

SoPa++: Leveraging explainability from hybridized RNN, CNN and weighted finite-state neural architectures

M.Sc. Thesis Defense

Atreya Shankar (799227), shankar.atreya@gmail.com

Cognitive Systems: Language, Learning, and Reasoning (M.Sc.)

1st Supervisor: Dr. Sharid Loáiciga, University of Potsdam

2nd Supervisor: Mathias Müller, M.A., University of Zurich

Foundations of Computational Linguistics

Department of Linguistics

University of Potsdam, SoSe 2021

July 8, 2021

Overview

1 Introduction

2 Background concepts

3 Data and methodologies

4 Results

5 Discussion

6 Conclusions

7 Future work

Motivation

- Trend of increasingly complex deep learning models achieving SOTA performance on ML and NLP tasks (Figure 1)
- To address emerging concerns such as inductive biases, several studies make arguments for research into XAI; for example [Danilevsky et al. \(2020\)](#) and [Arrieta et al. \(2020\)](#)
- [Schwartz et al. \(2018\)](#) approach XAI in NLP by proposing an explainable hybridized neural architecture called **Soft Patterns** (SoPa; Figure 2)
- SoPa provides **localized** and **indirect** explainability despite being suited for globalized and direct **explanations by simplification**

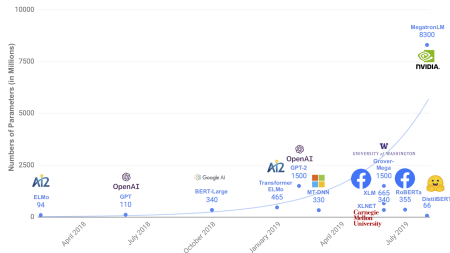


Figure 1: Parameter counts of recently released pre-trained language models; figure taken from [Sanh et al. \(2019\)](#)

SoPa: Bridging CNNs, RNNs, and Weighted Finite-State Machines

Roy Schwartz* ♦♦ Sam Thomson* ♦ Noah A. Smith ♦

♦Paul G. Allen School of Computer Science & Engineering, University of Washington

♦Language Technologies Institute, Carnegie Mellon University

▽Allen Institute for Artificial Intelligence

{roysch,nasmith}@cs.washington.edu, sthompson@cs.cmu.edu

Figure 2: Excerpt from [Schwartz et al. \(2018\)](#)

Objective and research questions

Objective:

- Address limitations of SoPa by proposing **SoPa++**, which could allow for effective explanations by simplification.

Process:

- We study the performance and explanations by simplification of SoPa++ on the Facebook Multilingual Task Oriented Dialog (**FMTOD**) data set from [Schuster et al. \(2019\)](#); focusing on the English-language intent classification task.

Research questions:

- 1 Does SoPa++ provide **competitive** performance?
- 2 To what extent does SoPa++ contribute to **effective** explanations by simplification?
- 3 What **interesting and relevant** explanations can SoPa++ provide?

Overview

1 Introduction

2 Background concepts

3 Data and methodologies

4 Results

5 Discussion

6 Conclusions

7 Future work

Explainability

- Transparency is a passive feature that a model exhibits
- Explainability is an active feature that involves target audiences (Figure 3)
- [Arrieta et al. \(2020\)](#) explore a taxonomy of post-hoc explainability techniques
- Explainability techniques can provide meaningful insights into decision boundaries within black-box models (Figure 4)
- Prominent explainability techniques include local explanations, feature relevance and **explanations by simplification**

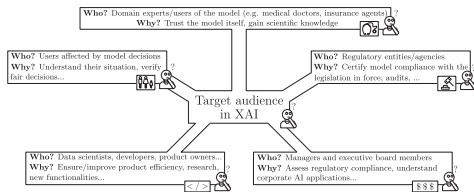
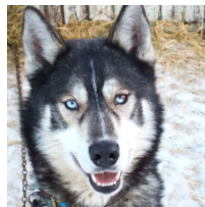
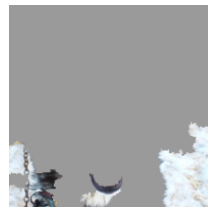


