AI SAFETY WORKSHOP
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A Comparison of Uncertainty Estimation Approaches in Deep Learning Components for Autonomous Vehicle Applications

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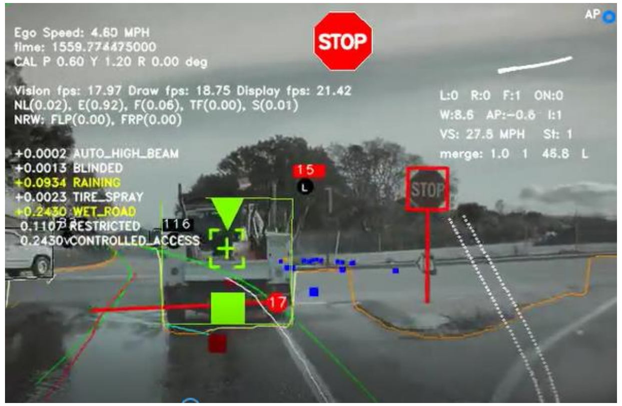
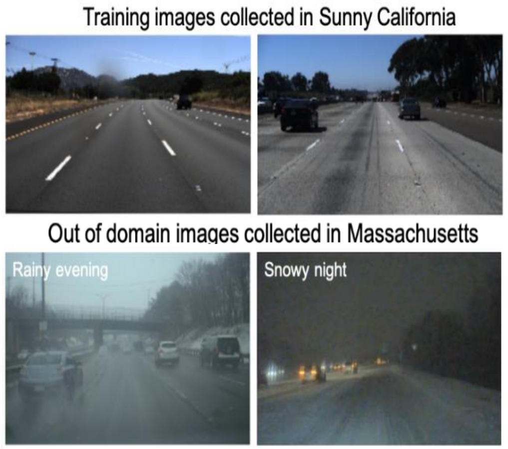
OUTLINE

- Motivation
- Comparison of Uncertainty Estimation Methods
- Conclusions & Recommendations

Motivation

AV Software Pipeline.





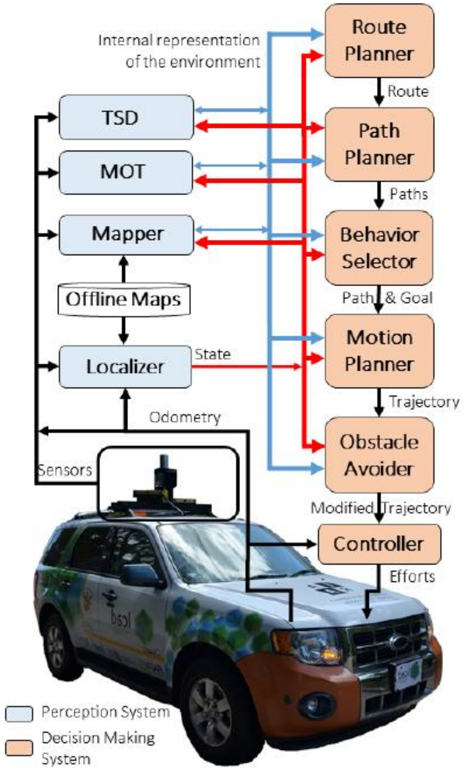


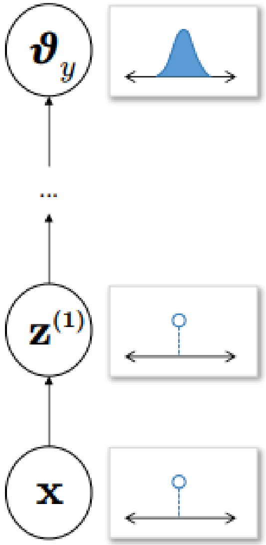
Image Credits: Tesla

Typical Modular Architecture for self-driving cars
C Badue, R Guidolini, et al. "***Self-Driving Cars: A Survey***". Oct. 2019.

