

Some Extensions of Neural Machine Translation for Auto-formalization of Mathematics

Qingxiang Wang, Cezary Kaliszyk, Josef Urban

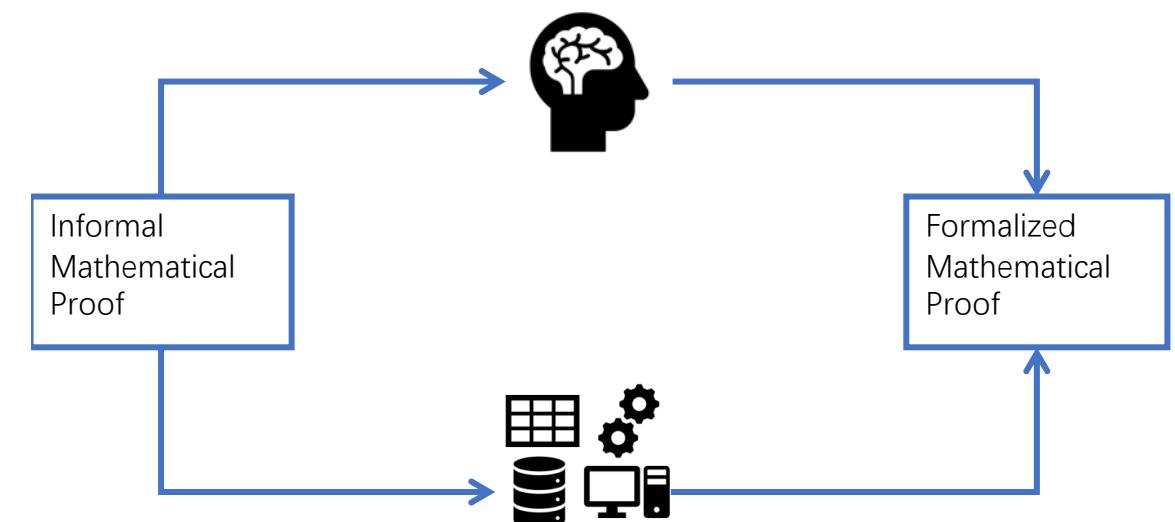
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Overview

- Auto-Formalization with Deep Learning
- Universal Approximation
- Supervised NMT (Luong et al.)
- Unsupervised NMT (Lample et al.)
- NMT with Type Elaboration
- Summary

Auto-Formalization with Deep Learning



Universal Approximation

Theorem 2. *Let σ be any continuous sigmoidal function. Then finite sums of the form*

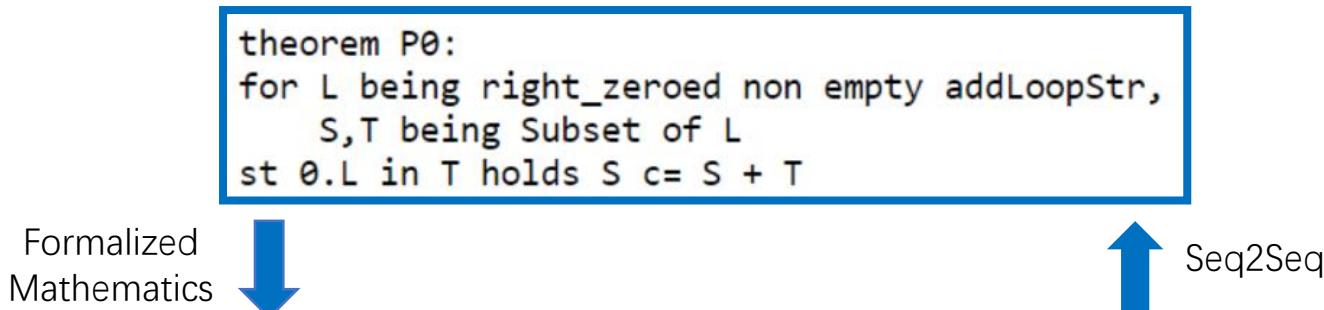
$$G(x) = \sum_{j=1}^N \alpha_j \sigma(y_j^T x + \theta_j)$$

are dense in $C(I_n)$. In other words, given any $f \in C(I_n)$ and $\varepsilon > 0$, there is a sum, $G(x)$, of the above form, for which

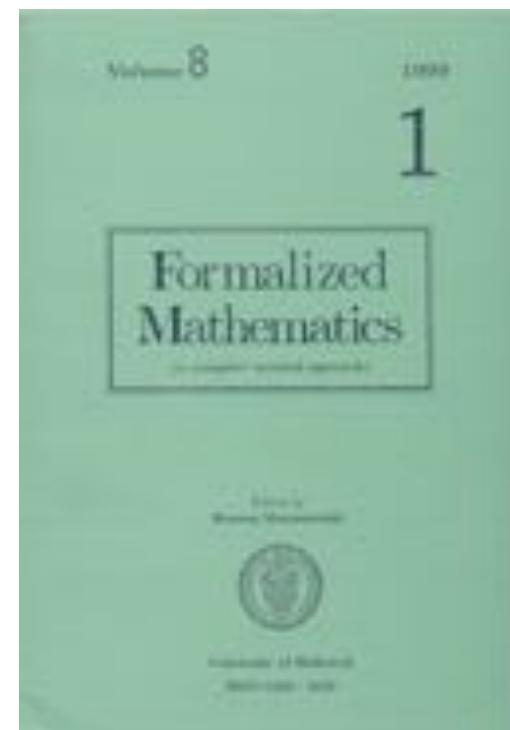
$$|G(x) - f(x)| < \varepsilon \quad \text{for all } x \in I_n.$$

Supervised NMT (Luong et al.)