Figure 3: Examples of various target audiences in XAI; figure taken from [Arrieta et al. \(2020\)](#)



(a) Husky classified as wolf



(b) Explanation

Figure 4: Local explanation for “Wolf” classification decision, figure taken from [Ribeiro et al. \(2016\)](#)

SoPa: Weighted Finite-State Automaton (WFA)

Definition 1 (Semiring; Kuich and Salomaa 1986)

A semiring is a set \mathbb{K} along with two binary associative operations \oplus (addition) and \otimes (multiplication) and two identity elements: $\bar{0}$ for addition and $\bar{1}$ for multiplication. Semirings require that addition is commutative, multiplication distributes over addition, and that multiplication by $\bar{0}$ annihilates, i.e., $\bar{0} \otimes a = a \otimes \bar{0} = \bar{0}$.

- Semirings follow the following generic notation: $\langle \mathbb{K}, \oplus, \otimes, \bar{0}, \bar{1} \rangle$.
- **Max-sum** semiring: $\langle \mathbb{R} \cup \{-\infty\}, \max, +, -\infty, 0 \rangle$
- **Max-product** semiring: $\langle \mathbb{R}_{>0} \cup \{-\infty\}, \max, \times, -\infty, 1 \rangle$

Definition 2 (Weighted finite-state automaton; Peng et al. 2018)

A weighted finite-state automaton over a semiring \mathbb{K} is a 5-tuple $\mathcal{A} = \langle \Sigma, \mathcal{Q}, \Gamma, \lambda, \rho \rangle$, with:

- a finite input alphabet Σ ;
- a finite state set \mathcal{Q} ;
- transition matrix $\Gamma : \mathcal{Q} \times \mathcal{Q} \times (\Sigma \cup \{\epsilon\}) \rightarrow \mathbb{K}$;
- initial vector $\lambda : \mathcal{Q} \rightarrow \mathbb{K}$;
- and final vector $\rho : \mathcal{Q} \rightarrow \mathbb{K}$.

SoPa: Computational graph

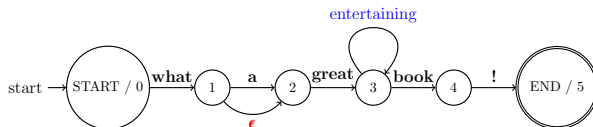


Figure 5: WFA slice: linear-chain FA with self-loop (blue), ϵ (red) and main-path (black) transitions; figure adapted from [Schwartz et al. \(2018\)](#)

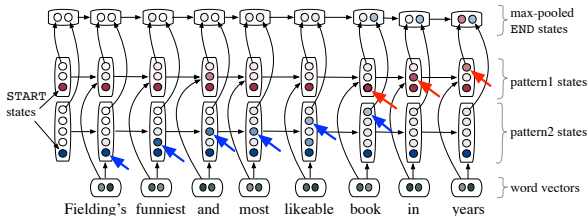


Figure 6: SoPa's partial computational graph; figure taken from [Schwartz et al. \(2018\)](#)

SoPa: Post-hoc explainability techniques

- SoPa provides two post-hoc explainability techniques; namely **local explanations** and **feature relevance**
- Local explanations gather highest scoring phrases across the training data (Figure 7)
- Feature relevance perturbs inputs using an occlusion technique to determine the highest impact phrases for a classification decision (Figure 8)
- Overall, both techniques are **localized** and **indirect**
- WFAs have a rich theoretical background which can be exploited for more direct and globalized explanations

	Highest Scoring Phrases				
Patt. 1	thoughtful and entertaining gentle poignant	, astonishingly , , and	reverent articulate thought-provoking mesmerizing uplifting	portrait cast film portrait story	of of with of in
Patt. 2	's this this a is	€ € € € €	uninspired bad leaden half-assed clumsy ,SL	story on comedy film the	. purpose . . writing