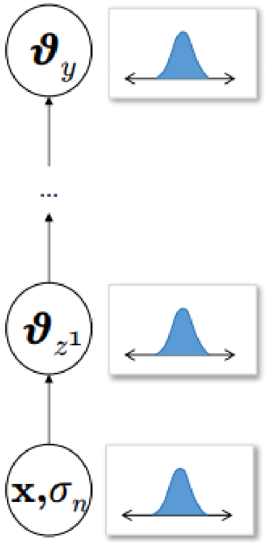
- Autonomous Vehicles (AVs) are **typically built of a pipeline of individual components linking sensor inputs to motor outputs**
- Deal with **dynamic, non-stationary and highly unpredictable environments**
- **Ensuring safety** in an AV requires the **identification of unfamiliar contexts**

Uncertainty Estimation Methods

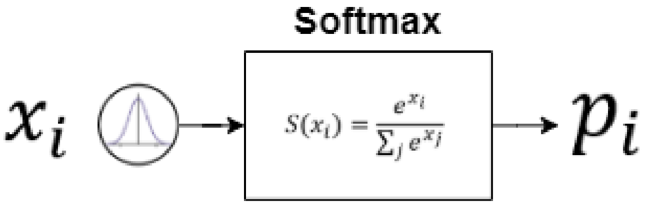
- **Methods limited to Aleatoric Uncertainty**
  - Outputs as parameters for a probability distribution
  - Inputs, activation functions and outputs as probability distributions
  - Softmax logits as parameters of a probability distribution



Outputs as parameters of a probability distributions



Inputs, activation functions and outputs as probability distributions



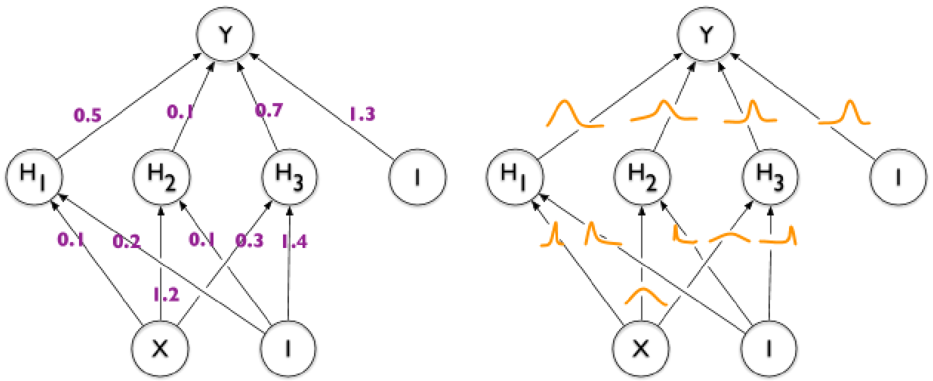
$$\hat{\mathbf{x}}_i | \mathbf{W} \sim \mathcal{N}(\mathbf{f}_i^{\mathbf{W}}, (\sigma_i^{\mathbf{W}})^2)$$
$$\hat{\mathbf{p}}_i = \text{Softmax}(\hat{\mathbf{x}}_i).$$

Softmax logits as probability distributions

__Image Credits:__ Gast, J., & Roth, S. (2018). __Lightweight probabilistic deep networks__. In Proceedings of the IEEE Conference on Computer Vision and Pattern Recognition (pp. 3369-3378).

Uncertainty Estimation Methods

- Methods for Estimating Epistemic Uncertainty

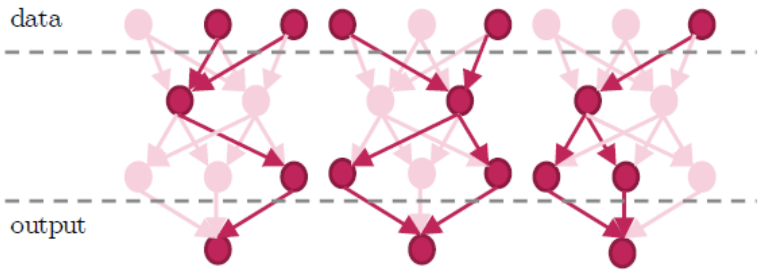


Bayesian Neural Network

$$p(\mathbf{w}|\mathcal{D}) = \frac{p(\mathcal{D}|\mathbf{w})p(\mathbf{w})}{p(\mathcal{D})} = \frac{p(\mathcal{D}|\mathbf{w})p(\mathbf{w})}{\int p(\mathcal{D}|\mathbf{w})p(\mathbf{w})d\mathbf{w}}$$

