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

M.Sc. Thesis Defense

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Introduction   Background concepts   Data and methodologies   Results   Discussion   Conclusions   Further work   Bibliography
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Overview

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 **So**ft **Pa**tterns (SoPa; Figure 2)

- SoPa provides **localized** and **indirect** explainability despite being suited for globalized and direct **explanations by simplification**
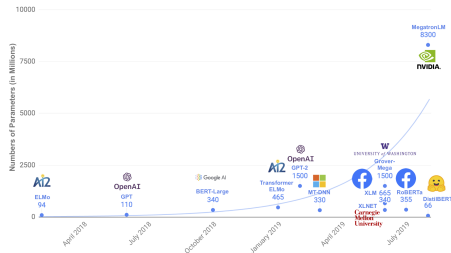

Figure 1: Parameter counts of recently released pre-trained language models; figure taken from Sanh et al. (2019)

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

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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?

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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**
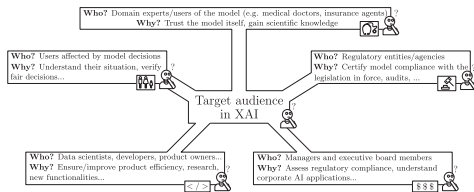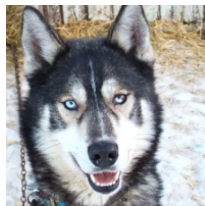

Figure 3: Examples of various target audiences in XAI; figure taken from Arrieta et al. (2020)

(a) Husky classified as wolf   (b) Explanation

Figure 4: Local explanation for "Wolf" classification decision, figure taken from Ribeiro et al. (2016)

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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 $\Gamma : \mathcal{Q} \times \mathcal{Q} \times (\Sigma \cup \{\epsilon\}) \to \mathbb{K}$;
– initial vector $\lambda : \mathcal{Q} \to \mathbb{K}$;
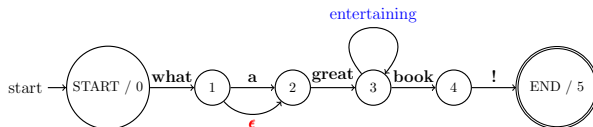– and final vector $\rho : \mathcal{Q} \to \mathbb{K}$.

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)
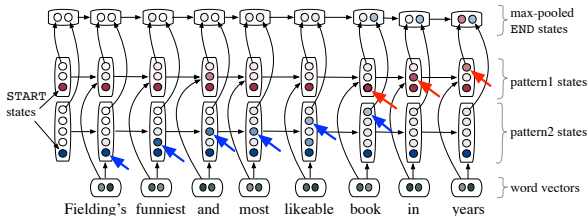

Figure 6: SoPa's partial computational graph; figure taken from Schwartz et al. (2018)

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

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

Analyzed Documents

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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)

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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 ± standard-deviation format

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

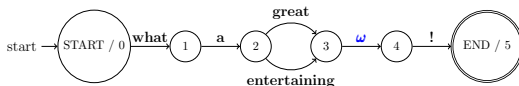**Table 1:** Summary statistics and examples for the preprocessed FMTOD data set

SoPa++: WFA-ω and TauSTE

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

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

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

- TauSTE$'(x)$ implies the backward pass and **not** the gradient in this context
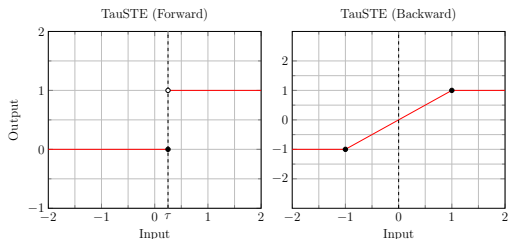- Flavors of STEs are being extensively researched, such as in Yin et al. (2019)

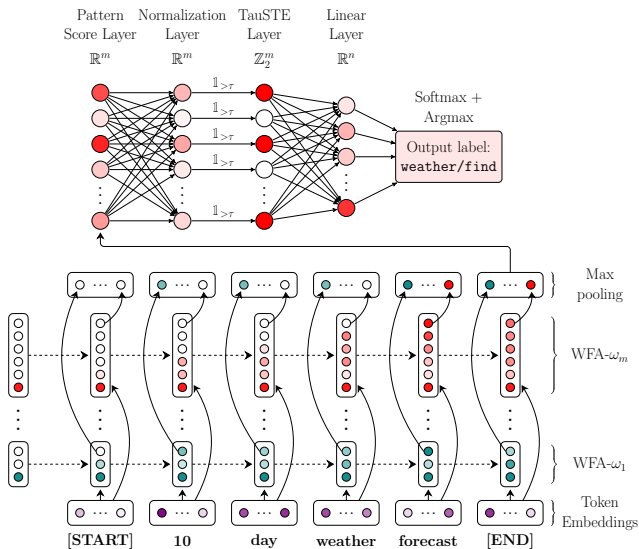**Figure 10:** TauSTE's forward and backward passes

