ML-EXray: Visibility into ML Deployment on the Edge

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Google

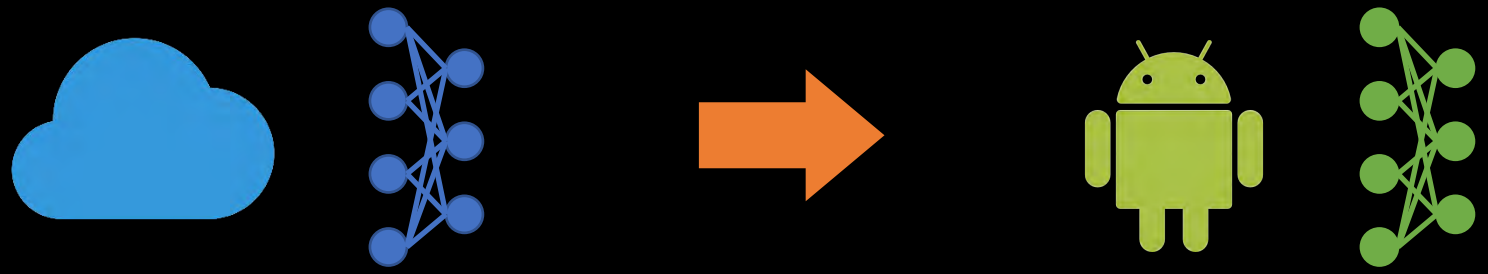
Edge ML

Low Latency

Privacy & Security

Low Power

ML Deployment on the Edge



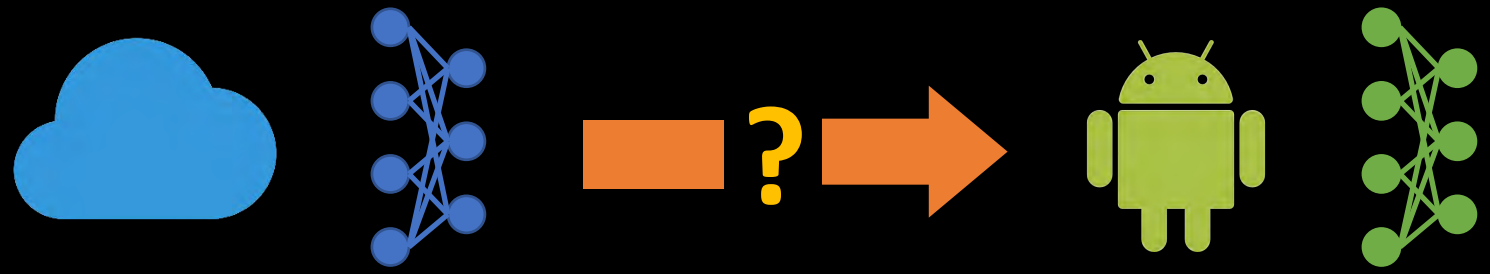
Dog: 0.95

Cat: 0.33

Deployed model can have *mismatching* performance, and often there is *little clue* what this may happen.

There is a *disconnect* between model developers and app developers

The Disconnect



Model Performance

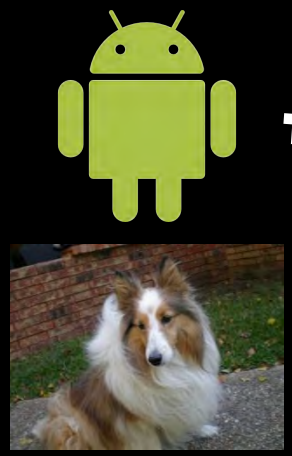
- Accuracy
- Latency & throughput

Deployment Performance

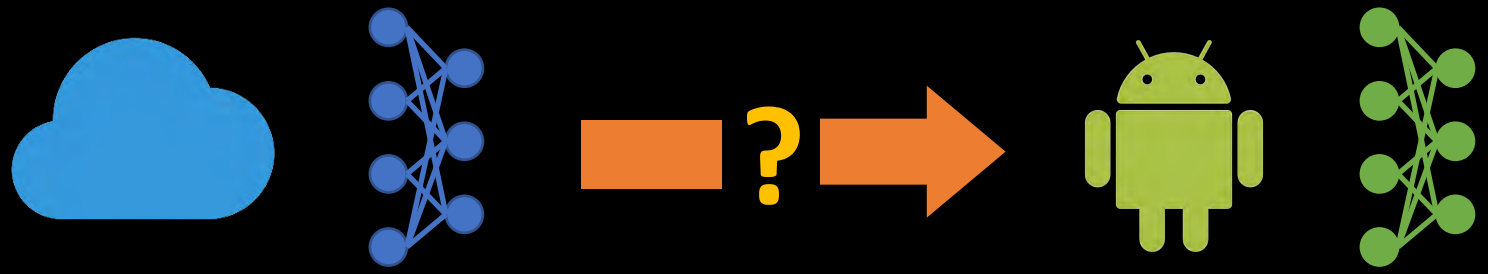
- End-to-end latency
- Power consumption
- Memory footprint

Design choices made for training are often *lost during the handoff*
Design choices may *conflict with heterogenous hardware*

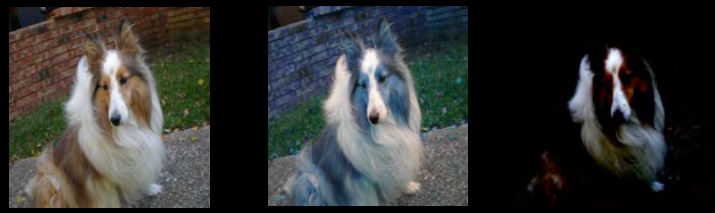
An Image Classifier Example



What could possibly go wrong?



- Preprocessing bugs



- Quantization issues

- Kernel optimization v.s. heterogenous hardware

Challenge: How to debug?

- *Low awareness* of potential issues
- *Little visibility* into the edge black box
- *Tedious reverse engineering* to debug

Dog: 0.95

RGB [0,1]

Dog: 0.45

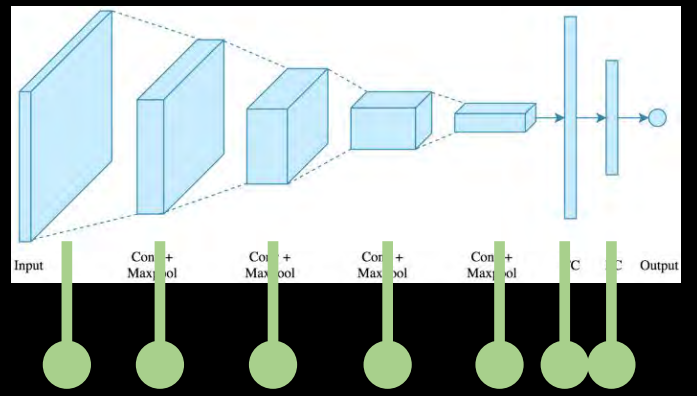
BGR [0,1]

Dog: 0.25

RGB [-1,1]