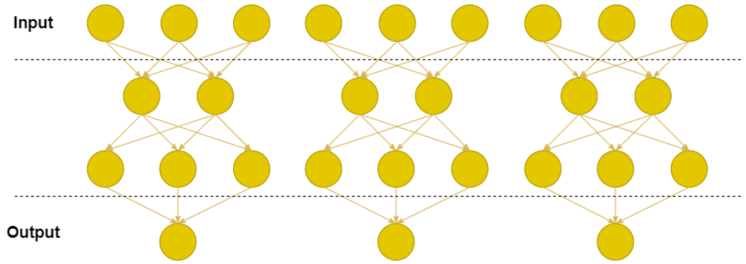
$$p(\mathbf{y}^*|\mathbf{x}^*, \mathcal{D}) = \int p(\mathbf{y}^*|\mathbf{x}^*, \mathbf{w})p(\mathbf{w}|\mathcal{D})d\mathbf{w}$$

Image Credits: *Blundell, C., Cornebise, J., Kavukcuoglu, K., & Wierstra, D. (2015, July).* ***Weight uncertainty in neural networks****. In Proceedings of the 32nd International Conference on International Conference on Machine Learning-Volume 37 (pp. 1613-1622).*



Monte Carlo Dropout

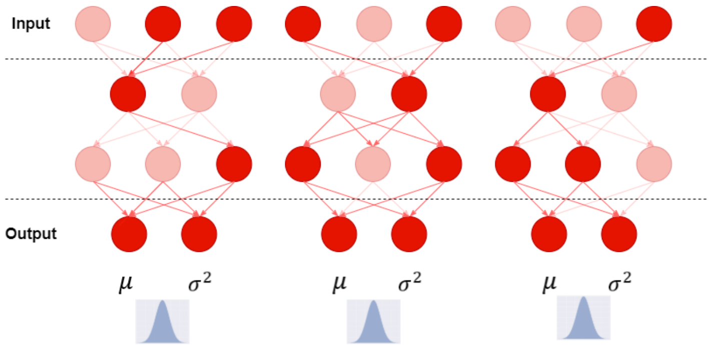
Image Credits: *Hubschneider, C., Hutmacher, R., & Zöllner, J. M. (2019, October).* ***Calibrating Uncertainty Models for Steering Angle Estimation****. In 2019 IEEE Intelligent Transportation Systems Conference (ITSC) (pp. 1511-1518). IEEE.*



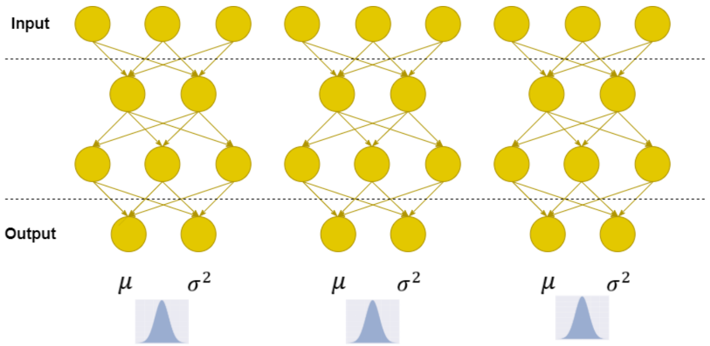
Simple Deep Ensemble

Uncertainty Estimation Methods

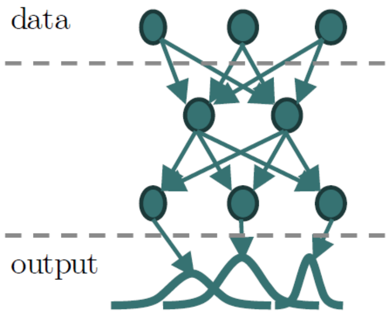
- Methods for Estimating Aleatoric & Epistemic Uncertainty



