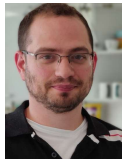
Data Efficiency Estimation from Tiny Datasets: Sparse Polarization Biometric Case Study

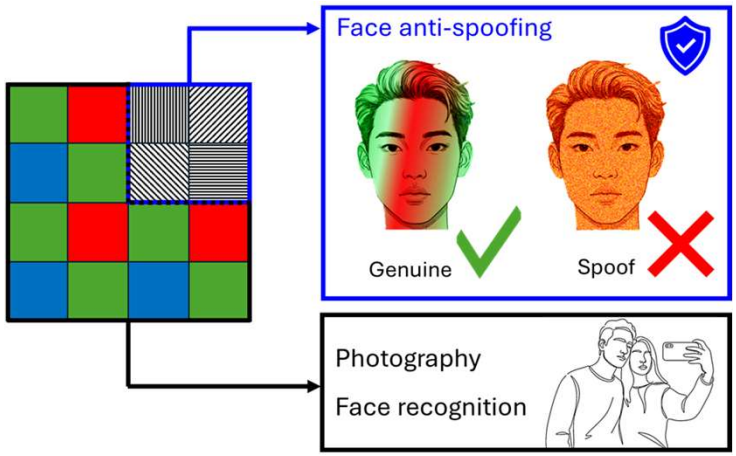
This talk draws from our paper:

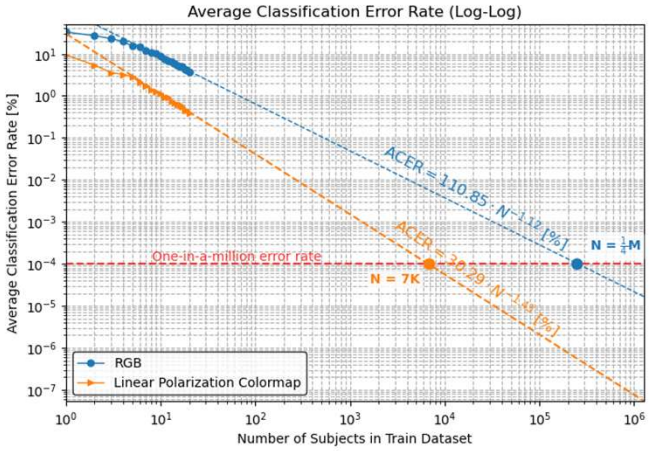
Kim, J., Pelz, A., Scherer, M., & Mendlovic, D. (2025). ***On the Effectiveness of Sparse Linear Polarization Pixels for Face Anti-Spoofing. IEEE Sensors Journal***

Kim JaeSeong (Jae)



Abraham (Avi) Pelz





Dr. Michael Scherer

Prof. David Mendlovic

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Face Anti-Spoofing

- **Face Spoofing:** Attackers might bypass Face ID security using printed photos or video replays. Both attacks operate purely in the **RGB** domain.
  - Therefore, **RGB** is **not** the **optimal** domain for face anti-spoofing.
  - However, RGB datasets contain over one hundred thousand images, and we cannot fairly compare a model trained on these datasets to a model trained on a novel modality with a **tiny dataset**.
  - **Challenge**: Estimate a novel modality's performance on a large-scale dataset without collecting it?

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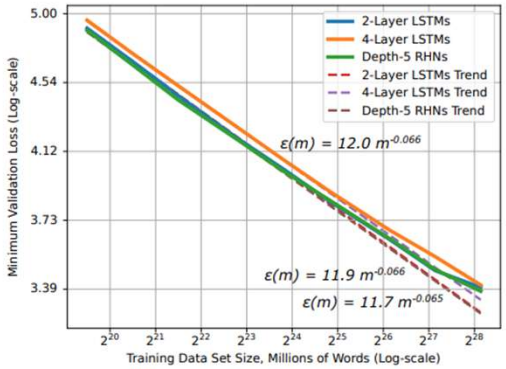
Data Scaling

- Neural networks' error **scales** with train set size (power law):

$$\log(\text{Test Error}) \propto \log\left(\frac{1}{\text{Train Set Size}}\right)$$

  - **Standard Use**: Comparing NN architectures.
  - **Our Twist**: Fixing the architecture to isolate data efficiency.
  - **Hypothesis**: RGB requires a polynomial factor more data than polarization.

