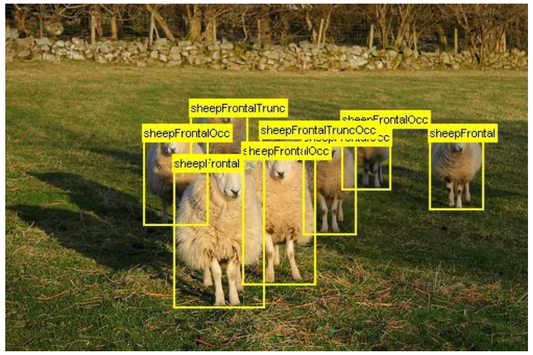


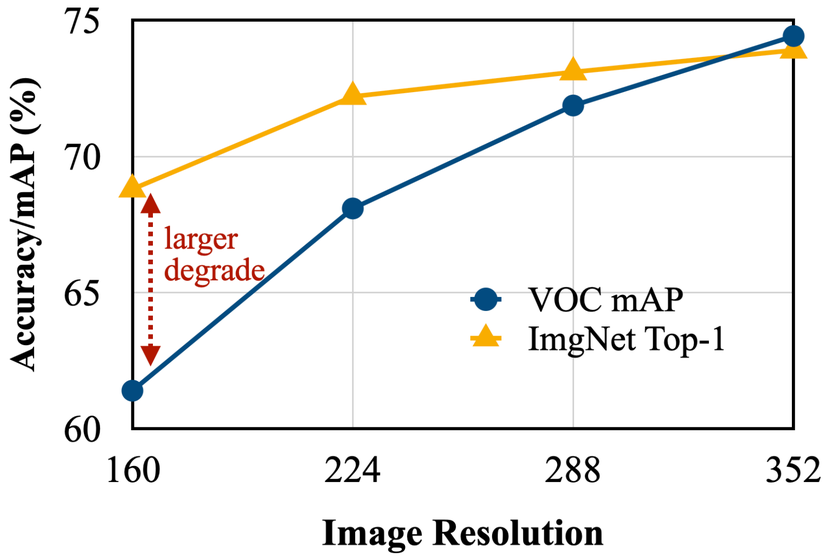


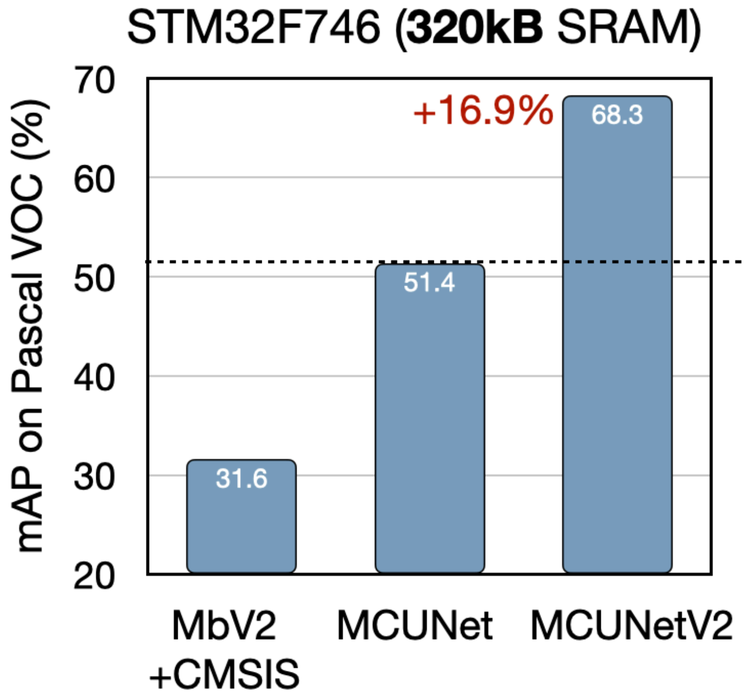
MCUNetV2: Patch-based Inference

Advancing object detection by allowing a larger resolution

- Resolution is more important for detection than classification
- Our method significantly improves objection detection by double digits

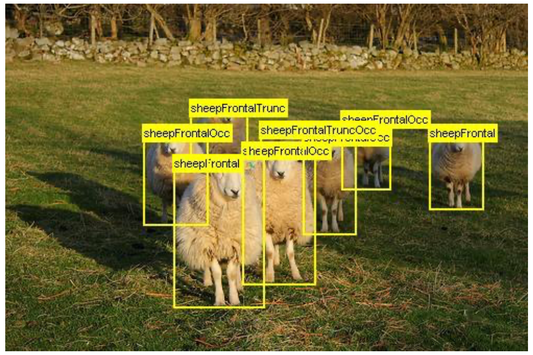






MCUNetV2: Patch-based Inference

Advancing object detection by allowing a larger resolution



Face/mask detection

Person detection

Tiny On-Device Training

- **Sparse Update**
- **Tiny Training Engine (TTE)**

On-Device Training Under 256KB SRAM [Lin *et al.*, NeurIPS 2022]

Can We Learn on the Edge?

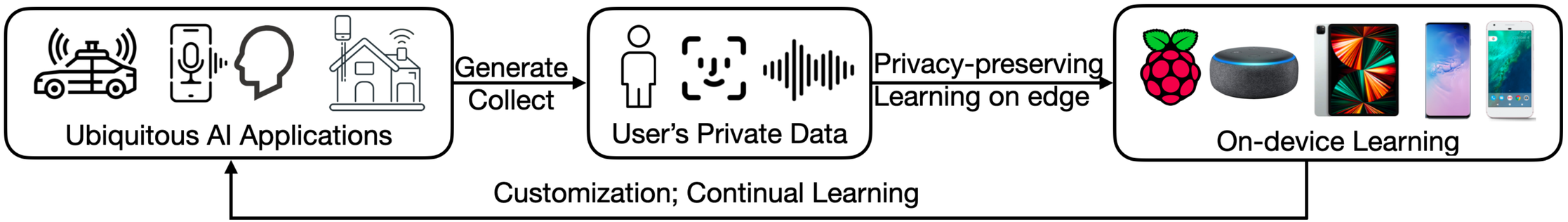
From tinyML inference to training

- On-device learning:
  - **customization** by adapting to user data / **life-long** learning
  - better **privacy**, lower **cost**

Can We Learn on the Edge?

From tinyML inference to training

A **virtuous cycle**:



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Can We Learn on the Edge?

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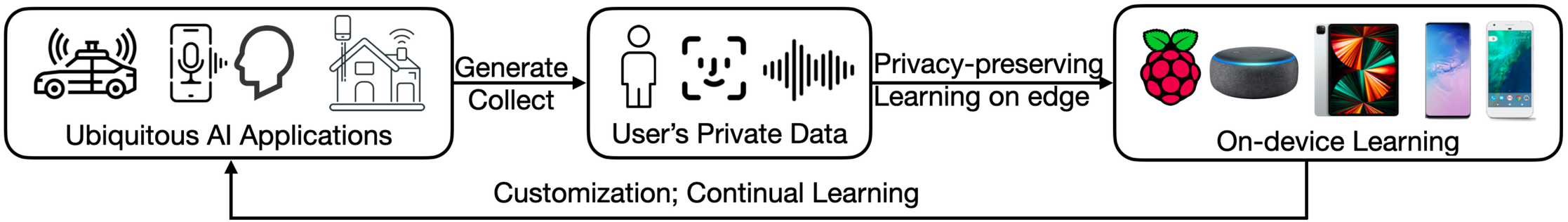
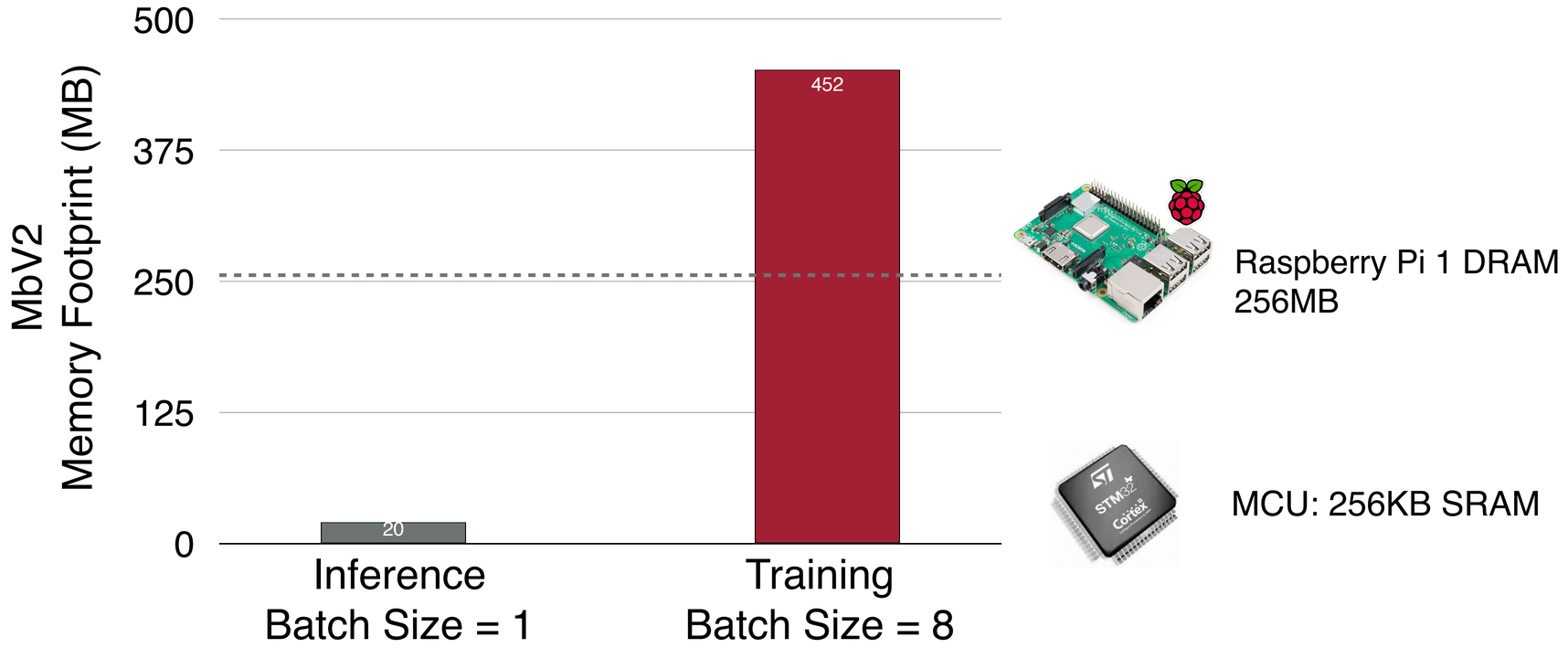


- On-device learning:
  - **customization** by adapting to user data / **life-long** learning
  - better **privacy**, lower **cost**
- Training is more **expensive** than inference
  - For example, store intermediate activation, extra back-propagation, etc.

Training Memory is the Key Bottleneck

- Edge devices have tight memory constraints. The training memory footprint of neural networks can easily exceed the limit.



TinyTL: Reduce Activations, Not Trainable Parameters for Efficient On-Device Learning [Cai *et al.*, NeurIPS 2020]

On-Device Training Under 256KB Memory

- **Training** is more expensive than **inference** due to back-propagation, making it hard to fit IoT devices (e.g., MCU only has 256KB SRAM).

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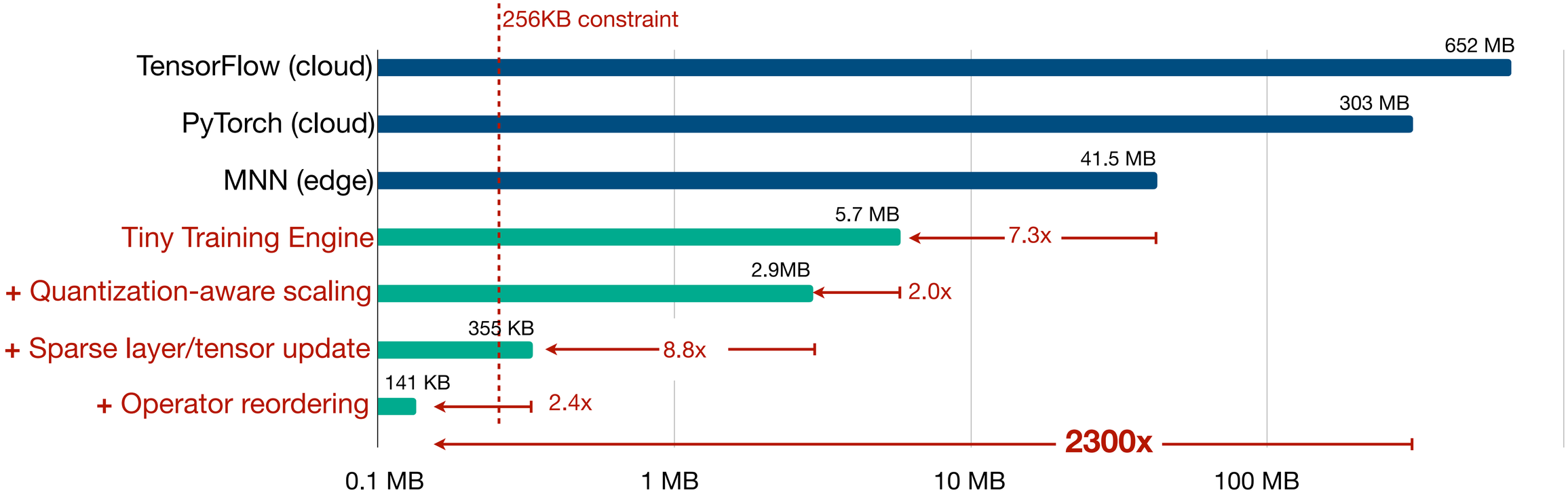
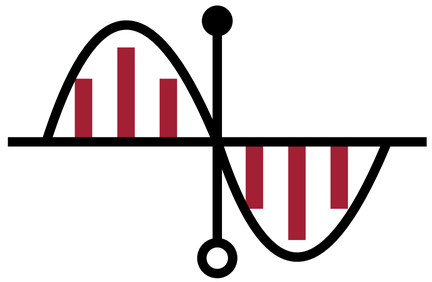
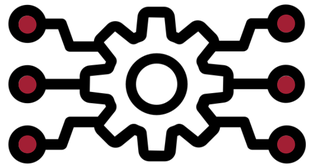


On-Device Training Under 256KB Memory



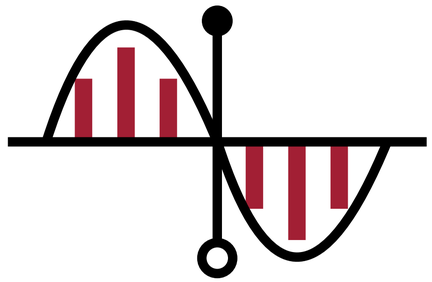
1. Quantization-aware scaling

2. Sparse layer/tensor update



3. Tiny Training Engine

On-Device Training Under 256KB Memory



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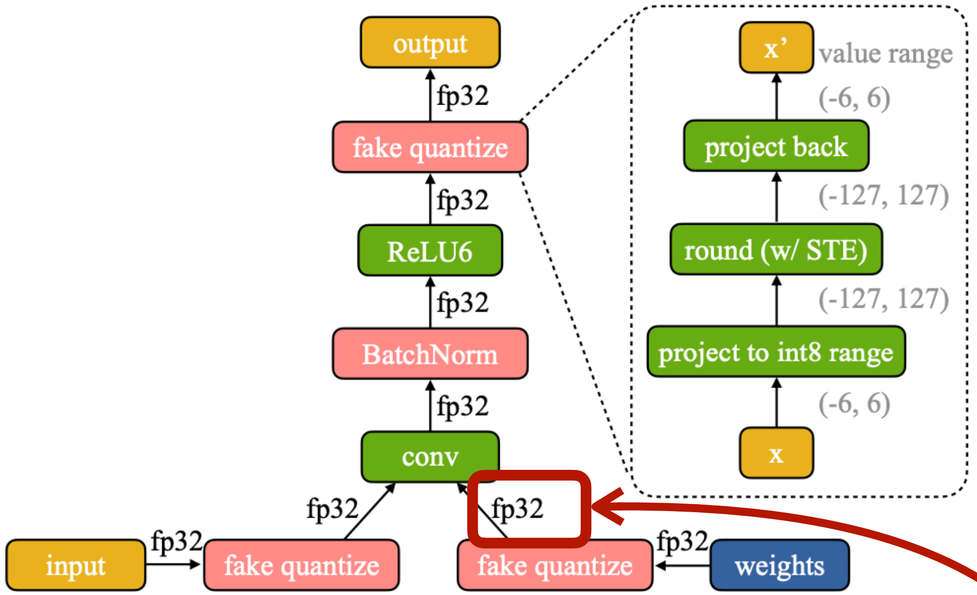
3. Tiny Training Engine