- Default: two-layer LSTM with attention.
- Lots of configurable hyper-parameters:
(Attention, Layers, Unit Size, Unit Type, Residual, Encoding, Optimizers, etc)
- Formal abstracts of *Formalized mathematics*, which are generated latex from Mizar (v8.0.01_5.6.1169)
- 1,056,478 pairs of Latex– Mizar sentences in 90:10.



- (1) Let us consider a right zeroed, non empty additive loop structure L , and subsets S, T of L . If $0_L \in T$, then $S \subseteq S + T$.

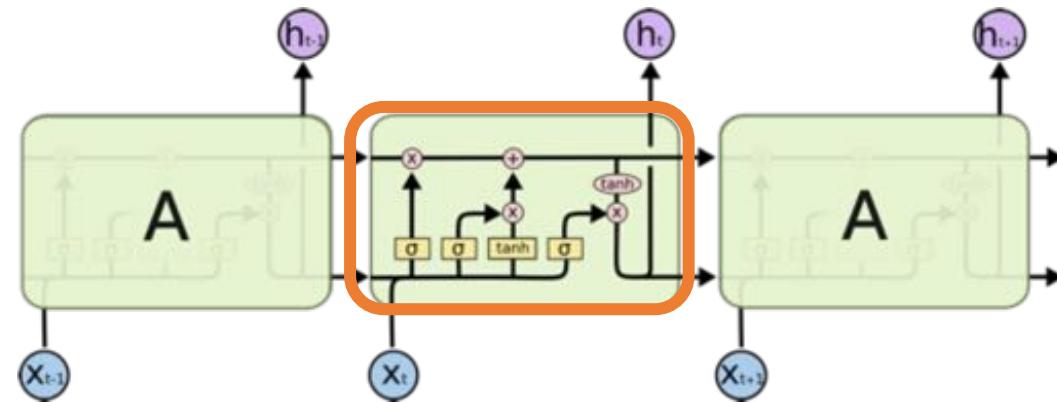


Supervised NMT (Luong et al.)

Latex	If \$ X \mathrel{=} \text{\rm the } \sim \{ \{ \{ \text{\rm carrier} \} \sim \{ \text{\rm of} \} \sim \{ \text{\rm } \} \} \{ A_9 \} \$ and \$ X \$ is plane , then \$ \{ A_9 \} \$ is an affine plane .
Mizar	X = the carrier of AS & X is being_plane implies AS is AffinPlane ;
Latex	If \$ \{ s_9 \} \$ is convergent and \$ \{ s_8 \} \$ is a subsequence of \$ \{ s_9 \} \$, then \$ \{ s_8 \} \$ is convergent .
Mizar	seq is convergent & seq1 is subsequence of seq implies seq1 is convergent ;

Supervised NMT (Luong et al.)

- Memory-cell unit types

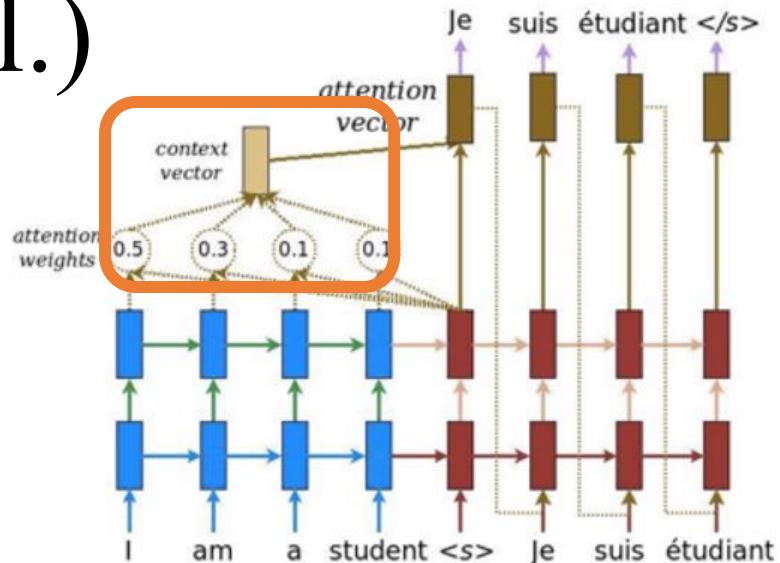


Parameter	Final Test	Final Test	Identical	Identical
	Perplexity	BLEU	Statements (%)	No-overlap (%)
LSTM	3.06	41.1	40121 (38.12%)	6458 (13.43%)
GRU	3.39	34.7	37758 (35.88%)	5566 (11.57%)
Layer-norm LSTM	11.35	0.4	11200 (10.64%)	1 (0%)

Table 5. Evaluation on type of memory cell (attention not enabled)

Supervised NMT (Luong et al.)

