Uncertainty Quantification with Conformal Prediction: AI Application in Interferometry and Medicine

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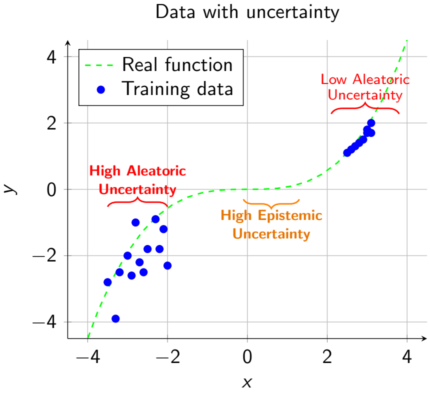
Why Uncertainty Matters

- AI systems can be confidently wrong
- Need for calibrated, trustworthy AI prediction
- In interferometry:
  - affects physical accuracy
- In medicine:
  - guides clinical decision and patient safety
- Improves interpretability and reduces overconfidence.

Aleatoric vs. Epistemic Uncertainty



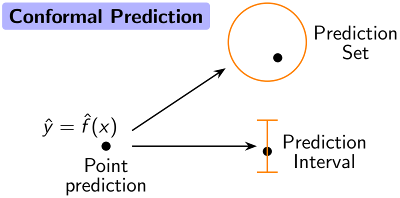
Aleatoric Uncertainty

Irreducible noise in the data

Epistemic Uncertainty

Lack of knowledge or data.
$\Rightarrow$ Reducible with more data!

What is Conformal Prediction?



- Predictor $\hat{f} : \mathcal{X} \to \mathcal{Y}$
- The sets from conformal prediction satisfy

$$\mathbb{P}(y \in \mathcal{C}(x)) \geq 1 - \alpha$$

- Adapts to noise by widening prediction intervals.
- Sensitive to unfamiliar data — larger prediction sets indicate model uncertainty.
- Model-agnostic, distribution free

How Conformal Prediction Works

1. Define nonconformity score

- Classification: $s(x, y) = 1 - \hat{p}(y \mid x)$
- Regression: $s(x, y) = |y - \hat{f}(x)|$

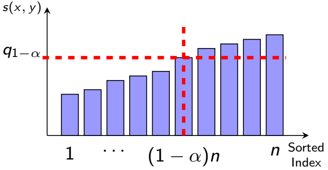
Larger scores $\Rightarrow$ worse agreement

2. Use calibration dataset

- Given $\{x_i, y_i\}_{i=1}^{n}$, compute nonconformity scores:

$$s_i = s(x_i, y_i)$$

3. Determine quantile threshold



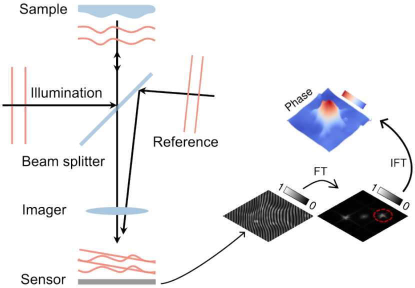
$$\mathbb{P}(s \leq q_{1-\alpha}) \geq 1 - \alpha, \text{ such that}$$
$$q_{1-\alpha} = \lceil (n+1)(1-\alpha) \rceil - \text{th}$$
smallest value of $s_1, \ldots, s_n$

4. Define the prediction set for new data

- Regression: $\mathcal{C}_\alpha(x_{test}) = [\hat{f}(x_{test}) \pm q_{1-\alpha}]$
- Classification: $\mathcal{C}_\alpha(x_{test}) = \{y \mid 1 - \hat{p}(y|x_{test}) \leq q_{1-\alpha}\}$

Larger set $\Rightarrow$ greater model uncertainty.

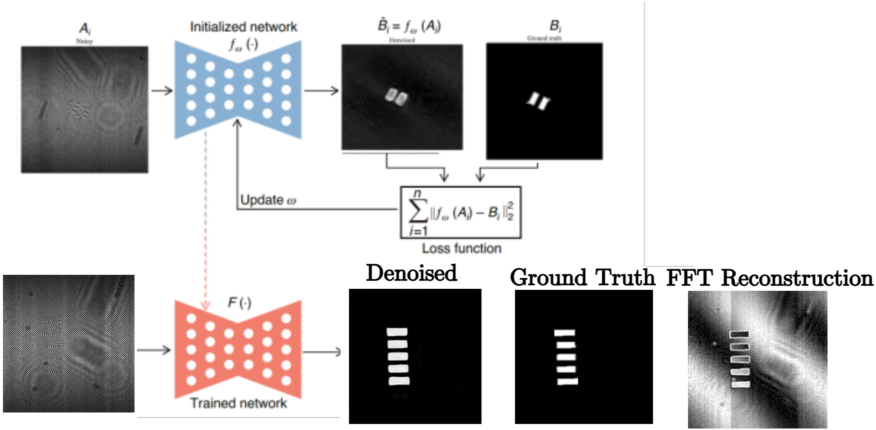
Application I: Interferometry



- Off-axis Interferometry
- Need: Confidence in phase reconstruction
- Task: Denoised an interferograms images
- On-going work