1. Quantization-Aware Scaling (QAS)

Real quantized graphs save memory, but are hard to quantize

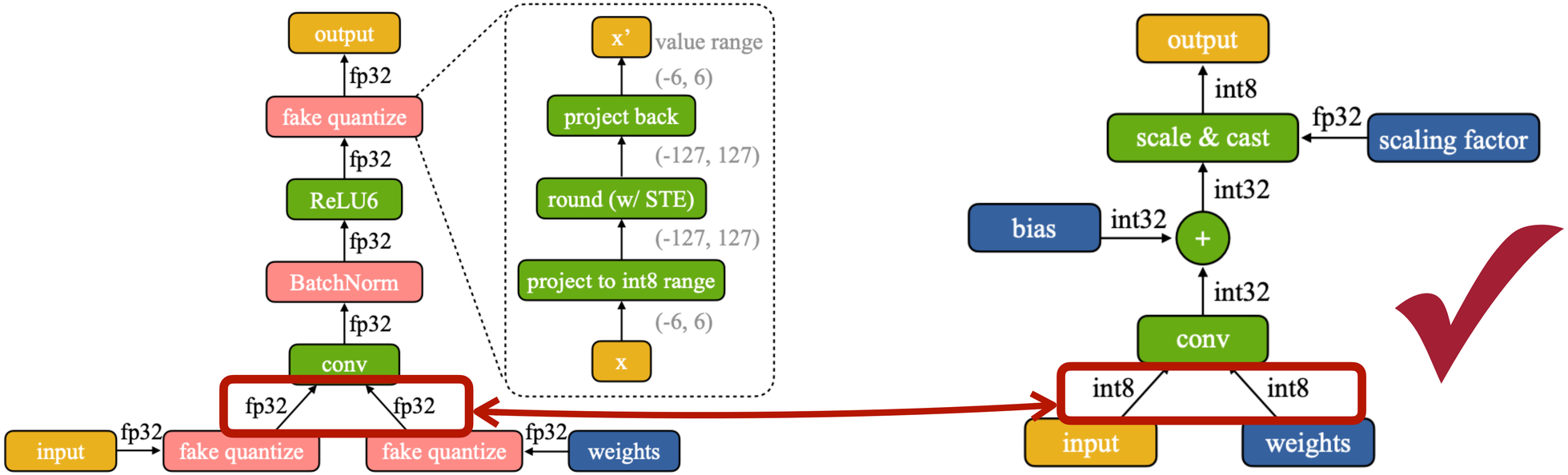


(a) Fake Quantization
(quantization aware training)

Most intermediate tensors are **still in FP32** format in fake quantization, thus cannot save memory footprint

1. Quantization-Aware Scaling (QAS)

Real quantized graphs save memory, but are hard to quantize



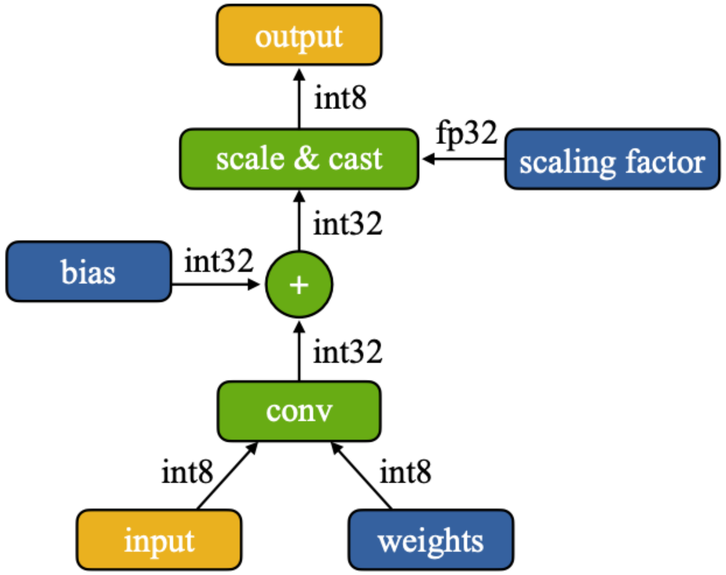
(a) Fake Quantization
(quantization aware training)

(b) Real Quantization
(inference/on-device training)

All tensors are in **int8/int32 format** for real quantization,
thus save memory footprint, but leading to optimization difficulty

1. Quantization-Aware Scaling (QAS)

Quantized graphs save memory, but are hard to quantize

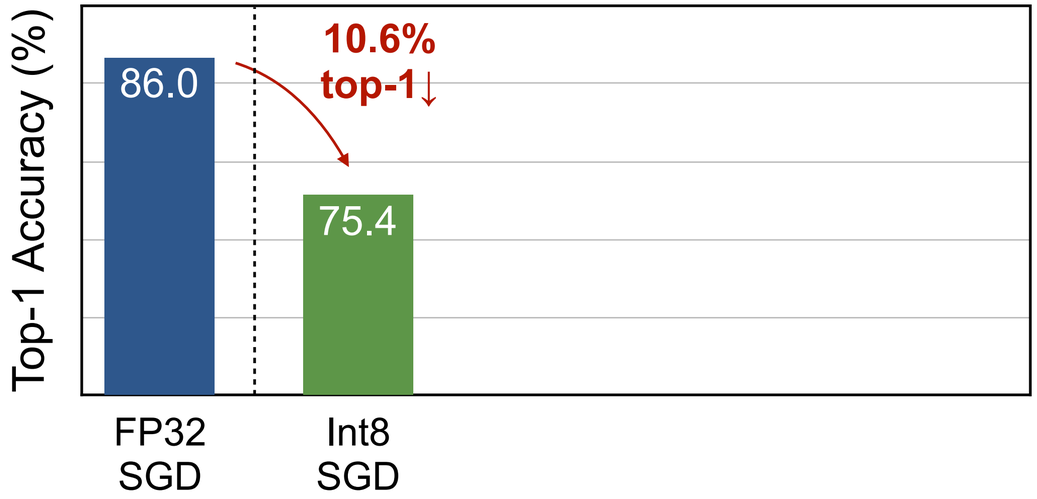


(a) Real Quantization

Making training difficult:

- Mixed precisions: int8/int32/fp32…
- Lack BatchNorm

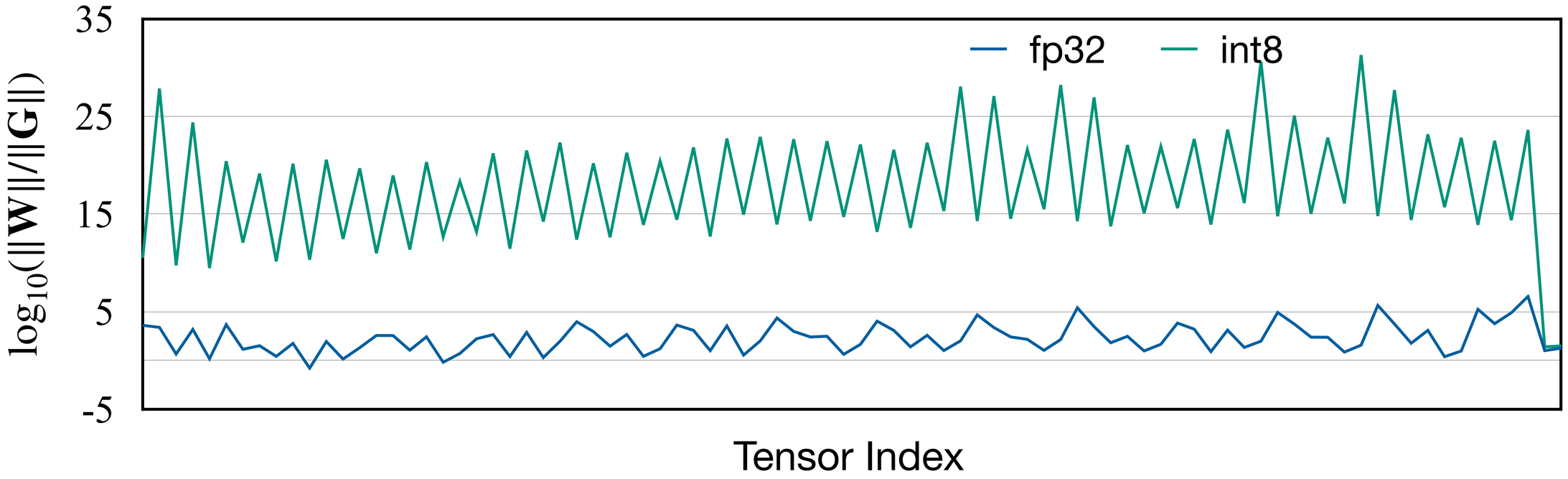
Performance Comparison (average on 10 datasets)



1. Quantization-Aware Scaling (QAS)

Quantization leads to distorted gradient magnitudes

- Why is the training convergence worse?
- The scale of weight and gradients does not match in ***real quantized training!***



1. Quantization-Aware Scaling (QAS)

QAS addresses the optimization difficulty of quantized graphs

Quantization overview

$$\bar{\mathbf{y}}_{\texttt{int8}} = \texttt{cast2int8}[s_{\texttt{fp32}} \cdot (\bar{\mathbf{W}}_{\texttt{int8}} \bar{\mathbf{x}}_{\texttt{int8}} + \bar{\mathbf{b}}_{\texttt{int32}})],$$

Per Channel scaling

$$\mathbf{W} = s_{\mathbf{W}} \cdot (\mathbf{W}/s_{\mathbf{W}}) \overset{\text{quantize}}{\approx} s_{\mathbf{W}} \cdot \bar{\mathbf{W}}, \quad \mathbf{G}_{\bar{\mathbf{W}}} \approx s_{\mathbf{W}} \cdot \mathbf{G}_{\mathbf{W}},$$

Weight and gradient ratios are off by $S_{\mathbf{W}}^{-2}$

$$\|\bar{\mathbf{W}}\|/\|\mathbf{G}_{\bar{\mathbf{W}}}\| \approx \|\mathbf{W}/s_{\mathbf{W}}\|/\|s_{\mathbf{W}} \cdot \mathbf{G}_{\mathbf{W}}\| = \boxed{s_{\mathbf{W}}^{-2}} \cdot \|\mathbf{W}\|/\|\mathbf{G}\|.$$

Thus, re-scale the gradients

$$\tilde{\mathbf{G}}_{\bar{\mathbf{W}}} = \mathbf{G}_{\bar{\mathbf{W}}} \cdot s_{\mathbf{W}}^{-2}, \quad \tilde{\mathbf{G}}_{\bar{\mathbf{b}}} = \mathbf{G}_{\bar{\mathbf{b}}} \cdot s_{\mathbf{W}}^{-2} \cdot s_{\mathbf{x}}^{-2} = \mathbf{G}_{\bar{\mathbf{b}}} \cdot s^{-2}$$

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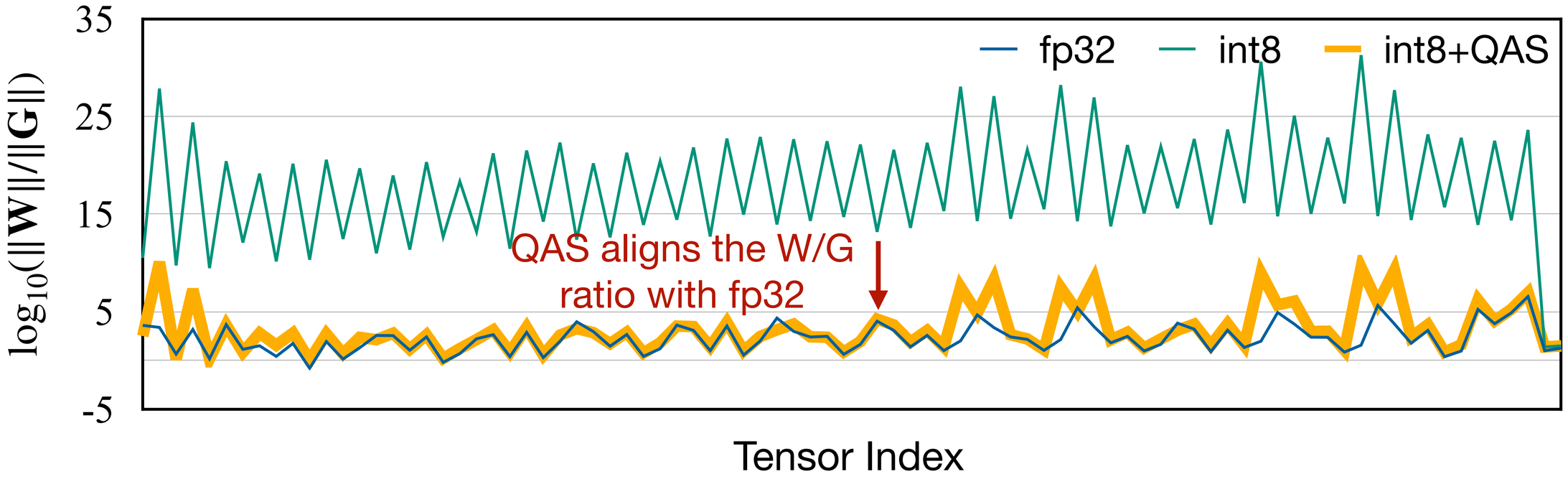
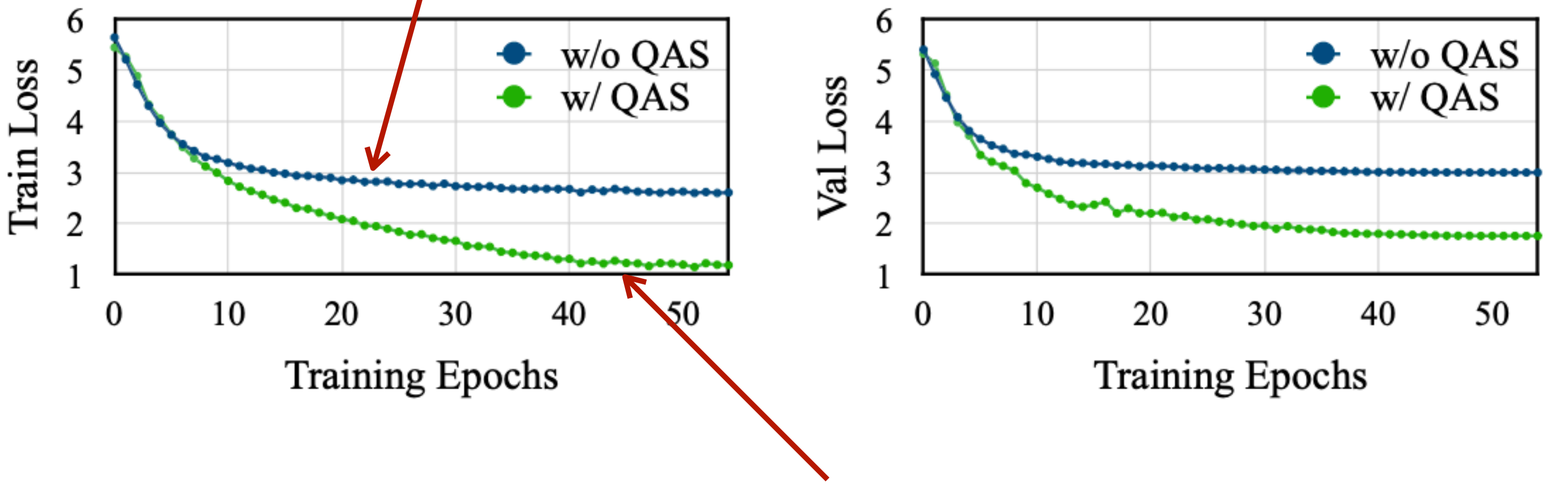