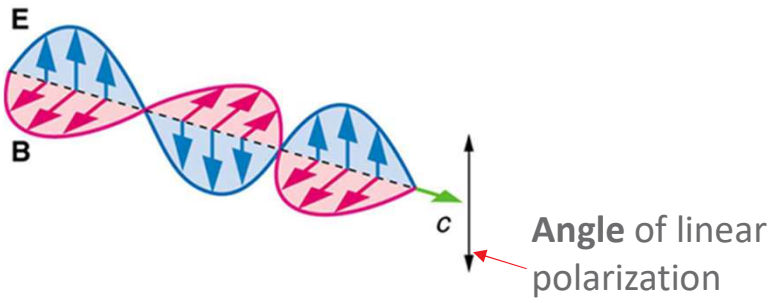


J. Hestness et al., "Deep learning scaling is predictable, empirically," 2017, arXiv:1712.00409.

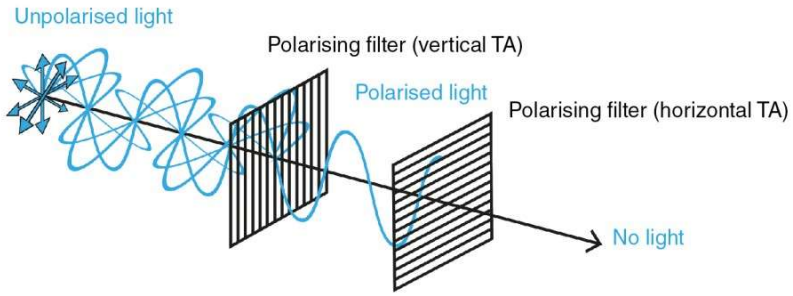
What is Polarization?

- Light is characterized by frequency (color), amplitude (brightness) and **polarization** - the latter describes the **geometric orientation** of oscillations.
- The **angle** & **degree** of light's linear polarization from a surface provide cues about its characteristics.

Light wave with 100% **degree** of linear polarization:



Filtering unpolarized light to polarized light:



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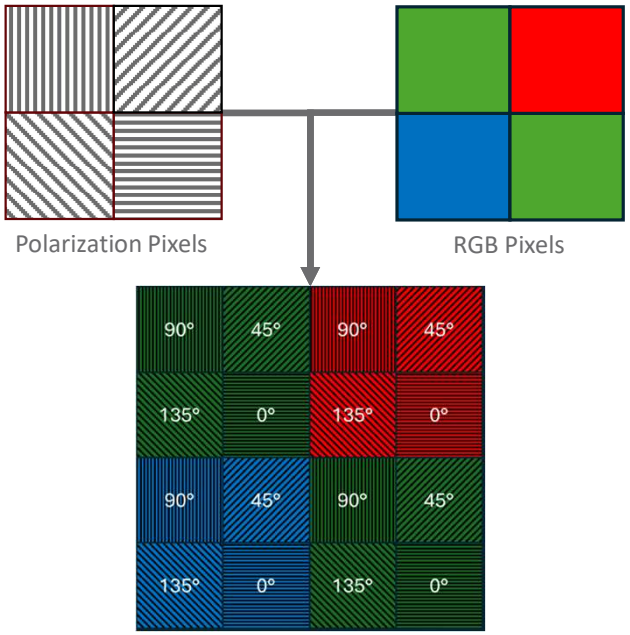
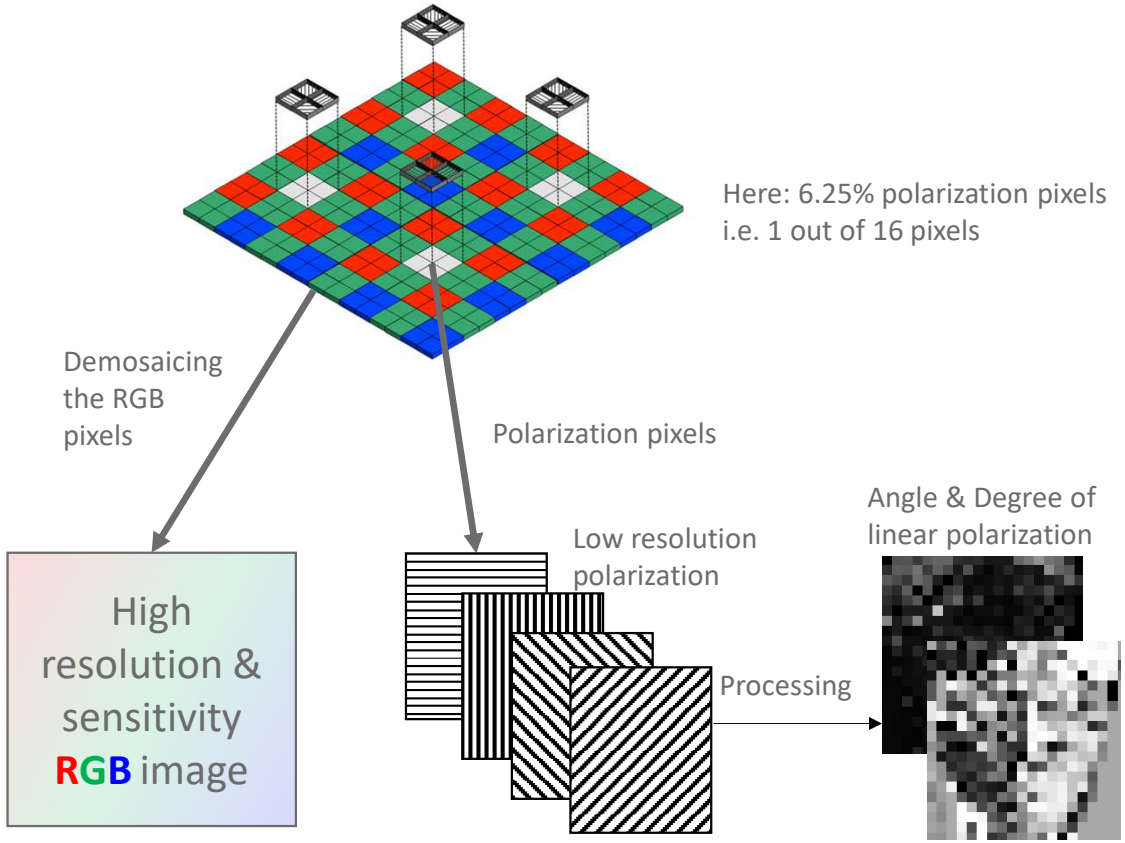
Simultaneously Capturing Polarization & Photography Data