Figure 7: Ranked local explanations from SoPa; table taken from [Schwartz et al. \(2018\)](#)

Analyzed Documents

it 's dumb , but more importantly , it 's just not scary

though moonlight mile is replete with **acclaimed actors and actresses** and tackles a subject that 's **potentially moving** , the movie is *too predictable* and *too self-conscious to reach* a level of **high drama**

While **its careful pace and** seemingly *opaque story* may not satisfy every moviegoer 's appetite, the film 's final scene is **soaringly , transparently moving**

Figure 8: Feature relevance outputs from SoPa; table taken from [Schwartz et al. \(2018\)](#)

Overview

1 Introduction

2 Background concepts

3 Data and methodologies

4 Results

5 Discussion

6 Conclusions

7 Future work

FMTOD: Summary statistics

Class and description	Frequency	Utterance length [†]	Example [‡]
0: alarm/cancel_alarm	1791	5.6 ± 1.9	cancel weekly alarm
1: alarm/modify_alarm	566	7.1 ± 2.5	change alarm time
2: alarm/set_alarm	5416	7.5 ± 2.5	please set the new alarm
3: alarm/show_alarms	914	6.9 ± 2.2	check my alarms.
4: alarm/snooze_alarm	366	6.1 ± 2.1	pause alarm please
5: alarm/time_left_on_alarm	344	8.6 ± 2.1	minutes left on my alarm
6: reminder/cancel_reminder	1060	6.6 ± 2.2	clear all reminders.
7: reminder/set_reminder	5549	8.9 ± 2.5	birthday reminders
8: reminder/show_reminders	773	6.8 ± 2.2	list all reminders
9: weather/check_sunrise	101	6.7 ± 1.7	when is sunrise
10: weather/check_sunset	136	6.7 ± 1.7	when is dusk
11: weather/find	14338	7.8 ± 2.3	jacket needed?
Σ/μ	31354	7.7 ± 2.5	—

[†] Summary statistics follow the mean \pm standard-deviation format

[‡] Short and simple examples were chosen for brevity and formatting purposes

Table 1: Summary statistics and examples for the preprocessed FMTOD data set

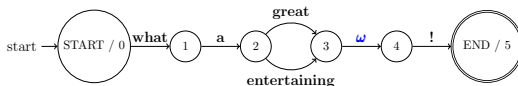
SoPa++: WFA- ω and TauSTE

Figure 9: WFA- ω slice: strict linear-chain FA with ω (blue) and main-path (black) transitions

$$\text{TauSTE}(x) = \begin{cases} 1 & x \in (\tau, +\infty) \\ 0 & x \in (-\infty, \tau] \end{cases}$$

$$\text{TauSTE}'(x) = \begin{cases} 1 & x \in (1, +\infty) \\ x & x \in [-1, 1] \\ -1 & x \in (-\infty, -1) \end{cases}$$

- $\text{TauSTE}'(x)$ implies the backward pass and **not** the gradient in this context
- Flavours of STEs are being extensively researched, such as in [Yin et al. \(2019\)](#)