1. Quantization-Aware Scaling (QAS)

QAS addresses the optimization difficulty of quantized graphs

Without QAS, poor convergence

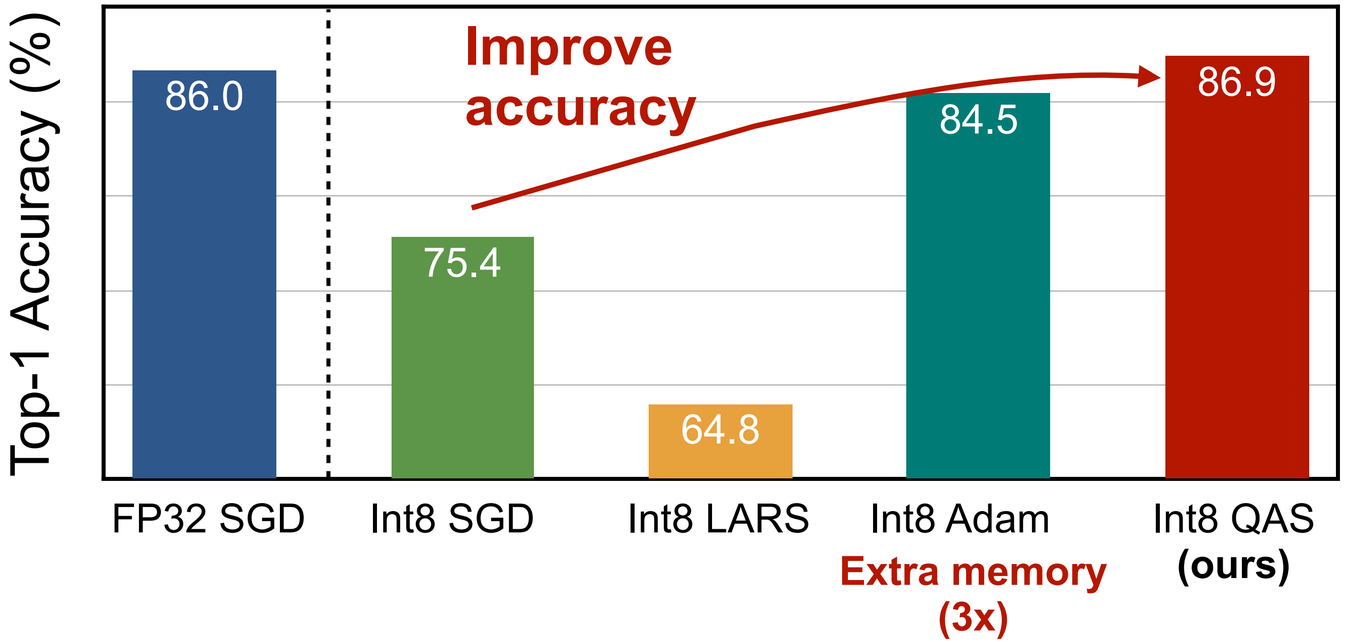


With QAS, better convergence

After applying QAS, the convergence of real quantized is stable.

1. Quantization-Aware Scaling (QAS)

QAS addresses the optimization difficulty of quantized graphs

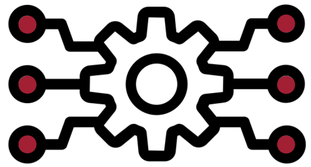


QAS improves the accuracy over naive int8 training, and shows no inferior performance than fp32 results.

On-Device Training Under 256KB Memory

1. Quantization-aware scaling

2. Sparse layer/tensor update



3. Tiny Training Engine

Training Memory is the Key Bottleneck

Question: Why training memory is much larger than inference?

Answer: Because of intermediate **activations**

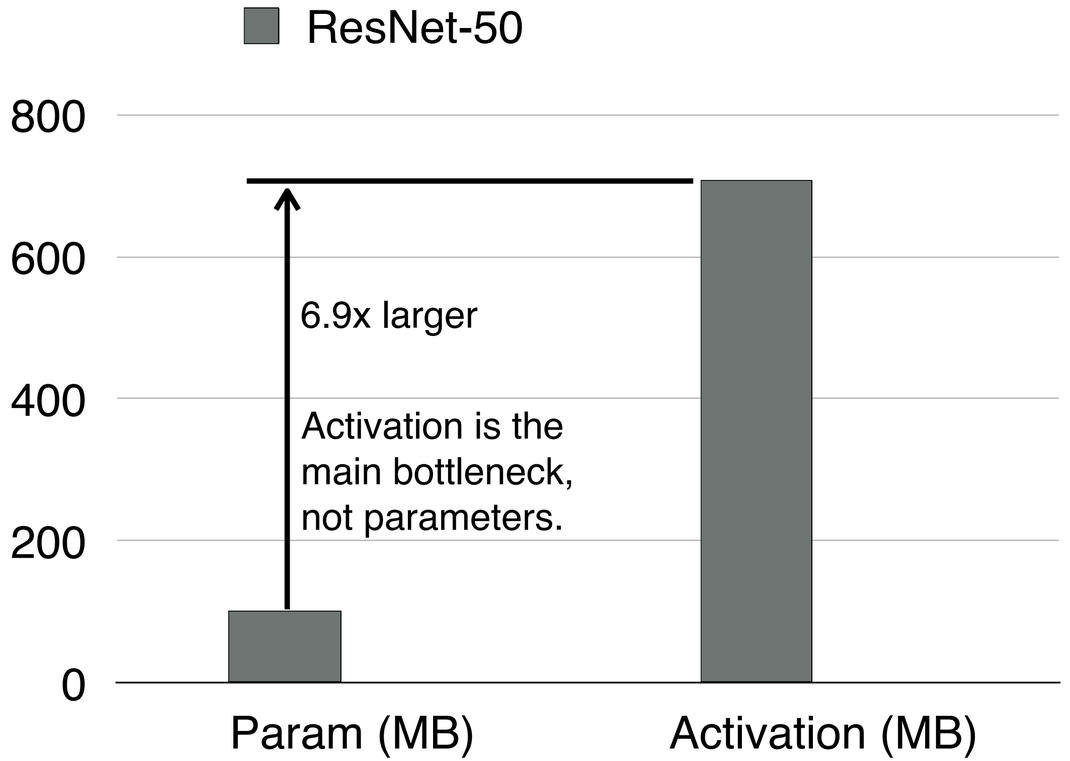
Forward: $\mathbf{a}_{i+1} = \mathbf{a}_i \mathbf{W}_i + \mathbf{b}_i$

Backward: $\frac{\partial L}{\partial \mathbf{W}_i} = \mathbf{a}_i^T \frac{\partial L}{\partial \mathbf{a}_{i+1}}$

- Inference does not need to store activations, training does.
- Activations grows linearly with batch size, which is always 1 for inference.
- Even with bs=1, activations are usually larger than model weights.

TinyTL: Reduce Activations, Not Trainable Parameters for Efficient On-Device Learning [Cai *et al.*, NeurIPS 2020]

Training Memory is the Key Bottleneck



- Activation is the main bottleneck for on-device learning, not parameters.

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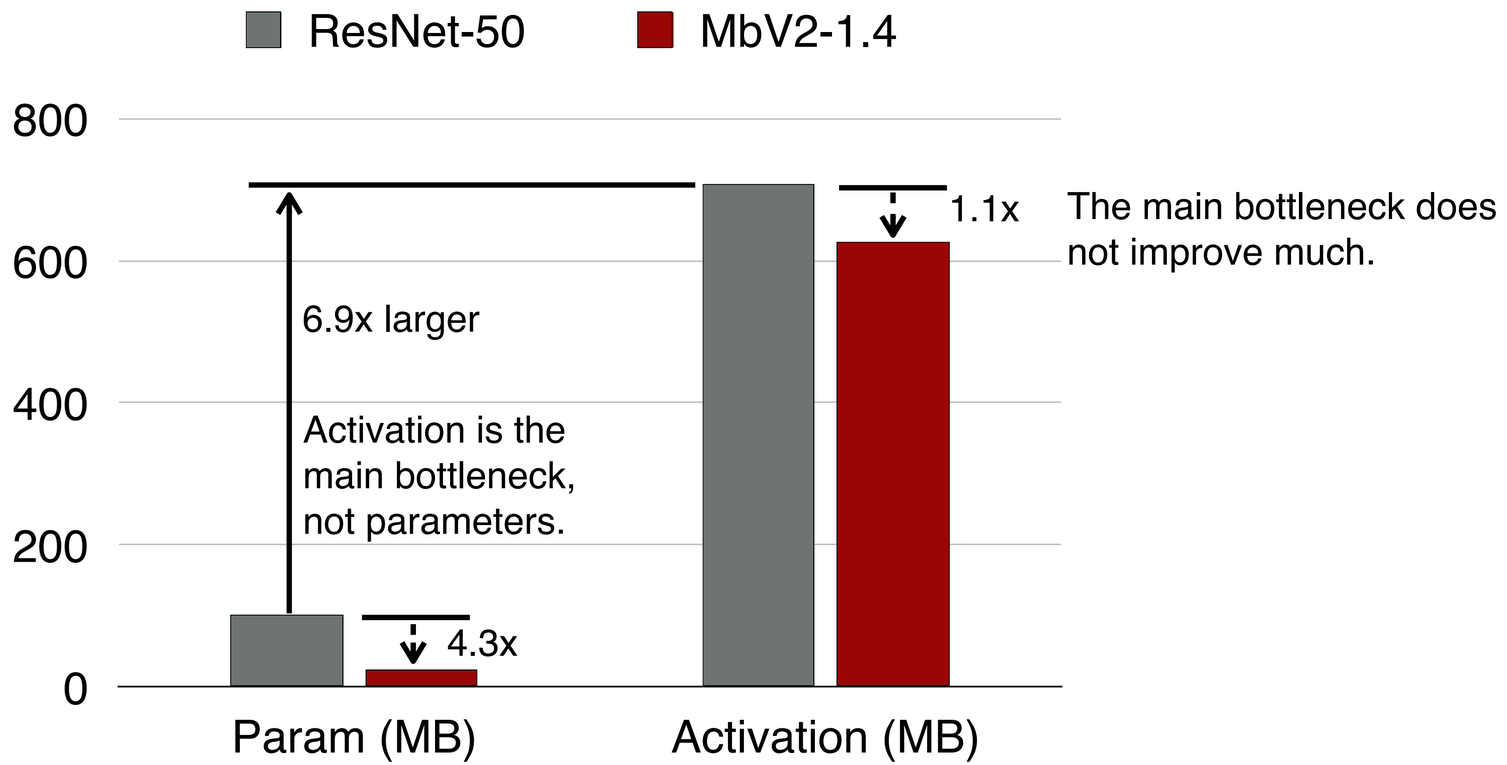
Training Memory is the Key Bottleneck

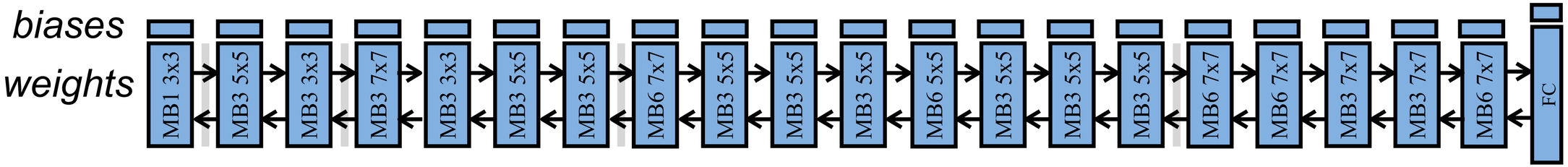


- Activation is the main bottleneck for on-device learning, not parameters.
- Previous methods focus on reducing the number of parameters or FLOPs, while the main bottleneck does not improve much.

TinyTL: Reduce Activations, Not Trainable Parameters for Efficient On-Device Learning [Cai *et al.*, NeurIPS 2020]

2. Sparse Layer/Tensor Update

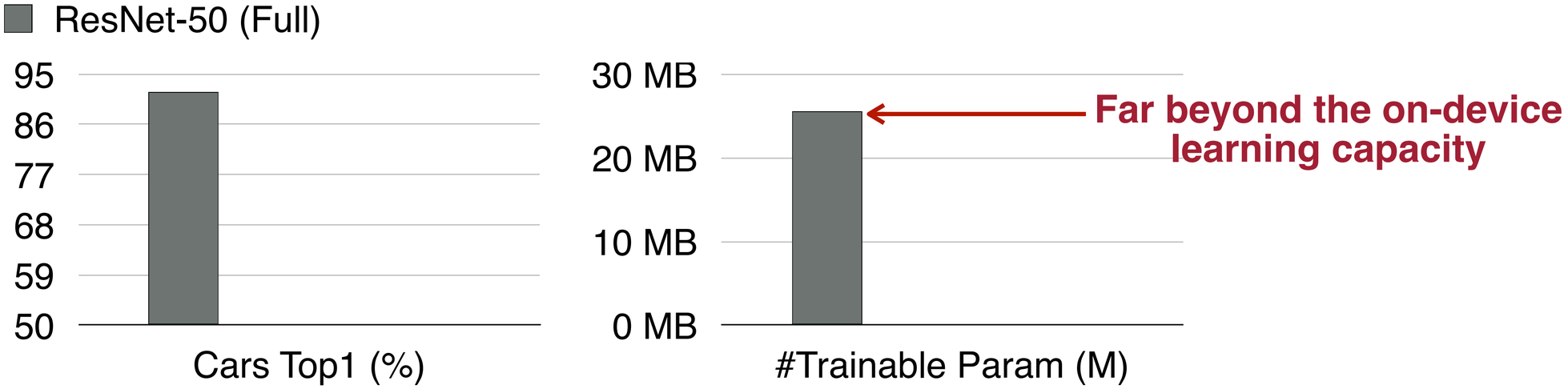
Full update



Model: ProxylessNAS-Mobile

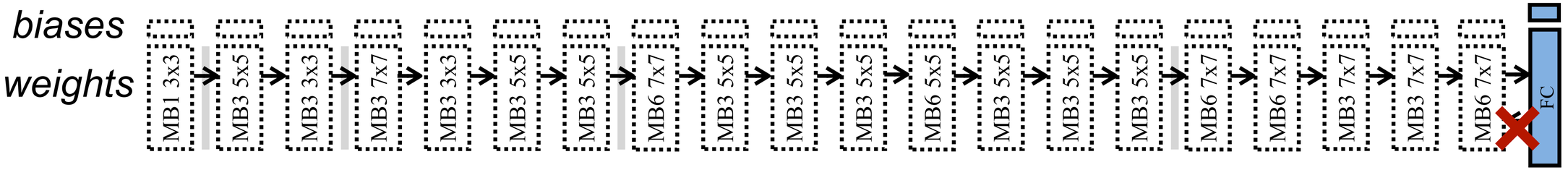
Updating the whole model is **too expensive**:

- Need to save all intermediate activation (quite large)
- Need to store the updated weights in SRAM (Flash is read-only)



2. Sparse Layer/Tensor Update

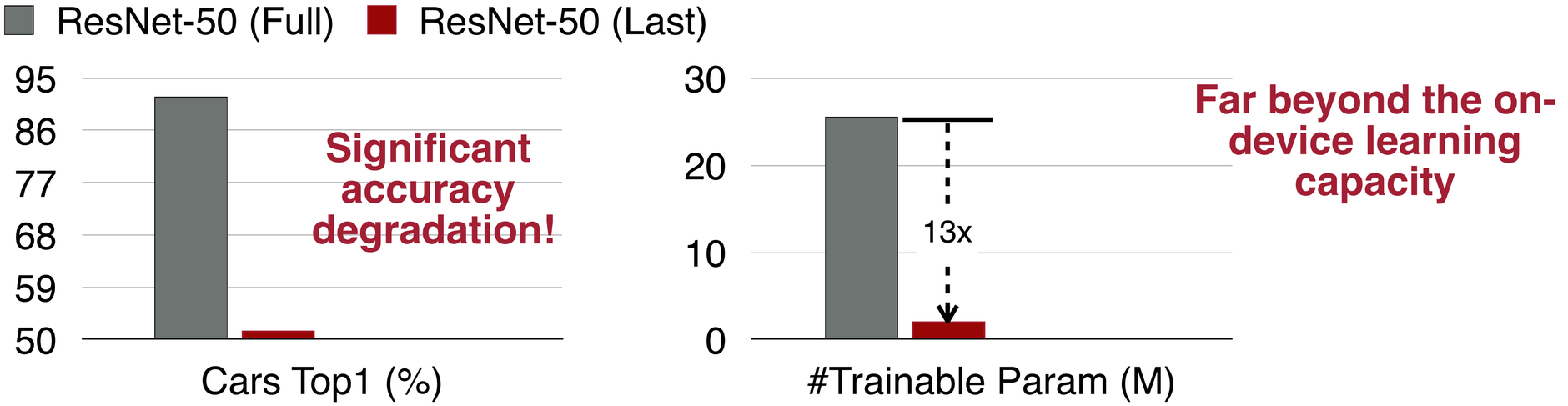
Last layer update



Model: ProxylessNAS-Mobile

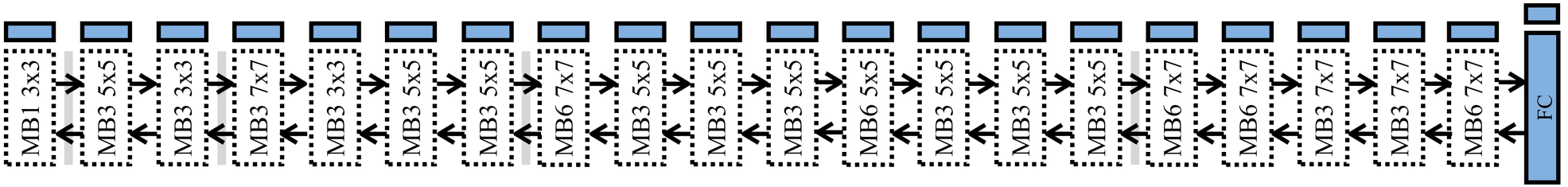
Updating only the last cheap

- No need to back propagating to previous layers
- But the accuracy is low and not ideal.