Coral

ARDUINO

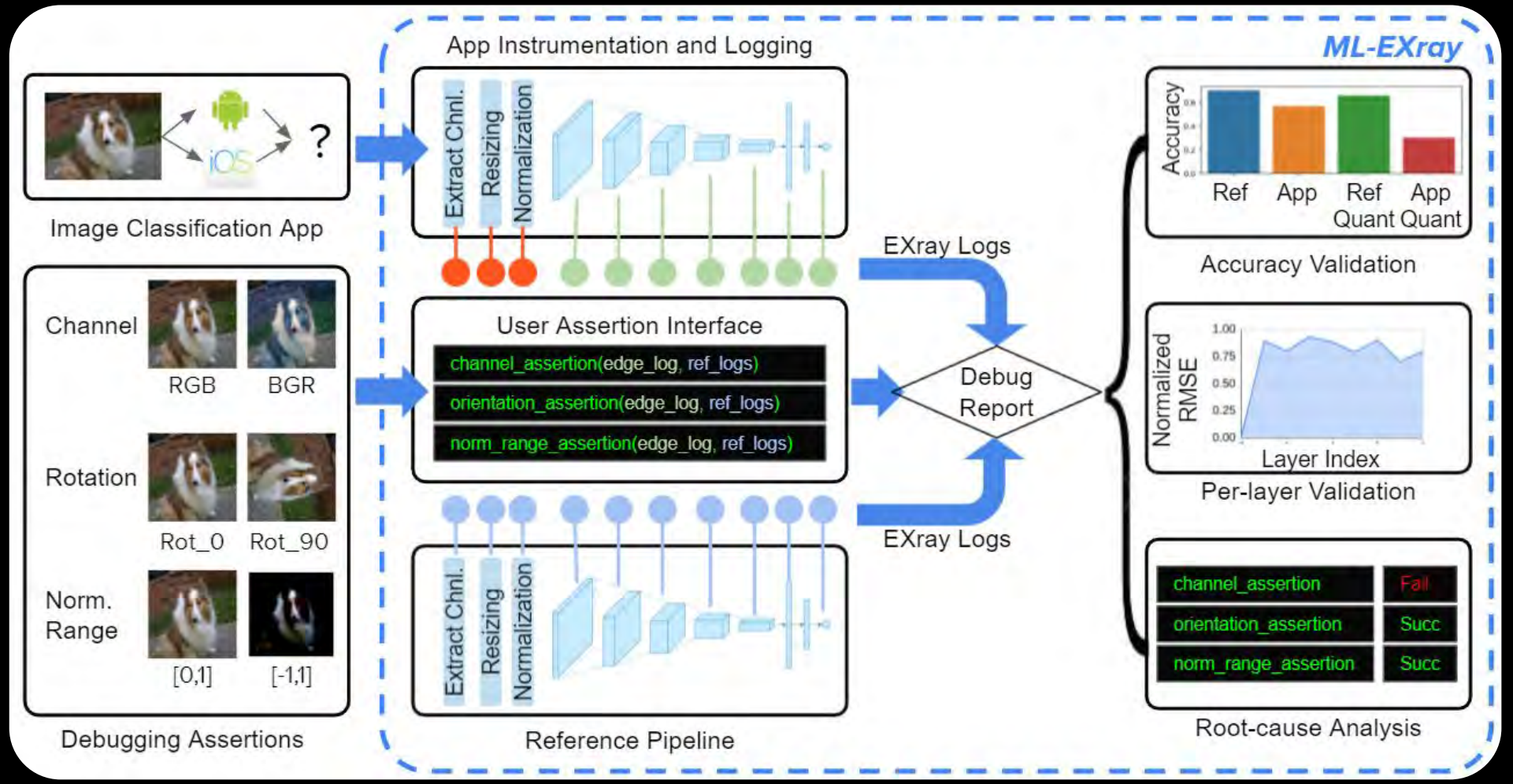


Per-layer weight, bias, output

ML-EXray Contributions

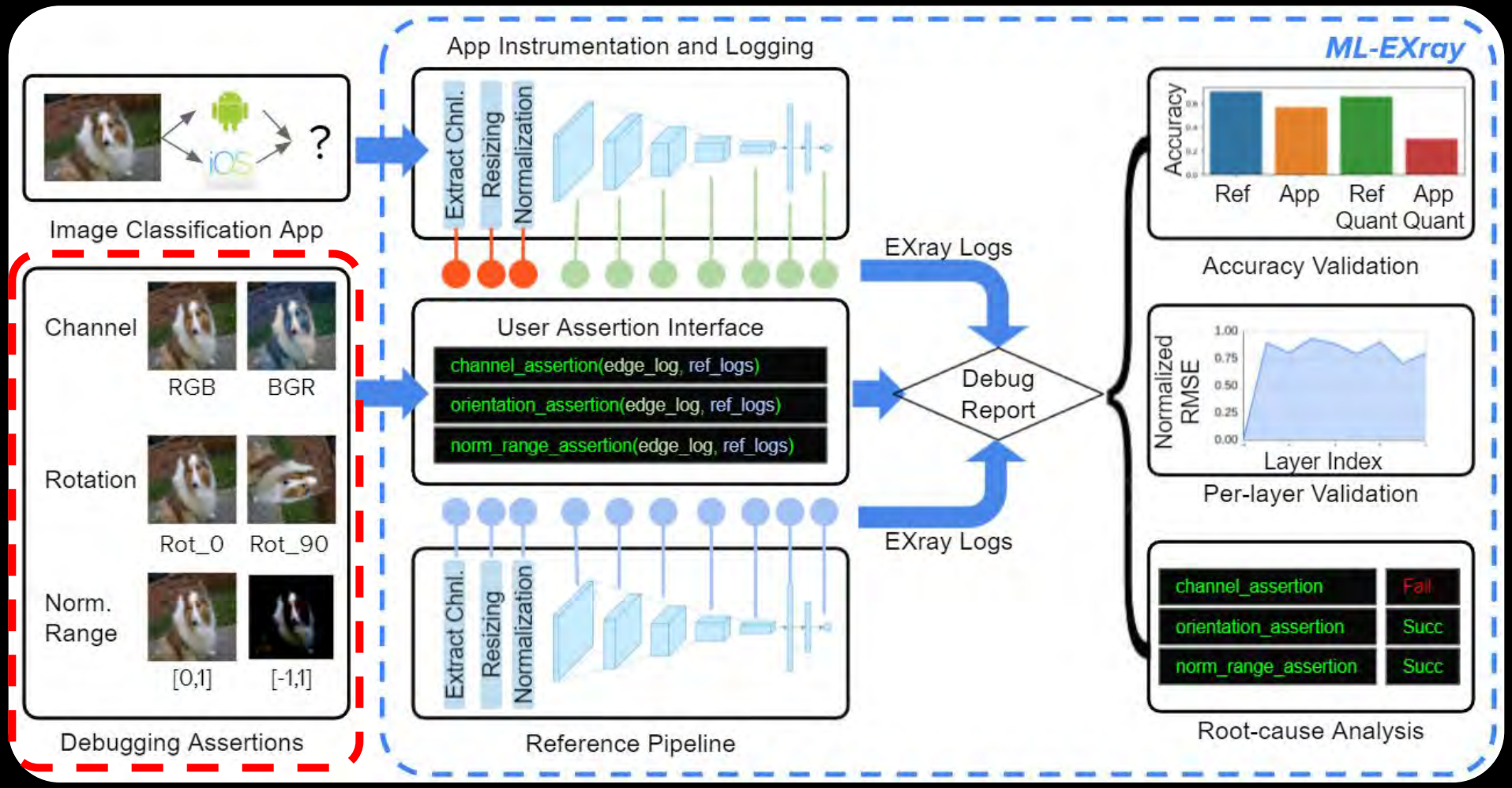
- *Visibility:* Instrumentation APIs for layer-level details
- *Bridging the disconnect:* Reference pipelines and data playback
- *Automated debugging:* Programming model for deployment validation
- *Awareness of deployment issues:* Uncovering deployment issues and their impact