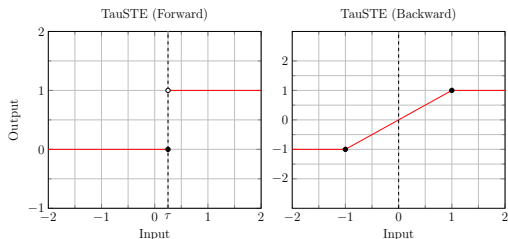


Figure 10: TauSTE's forward and backward passes

SoPa++: Computational graph

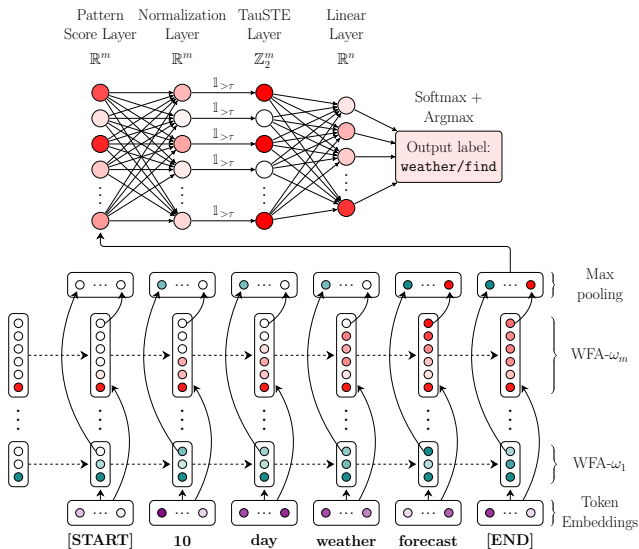


Figure 11: SoPa++ computational graph; flow of graph is from bottom to top and left to right

SoPa++: Regular Expression (RE) proxy

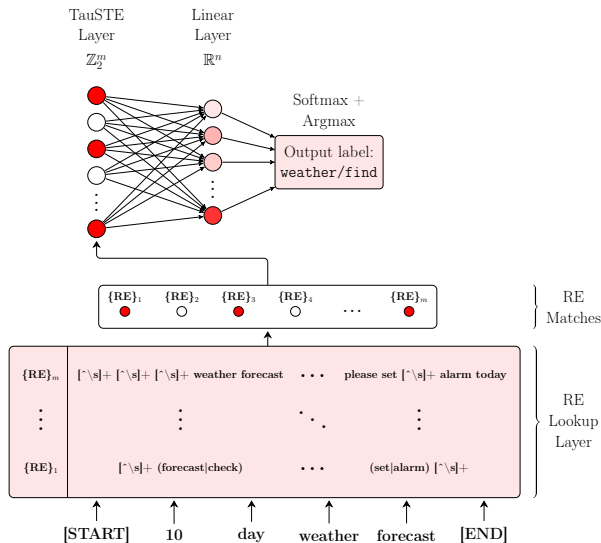


Figure 12: RE proxy computational graph; flow of graph is from bottom to top and left to right

SoPa vs. SoPa++

Characteristic	SoPa	SoPa++
Text casing	True-cased	Lower-cased
Token embeddings	GloVe 840B 300-dimensions	GloVe 6B 300-dimensions
WFAs	Linear-chain WFA's with ϵ , self-loop and main-path transitions	Strict linear-chain WFA- ω 's with ω and main-path transitions
Hidden layers	Multi-layer perceptron after max-pooling	Layer normalization, TauSTE and linear transformation after max-pooling
Post-hoc explainability technique(s)	Local explanations, feature relevance	Explanations by simplification

Table 2: Summarized differences for SoPa vs. SoPa++

Research Question 1: Competitive performance

Model size	Patterns hyperparameter P	Parameter count
Small	6-10_5-10_4-10_3-10	1,260,292
Medium	6-25_5-25_4-25_3-25	1,351,612
Large	6-50_5-50_4-50_3-50	1,503,812

Table 3: Three different SoPa++ model sizes used during training

- RQ 1: Does SoPa++ provide **competitive** performance?
- Competitive accuracy range: **96.6-99.5%** (Schuster et al., 2019; Zhang et al., 2019; Zhang et al., 2020)
- Upsampling minority classes to mitigate data imbalance
- Grid-search with three model sizes, varying τ -thresholds: $\{0.00, 0.25, 0.50, 0.75, 1.00\}$ and 10 random seed iterations
- $3 \times 5 \times 10 = 150$ model runs
- Evaluation and comparison on the test set

Research Question 2: Effective explanations

- RQ 2: To what extent does SoPa++ contribute to **effective** explanations by simplification?
- Effective explanations by simplification require **simpler model**, **similar performance** and **maximizing resemblance** to antecedent
- Similar performance \Rightarrow compare test set evaluations
- Maximum resemblance \Rightarrow minimum distances over test set
- Softmax distance norm:

$$\delta_{\sigma}(\mathbf{y}) = \|\sigma_{\mathcal{S}}(\mathbf{y}) - \sigma_{\mathcal{R}}(\mathbf{y})\|_2 = \sqrt{\sum_{i=1}^n (\sigma_{\mathcal{S}_i}(\mathbf{y}) - \sigma_{\mathcal{R}_i}(\mathbf{y}))^2}$$