2. Sparse Layer/Tensor Update

Bias-only update



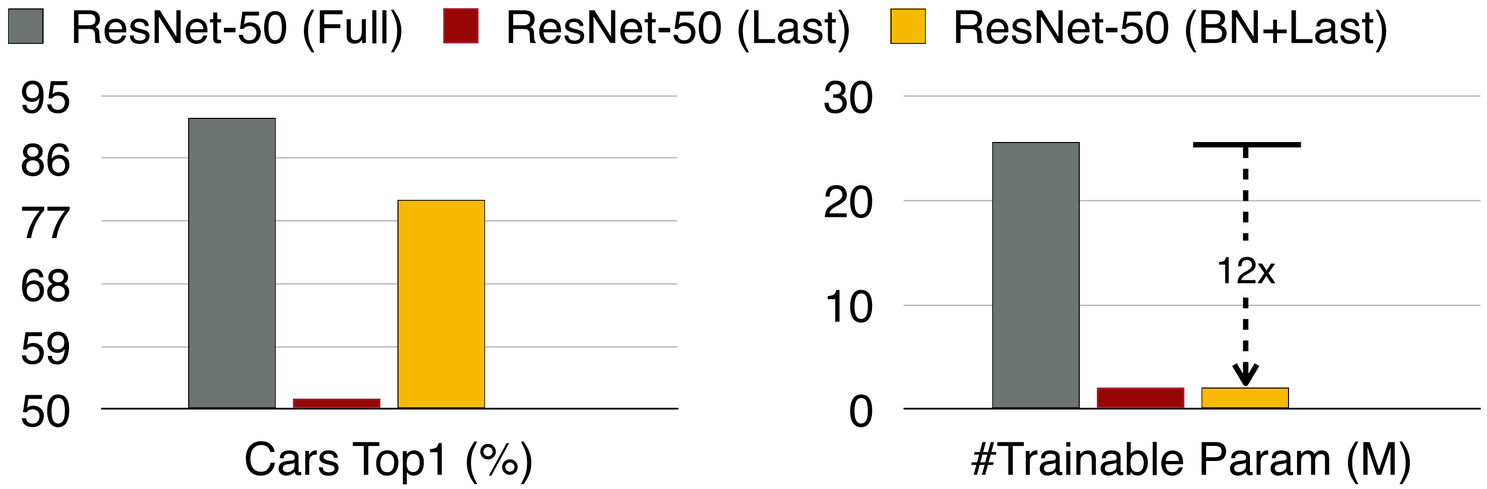
Model: ProxylessNAS-Mobile

Updating the only the bias part

- No need to store the activations
- Back propagating to the first layer.

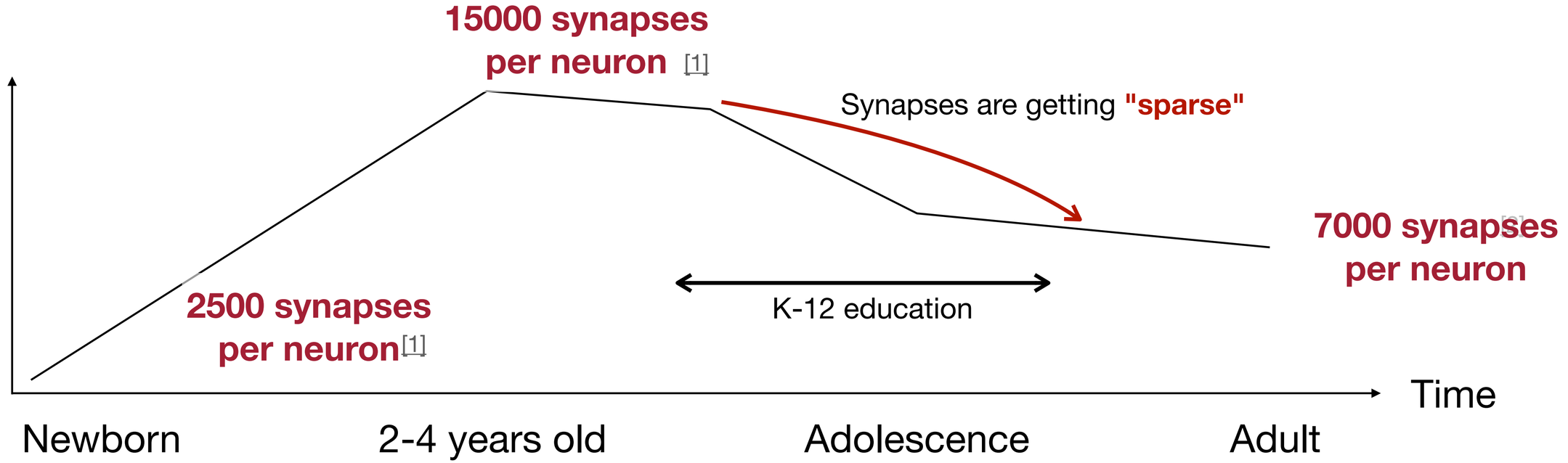
$$d\mathbf{W} = f(\mathbf{X}, d\mathbf{Y})$$

$$d\mathbf{b} = f(d\mathbf{Y})$$



2. Sparse Layer/Tensor Update

Updated synapses are sparse

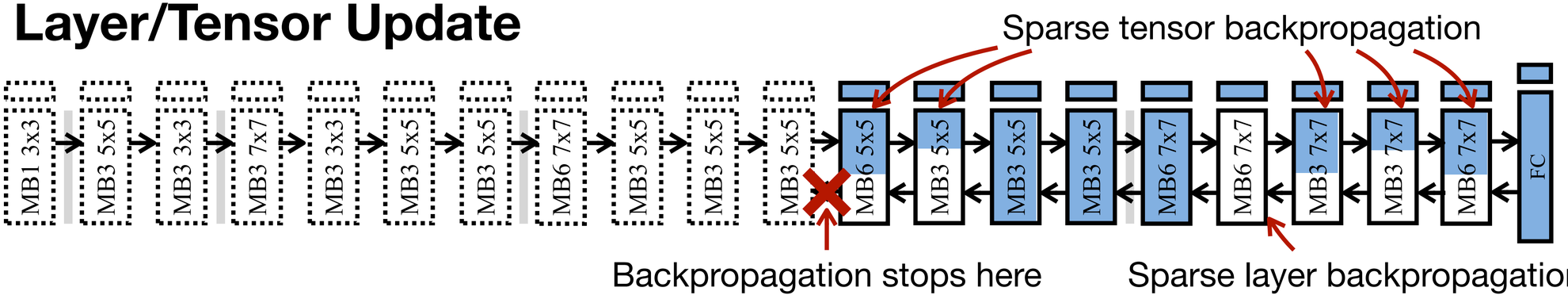


Do We Have Brain to Spare? [Drachman DA, Neurology 2004]
Peter Huttenlocher (1931–2013) [Walsh, C. A., Nature 2013]

Data Source: 1, 2
Slide Inspiration: Alila Medical Media

2. Sparse Layer/Tensor Update

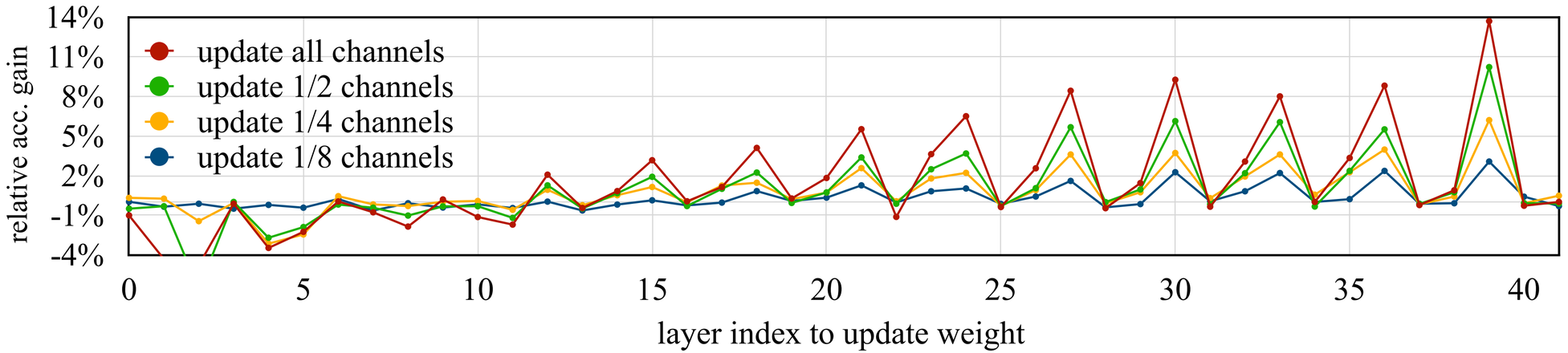
Sparse Layer/Tensor Update



Model: ProxylessNAS-Mobile

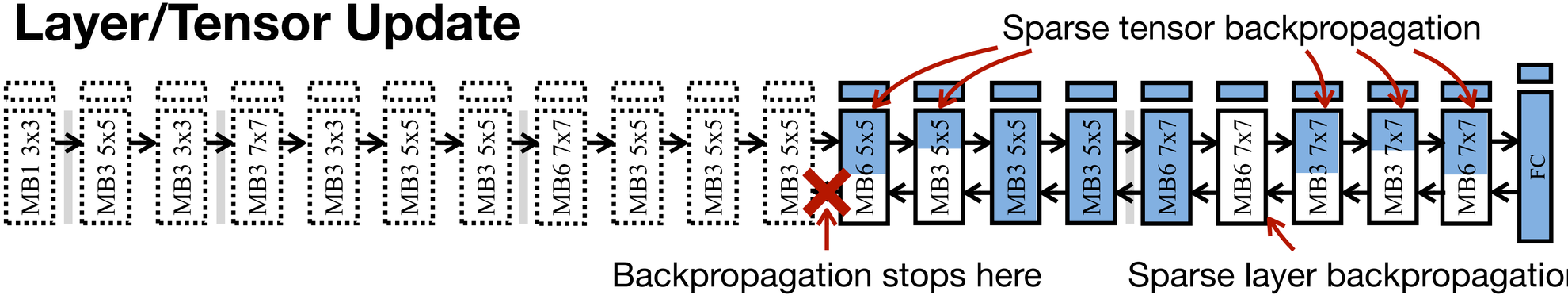
Updating the sparse tensors / layers

- Some layers are more important than others



2. Sparse Layer/Tensor Update

Sparse Layer/Tensor Update



Model: ProxylessNAS-Mobile

Updating the sparse tensors / layers

- Some layers are more important than others
- No need to back propagate the early layers
- Only need to store a subset of the activations.

Activation to store: (N, M)

Weight in SRAM: (M, H)

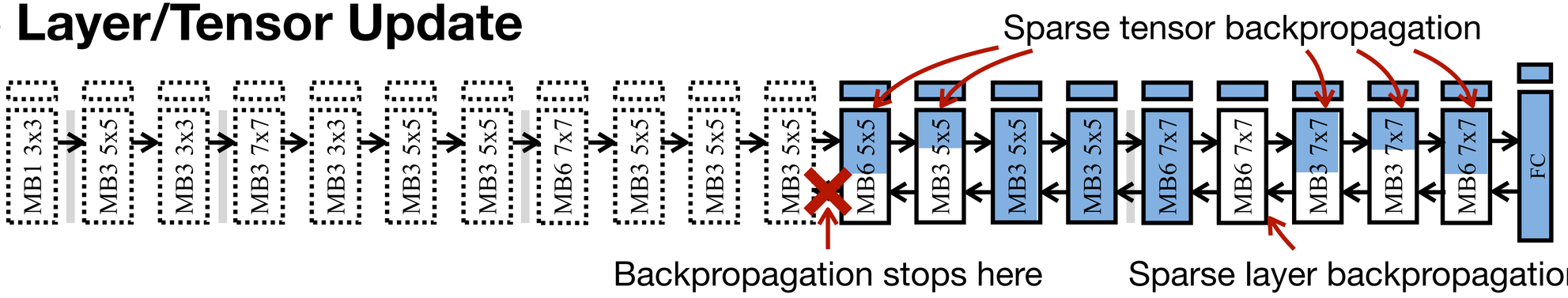
Reduce by 4x

Activation to store: (N, 0.25*M)

Weight in SRAM: (0.25*M, H)