Dense Polarization Sensor



50% drop in RGB resolution & sensitivity!

Sparse Polarization Sensor



From: Kurita, Teppei et al. "Simultaneous Acquisition of High Quality RGB Image and Polarization Information using a Sparse Polarization Sensor." 2023 IEEE/CVF Winter Conference on Applications of Computer Vision (WACV)

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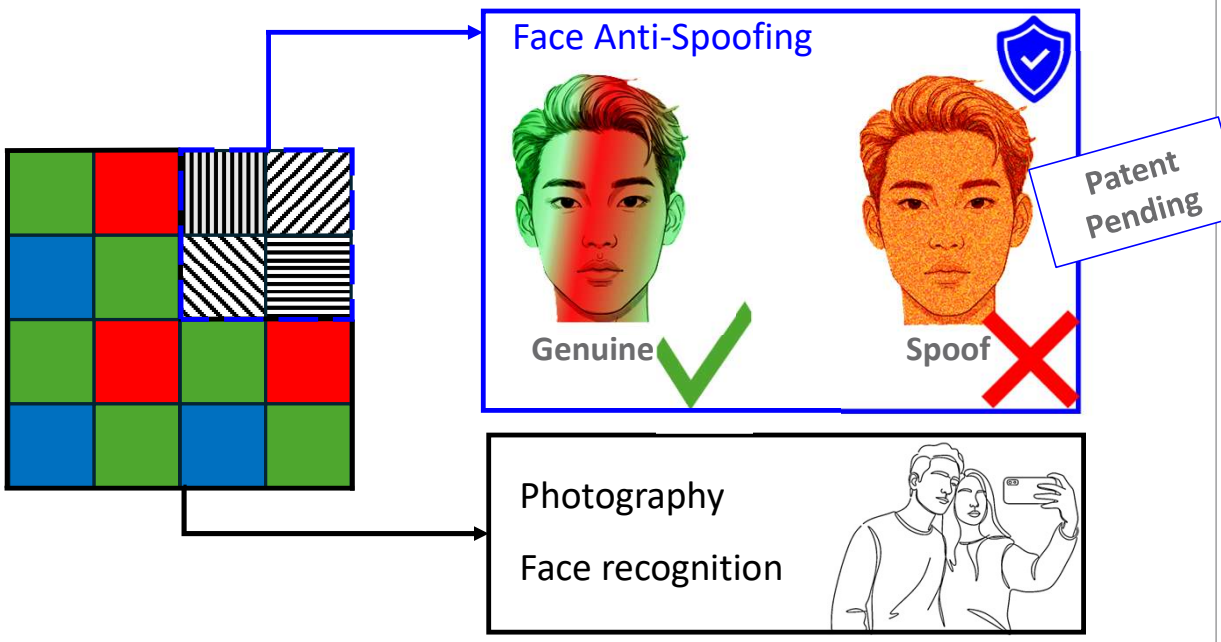
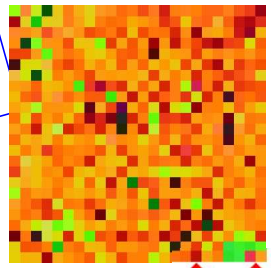
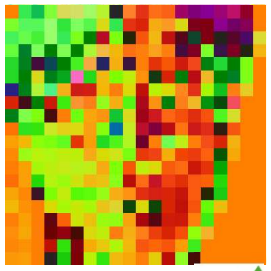
Ultra-Sparse Polarization for Face Anti-Spoofing