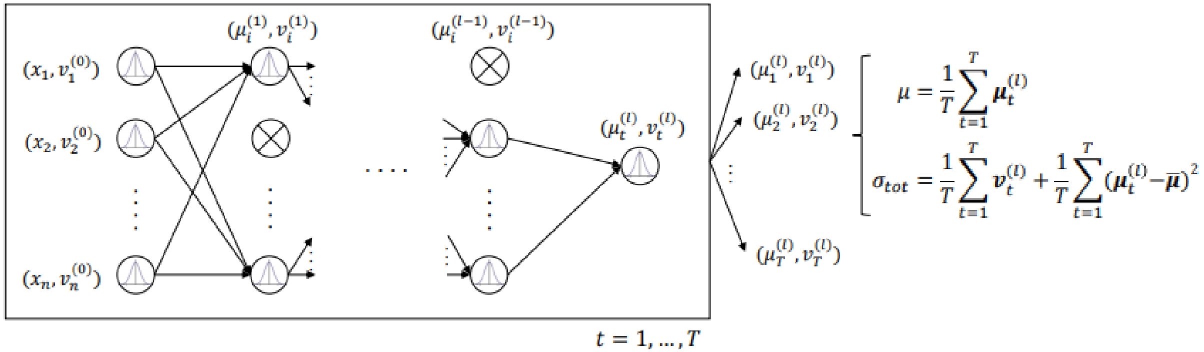
MCD & Outputs as parameters of a probability distributions



Deep Ensembles & Outputs as parameters of a probability distributions



Mixture Density Network



Input, activation functions and output as probability distributions (ADF) & MCD

Image Credits: *Hubschneider, C., Hutmacher, R., & Zöllner, J. M. (2019, October).* ***Calibrating Uncertainty Models for Steering Angle Estimation****. In 2019 IEEE Intelligent Transportation Systems Conference (ITSC) (pp. 1511-1518). IEEE.*

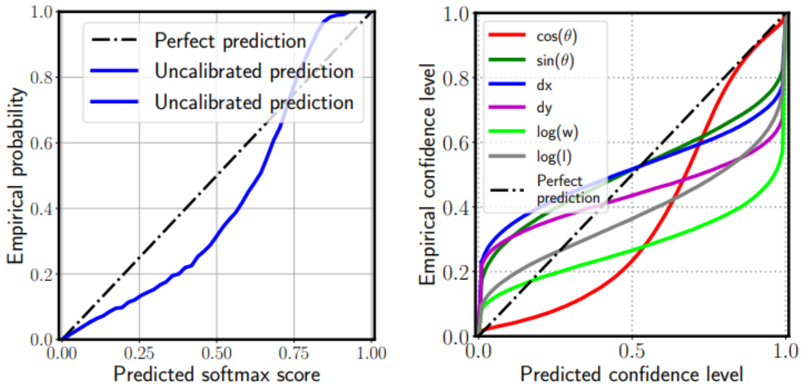
Image Credits: *Loquercio, A., Segu, M., & Scaramuzza, D. (2020).* ***A general framework for uncertainty estimation in deep learning****. IEEE Robotics and Automation Letters, 5(2), 3153-3160.*

Quality Metrics for Uncertainty Estimation Methods

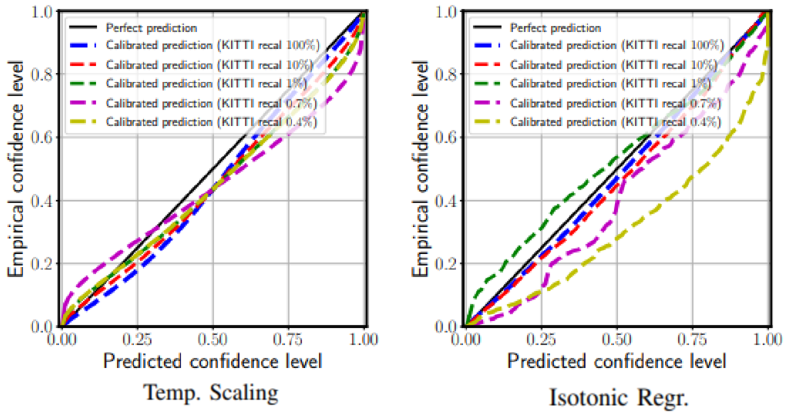
Classification
- NLL
- Brier Score
- AUCs