ML-EXray Overview



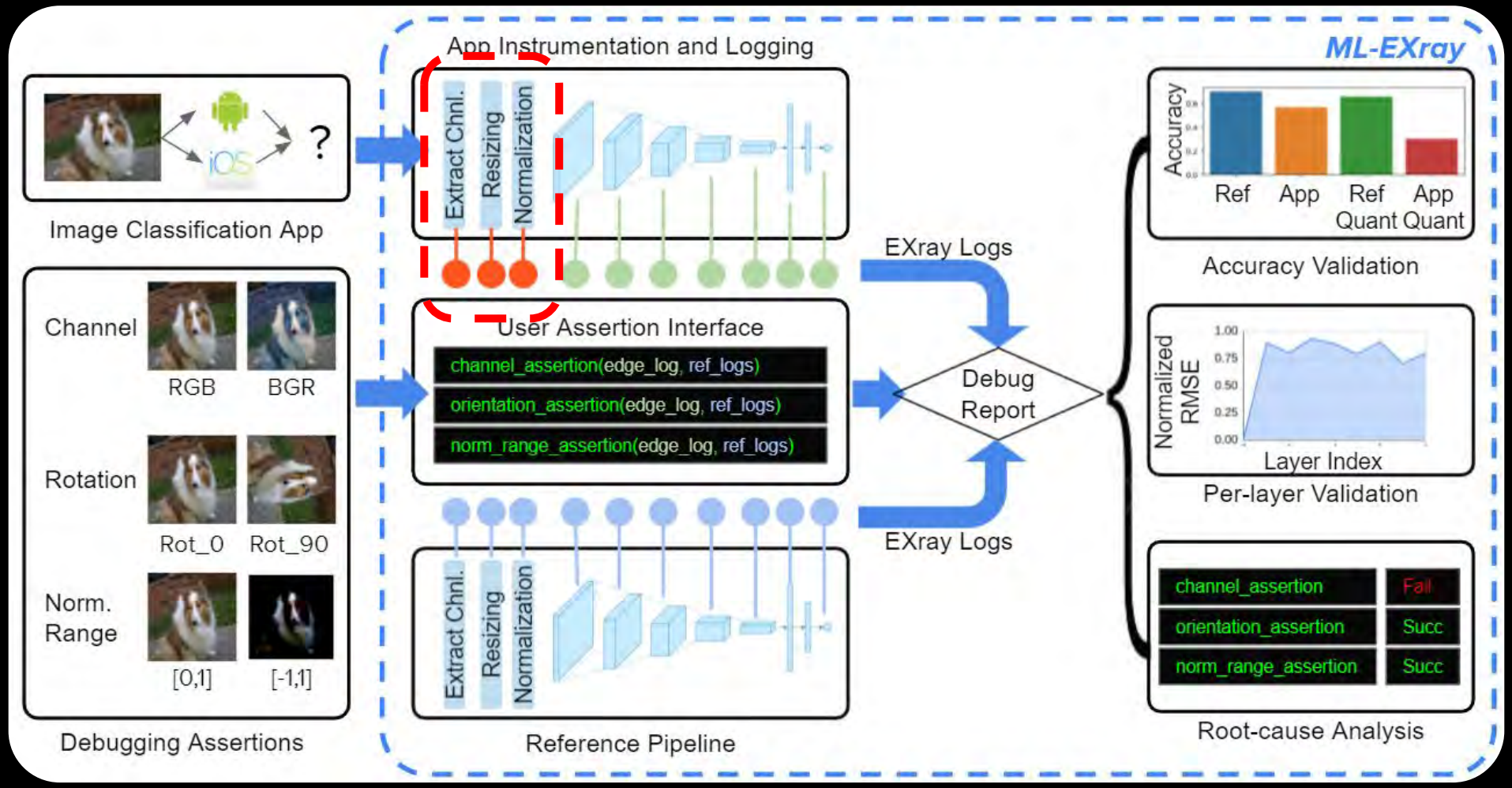
- Easy-to-use API w/ low overhead
- End-to-end performance validation
- Per-layer latency measurement and output validation
- Extensibility: user-defined logging, reference pipeline, and assertions