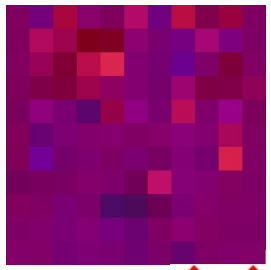


Patent Pending

Simulating sparsity (e.g. sampling):


Printed Spoof


Genuine Face


Replay Spoof

Spoofs stand out even in Ultra-Sparse Polarization of 0.25% polarization pixels (1 out of 400 pixels)
→ 99.75% pixels dedicated to photography

Existing solution:
Additional depth sensor = **Higher cost, weight and power consumption**!

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Comparing Modalities Without Data Scaling: Ultra-Sparse Polarization Outperforms RGB

- Repeat 100 training sessions for each modality:
  - **Randomly sample** a train/validation split
  - **Fine-tune** a pre-trained backbone with a binary classification layer (**genuine vs. spoof**)
  - **Average** the validation results across all training sessions

Input	Results - Average Classification Error Rate
RGB	3.8%
Dense Polarization	0.32%
Ultra-Sparse Polarization (1 out of 400 pixels)	0.39%

Tenfold reduction!

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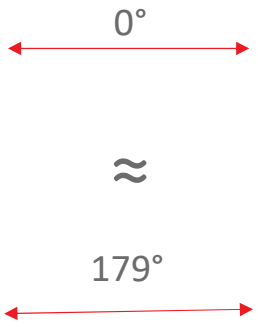
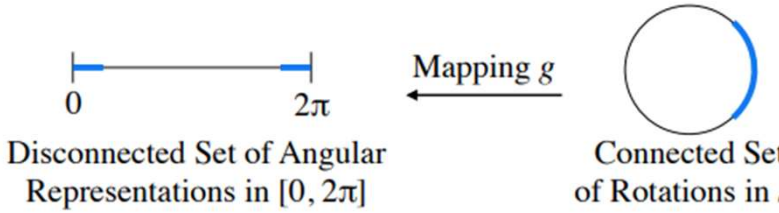
Polarization Data Representation Considerations

- Do both **angle & degree** of linear polarization support face anti-spoofing?
  - **Yes**, but the **angle** is more discriminative.
- Is one channel enough to represent the angle of linear polarization?
  - **No**, single-channel representation causes **discontinuities** due to orientations' cyclic nature (0°↔180° cyclic boundary).
  - **Solution - Two channels Cartesian representation:**