Regression
- NLL

Calibration
- ECE
- MCE
- AUCC



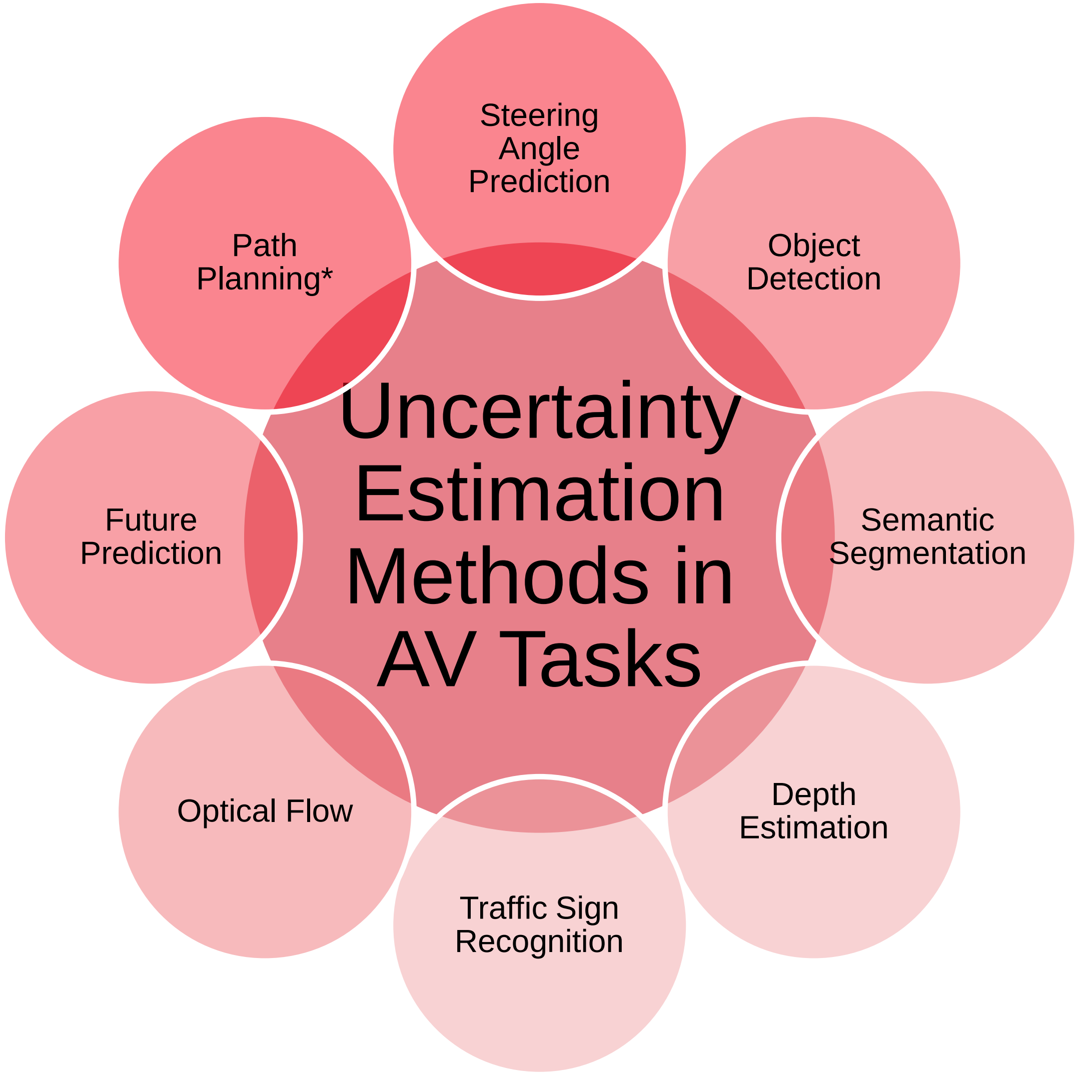
Reliability Diagrams



Reliability Diagrams after Calibration

__Image Credits:__ Feng, D., Rosenbaum, L., Glaeser, C., Timm, F., & Dietmayer, K. (2019). __Can we trust you? on calibration of a probabilistic object detector for autonomous driving__. arXiv preprint arXiv:1909.12358.