Customization



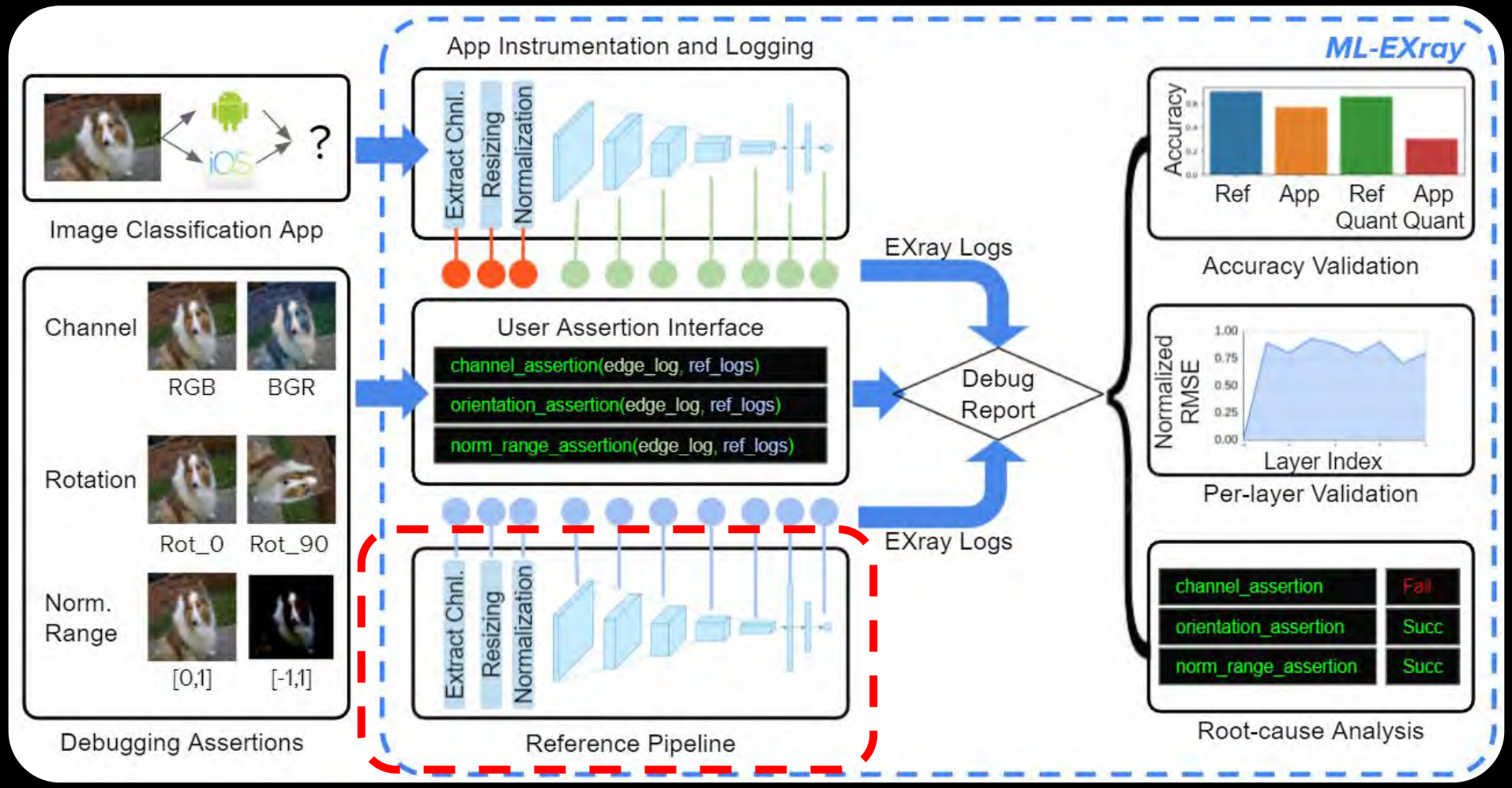
***Assertion functions**: users can define custom debugging assertions to validate suspected issues, such as input channel arrangement, orientation, and normalization range.*

Customization



***Log elements**:* users can instrument the app at any point throughout the pipeline to log custom variables for different debugging purposes.

Customization



***Reference Pipelines**:* users can provide alternative pipelines as references, such as a previous successful deployment pipeline on a different device.

Instrumentation APIs & Data Model

A suite of APIs in C++, Java, Python

```
// (C++)
MLEXray->on_inf_start();
TfLiteStatus s = m_interpreter->Invoke();
MLEXray->on_inf_stop(&m_interpreter);
```

Assertion function

```
def channel_assertion(edge_out, ref_out) {
    if not np.allclose(edge_out, ref_out):
        edge_out = cv2.cvtColor(edge_out,
        cv2.COLOR_BGR2RGB)
        if np.allclose(edge_out, ref_out):
            raise AssertionError('BGR->RGB')}
```

Data Model

Input / Output

- Model I/O
- Per-layer I/O
- Pre-processing I/O
- User-defined I/O

Performance

- End-to-end Latency
- Per-layer Latency
- Memory usage

Peripheral

- Orientation
- Motion
- Lighting

Reference Pipelines and Playback

Reference ML Pipeline

- Cloud model
- Correct pre-processing
- No model optimization
- Default standard kernels

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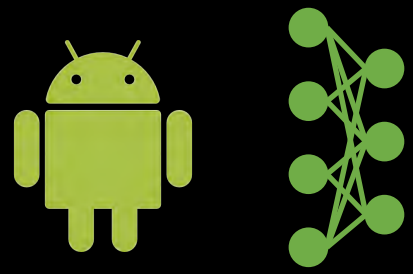
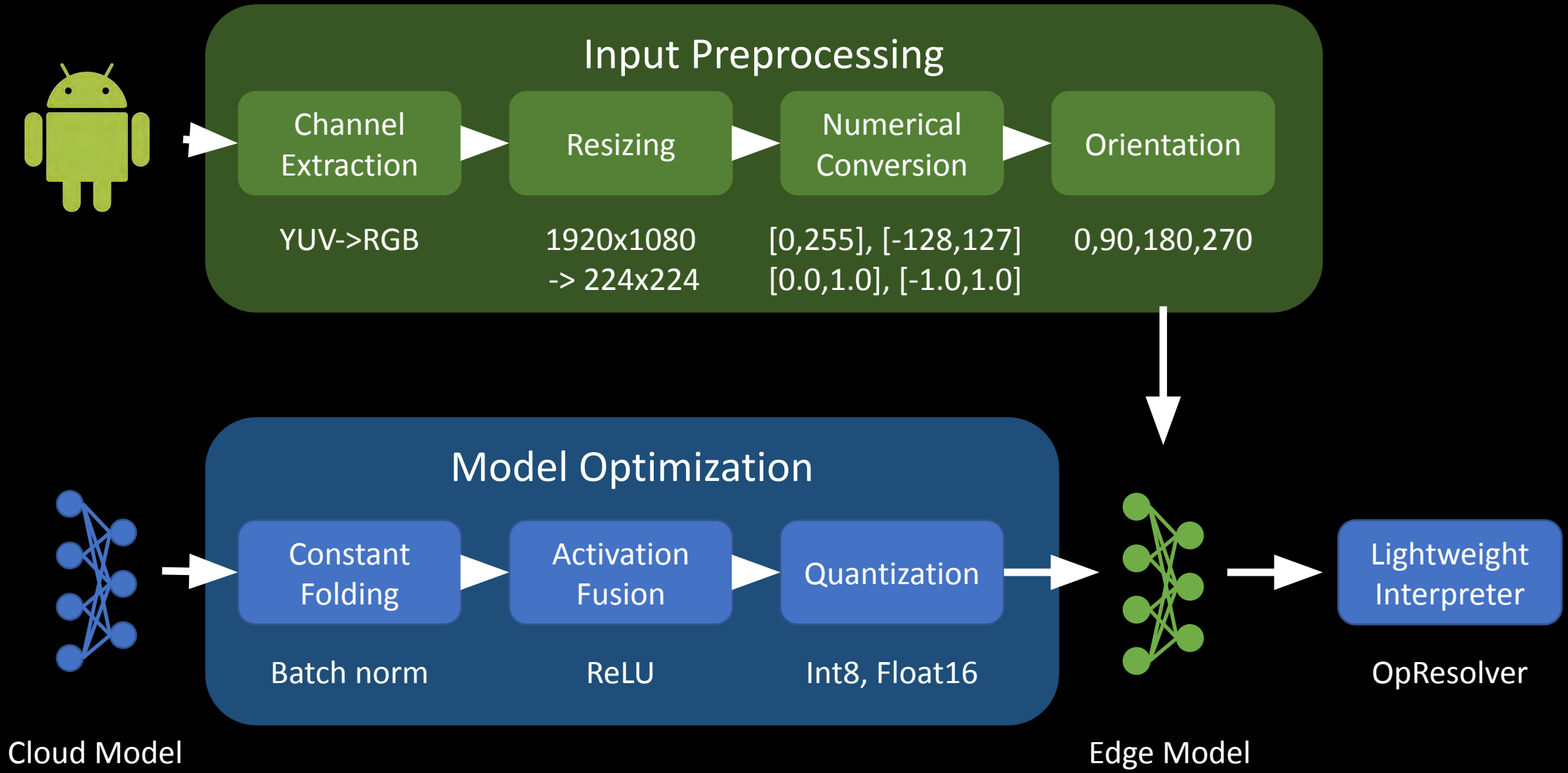