$$[\cos(2\theta), \sin(2\theta)]$$

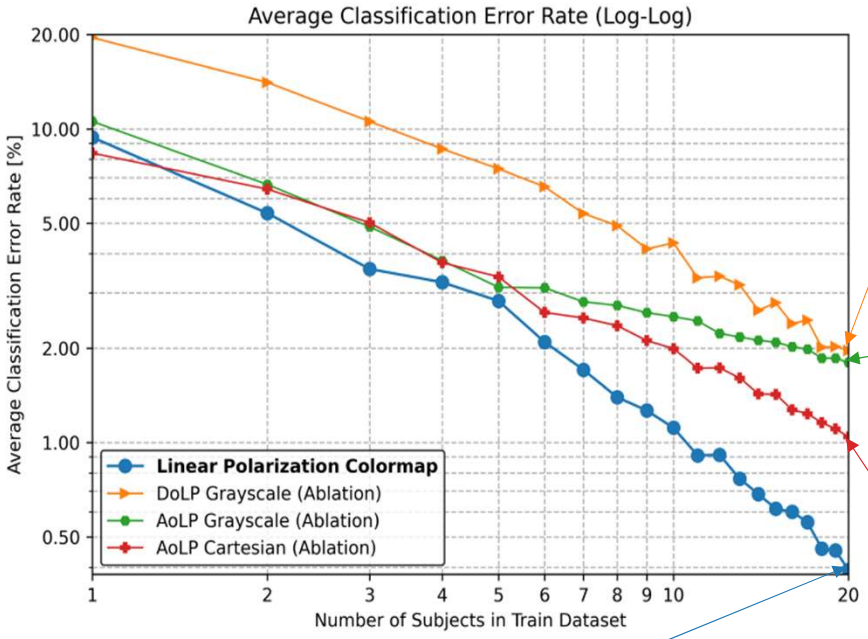


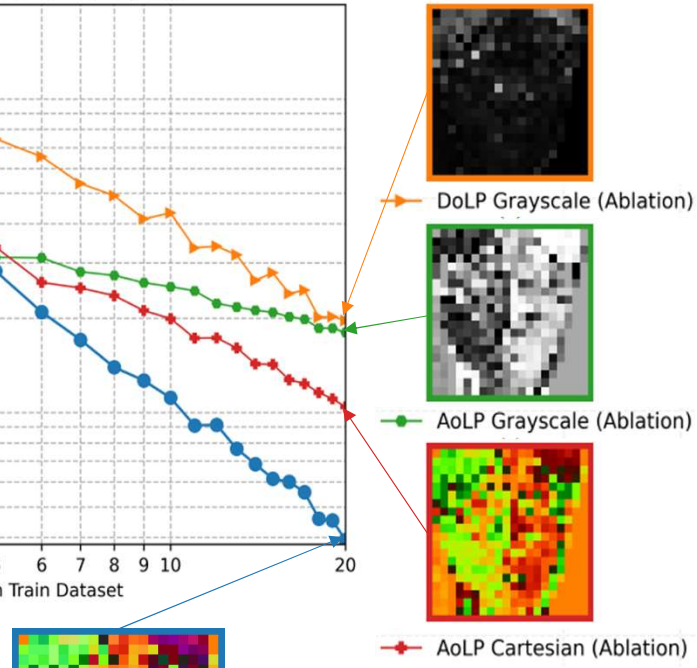


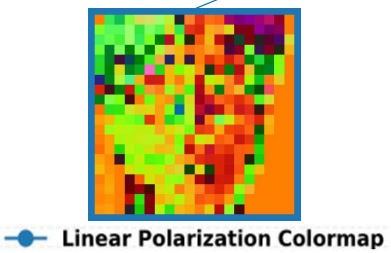
Cartesian vs. standard representation of angle, taken from: Zhou, Y., Barnes, C., Lu, J., Yang, J., & Li, H. On the Continuity of Rotation Representations in Neural Networks. 2019 IEEE/CVF Conference on Computer Vision and Pattern Recognition (CVPR)

Polarization Data Representation Ablation

- Methodology:
  - Trained models with different **representations** with varying **training** set **sizes**.
- Finding:
  - **Our representation** achieves lowest error for any train set size.
  - **Angle of linear polarization** alone doubles the error.
  - **Single channel representation of the angle** double the error again.
  - Using the **degree of linear polarization** **instead** of its angle further increases the error.