- Attention

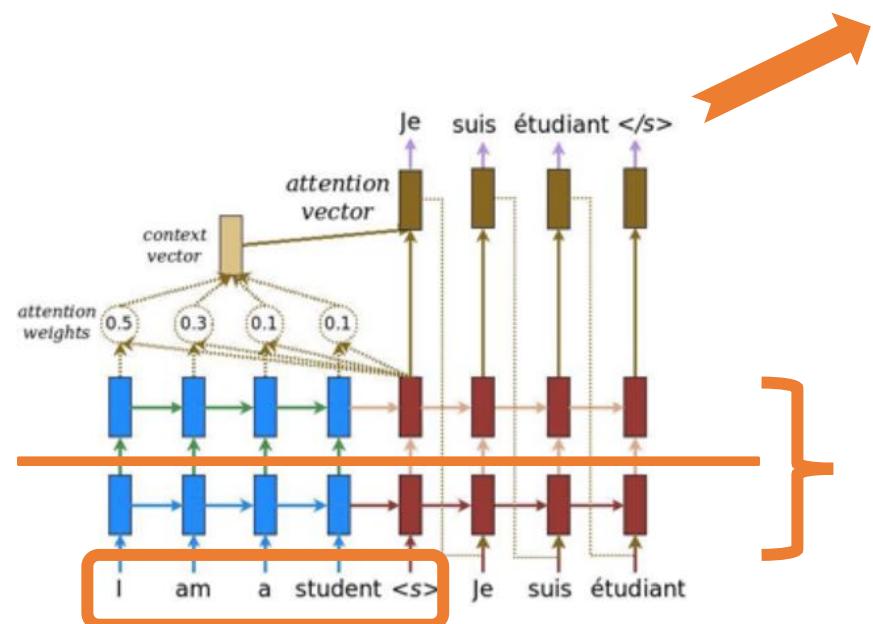


Parameter	Final Test	Final Test	Identical	Identical
	Perplexity	BLEU	Statements (%)	No-overlap (%)
No Attention	3.06	41.1	40121 (38.12%)	6458 (13.43%)
Bahdanau	3	40.9	44218 (42.01%)	8440 (17.55%)
Normed Bahdanau	1.92	63.5	60192 (57.19%)	18057 (37.54%)
Luong	1.89	64.8	60151 (57.15%)	18013 (37.45%)
Scaled Luong	2.13	65	60703 (57.68%)	18105 (37.64%)

Table 6. Evaluation on type of attention mechanism (LSTM cell)

Supervised NMT

- Residuals, layers, etc.

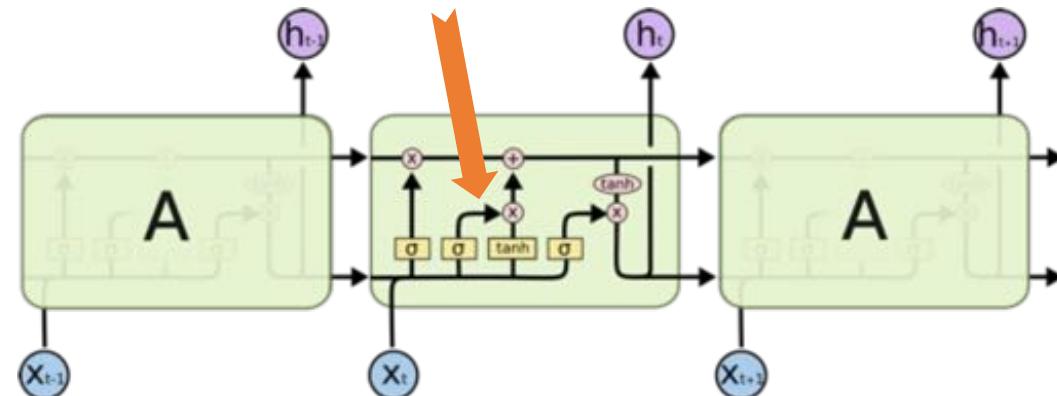


Parameter	Final Test Perplexity	Final Test BLEU	Identical Statements (%)	Identical No-overlap (%)
2-Layer	3.06	41.1	40121 (38.12%)	6458 (13.43%)
3-Layer	2.10	64.2	57413 (54.55%)	16318 (33.92%)
4-Layer	2.39	45.2	49548 (47.08%)	11939 (24.82%)
5-Layer	5.92	12.8	29207 (27.75%)	2698 (5.61%)
6-Layer	4.96	20.5	29361 (27.9%)	2872 (5.97%)
2-Layer Residual	1.92	54.2	57843 (54.96%)	16511 (34.32%)
3-Layer Residual	1.94	62.6	59204 (56.25%)	17396 (36.16%)
4-Layer Residual	1.85	56.1	59773 (56.79%)	17626 (36.64%)
5-Layer Residual	2.01	63.1	59259 (56.30%)	17327 (36.02%)
6-Layer Residual	NaN	0	0 (0%)	0 (0%)
2-Layer Adam	1.78	56.6	61524 (58.46%)	18635 (38.74%)
3-Layer Adam	1.91	60.8	59005 (56.06%)	17213 (35.78%)
4-Layer Adam	1.99	51.8	57479 (54.61%)	16288 (33.86%)
5-Layer Adam	2.16	54.3	54670 (51.94%)	14769 (30.70%)
6-Layer Adam	2.82	37.4	46555 (44.23%)	10196 (21.20%)
2-Layer Adam Res.	1.75	56.1	63242 (60.09%)	19716 (40.97%)
3-Layer Adam Res.	1.70	55.4	64512 (61.30%)	20534 (42.69%)
4-Layer Adam Res.	1.68	57.8	64399 (61.19%)	20353 (42.31%)
5-Layer Adam Res.	1.65	64.3	64722 (61.50%)	20627 (42.88%)
6-Layer Adam Res.	1.66	59.7	65143 (61.90%)	20854 (43.35%)
2-Layer Bidirectional	2.39	69.5	63075 (59.93%)	19553 (40.65%)
4-Layer Bidirectional	6.03	63.4	58603 (55.68%)	17222 (35.80%)
6-Layer Bidirectional	2	56.3	57896 (55.01%)	16817 (34.96%)
2-Layer Adam Bi.	1.84	56.9	64918 (61.68%)	20830 (43.30%)
4-Layer Adam Bi.	1.94	58.4	64054 (60.86%)	20310 (42.22%)
6-Layer Adam Bi.	2.15	55.4	60616 (57.59%)	18196 (37.83%)
2-Layer Bi. Res.	2.38	24.1	47531 (45.16%)	11282 (23.45%)
4-Layer Bi. Res.	NaN	0	0 (0%)	0 (0%)
6-Layer Bi. Res.	NaN	0	0 (0%)	0 (0%)
2-Layer Adam Bi. Res.	1.67	62.2	65944 (62.66%)	21342 (44.37%)
4-Layer Adam Bi. Res.	1.62	66.5	65992 (62.70%)	21366 (44.42%)
6-Layer Adam Bi. Res.	1.63	58.3	66237 (62.93%)	21404 (44.50%)