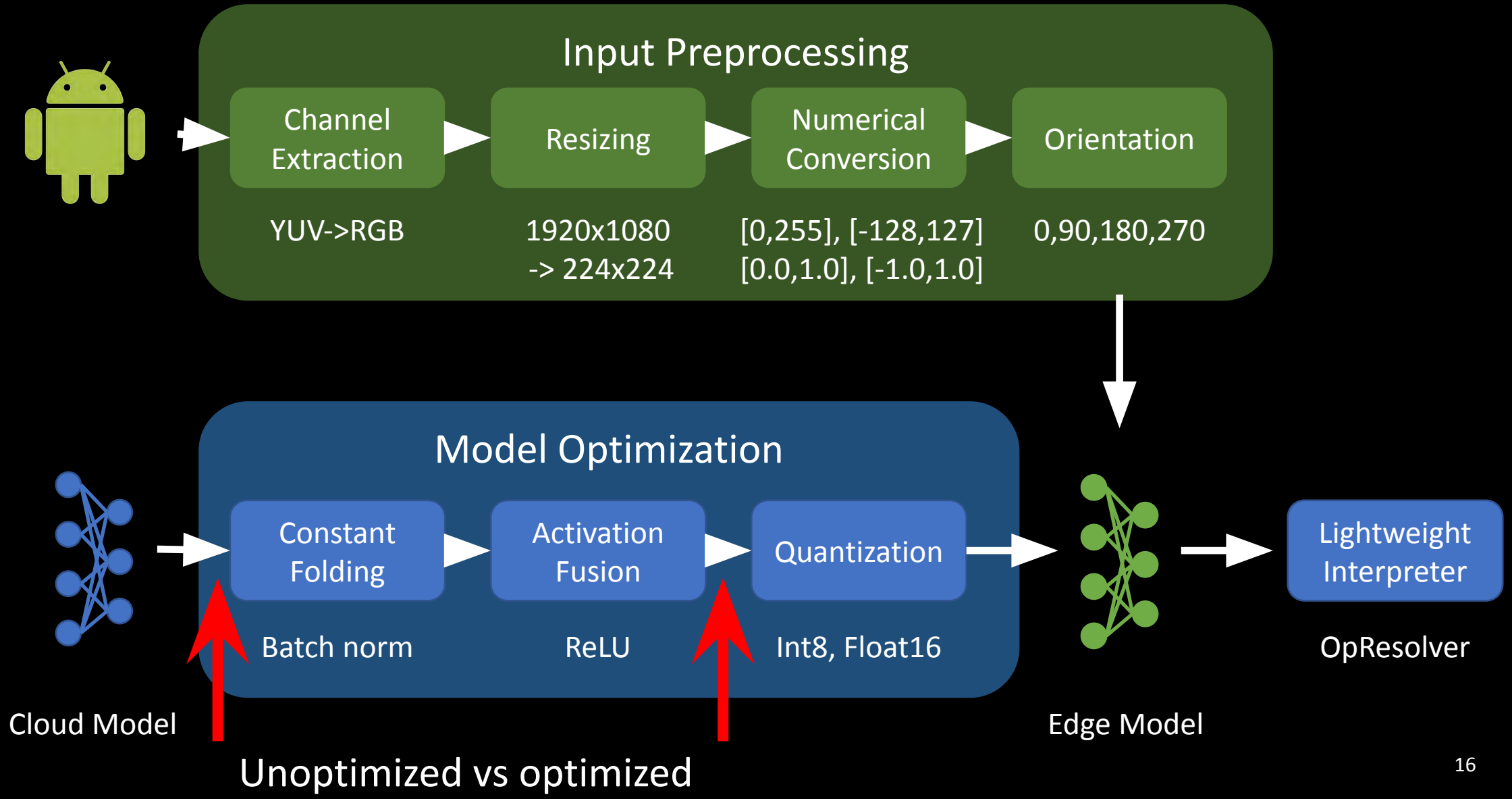
Edge ML Pipeline

- Edge model
- User pre-processing code
- Optimized model
- Edge device specific kernels (e.g. optimized op resolver)

