



Deep Learning for Healthcare

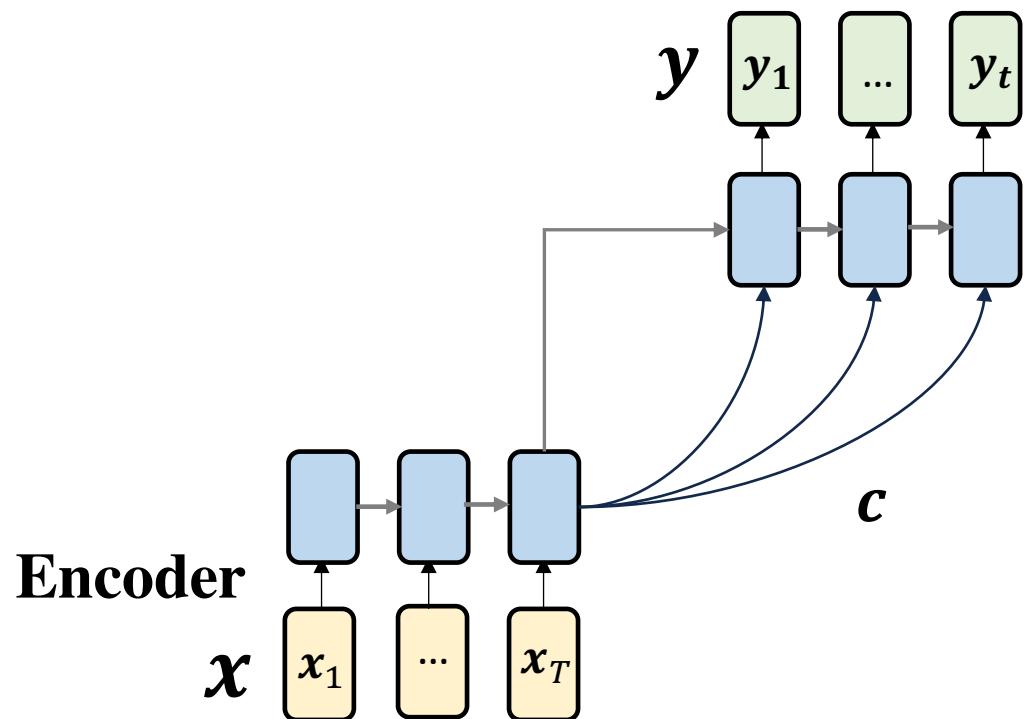
Attention
mechanism

Jimeng Sun

Outline

- Attention model
- Healthcare applications
 - Attention model over longitudinal EHR data (RETAIN)
 - Attention model over medical ontology (GRAM)
 - Attention model over clinical text (CAML)
 - Attention model electrocardiography (MINA)

Review: Encoder-Decoder Sequence-to-Sequence Model



$$c = h_T = f(h_{T-1}, x_T)$$

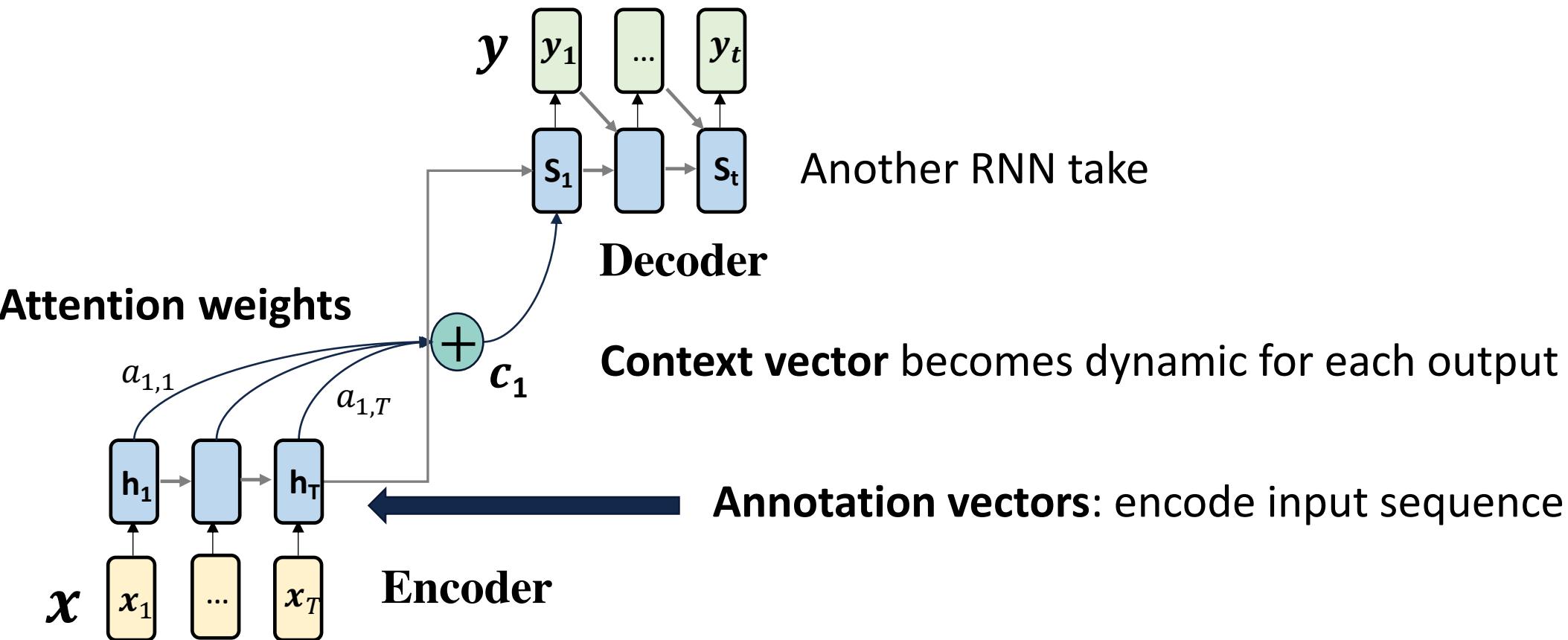
Static context vector has limited capacity in modeling long sequences