Table 7. Evaluation on various hyperparameters w.r.t. layers

Supervised NMT (Luong et al.)

- Unit dimension in cell



Parameter	Final Test Perplexity	Final Test BLEU	Identical Statements (%)	Identical No-overlap (%)	Training Time (hrs.)
128 Units	3.06	41.1	40121 (38.12%)	6458 (13.43%)	1
256 Units	1.59	64.2	63433 (60.27%)	19685 (40.92%)	3
512 Units	1.6	67.9	66361 (63.05%)	21506 (44.71%)	5
1024 Units	1.51	61.6	69179 (65.73%)	22978 (47.77%)	11
2048 Units	2.02	60	59637 (56.66%)	16284 (33.85%)	31

Table 8. Evaluation on number of units

Supervised NMT (Luong et al.)

	Identical Statements	0	≤ 1	≤ 2	≤ 3
Best Model - 1024 Units	69179 (total) 22978 (no-overlap)	65.73% 47.77%	74.58% 59.91%	86.07% 70.26%	88.73% 74.33%
Top-5 Greedy Cover - 1024 Units - 4-Layer Bi. Res. - 512 Units - 6-Layer Adam Bi. Res. - 2048 Units	78411 (total) 28708 (no-overlap)	74.50% 59.68%	82.07% 70.85%	87.27% 78.84%	89.06% 81.76%
Top-10 Greedy Cover - 1024 Units - 4-Layer Bi. Res. - 512 Units - 6-Layer Adam Bi. Res. - 2048 Units - 2-Layer Adam Bi. Res. - 256 Units - 5-Layer Adam Res. - 6-Layer Adam Res. - 2-Layer Bi. Res.	80922 (total) 30426 (no-overlap)	76.89% 63.25%	83.91% 73.74%	88.60% 81.07%	90.24% 83.68%
Union of All 39 Models	83321 (total) 32083 (no-overlap)	79.17% 66.70%	85.57% 76.39%	89.73% 82.88%	91.25% 85.30%

Table 9. Coverage w.r.t. a set of models and edit distances

- But generates gibberish when we tried arbitrary LaTeX statements on the trained model... ☹