2. Sparse Layer/Tensor Update

Sparse Layer/Tensor Update



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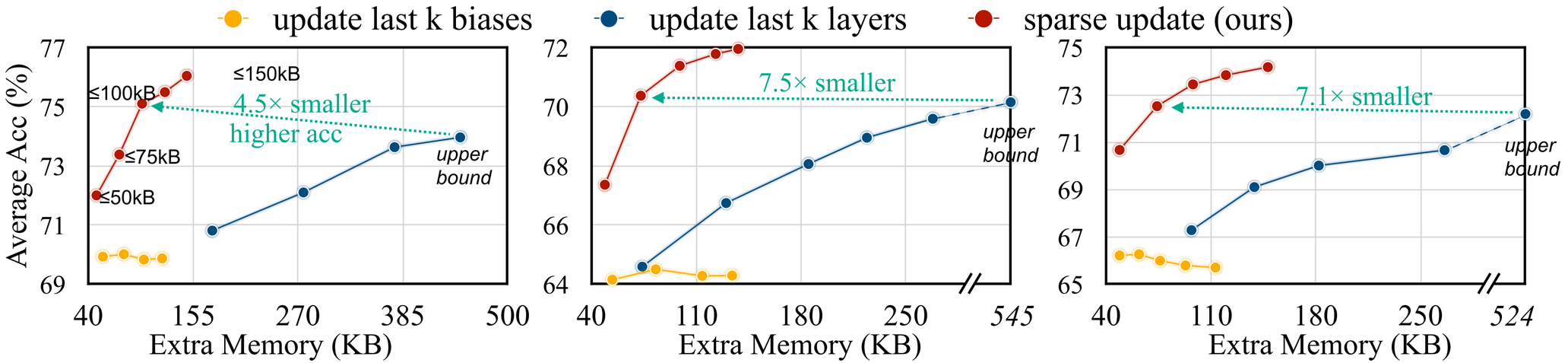
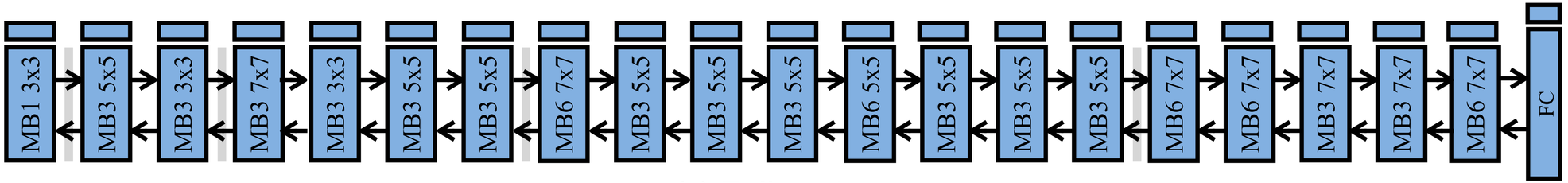
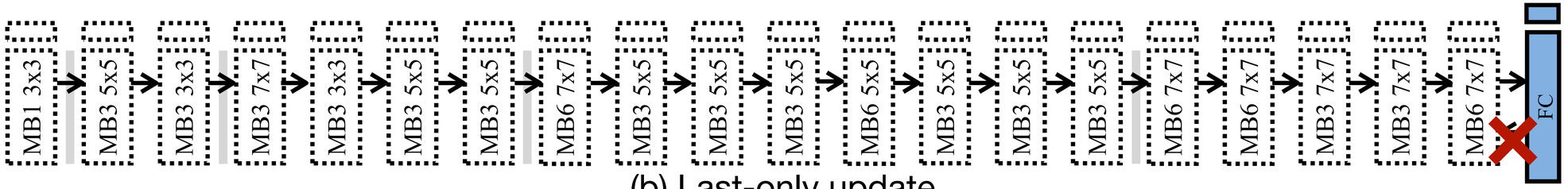


(a) MCUNet-5FPS (b) MbV2-w0.35 (c) Proxyless-w0.3

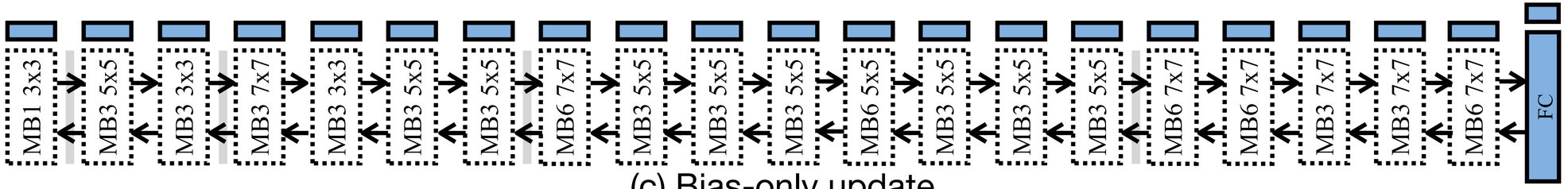
Update Paradigms Comparison



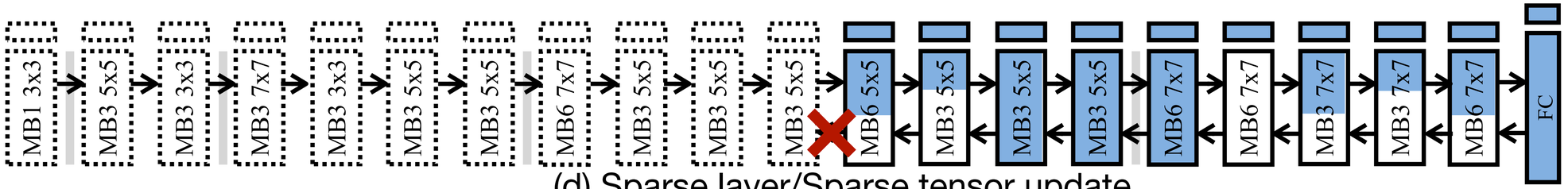
(a) Full update



(b) Last-only update



(c) Bias-only update

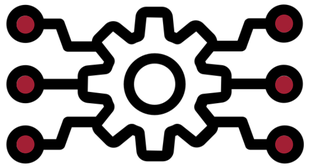


(d) Sparse layer/Sparse tensor update

On-Device Training Under 256KB Memory

1. Quantization-aware scaling

2. Sparse layer/tensor update



3. Tiny Training Engine

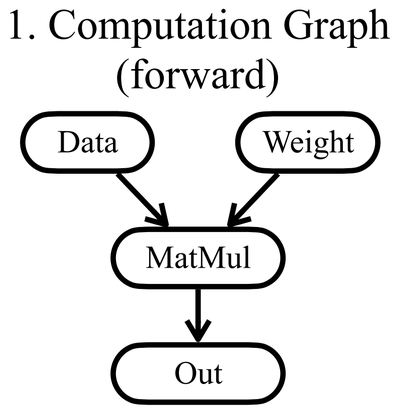
3. Tiny Training Engine (TTE)

Existing frameworks cannot fit

- **Runtime** is heavy
  - Heavy dependencies and large binary size (>**100MB** static memory)
  - Auto-diff at runtime; low edge efficiency
- **Memory** is heavy
  - A lot of intermediate (and unused) buffers
  - Has to compute full gradients

3. Tiny Training Engine (TTE)

Workflow of conventional training engine



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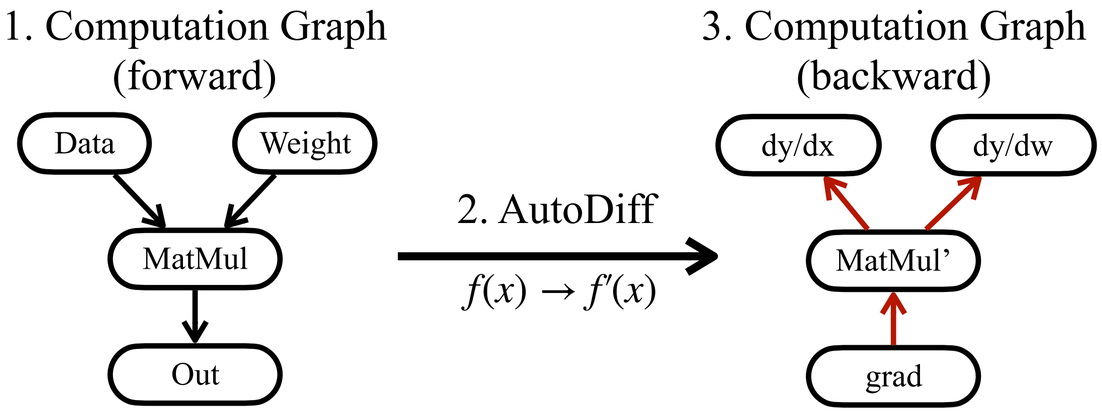
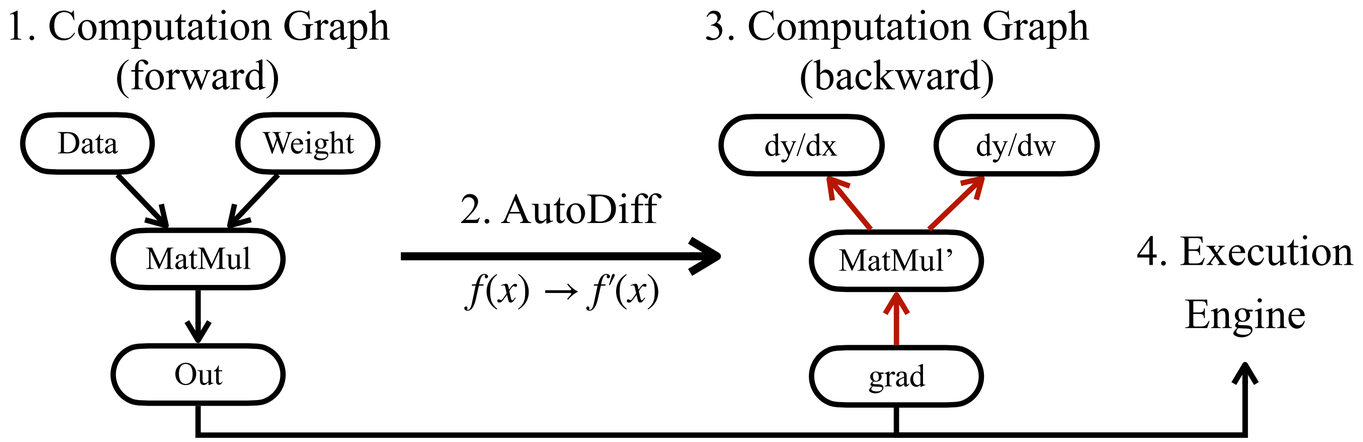
Workflow of conventional training engine



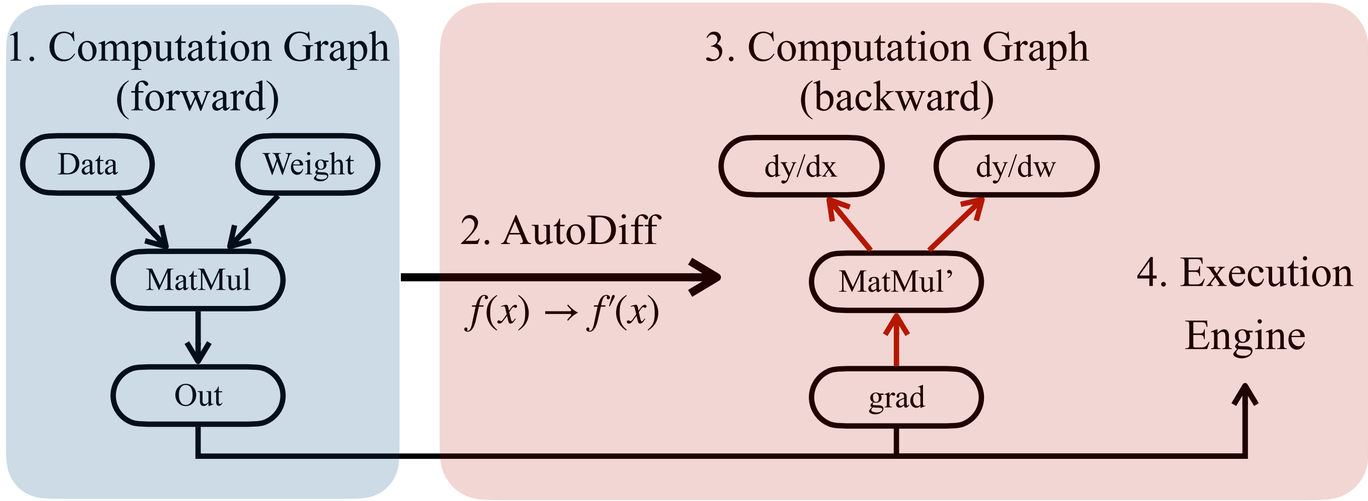
3. Tiny Training Engine (TTE)

Workflow of conventional training engine



3. Tiny Training Engine (TTE)

Workflow of conventional training engine



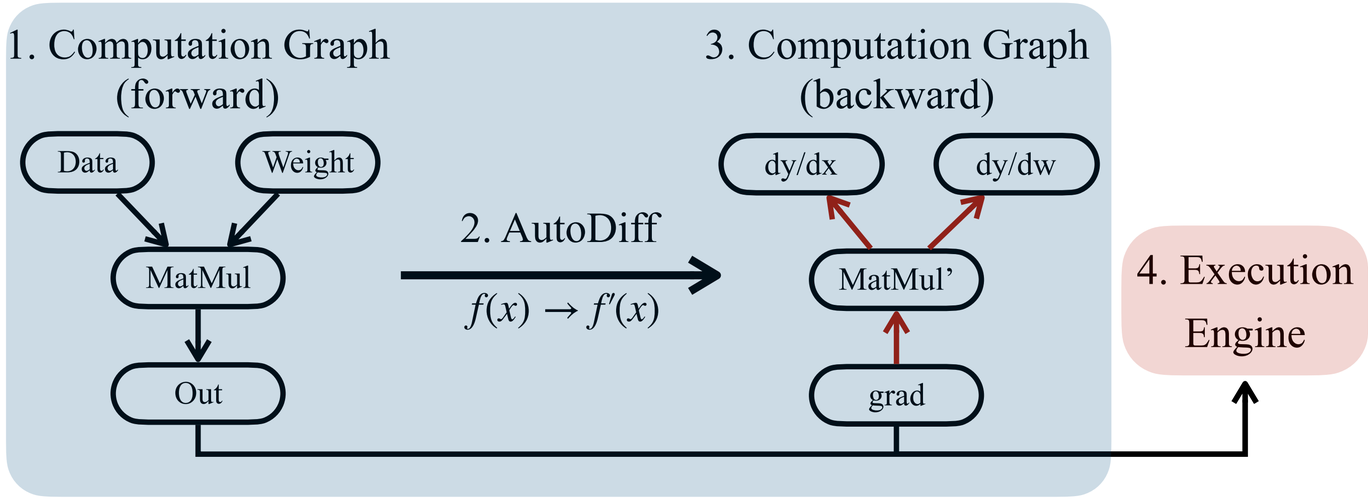
: Compile-Time

: Runtime

Conventional training framework focus on **flexibility**,
and the auto-diff is performed at **runtime**.
Thus, any optimizations will lead to runtime overhead.

3. Tiny Training Engine (TTE)

TTE: Move workload from runtime to compile time



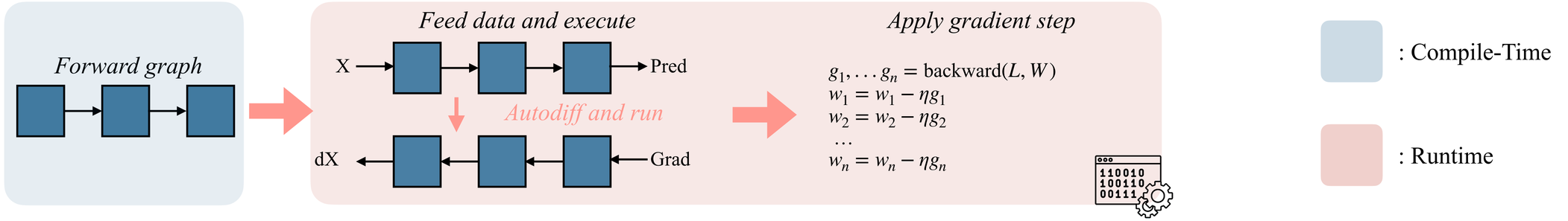
: Compile-Time

: Runtime

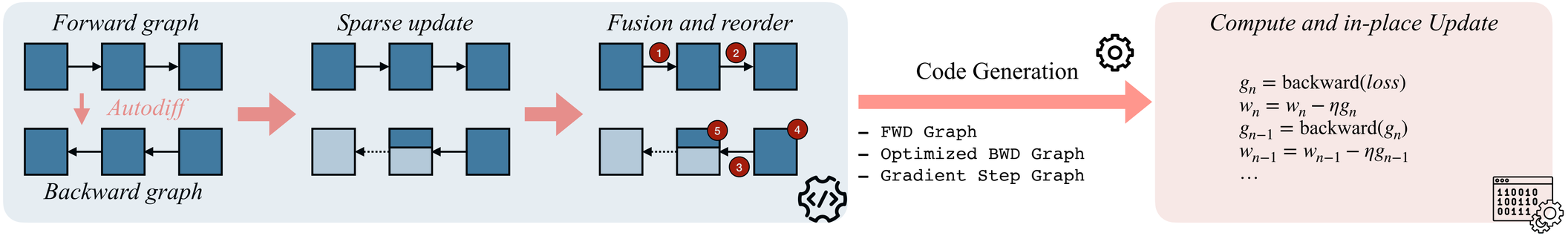
TTE moves most workload from runtime to **compile-time**,
thus minimizes the **runtime overhead**,
also enables opportunities for **extensive graph optimizations**.