A Basic Reference Pipeline Example



User-defined Reference Pipelines



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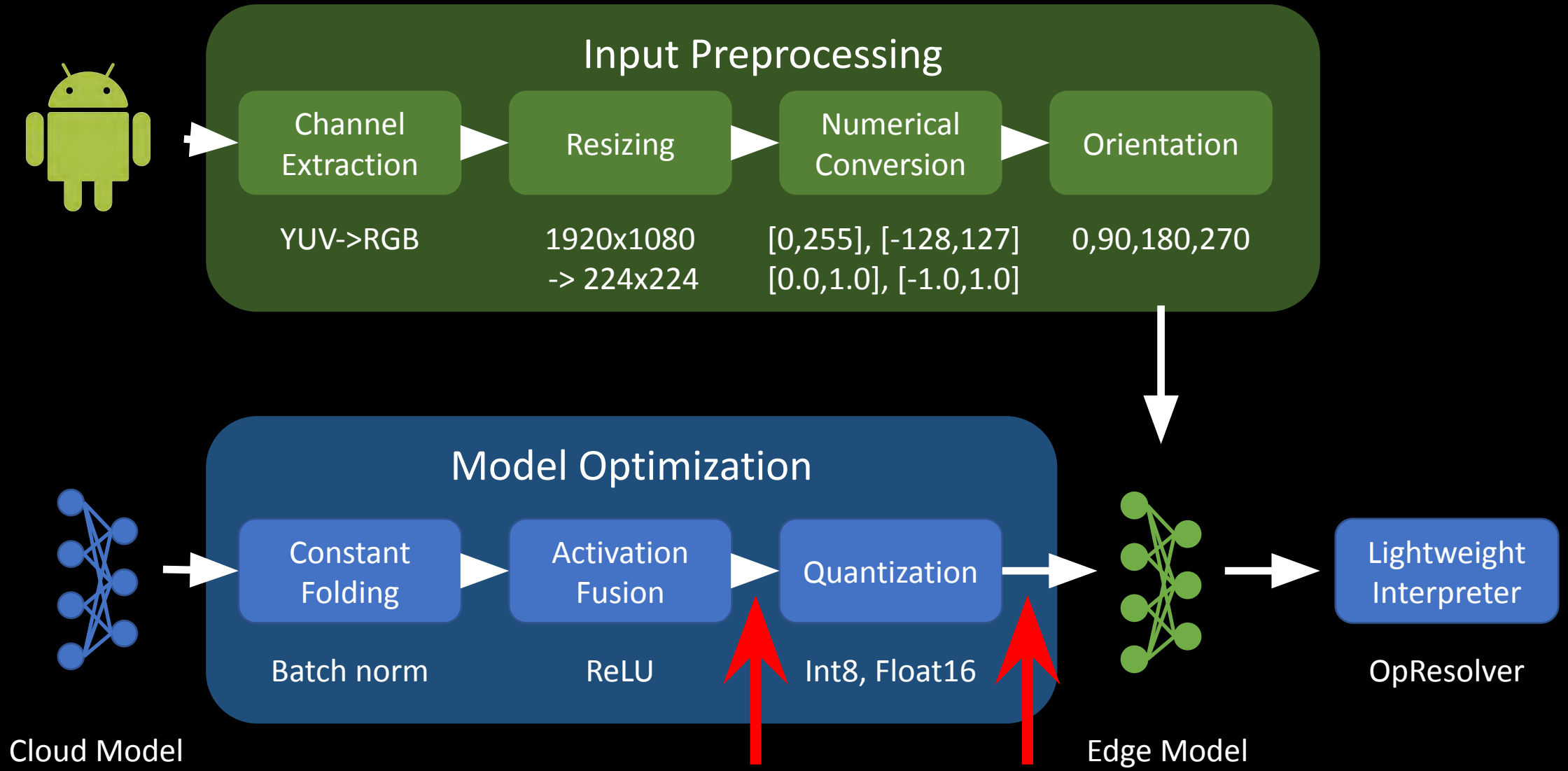
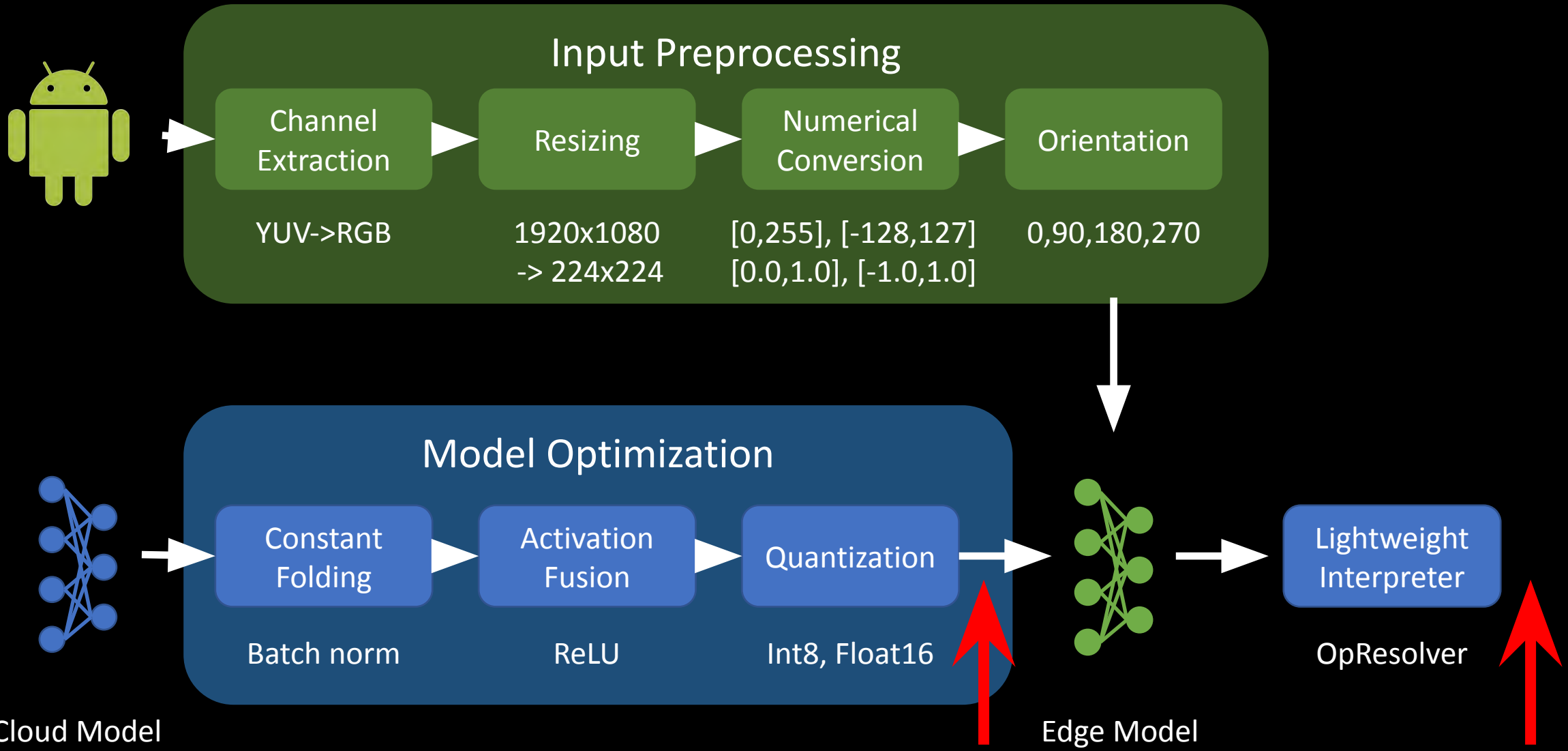
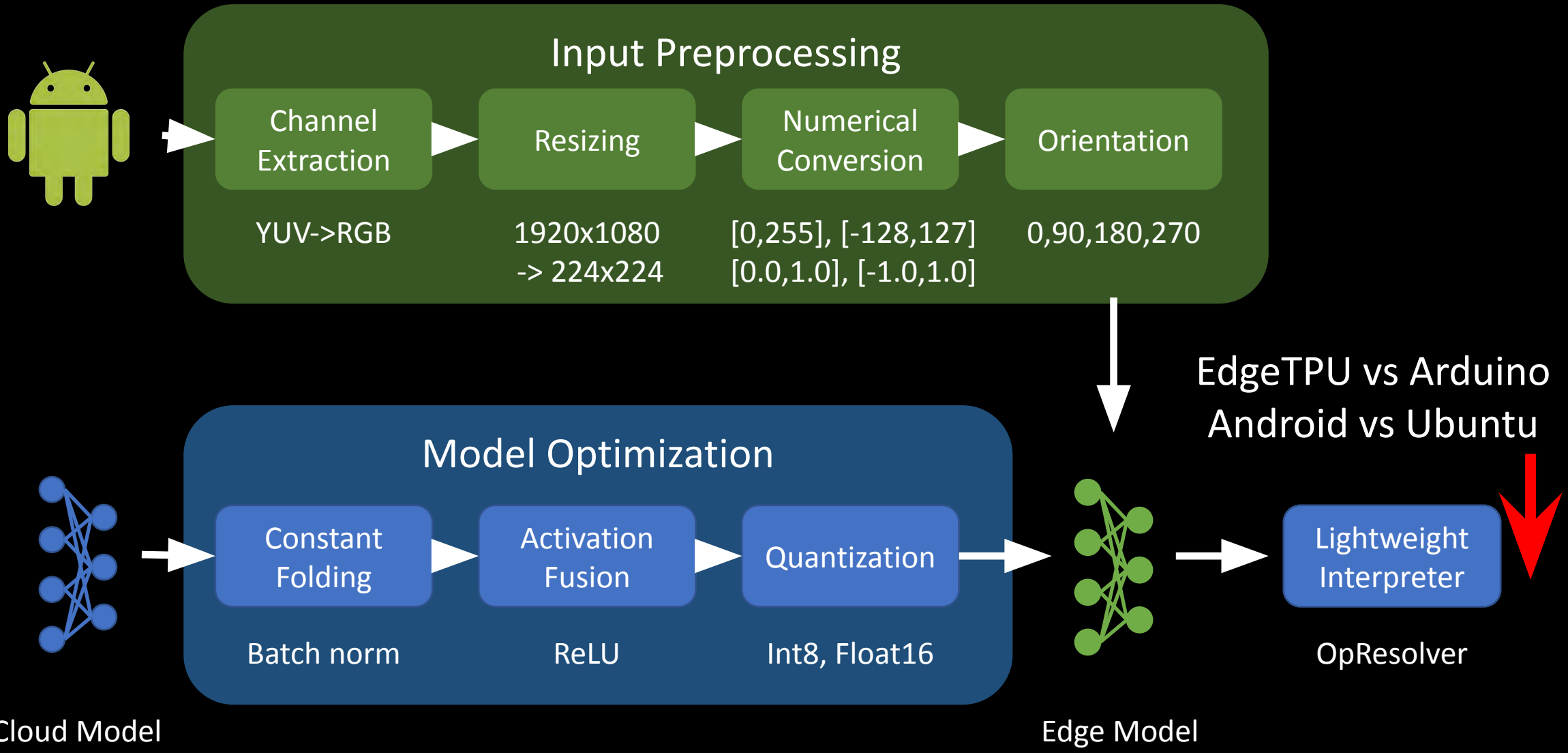