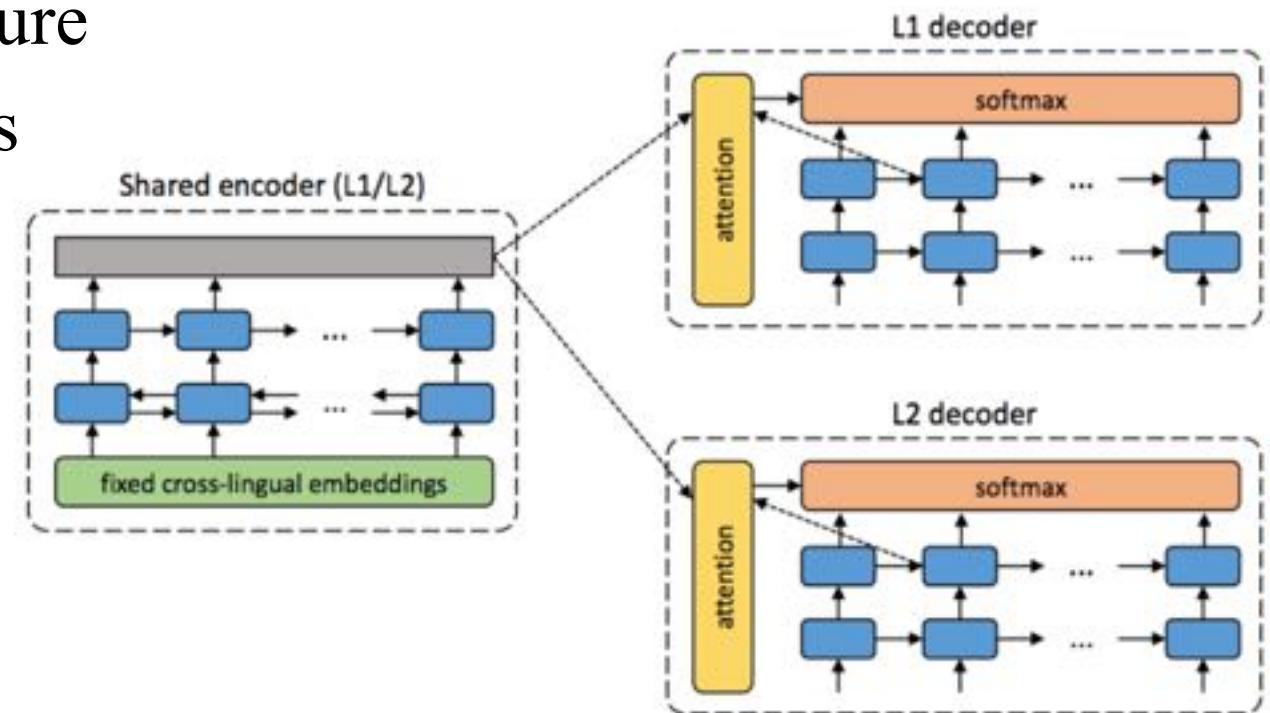
Supervised NMT (Luong et al.)

```
#/gibberish.txt
1 let S T S be the Arens-Port space ;
2 from [ ] [ ] Arens-Port Space is not locally connected [ ] , S T S is not a locally connected space
3 the result follows from [ ] [ ] Components and Quasicomponents of Arens-Port Space are equal [ ] ;
4 qed ;
5 let S M_<=3 = Metric C (A_<=3 , d_<=3) >right 3 S and S M_>=3 = Metric C (A_>=3 , d_>=3) >right 3 S be metric spaces ;
6 let S F : A_<=3 topo A_>=3 S be a mapping from S A_<=3 to S A_>=3 S ;
7 this is proved in [ ] [ ] Metric Space Continuity by Epsilon-Delta [ ] ;
8 qed I lemma ;
9 this is proved in [ ] [ ] Metric Space Continuity by Open Ball [ ] ;
10 qed ;
11 this is proved in [ ] [ ] Metric Space Continuity by Neighborhood [ ] ;
12 qed ;
13 let S G S and S H S be topological groups ;
14 let S f : G topo H S be a morphism ;
15 let (s, image) [ ] S hypercontinuous [ in ] Metric C (f) >right 3 S be [ ] [ ] definition : Hausdorff S
pose 1 Hausdorff ;
16 then its kernel [ ] S New Metric C (f) >right 3 S is [ ] [ ] definition : Closed Set C Topology S
closed in S G S ;
17 by [ ] [ ] image of Group Homomorphism is Subgroup [ ] , S New Metric C (f) >right 3 S
is closed in S hypercontinuous [ in ] Metric C (f) >right 3 S ;
18 because S f S is continuous [ ] , S New Metric C (f) >right 3 S = f >= S >= S New Metric C (f) >right 3 S
is [ ] [ ] definition : Closed Set C Topology S closed in S G S ;
19 qed ;
20 let S K = Metric C (A_<=3 , d_<=3) >right 3 S be a standard discrete metric space ;
21 let S L be a subset of S K S ;
22 then S L S is an open set of S K S ;
23 from the definition of standard discrete metric S NewMetric x , y in A_<=3 Metric C (x , y) >right 3 S = Meager [ cases ] ;
24 S x = y or y = x ;
25 S x = y or y = x ;
26 S x = y or y = x ;
27 NewMetric x , y ;
28 let S NeqSet M_<=3 M_>=3 S be such that S x = NeqSet M_<=3 M_>=3 S ;
29 let S x = M_<=3 S ;
30 let S y = M_>=3 S ;
31 NewMetric C (x) >right 3 S is the open S NeqSet M_<=3 M_>=3 S of S x S ;