SoPa++: Computational graph

Figure 11: SoPa++ computational graph; flow of graph is from bottom to top and left to right
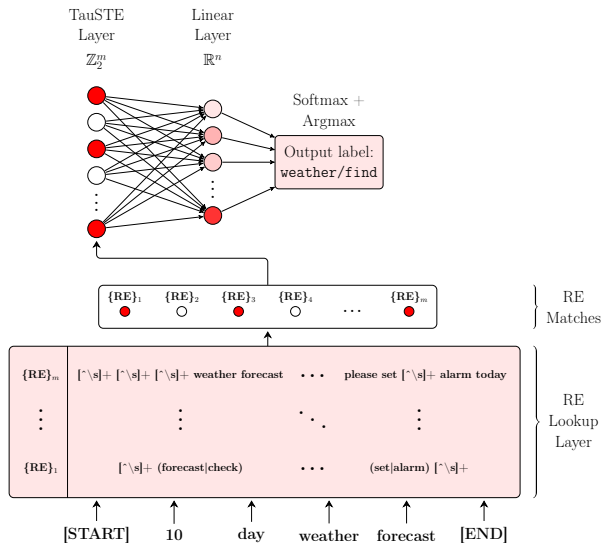
SoPa++: Regular Expression (RE) proxy

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:

$$\delta_\sigma(\boldsymbol{y}) = \|\boldsymbol{\sigma_S}(\boldsymbol{y}) - \boldsymbol{\sigma_R}(\boldsymbol{y})\|_2 = \sqrt{\sum_{i=1}^{n}(\sigma_{S_i}(\boldsymbol{y}) - \sigma_{R_i}(\boldsymbol{y}))^2}$$

- Binary -misalignment rate:

$$\delta_b(\boldsymbol{y}) = \frac{\|\boldsymbol{b_S}(\boldsymbol{y}) - \boldsymbol{b_R}(\boldsymbol{y})\|_1}{dim(\boldsymbol{b_S}(\boldsymbol{y}) - \boldsymbol{b_R}(\boldsymbol{y}))} = \frac{\sum_{i=1}^{n}|b_{S_i}(\boldsymbol{y}) - b_{R_i}(\boldsymbol{y})|}{dim(\boldsymbol{b_S}(\boldsymbol{y}) - \boldsymbol{b_R}(\boldsymbol{y}))}$$

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
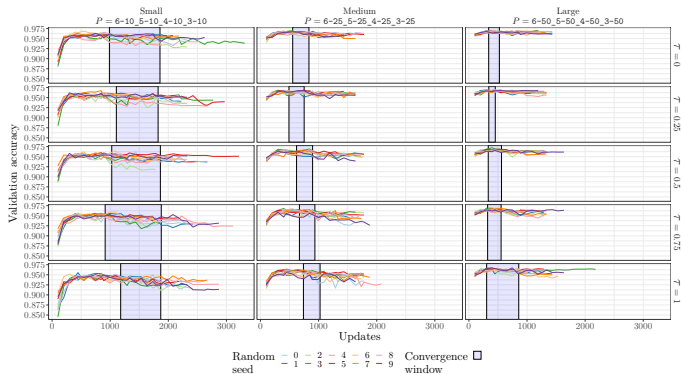
Research Question 1: Competitive performance

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

		Accuracy in % with mean $\pm$ standard-deviation				
Size	Parameters	$\tau=0.00$	$\tau=0.25$	$\tau=0.50$	$\tau=0.75$	$\tau=1.00$
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
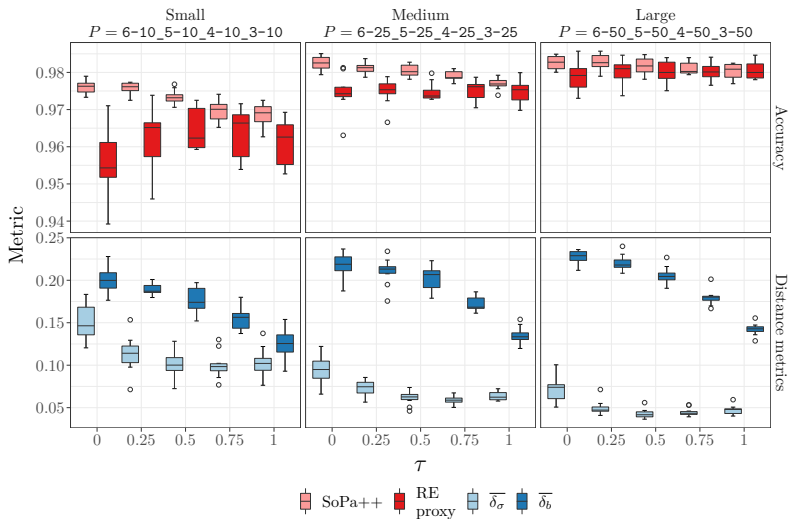