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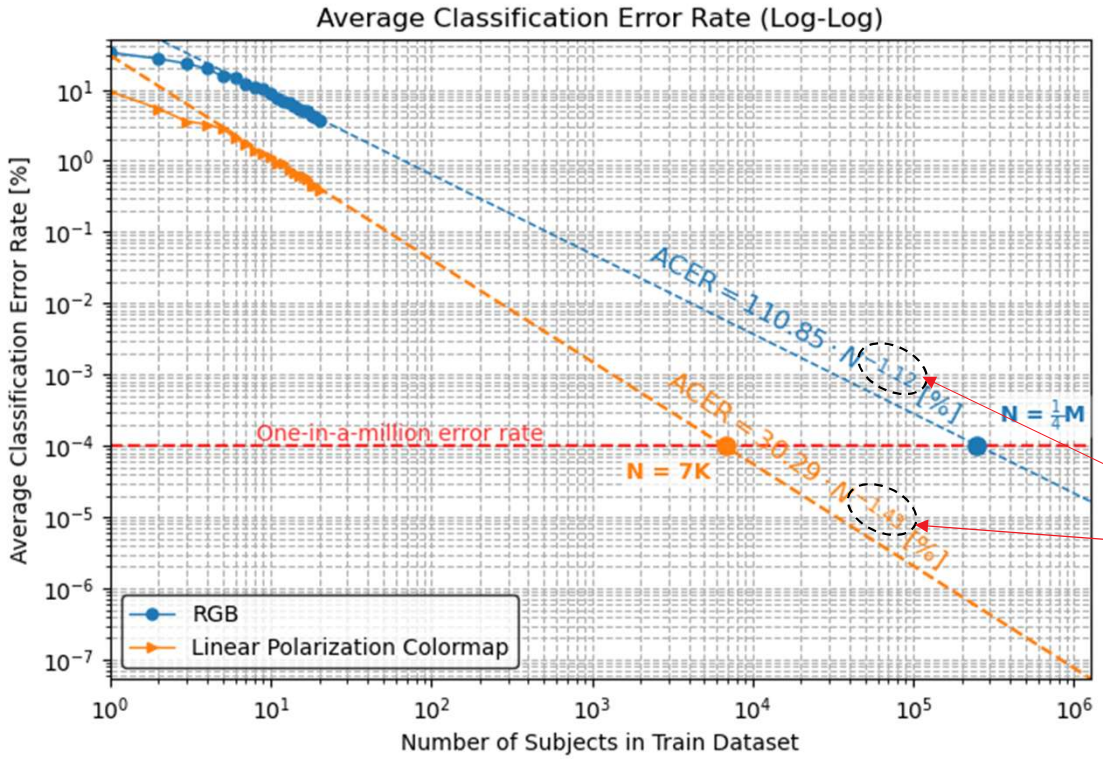
RGB and Polarization Accuracy Extrapolation



Power law's exponents

For a one-in-a-million error rate, a polarization-based NN requires only a few thousand subjects, whereas an RGB-based NN requires a quarter-million, making it unviable under current legal frameworks.

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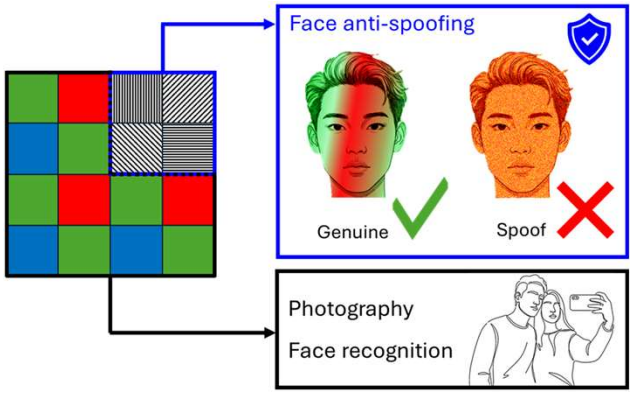
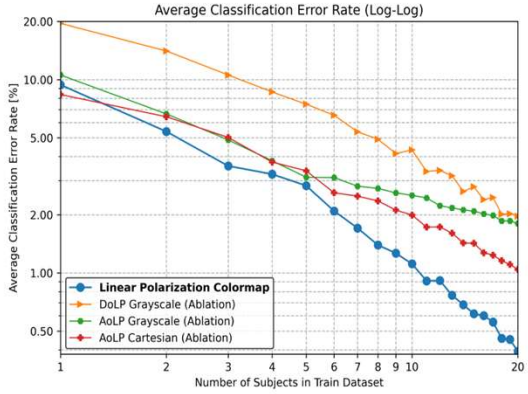
Conclusions

Ultra sparse linear **polarization** (**1 out of 400 pixels**) is more discriminative for face anti-spoofing than **full RGB** data



- Enabling cheap and reliable face biometrics on **low-cost single** sensor devices.

Small data ablation can evaluate data effectiveness **without full training**



- Less informative modalities/representations require a **polynomial** factor more data.

Paper's Link: DOI → IEEE

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