32 then by definition of S NeqSet M_<=3 M_>=3 S and S x S y = NewMetric C (x) >right 3 S = Metric S [ in ]
x > right 3 S ;
33 thus S NewMetric x , y in S x S y = M_<=3 M_>=3 S is NeqSet M_<=3 M_>=3 S ;
34 hence the result by definition of open set ;
35 qed ;
36 let S T = Metric C (E_3 , New) >right 3 S be an injective topological space ;
37 let S R = Metric C (E_3 , New) >right 3 S be a retract of S T S ;
38 then S R S is injective ;
39 by definition of retract there exists a continuous [ ] [ ] definition : Retraction C Topology S
retraction S r : S New E_3 of S T S ;
40 the_subsets_of_3 S C the_subsets_of_3 S C pos 3 , signs 6 2 is Retraction
41 the_subsets_of_3 S C the_subsets_of_3 S C pos 3 , signs 6 2 is beingHomeomorphism
42 func Toler ;
43 as S is locallyDirected OrderableSgn is not non-constituted-PlusBis non-empty dualAcceptor
for V be ReSequence of the_subsets_of_3 S C the_subsets_of_3 S C pos 3 is not the_subsets_of_
3 S C pos 3 is closedUnderLines for F be Function ex F be Function st F = F ;
44 let T be DAFFIndexSeq ;
45 the_subsets_of_3 S C the_subsets_of_3 S C pos 3 , T 3 is non CI TopSpace
46 func the_subsets_of_3 S C pos 3 , Stereomk_Space => the_subsets_of_3 S ;
47 func Toler ;
48 let M V : S S , K , H be non-empty set , A be Subset of TOP-REAL 2 st H = C with CA , dH 3 S
= for a , b be Real st a in Q & b
49 let f : A A be function of A , A ;
50 let a be Point of A ;
51 alignedMeet is terminating ;
52 func L : S S => Element of S ;
53 alignedMeet is terminating ;
54 func Toler ;
55 alignedMeet is terminating ;
56 func Toler ;
57 let G , H be TopSpace ;
58 let f : G H be homeo ;
59 c240 : for f be function st (f = g) is the_subsets_of_3 S for F be Function of the_subsets_of_
3 S C pos 3 , H = C with CA , dH 3 S , F be Function of the_subsets_of_3 S C pos 3 , F = H ;
60 for F being function st (f = F) is the_subsets_of_3 S holds if (x in G ;
61 [ ] the_subsets_of_3 S C pos 3 is Group holds (S) is group
62 let e be vertex of S ;