Figure 14: Visualization of model-pair accuracies and distance metrics

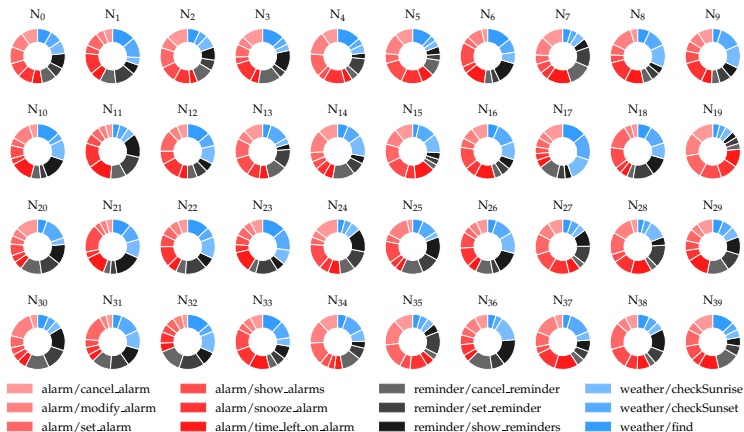# Research Question 3: Relevant explanations

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%

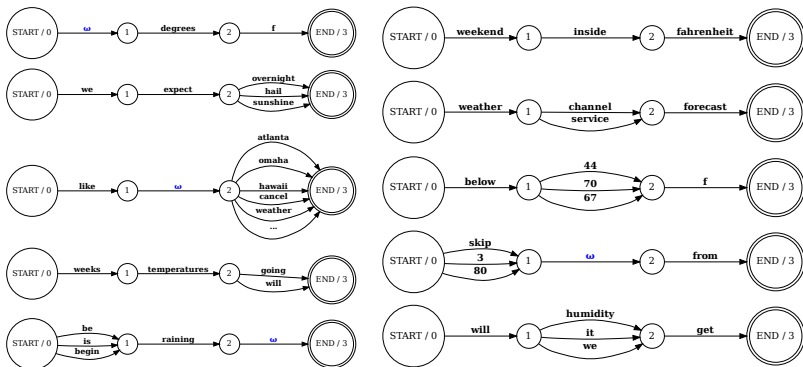## Research Question 3: Relevant explanations

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

Research Question 1: Competitive performance

Overview:

- 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)

- Observed best accuracy range for $\tau = 0.00$: **$97.6 - 98.3$**%

- SoPa++ offers **competitive** performance on FMTOD's English language intent detection task

Discussion:

- Other studies worked with true-cased text

- Observed performance is in the middle of competitive range

- Worth noting the sizes of competitive BERT-derived models with external data

Research Question 2: Effective explanations

Overview:

- 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

- **Effective** to the extent of: lowest accuracy differences ranging from **0.1 − 0.7%** and softmax distance norms ranging from **4.3 − 10.0%**

- Most effective for medium-large sized models with $\tau \in [0.50, 1.00]$

Discussion:

- No benchmark for effective explanations by simplification

- RE proxy may not necessarily always be transparent given size of RE lookup layer

- Target audience was omitted in this analysis

Research Question 3: Relevant explanations

Overview:

- RQ 3: What **interesting and relevant** explanations can SoPa++ provide?

- Similar lexical properties in branches

- USA-centric inductive biases

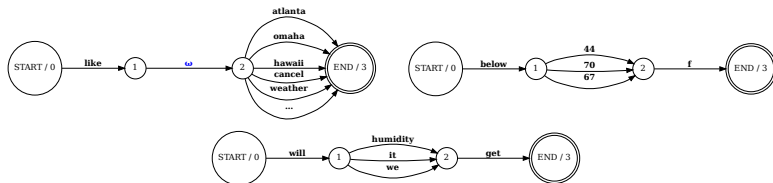- Pronoun-level inductive biases

Discussion:

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

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Conclusions

Objective:

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

Research questions:

1. Does SoPa++ provide **competitive** performance?
   - Best accuracy range: **97.6 − 98.3**% √

2. To what extent does SoPa++ contribute to **effective** explanations by simplification?
   - Lowest accuracy differences ranging from **0.1 − 0.7**% and softmax distance norms ranging from **4.3 − 10.0**% √
   - Target audience analysis omitted ✗

3. What **interesting and relevant** explanations can SoPa++ provide?
   - Regular expression samples from salient TauSTE neurons analyzed √
   - Linguistic features and inductive biases √
   - Small sample size ✗

Overview

Further work

Explainability:

- Are SoPa++'s explanations **useful** for its target audience?

Bias correction:

- Manual bias corrections through large-scale analysis of RE lookup layer
- Mitigate **ethical** issues of using black-box models?

Generalization:

- Possible to generalize branches with broad categories like locations and numbers
- For example, replace digital tokens with `\-?[\d]+\.?[\d]*`
- **Robustness** on unseen data?

Efficiency:

- **Parallelize** RE lookup layer
- Utilize GPU-based regular expression matching algorithms (**yu2013gpui**; Wang et al., 2011; Zu et al., 2012)

Thank you for your time and attention $\heartsuit$

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