- Binary misalignment rate:

$$\delta_b(\mathbf{y}) = \frac{\|\mathbf{b}_{\mathcal{S}}(\mathbf{y}) - \mathbf{b}_{\mathcal{R}}(\mathbf{y})\|_1}{\dim(\mathbf{b}_{\mathcal{S}}(\mathbf{y}) - \mathbf{b}_{\mathcal{R}}(\mathbf{y}))} = \frac{\sum_{i=1}^n |b_{\mathcal{S}_i}(\mathbf{y}) - b_{\mathcal{R}_i}(\mathbf{y})|}{\dim(\mathbf{b}_{\mathcal{S}}(\mathbf{y}) - \mathbf{b}_{\mathcal{R}}(\mathbf{y}))}$$

Research Question 3: Relevant explanations

- RQ 3: What **interesting and relevant** explanations can SoPa++ provide?
- Open-ended question, can answer in different ways
- Capitalize on the new linear layer \Rightarrow allows for direct analysis of relative linear weights
- Sample REs from RE lookup layer corresponding to salient TauSTE neurons
- Analyze REs for interesting linguistic features and inductive biases

Overview

1 Introduction

2 Background concepts

3 Data and methodologies

4 Results

5 Discussion

6 Conclusions

7 Future work

Research Question 1: Competitive performance

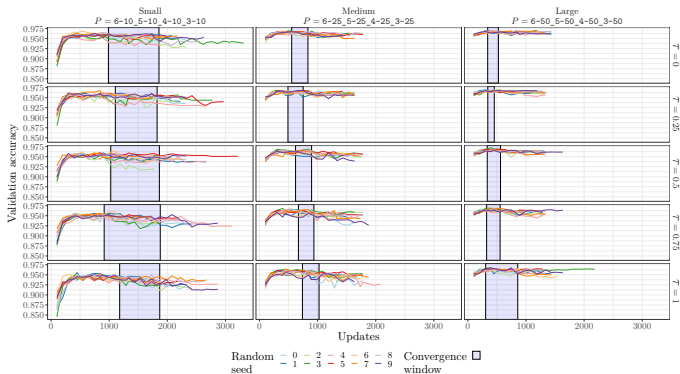


Figure 13: Validation accuracies of SoPa++ models against training updates

Size	Parameters	Accuracy in % with mean \pm standard-deviation				
		$\tau=0.00$	$\tau=0.25$	$\tau=0.50$	$\tau=0.75$	$\tau=1.00$
Small	1,260,292	97.6 \pm 0.2	97.6 \pm 0.2	97.3 \pm 0.2	97.0 \pm 0.3	96.9 \pm 0.3
Medium	1,351,612	98.3 \pm 0.2	98.1 \pm 0.1	98.0 \pm 0.2	97.9 \pm 0.1	97.7 \pm 0.1
Large	1,503,812	98.3 \pm 0.2	98.3 \pm 0.2	98.2 \pm 0.2	98.1 \pm 0.2	98.0 \pm 0.2