$$P_\theta(\mathcal{Y}|\mathcal{X}) = \prod_{j=1}^{J+1} P_\theta(y_j|y_{j-1}, \dots, y_1, \mathcal{X})$$

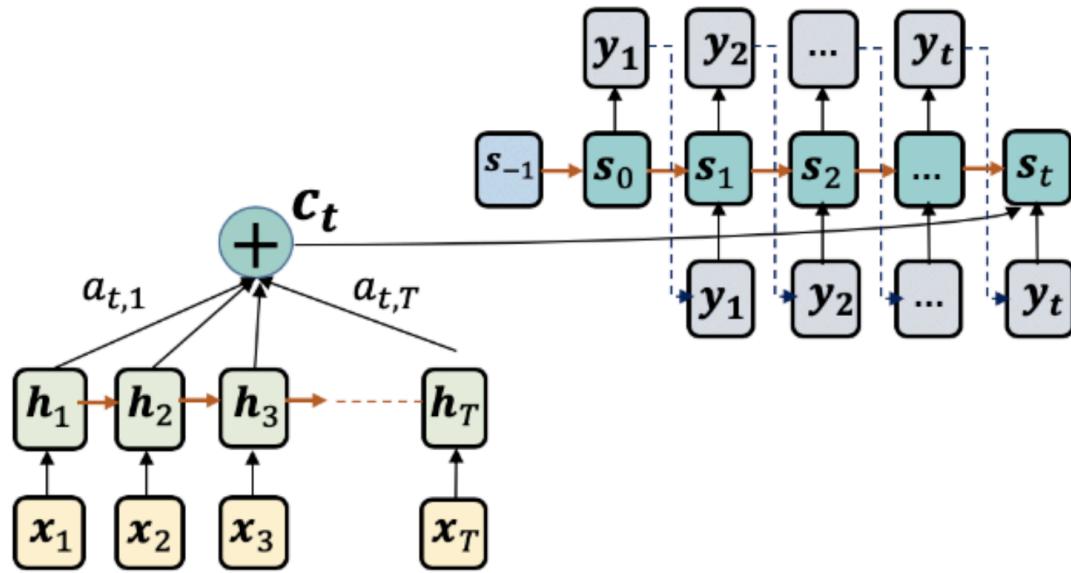
Decoder

$$P(y_t|y_{t-1}, \dots, y_1, c) = g(h_t, y_{t-1}, c)$$

Attention on RNN Model



Alignment model



- To quantify the alignment between input and output

$$e_{ij} = a(\mathbf{s}_{i-1}, \mathbf{h}_j)$$

- Dot-product attention

$$a(\mathbf{s}_{i-1}, \mathbf{h}_j) = \mathbf{s}_{i-1}^\top \mathbf{h}_j$$

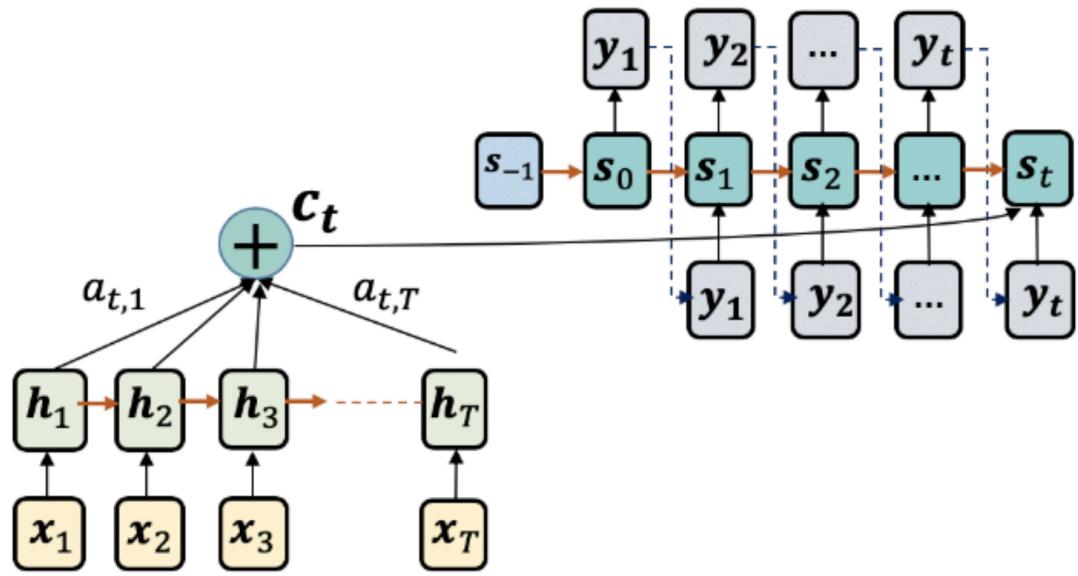