User-defined Reference Pipelines



User-defined Reference Pipelines



Deployment Validation and Assertions

- *End-to-end Performance Benchmark*

Accuracy Validation

- *Per-layer Validation*

Per-layer Validation

- *Running Assertions for Root-cause*

Root-cause Analysis

Evaluation

- Wide applicability
- System overhead
- Pre-processing bugs and impact
- Quantization issues and impact
- Sub-optimal kernels and latency

Wide Applicability

Task	Models	Assertions					
		Channel	Resizing	Normalization	Rotation	Quantization	Latency
Image classification	Mobilenet v1, v2, v3, Inception v3, Densenet_121, Resnet_50 v2	✔	✔	✔	✔	✔	✔
Object detection	SSD_Mobilenet_v1, FasterRCNN	✔	✔	✔	✔	✔	✔
Image segmentation	Deeplab v3	✔	✔	✔	✔	✔	✔
Speech recognition	Plain CNN, Yamnet		✔	✔		✔	✔
Text classification	NNLM, mobilebert					✔	✔

ML-EXray catches a wide range of deployment issues across different tasks

System Overhead

Lightweight

- Latency: a few ms increase
- Memory: < 5 MB

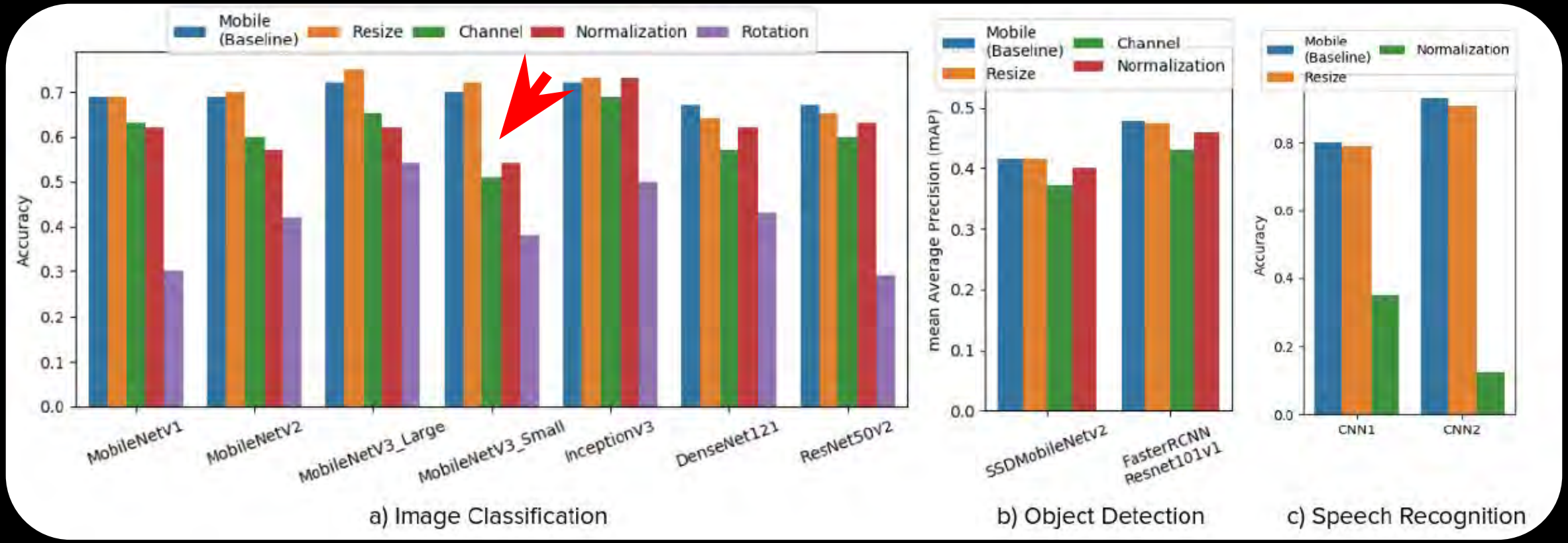
	Lat (ms) CPU only	Lat (ms) GPU enabled	Mem (MB)	Disk (KB/Frm)
Pixel 4	128.2±6.1	16.7±0.3	6.42	-
P4(Inst)	129.6±5.0	19.1±0.6	10.12	0.41
Pixel 3	157.0±6.7	28.4±0.4	9.26	-
P3(Inst)	158.3±7.3	30.0±0.5	12.37	0.41