3. Tiny Training Engine (TTE)

Enable graph optimizations (backward pruning, reordering, etc.)

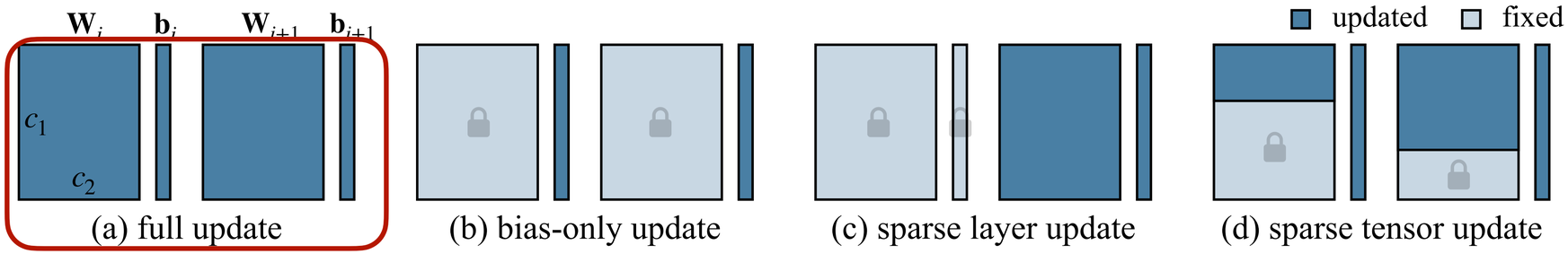


Conventional training framework performs most tasks at runtime.



Tiny Training Engine (ours) **separate** the environment of runtime and compile time.

3. Tiny Training Engine (TTE)



(a) full update (b) bias-only update (c) sparse layer update (d) sparse tensor update

Example from a matrix multiplication with full update

Forward

$$y = mul(x, w) + b$$

Backward

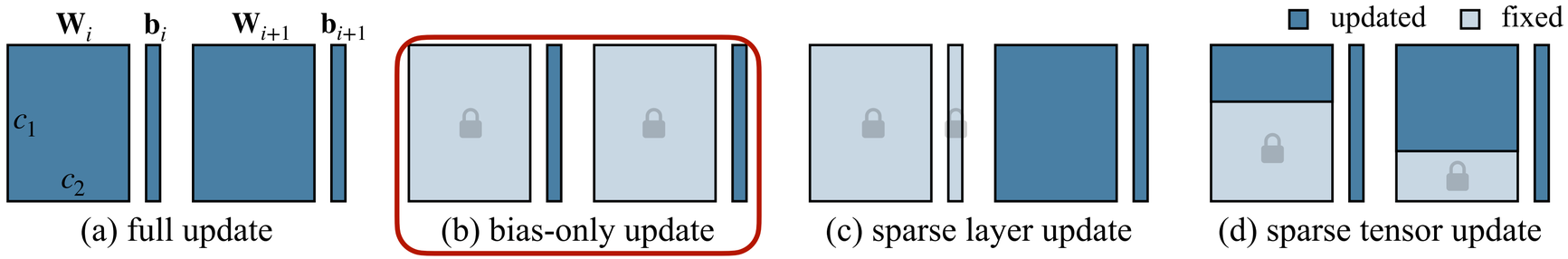
$$dy/dx = mul(G, w)$$

$$dy/dw = mul(G^T, X)$$

$$dy/db = sum(G)$$

```
fn (%x: Tensor[(10, 10), float32],
    %weight: Tensor[(10, 10), float32],
    %bias: Tensor[(10), float32]),
    %grad: Tensor[(10), float32]),
{
  # forward
  %0 = multiply(%x, %weight);
  %1 = add(%0, %bias);
  # backward
  %3 = multiply(%grad, %weight); ====> dy / dx
  %4 = transpose(%grad);
  %5 = multiply(%4, %x);         ====> dy / dw
  %6 = sum(%grad, axis=-1);      ====> dy / db
  (%3, %5, %6)
}
```

3. Tiny Training Engine (TTE)



(a) full update (b) bias-only update (c) sparse layer update (d) sparse tensor update

```
fn (%x: Tensor[(10, 10), float32, needs_grad=True],
    %weight: Tensor[(10, 10), float32, needs_grad=False],
    %bias: Tensor[(10), float32, needs_grad=True],
    %grad: Tensor[(10), float32]),
{
  # forward
  %0 = multiply(%x, %weight);
  %1 = add(%0, %bias);
  # backward
  %3 = multiply(%grad, %weight); ====> dy / dx
  %4 = transpose(%grad);
  %5 = multiply(%4, %x);         ====> dy / dw
  %6 = sum(%grad, axis=-1);      ====> dy / db
  (%3, %5, %6)
}
```

Annotate whether a tensor requires gradient or not

Forward

$$y = mul(x, w) + b$$

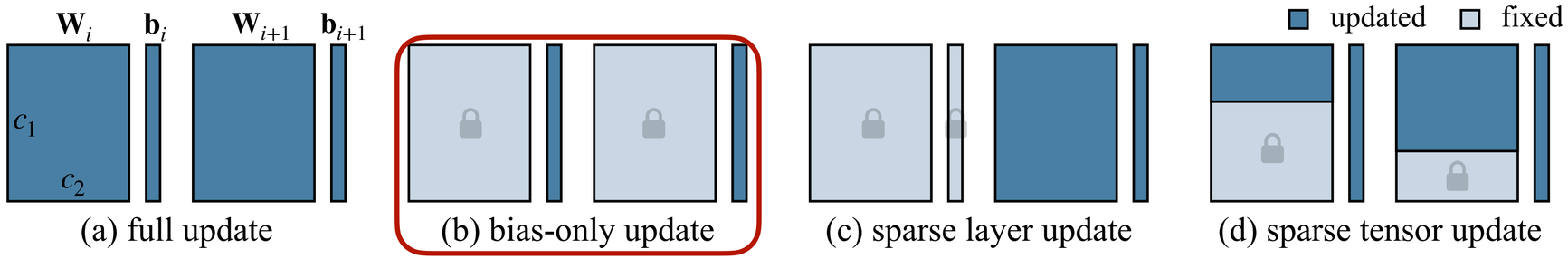
Backward

$$dy/dx = mul(G, w)$$

$$dy/dw = mul(G^T, X)$$

$$dy/db = sum(G)$$

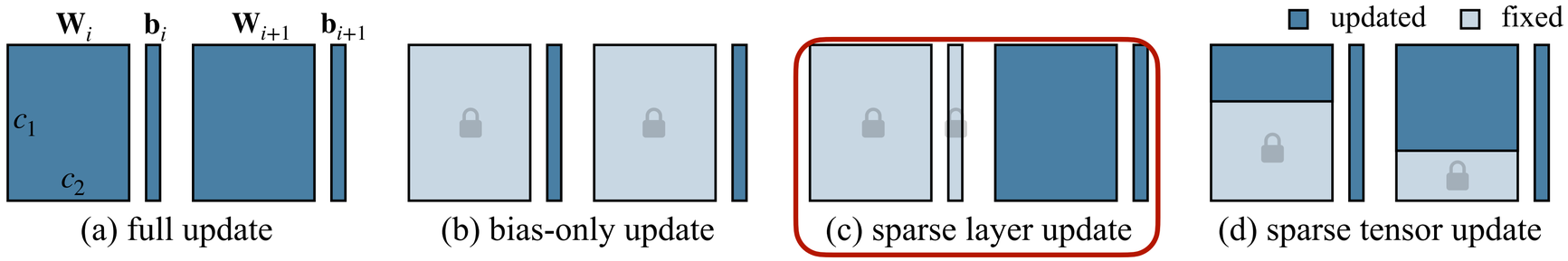
3. Tiny Training Engine (TTE)




```
fn (%x: Tensor[(10, 10), float32, needs_grad=True],
    %weight: Tensor[(10, 10), float32, needs_grad=False],
    %bias: Tensor[(10), float32, needs_grad=True],
    %grad: Tensor[(10), float32]),
{
  # forward
  %0 = multiply(%x, %weight);
  %1 = add(%0, %bias);
  # backward
  %3 = multiply(%grad, %weight); ====> dy / dx
  %4 = transpose(%grad);
  %5 = multiply(%4, %x);         ====> dy / dw
  %6 = sum(%grad, axis=-1);      ====> dy / db
  (%3, %5, %6)
}
```

Remove unnecessary computations from DAG via dependency analysis and dead-code elimination.

3. Tiny Training Engine (TTE)



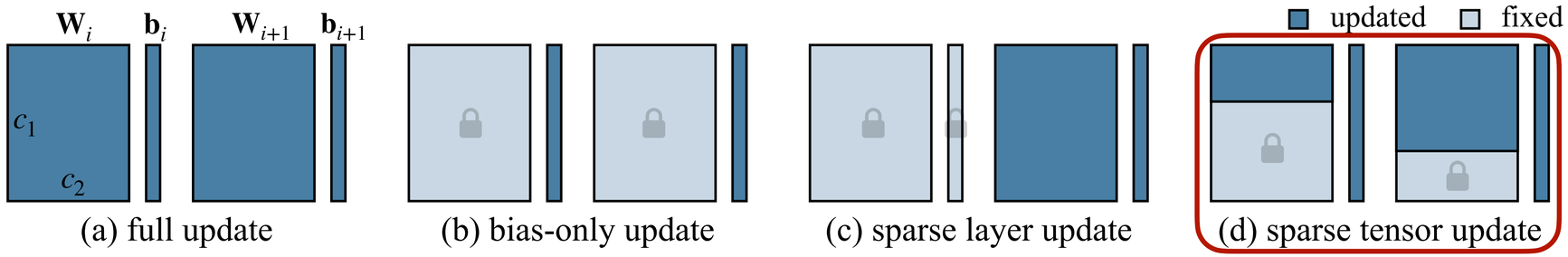
(a) full update (b) bias-only update (c) sparse layer update (d) sparse tensor update

```
fn (%x: Tensor[(10, 10), float32, needs_grad=False],
    %weight1: Tensor[(10, 10), needs_grad=False],
    %bias1: Tensor[(10), needs_grad=False],
    %weight2: Tensor[(10, 10), needs_grad=True],
    %bias2: Tensor[(10), needs_grad=True],
    ..........
    %grad: .., float32]),
{
  # ...
}
```

Freely annotate **ANY** parameters

TTE will trim the computation accordingly.

3. Tiny Training Engine (TTE)



(a) full update (b) bias-only update (c) sparse layer update (d) sparse tensor update

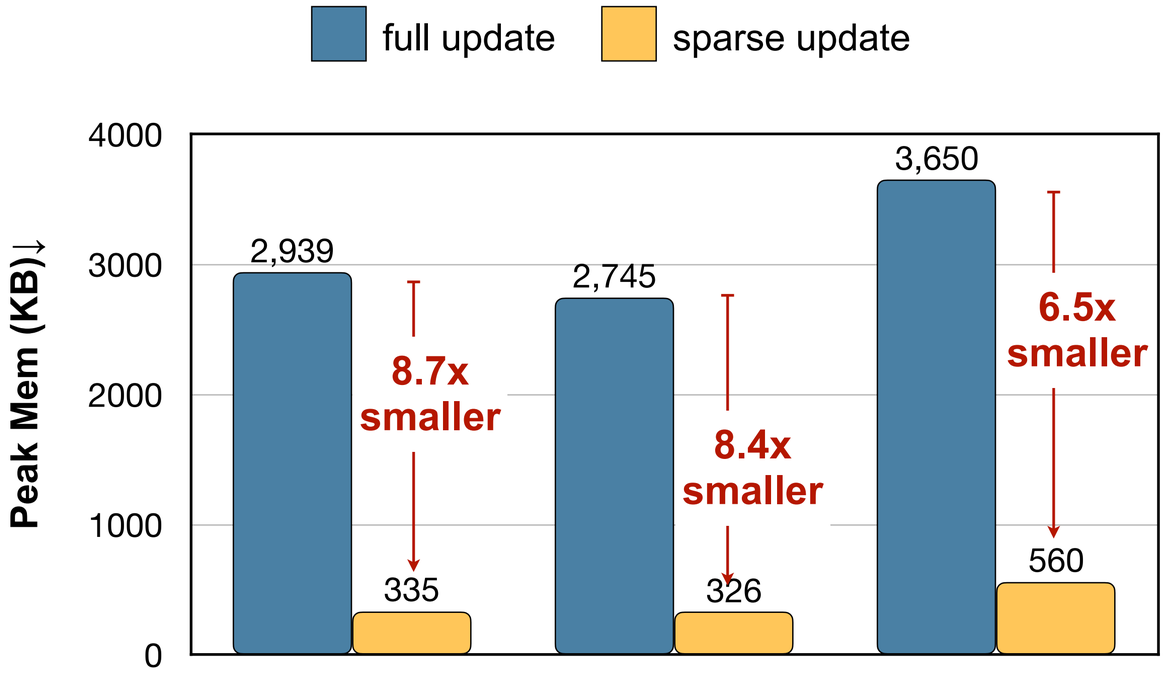
```
fn (%x: Tensor[(10, 10), float32],
    %weight: Tensor[(10, 10), float32],
    %bias: Tensor[(10), float32]),
    %grad: Tensor[(10), float32]),
{
  # forward
  %0 = multiply(%x, %weight);
  %1 = add(%0, %bias);
  # backward
  %3 = multiply(%grad, %weight);
  %4 = transpose(%grad)
  %5 = multiply(%4, %x);
  %6 = sum(%grad, axis=-1);
  (%3, %5, %6)
}
```

Automatically remove the buffers of pruned gradients from the computation graph.

```
fn (%x: Tensor[(10, 10), float32, needs_grad=True],
    %weight: Tensor[(20, 10), float32, needs_grad=0.5],
    %bias: Tensor[(20), float32, needs_grad=True],
    %grad: Tensor[(10, 20), float32]),
{
  # forward
  %0 = multiply(%x, %weight);
  %0.1 = slice(%x, begin=[0, 0], ends=[10, 10]);
  %1 = add(%0, %bias);
  # backward
  %3 = multiply(%grad, %weight);
  %4 = transpose(%grad)
  %5 = multiply(%4, %0.1);
  %6 = sum(%grad, axis=-1);
  (%3, %5, %6)
}
```

3. Tiny Training Engine (TTE)

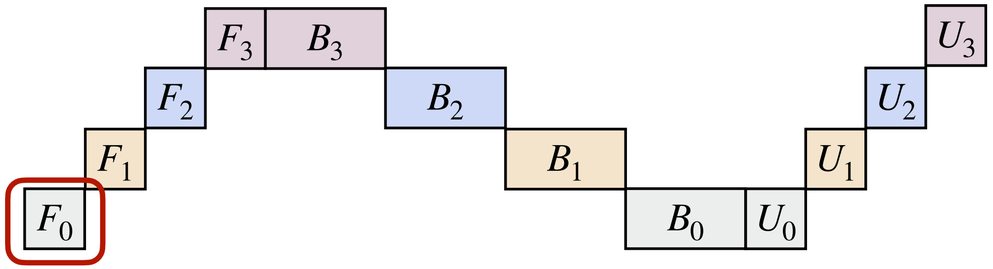
Sparse update results



- Tiny Training Engine supports backward graph pruning and sparse update at IR-level.
- After graph pruning, un-used weights and sub-tensors are pruned from DAG => 6.5-8.7x memory saving