63 the_subsets_of_3 S C the_subsets_of_3 S C pos 3 a = jpt S a = b is closedUnderLines & a =
b is closedUnderLines of S of X ;
64 f continuous if in C F 1+3 + S & C F 1+3 + S = (the_subsets_of_3 S C pos 3 ) + C S
= f 3 S 1 ;
65 func Toler ;
66 let H be standard d of S , L ;
67 let S be A of S ;
68 S is open set , S is open set holds S is open set holds S is open of H ;
69 func sth x , y in A & A = A , C x , y 3 = x ;
70 x = y ;
71 x = y ;
72 assume Toler : x = y & x = x & x = x & x = x & x = x & x = x & x = x ;
73 let X be cardinal number st # = INT C S 3 ;
74 let x be element ;
75 let S Tmn C x , d S be open-neighbor of x ;
76 for x , d being Element of signs 3 , d , d being Element of Permutations 3 st d in S & d "Tm" is
x , x & d = x , d & d = d ;
77 x = y in S implies S CVD C X , x 3 = x & x
78 func the carrier' of S set ;
79 func Toler ;
80 let T be injective box for S be injective TopSpace ;
81 S = S , {Z} , dH 3 S ;
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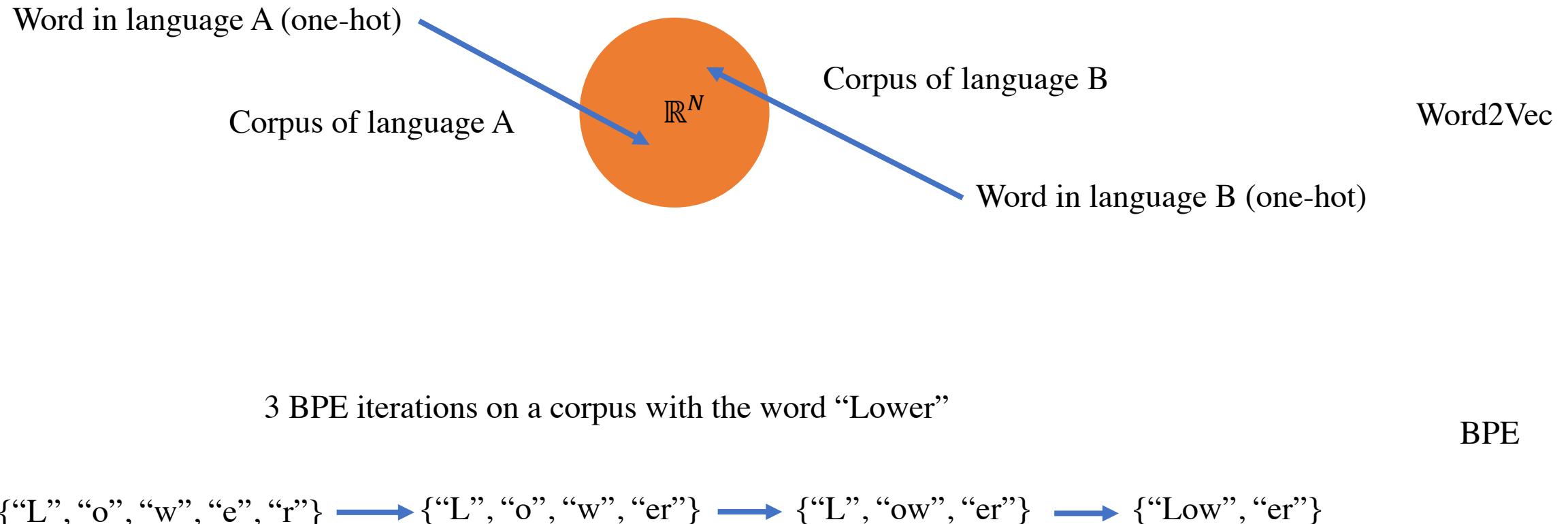
- Demo

Unsupervised NMT (Lample et al.)

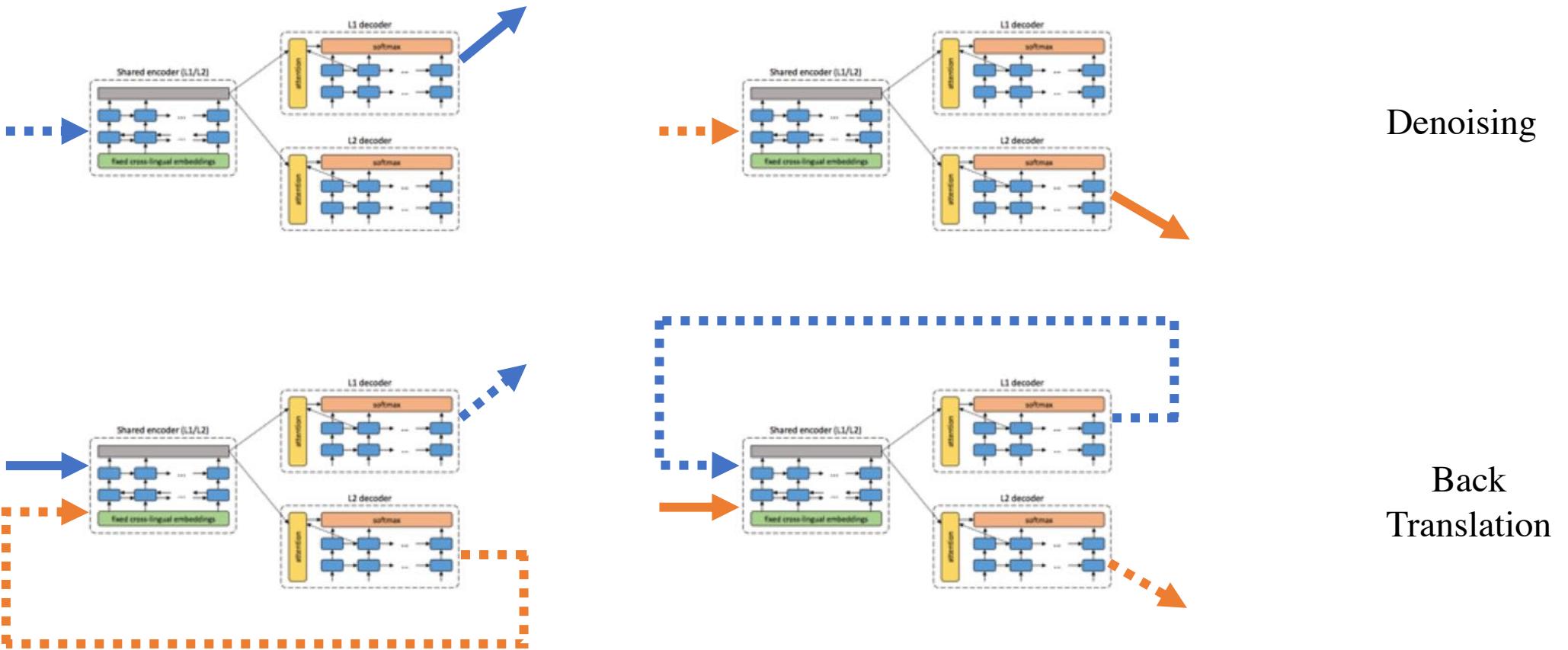
- Two monolingual corpora instead of one parallel corpora (ProofWiki - Mizar)
- Shared-encoder NMT architecture
- Fixed cross-lingual embeddings
 - Word2Vec
 - BPE (Byte Pair Encoding)
- Denoising and backtranslation



Unsupervised NMT (Lample et al.)



Unsupervised NMT (Lample et al.)



- Generating gibberish on our data... 😞

Unsupervised NMT (Lample et al.)

1 Let S Meff. $C \subseteq S \cup$ Speciale. \exists right. S be a preordered set. .
2 Let S H. S be a nonempty subset of $S \cup S$. .
3 Then S H. S is directed (iff \exists S H A Speciale. S is directed , where S H A Speciale. S denotes the lower closure of set .).
4 Let us assume that S H. S is directed .
5 Let S x , y. \exists m. S A Speciale. S .
6 By definition of lower closure S Speciale. $x \in$ Min. $S \subseteq$ Speciale. $x \in$ S and S Speciale. $y \in$ Min. $S \subseteq$ Speciale. $y \in$ S.