Easy to use

- a few LoC for different validation target

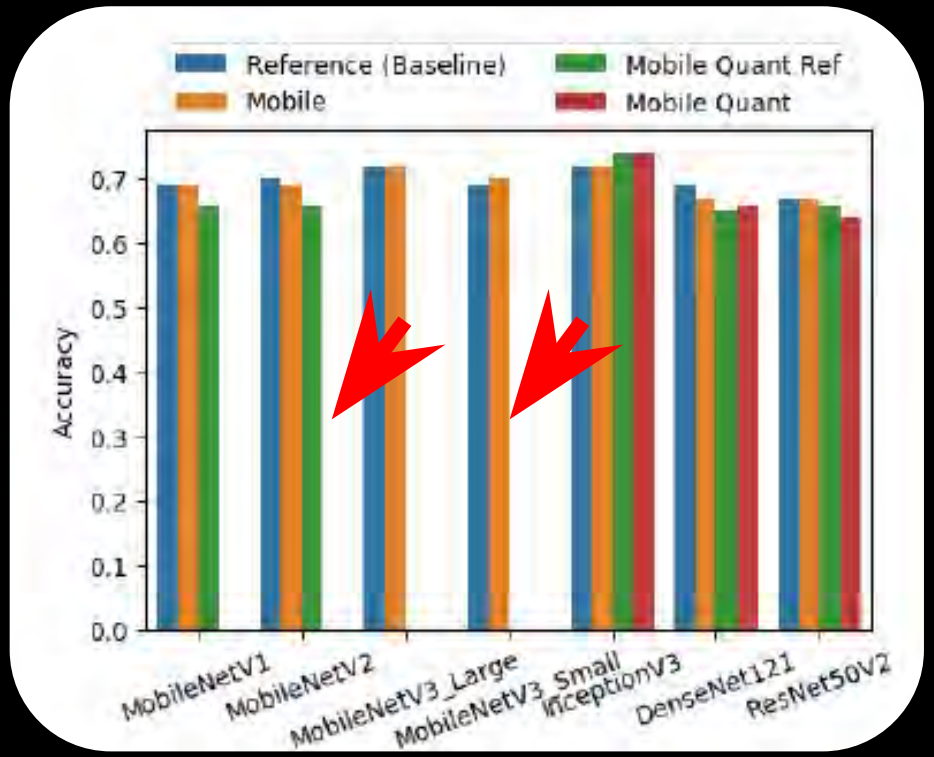
Debugging Target	Line of Code					
	W/ ML-EXRAY			W/O ML-EXRAY		
	Inst	Asrt	**Total**	Inst	Asrt	**Total**
Preprocessing	1	3	**4**	18	7	**25**
Quantization	4	9	**13**	82	183	**265**
Lat. & Mem.	4	4	**8**	14	8	**22**
Per-layer Lat.	2	6	**8**	14	90	**104**

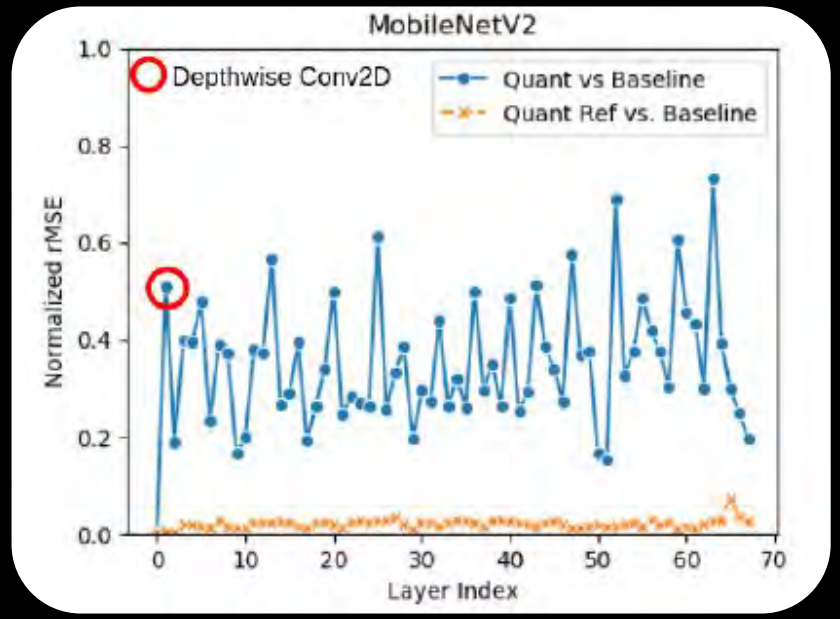
Pre-processing Bugs and Impact

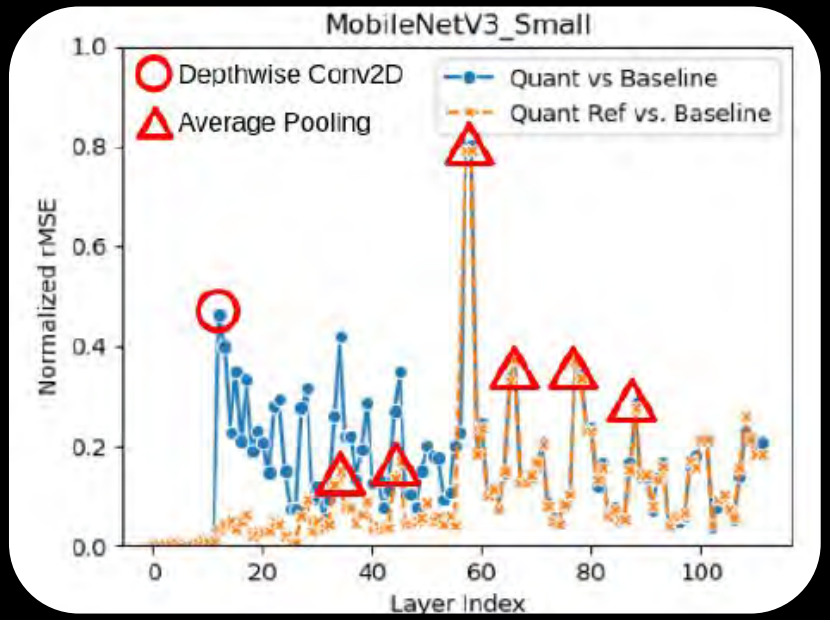


Eradicating these issues, ML-EXray can correct model performance by 5 - 40%

Localizing Quantization Issues







Quantized MobileNet not working well

Per-layer validation can easily localize the issue

Sub-optimal Kernels and Latency

Latency by layer type (MobileNet v2)

Layer Type (Count)	Mobile (ms)	Mobile Quant (ms)	Mobile Quant Ref (ms)	Emulator(x86) Mobile (ms)
D-Conv(17)	**95.4**	22.7	2885.2	120.0
Conv(35)	23.5	**32.3**	**18662.3**	**1409.8**
FC(1)	7.4	7.1	7.0	71.2
Mean(1)	6.1	5.6	5.0	2.5
Pad(4)	1.6	18.7	60.8	104.8
Add(10)	1.5	7.7	99.8	7.0
Softmax(1)	0.4	0.0	0.0	0.2
Quantize(1)	-	3.3	0.7	-
Total	136.26	97.816	21721.2	1715.7

Reference kernels may be more stable but much slower

Emulator is slow on convolution layers

Debug Your Edge ML

https://github.com/hangqiu/ML-EXray

https://arxiv.org/abs/2111.04779

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ML-EXray: Visibility into ML Execution on the Edge

Thank you!

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