3. Tiny Training Engine (TTE)

Re-ordering reduces memory footprint

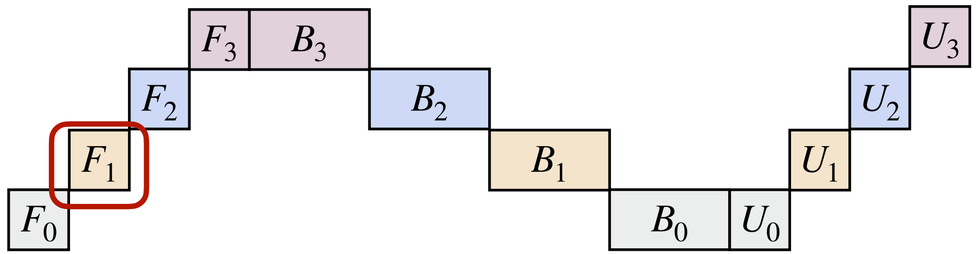


(a) Conventional way to update parameters

F: Forward, *B*: Backward, *U*: Update

3. Tiny Training Engine (TTE)

Re-ordering reduces memory footprint



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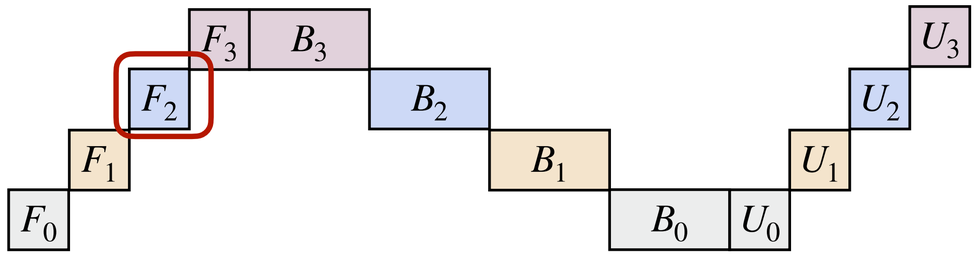
Re-ordering reduces memory footprint



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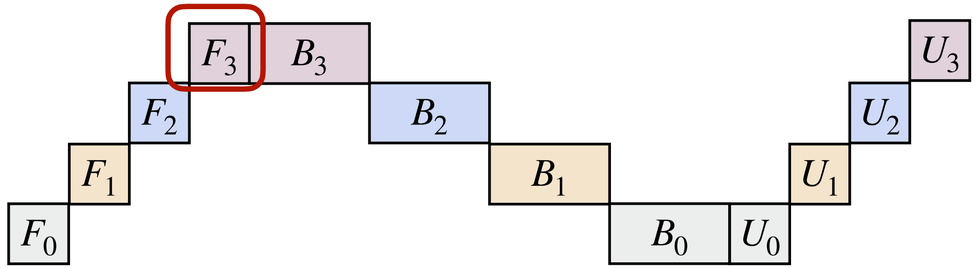
3. Tiny Training Engine (TTE)

Re-ordering reduces memory footprint



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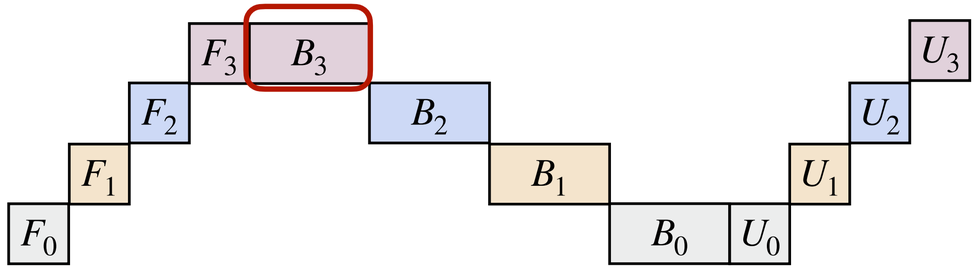
3. Tiny Training Engine (TTE)

Re-ordering reduces memory footprint



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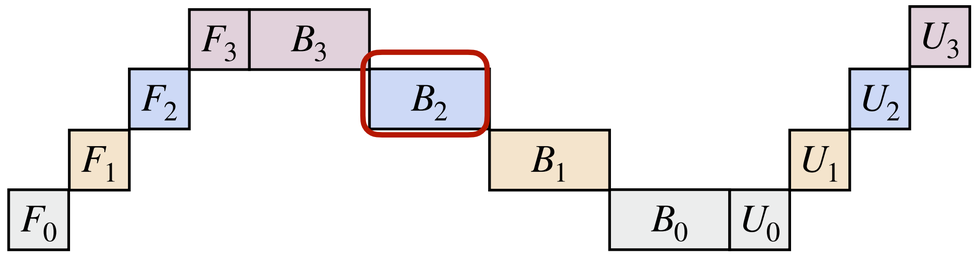
3. Tiny Training Engine (TTE)

Re-ordering reduces memory footprint



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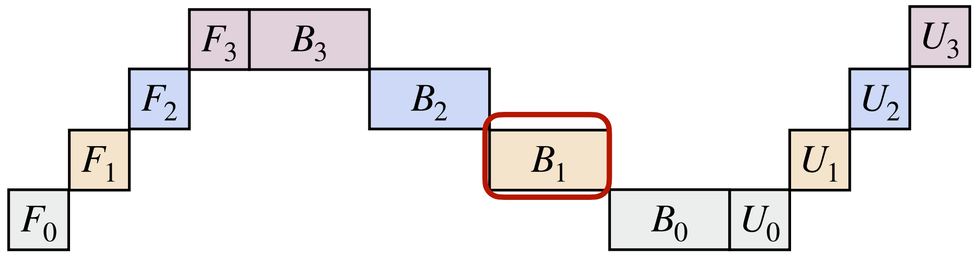
Re-ordering reduces memory footprint



(a) Conventional way to update parameters

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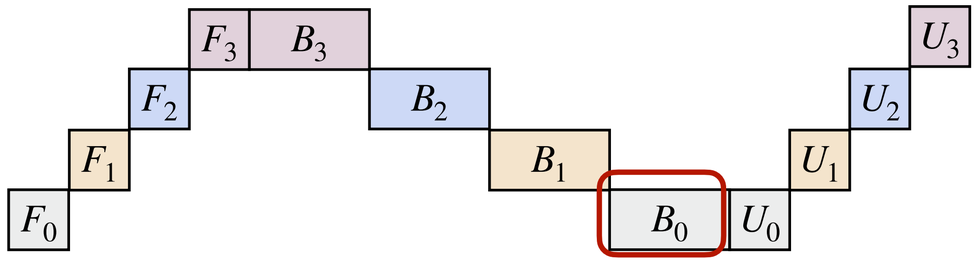
3. Tiny Training Engine (TTE)

Re-ordering reduces memory footprint



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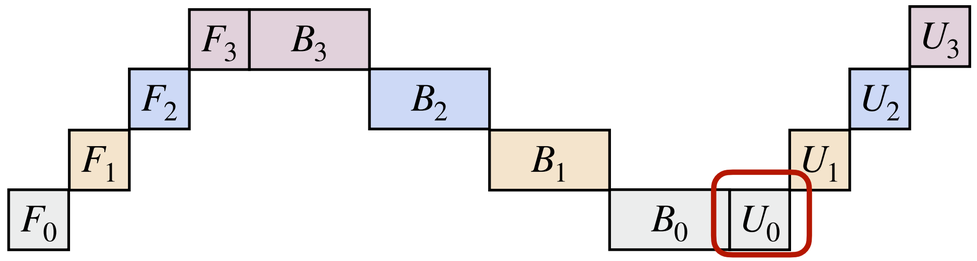
3. Tiny Training Engine (TTE)

Re-ordering reduces memory footprint



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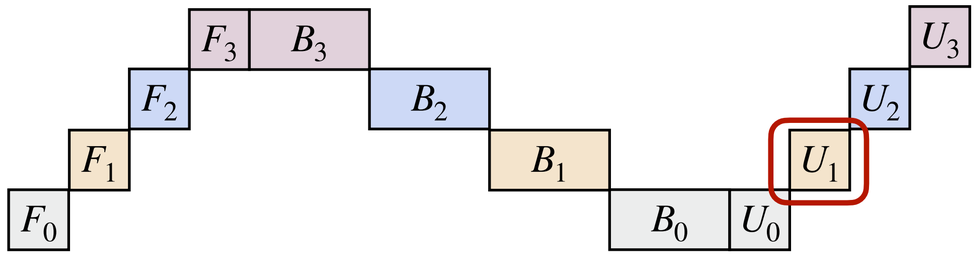
Re-ordering reduces memory footprint



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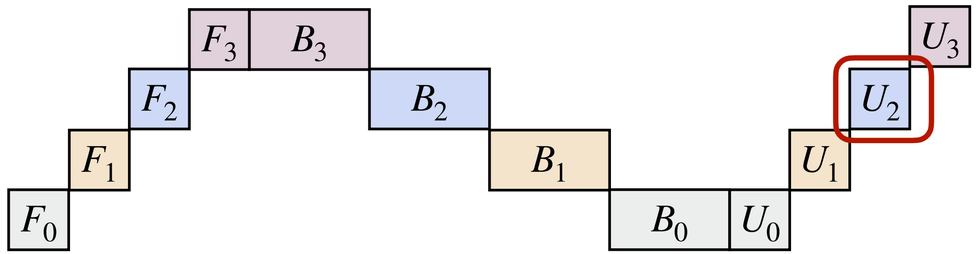
Re-ordering reduces memory footprint



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F: Forward, *B*: Backward, *U*: Update

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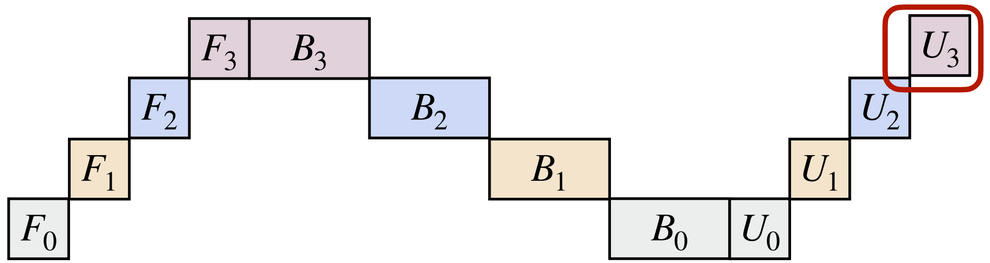
Re-ordering reduces memory footprint

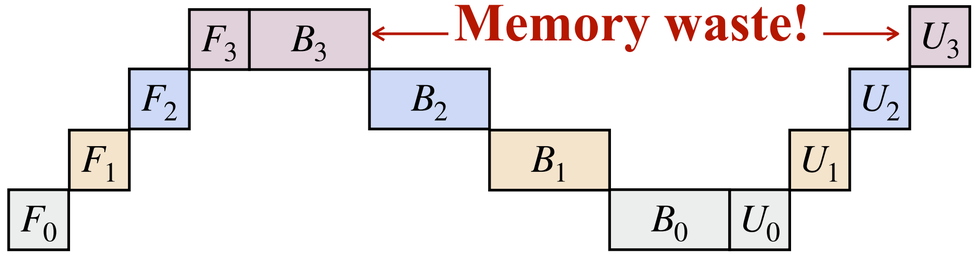


(a) Conventional way to update parameters

F: Forward, *B*: Backward, *U*: Update

3. Tiny Training Engine (TTE)

Re-ordering reduces memory footprint



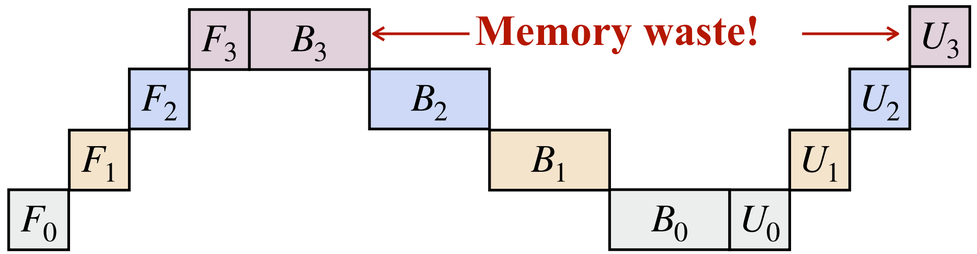
(a) Conventional way to update parameters

Operator life-cycle analysis reveals the **memory redundancy** in the optimization step.

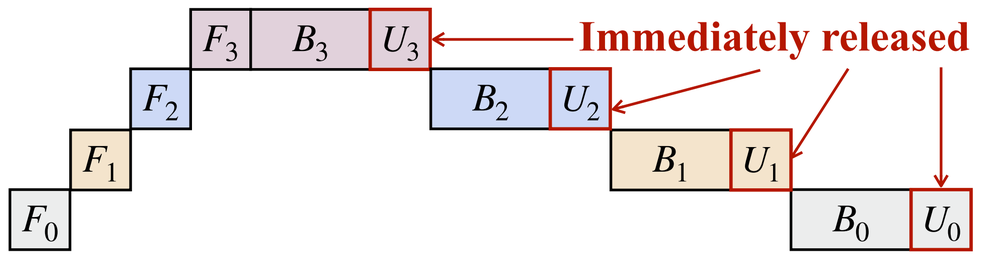
F: Forward, *B*: Backward, *U*: Update

3. Tiny Training Engine (TTE)

Re-ordering reduces memory footprint



(a) Conventional way to update parameters



(b) Operator re-ordering

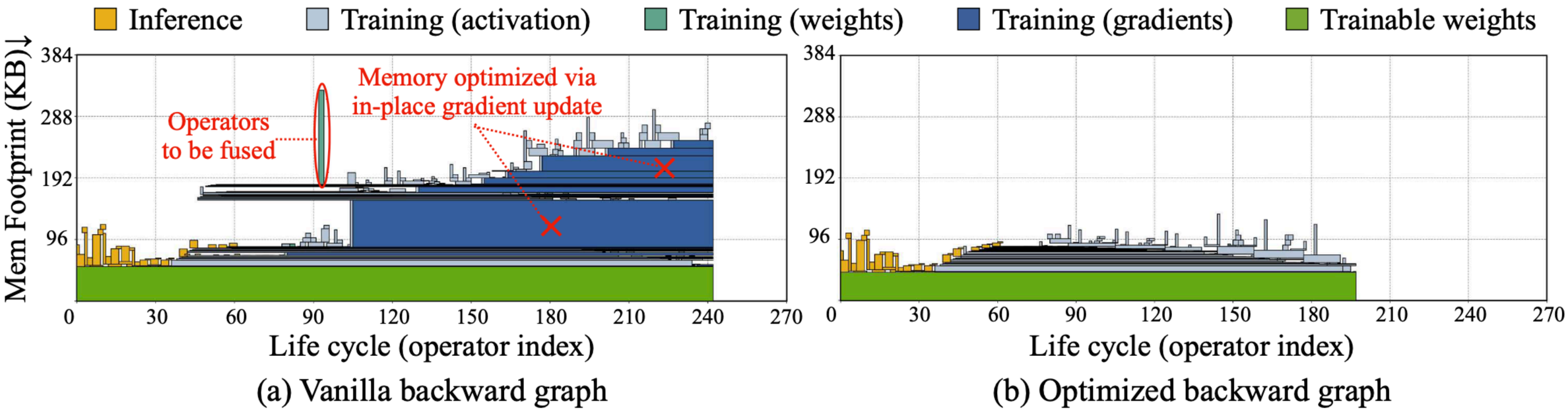
Operator life-cycle analysis reveals the **memory redundancy** in the optimization step.

After re-ordering, the **redundant memory usage is eliminated** from training.

F: Forward, *B*: Backward, *U*: Update

3. Tiny Training Engine (TTE)

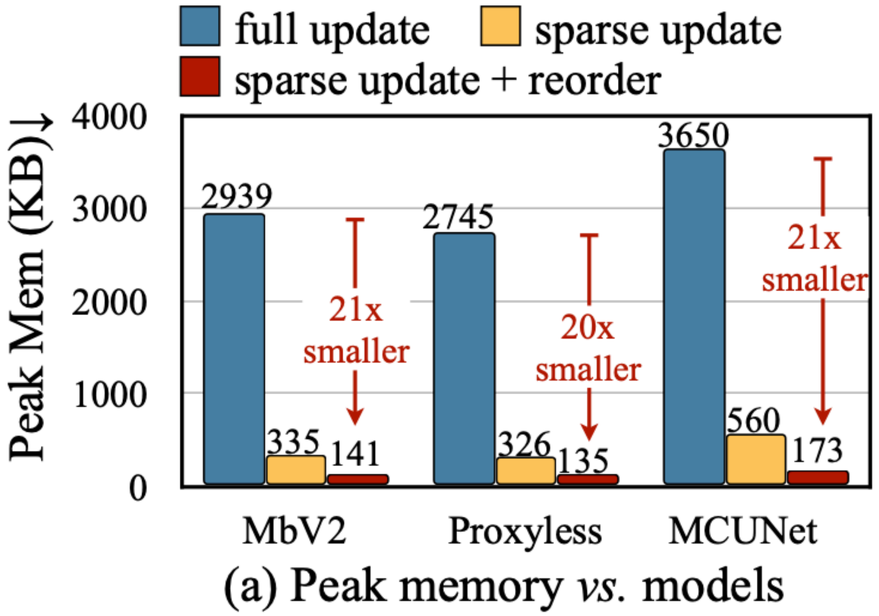
Re-ordering reduces memory footprint



Operator life-cycle analysis shows memory footprint can be greatly reduced by operator re-ordering.