Interferometry: Results I

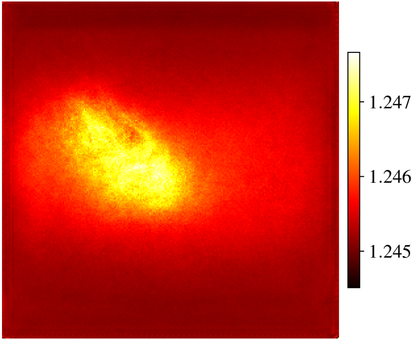
- Synthetic data
- Autoencoders for denoising (Inspired in U-net)



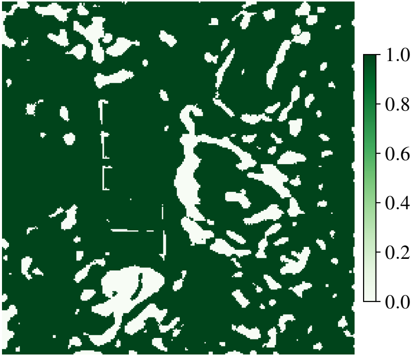
Interferometry: Results II

- Interval width adapts to noise/complexity
- Coverage close to theoretical guarantee

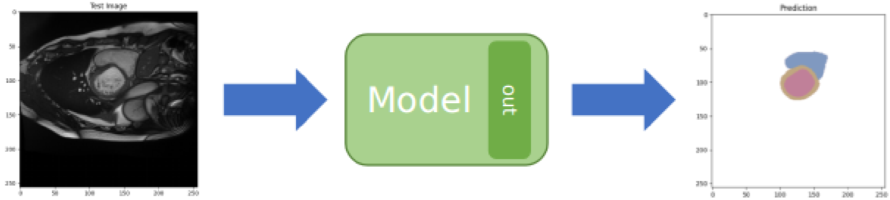
$\mathscr{C}_\alpha$ width with $q_{1-\alpha}$



Coverage. 0.841
(alpha = 0.9)



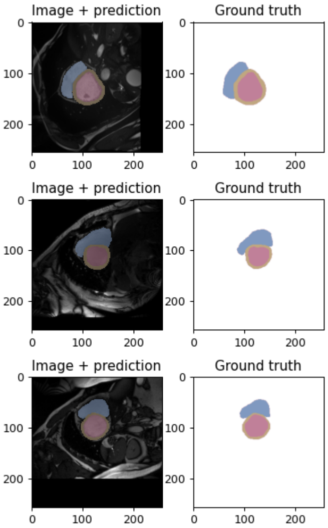
Application II: Medicine



- PTB-INTI collaboration (on-going work)
- Task: Image Segmentation
- Model pre-trained with the King's College London dataset[1].

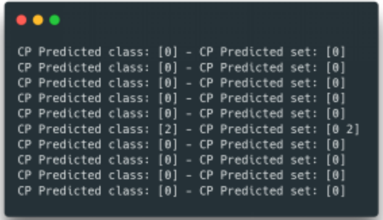
[1] Kerfoot E., et. al. *Left-Ventricle Quantification Using Residual U-Net*, STACOM 2018

Medicine: Results



ACDC dataset: https://www.creatis.insa-lyon.fr/Challenge/acdc/

- Model Predictions with Conformal prediction.



```
CP Predicted class: [0] - CP Predicted set: [0]
CP Predicted class: [0] - CP Predicted set: [0]
CP Predicted class: [0] - CP Predicted set: [0]
CP Predicted class: [0] - CP Predicted set: [0]
CP Predicted class: [0] - CP Predicted set: [0]
CP Predicted class: [2] - CP Predicted set: [0 2]
CP Predicted class: [0] - CP Predicted set: [0]
CP Predicted class: [0] - CP Predicted set: [0]
CP Predicted class: [0] - CP Predicted set: [0]
CP Predicted class: [0] - CP Predicted set: [0]
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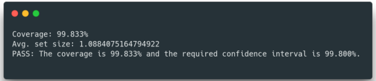
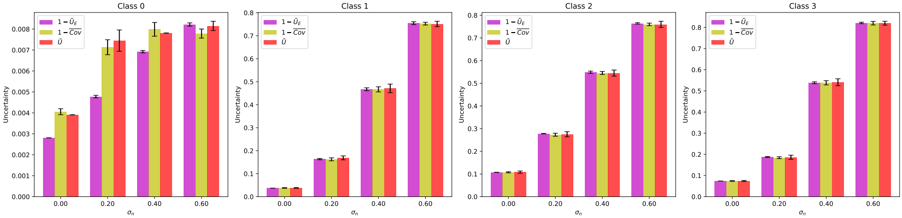
- Coverage Guarantee



```
Coverage: 99.833%
Avg. set size: 1.0884075164794922
PASS: The coverage is 99.833% and the required confidence interval is 99.800%.
```

Medicine: Results II

- Estimation of Uncertainties and Coverage per Class using a 10−Fold.



Conclusion and Future Work

- CP looks promising in terms of inform uncertainty.
- Fast, simple to implement, distribution-free guarantees $\rightarrow$ Great for offering as a service.
- Challenges
  - Data handling in terms implementation
  - Calibration data
  - Constant over the prediction set
- Future Work
  - Multivariate and structured output prediction sets.
  - Formalize the method for uncertainty evaluation.

Thank you!

Questions?