Table 4: Test accuracies of SoPa++ models

Research Question 2: Effective explanations

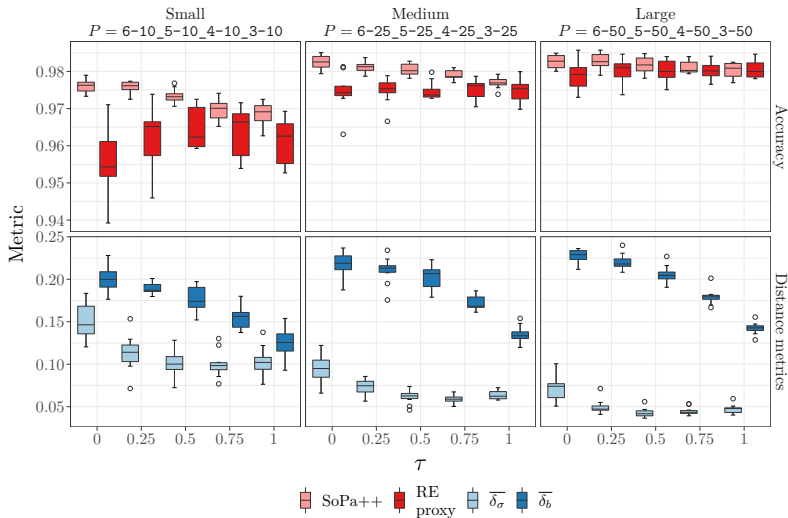


Figure 14: Visualization of model-pair accuracies and distance metrics

Research Question 3: Relevant explanations

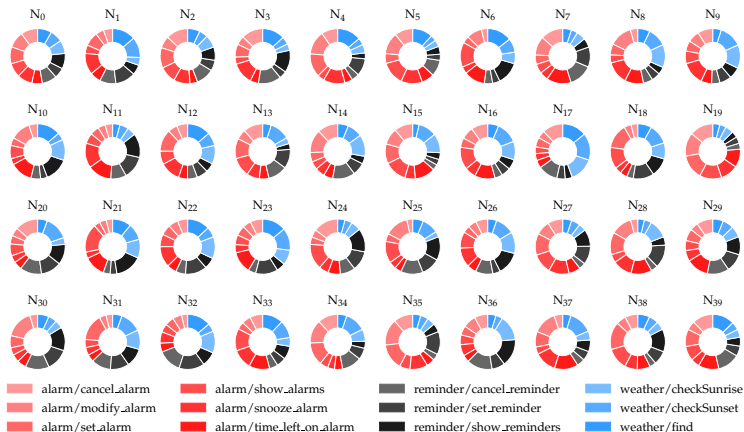


Figure 15: Relative linear layer weights applied to TauSTE neurons for the best performing small RE proxy model with a test accuracy of 97.4%

Research Question 3: Relevant explanations

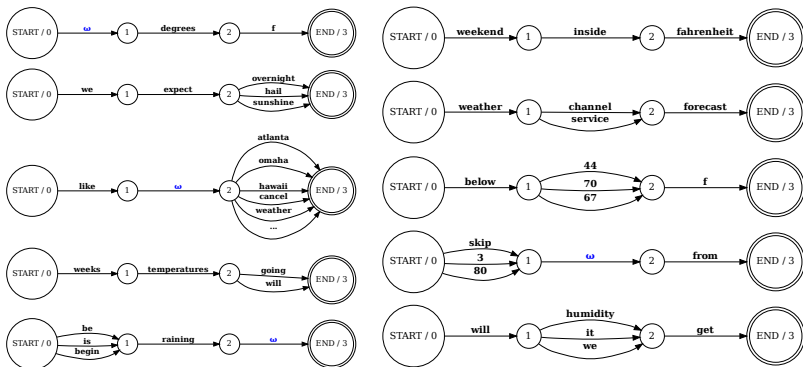


Figure 16: Ten sampled regular expressions from the RE lookup layer corresponding to TauSTE neuron 17 for the best performing small RE proxy model

Overview

1 Introduction

2 Background concepts

3 Data and methodologies

4 Results

5 Discussion

6 Conclusions

7 Future work

Overview

1 Introduction

2 Background concepts

3 Data and methodologies

4 Results

5 Discussion

6 Conclusions

7 Future work

Overview

1 Introduction

2 Background concepts

3 Data and methodologies

4 Results

5 Discussion

6 Conclusions

7 Future work

Bibliography I

Arrieta, Alejandro Barredo, Natalia Díaz-Rodríguez, Javier Del Ser, Adrien Bennetot, Siham Tabik, Alberto Barbado, Salvador García, Sergio Gil-López, Daniel Molina, Richard Benjamins, et al. (2020). “Explainable Artificial Intelligence (XAI): Concepts, taxonomies, opportunities and challenges toward responsible AI”. In: *Information Fusion* 58, pp. 82–115.