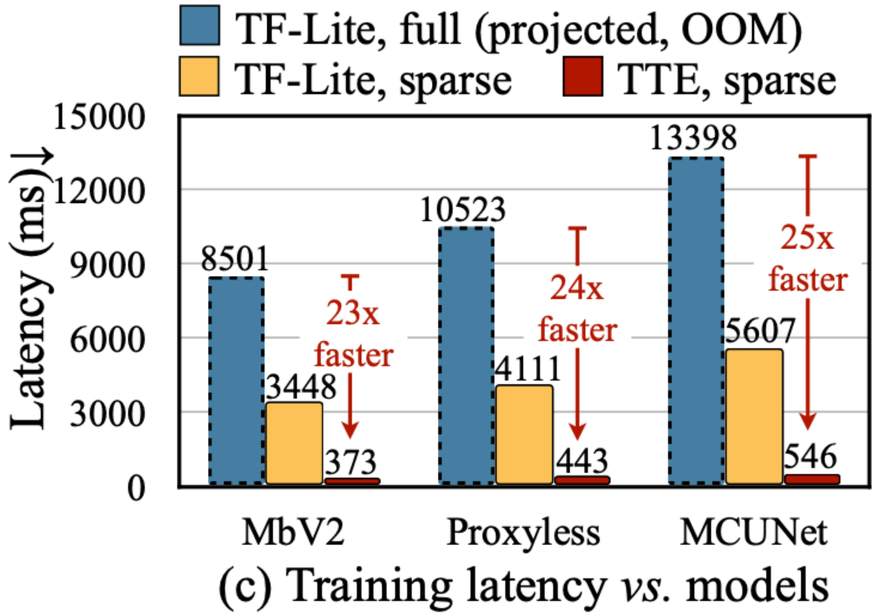
3. Tiny Training Engine (TTE)

Smaller memory usage, faster training speed



(a) Peak memory *vs.* models

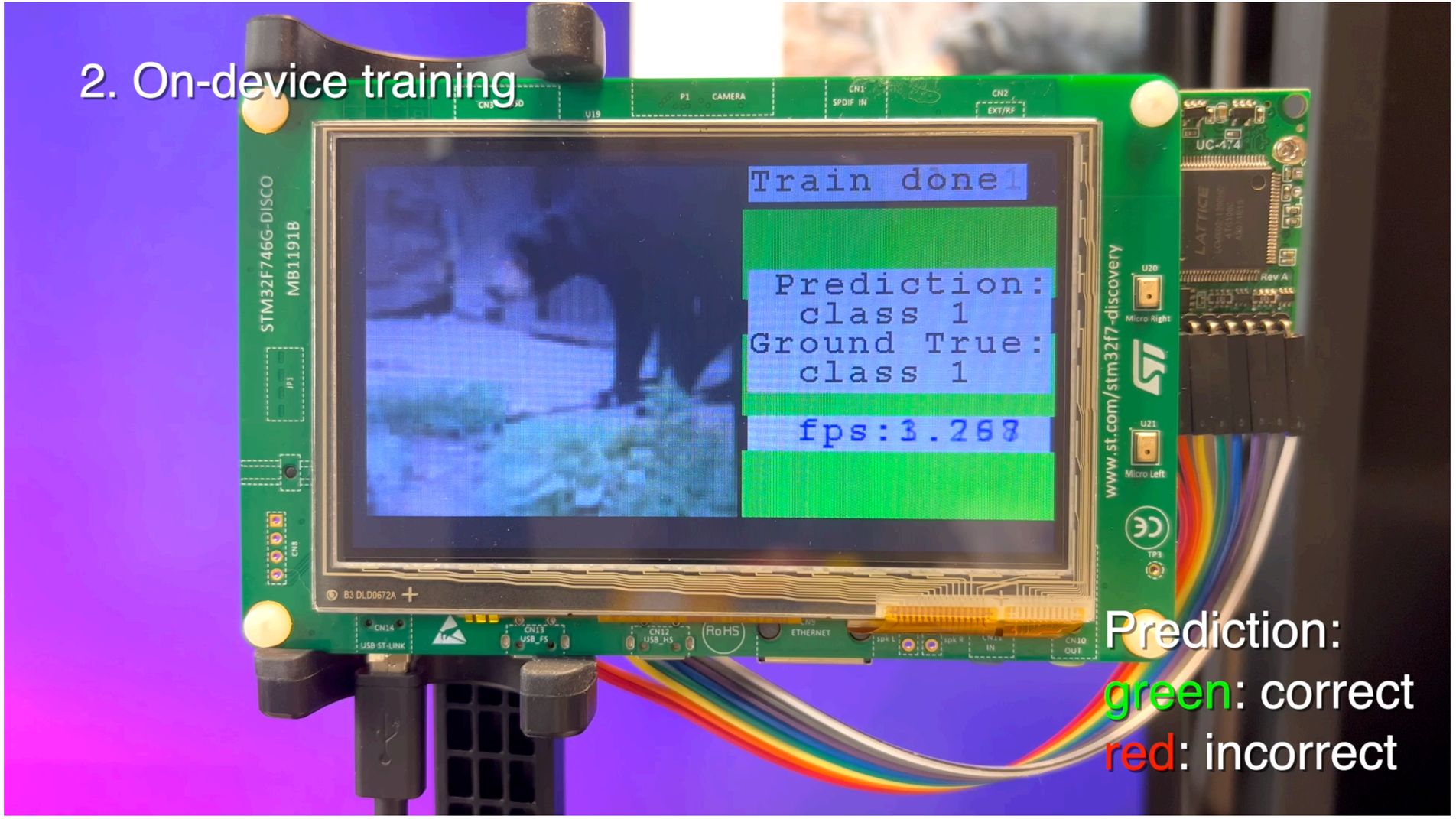
20x smaller memory



(c) Training latency *vs.* models

23x faster speed

2. On-device training



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https://youtu.be/XaDCO8YtmBw

Media Report

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System brings deep learning to "internet of things" devices

Advance could enable artificial intelligence on household appliances while enhancing data security and energy efficiency.

Watch Video

Daniel Ackerman | MIT News Office
November 13, 2020

PRESS INQUIRIES

MIT researchers have developed a system, called MCUNet, that brings machine learning to microcontrollers. The advance could enhance the function and security of devices connected to the Internet of Things (IoT).

(Homepage highlight)

MIT News
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Tiny machine learning design alleviates a bottleneck in memory usage on internet-of-things devices

New technique applied to small computer chips enables efficient vision and detection algorithms without internet connectivity.

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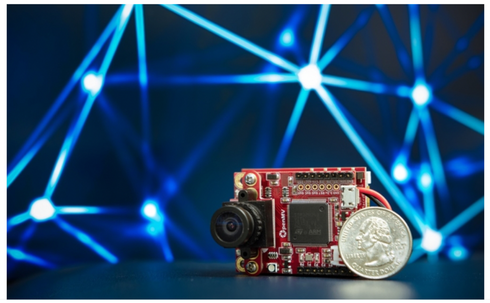
Lauren Hinkel | MIT-IBM Watson AI Lab
December 8, 2021

PRESS INQUIRIES



An MIT team's tinyML vision system outperforms other models in many image classification and detection tasks.

Photo courtesy of the researchers.

MIT News
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Learning on the edge

A new technique enables AI models to continually learn from new data on intelligent edge devices like smartphones and sensors, reducing energy costs and privacy risks.

Adam Zewe | MIT News Office
October 4, 2022

PRESS INQUIRIES

A machine-learning model on an intelligent edge device allows it to adapt to new data and make better predictions. For instance, training a model on a smart keyboard could enable the keyboard to continually learn from the user's writing.

Image: Digital collage by Jose-Luis Olivares, MIT, using stock images and images derived from MidJourney AI.

(Homepage highlight)

MCUNet: Tiny Deep Learning on IoT Devices [Lin *et al.*, NeurIPS 2020]
MCUNetV2: Memory-Efficient Patch-based Inference for Tiny Deep Learning [Lin *et al.*, NeurIPS 2021]
On-Device Training Under 256KB Memory [Lin *et al.*, NeurIPS 2022]

Open Source

mit-han-lab / mcunet Public

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master | 2 branches | 0 tags

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MCUNet: Tiny Deep

This is the official implementation of th

website | paper | paper (v2) | de

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Code | Issues | Pull requests | Actions

master | 1 branch | 0 tags

README.md

TinyEngine

This is the official implementation of TinyEngine,
Microcontrollers. TinyEngine is a part of MCUNet,
co-design framework for tiny deep learning on mi
tight memory budgets.

The MCUNet and TinyNAS repo is here.

MCUNetV1 | MCUNetV2 | MCUNetV3

mit-han-lab / tiny-training Public

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main | 1 branch | 0 tags | Go to file | Add file | Code

Lyken17 Merge branch 'main' of https://github.com/mit-han... f8dfb50 yesterday 4 commits

algorithm	prepare open source	2 days ago
compilation	prepare open source	2 days ago
figures	refine qas_accuracy figure	yesterday
.gitignore	prepare open source	2 days ago
.gitmodules	prepare open source	2 days ago
LICENSE	prepare open source	2 days ago
README.md	minor update	yesterday
assets	prepare open source	2 days ago
configs	prepare open source	2 days ago

README.md

On-Device Training Under 256KB Memory

About

On-Device Training Under 256KB Memory [NeurIPS'22]

tinytraining.mit.edu

edge-ai | on-device-training | learning-on-the-edge

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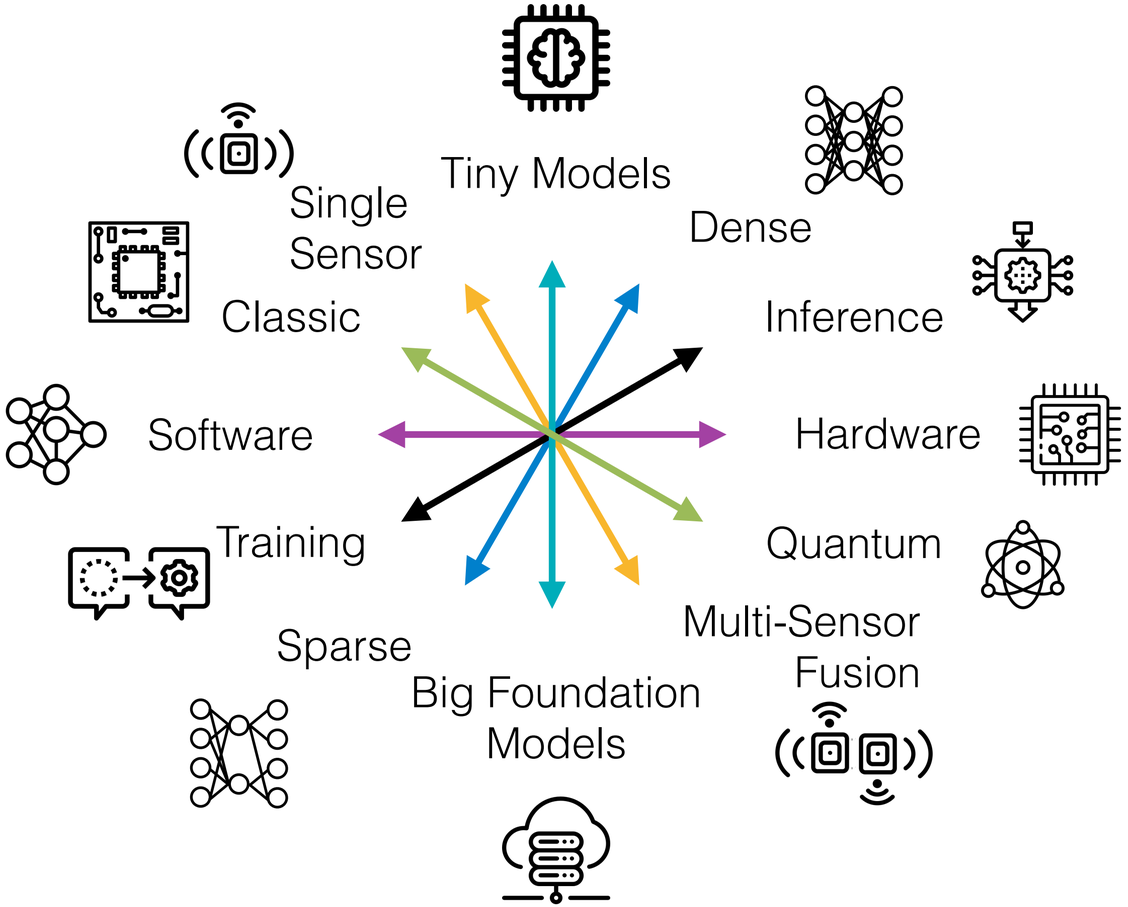

1. *Learning both Weights and Connections for Efficient Neural Network, NeurIPS'15*
2. *Deep Compression, ICLR'16*
3. *AMC, ECCV'18*
4. *ProxylessNAS, ICLR'19*
5. *Once For All, ICLR'20*
6. *HAT, ACL'20*
7. *Anycost GAN, CVPR'21*
8. *SPVNAS, ECCV'21*
9. *Lite Pose, CVPR'22*
10. *NAAS, DAC'21*
11. *QuantumNAS, HPCA'22*
12. *QuantumNAT, DAC'22*
13. *QOC, DAC'22*
14. *MCUNet, NeurIPS'20*
15. *MCUNet-V2, NeurIPS'21*
16. *TinyTL, NeurIPS'20*
17. *MCUNet-V3, Arxiv'22*
18. *DGC, ICLR'18*
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27. *PointAcc, Micro'20*
28. *TorchSparse, SysML'22*

New Course: TinyML and Efficient Deep Learning Computing

MIT 6.S965: https://efficientml.ai

6.S965 Logistics Schedule

TinyML and Efficient Deep Learning

6.S965 • Fall 2022 • MIT

Have you found it difficult to deploy neural networks on mobile devices and IoT devices? Have you ever found it too slow to train neural networks? This course is a deep dive into efficient machine learning techniques that enable powerful deep learning applications on resource-constrained devices. Topics cover efficient inference techniques, including model compression, pruning, quantization, neural architecture search, and distillation; and efficient training techniques, including gradient compression and on-device transfer learning; followed by application-specific model optimization techniques for videos, point cloud, and NLP; and efficient quantum machine learning. Students will get hands-on experience implementing deep learning applications on microcontrollers, mobile phones, and quantum machines with an open-ended design project related to mobile AI.

- **Time:** Tuesday/Thursday 3:30-5:00 pm Eastern Time
- **Location:** 36-156
- **Office Hour:** Thursday 5:00-6:00 pm Eastern Time, 38-344 Meeting Room
- **Discussion:** Piazza
- **Homework submission:** Canvas
- **Online lectures:** The lectures will be streamed on YouTube.
- **Resources:** MIT HAN Lab, Github, TinyML, MCUNet, OFA
- **Contact:** Students should ask all course-related questions on Piazza. For external inquiries, personal matters, or emergencies, you can email us at *6s965-fall2022-staff@mit.edu*.

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- This course is a deep dive into efficient machine learning techniques that enable powerful deep learning applications on resource-constrained devices.

Anonymous Student Feedback Collected from Mid-term

I really like how structured the labs are, and being able to see actual implementations of the techniques we learn about.

This is honestly one of the best set up courses I've taken at MIT

I love how we are using microntroller and focusing on application instead of just theories.

I managed the weekly labs and lectures by only watching the course on YouTube. As a researcher, I gained some valuable knowledge from your course. Excellent slides and teaching and useful labs.

I like the class and I have been able to follow the class easily (which had rarely happened to me in my previous courses)