Uncertainty Estimation Methods in AV Tasks



Contribution Summary

Method	Autonomous Vehicle Task	Uncertainty Captured		Comparison Criteria			
		Aleatoric	Epistemic	Out-of-the box Calibration	Computational Budget	Memory Footprint	Changes in DNN
Softmax logits as parameters of a prob. dist.	- Object Detection [Feng *et al.*, 2019b]	✓	✗	Bad	Fair	Slow	Small
Outputs as parameters of a prob. dist.	- Object Detection [Feng *et al.*, 2019b]	✓	✗	Bad	Fair	Slow	Small
Inputs, activation and output as prob. dist. & ADF	- Optical Flow [Gast and Roth, 2018]	✓	✗	Undefined	Low	Low	Mid
Point estimate & MCD regression	- Steering Angle Prediction [Hubschneider *et al.*, 2019; Michelmore *et al.*, 2018; Michelmore *et al.*, 2019]	✗	✓	Fair	Fair	Low	None
Softmax & MCD	- Traffic Sign Recognition [Henne *et al.*, 2020] - Semantic Segmentation [Phan *et al.*, 2019; Mukhoti and Gal, 2018; Gustafsson *et al.*, 2019]	✗	✓	Fair	Fair	Low	None
Deep Ensembles	- Steering Angle Prediction [Hubschneider *et al.*, 2019] - Traffic Sign Recognition [Henne *et al.*, 2020] - Semantic Segmentation [Gustafsson *et al.*, 2019] - Depth Estimation [Gustafsson *et al.*, 2019]	✓	✓	Good	High	High	Small
Bootstrap Ensembles	- Steering Angle Prediction [Hubschneider *et al.*, 2019] - Optical Flow [Ilg *et al.*, 2018]	✓	✓	Bad	Fair	Fair	Mid
Softmax logits as parameters of a prob. dist. & MCD	- Object Detection [Feng *et al.*, 2018]	✓	✓	Fair	High	Low	Small
Outputs as parameters of a prob. dist. & MCD	- Object Detection [Feng *et al.*, 2018] - Steering Angle Prediction [Lee *et al.*, 2019b; Lee *et al.*, 2019c; Lee *et al.*, 2019a] - Depth Estimation [Gustafsson *et al.*, 2019]	✓	✓	Fair	High	Low	Small
Inputs, activation and output as prob. dist. & ADF &MCD	- Steering Angle Prediction [Loquercio *et al.*, 2020]	✓	✓	Undefined	High	Low	Mid
MDNs	- Steering Angle Prediction [Hubschneider *et al.*, 2019; Choi *et al.*, 2018] - Future Prediction [Makansi *et al.*, 2019]	✓	✓	Bad	Low	Low	None
MDNs with stages	- Future Prediction [Makansi *et al.*, 2019]	✓	✓	Undefined	Low	Low	High

Table 1: Uncertainty Estimation Methods Comparison

Comparison Criteria for Uncertainty Estimation Methods in DNNs

Common Methods

*More details in:
Arnez, F., Espinoza, H., Radermacher, A., & Terrier, F. ***A Comparison of Uncertainty Estimation Approaches in Deep Learning Components for Autonomous Vehicle Applications****. Proceedings of the Workshop on Artificial Intelligence Safety 2020, vol 2640, ISSN:1673-0073*

Conclusions & Recommendations

- DE method has become a gold-standard for uncertainty quantification in many AV tasks
- Consider Sampling-free methods and multi-modal probability distributions in the outputs
- Uncertainty estimation methods are not calibrated (overconfident or under confident)
- Assess the robustness of DL uncertainty estimation methods under dataset-shift conditions
- Monitor uncertainty from DL components for risk assessment at runtime

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