Danilevsky, Marina, Kun Qian, Ranit Aharonov, Yannis Katsis, Ban Kawas, and Prithviraj Sen (Dec. 2020). “A Survey of the State of Explainable AI for Natural Language Processing”. In: *Proceedings of the 1st Conference of the Asia-Pacific Chapter of the Association for Computational Linguistics and the 10th International Joint Conference on Natural Language Processing*. Suzhou, China: Association for Computational Linguistics, pp. 447–459. URL: <https://www.aclweb.org/anthology/2020.aacl-main.46>.

Kuich, Werner and Arto Salomaa (1986). “Linear Algebra”. In: *Semirings, automata, languages*. Springer, pp. 5–103.

Peng, Hao, Roy Schwartz, Sam Thomson, and Noah A. Smith (2018). “Rational Recurrences”. In: *Proceedings of the 2018 Conference on Empirical Methods in Natural Language Processing*. Brussels, Belgium: Association for Computational Linguistics, pp. 1203–1214. DOI: 10.18653/v1/D18-1152. URL: <https://www.aclweb.org/anthology/D18-1152>.

Bibliography II

Ribeiro, Marco Tulio, Sameer Singh, and Carlos Guestrin (2016). ““Why Should I Trust You?”: Explaining the Predictions of Any Classifier”. In: *Proceedings of the 22nd ACM SIGKDD International Conference on Knowledge Discovery and Data Mining, San Francisco, CA, USA, August 13-17, 2016*, pp. 1135–1144.

Sanh, Victor, Lysandre Debut, Julien Chaumond, and Thomas Wolf (2019). “DistilBERT, a distilled version of BERT: smaller, faster, cheaper and lighter”. In: *NeurIPS EMC² Workshop*.

Schuster, Sebastian, Sonal Gupta, Rushin Shah, and Mike Lewis (June 2019). “Cross-lingual Transfer Learning for Multilingual Task Oriented Dialog”. In: *Proceedings of the 2019 Conference of the North American Chapter of the Association for Computational Linguistics: Human Language Technologies, Volume 1 (Long and Short Papers)*. Minneapolis, Minnesota: Association for Computational Linguistics, pp. 3795–3805. DOI: 10.18653/v1/N19-1380. URL: <https://www.aclweb.org/anthology/N19-1380>.

Schwartz, Roy, Sam Thomson, and Noah A. Smith (July 2018). “Bridging CNNs, RNNs, and Weighted Finite-State Machines”. In: *Proceedings of the 56th Annual Meeting of the Association for Computational Linguistics (Volume 1: Long Papers)*. Melbourne, Australia: Association for Computational Linguistics, pp. 295–305. DOI: 10.18653/v1/P18-1028. URL: <https://www.aclweb.org/anthology/P18-1028>.

Bibliography III

Yin, Penghang, Jiancheng Lyu, Shuai Zhang, Stanley J. Osher, Yingyong Qi, and Jack Xin (2019). “Understanding Straight-Through Estimator in Training Activation Quantized Neural Nets”. In: *International Conference on Learning Representations*. URL: <https://openreview.net/forum?id=Skh4jRcKQ>.

Zhang, Li, Qing Lyu, and Chris Callison-Burch (Dec. 2020). “Intent Detection with WikiHow”. In: *Proceedings of the 1st Conference of the Asia-Pacific Chapter of the Association for Computational Linguistics and the 10th International Joint Conference on Natural Language Processing*. Suzhou, China: Association for Computational Linguistics, pp. 328–333. URL: <https://www.aclweb.org/anthology/2020.aacl-main.35>.

Zhang, Zhichang, Zhenwen Zhang, Haoyuan Chen, and Zhiman Zhang (2019). “A joint learning framework with bert for spoken language understanding”. In: *IEEE Access* 7, pp. 168849–168858.