7 By definition of directed subset S Speciale. x Min. $S \subseteq$ A Speciale. x Min. y A Speciale. $y \in$ S.
8 By definition of reflexivity S A Speciale. $x \in$ S.
9 By definition of lower closure S A Min. S A Speciale. S .
10 Thus by definition of transitivity S Speciale. x Min. S A Speciale. x A Speciale. x Min. y A Speciale. $y \in$ S.
11 Thus by definition S H A Speciale. S is directed .
12 (end 1 lemma)
13 Let us assume that S H. A Speciale. S is directed .
14 Let S x , y. \exists m. S .
15 By definition of reflexivity S A Speciale. $x \in$ Min. y A Speciale. $y \in$ S.
16 By definition of lower closure S x , y. \exists m. S A Speciale. S .
17 By definition of directed subset S Speciale. x Min. $S \subseteq$ A Speciale. x A Speciale. x Min. y A Speciale. $y \in$ S.
18 By definition of lower closure S Speciale. $x \in$ Min. $S \subseteq$ A Speciale. $x \in$ S.
19 Thus by definition of transitivity S Speciale. x Min. $S \subseteq$ A Speciale. $x \in$ Min. y A Speciale. $y \in$ S.
20 Thus by definition S H. S is directed .
21 (end)

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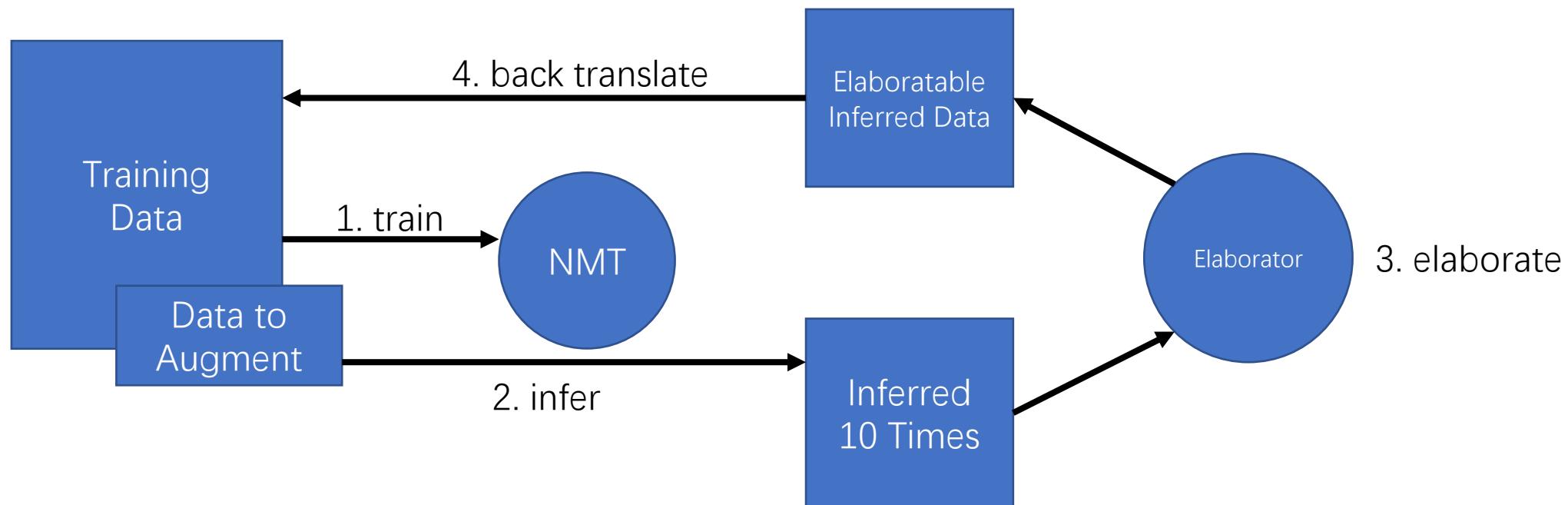
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NMT with Type Elaboration

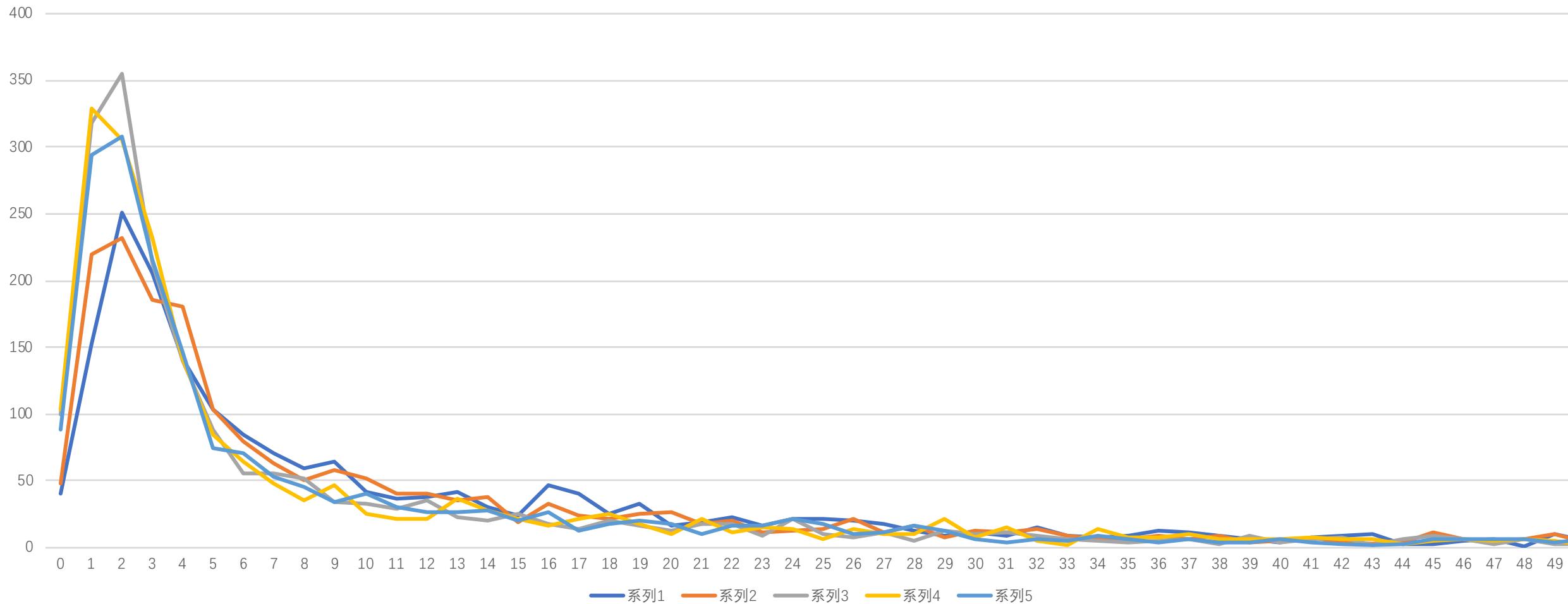
- Still Luong's NMT, but with Mizar \rightarrow TPTP (prefix format) as data.
- Augment our data through type elaboration and iterative training.



- Performance stabilizes after a few iterations... ☹

NMT with Type Elaboration

Distribution of Edit Distances



Summary

- For auto-formalization, we hit a wall with NMT techniques with limited data.
- Focus on obtaining high-quality data.
- This is still a direction worth going as manual translation is too costly.

Thanks

All historical orientation is only living when we learn to see what is ultimately essential is due to our own interpreting in the free rethinking by which we gain detachment from all erudition.

Martin Heidegger – The Metaphysical Foundations of Logic