- General dot-product attention

$$a(\mathbf{s}_{i-1}, \mathbf{h}_j) = \mathbf{s}_{i-1}^\top \mathbf{W}_a \mathbf{h}_j$$

- Additive attention

$$a(\mathbf{s}_{i-1}, \mathbf{h}_j) = \mathbf{v}_a^\top \tanh(\mathbf{W}_a[\mathbf{s}_{i-1}, \mathbf{h}_j] + \mathbf{b}_a)$$

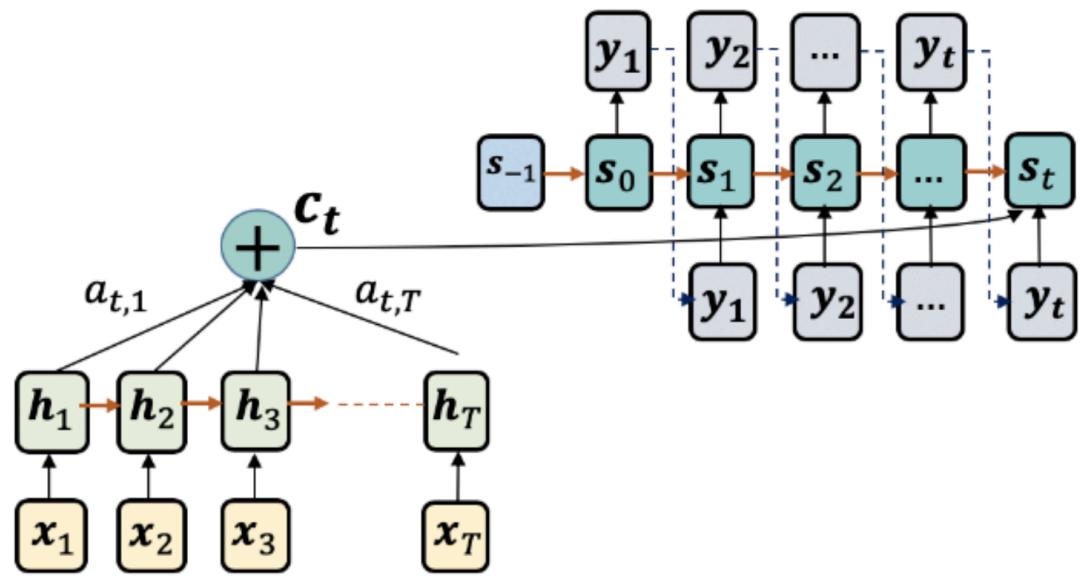
Attention weights



- Attention weight is the normalized version of the alignment model

$$a_{ij} = \frac{\exp e_{ij}}{\sum_{k=1}^T \exp e_{ik}}$$

Decoder



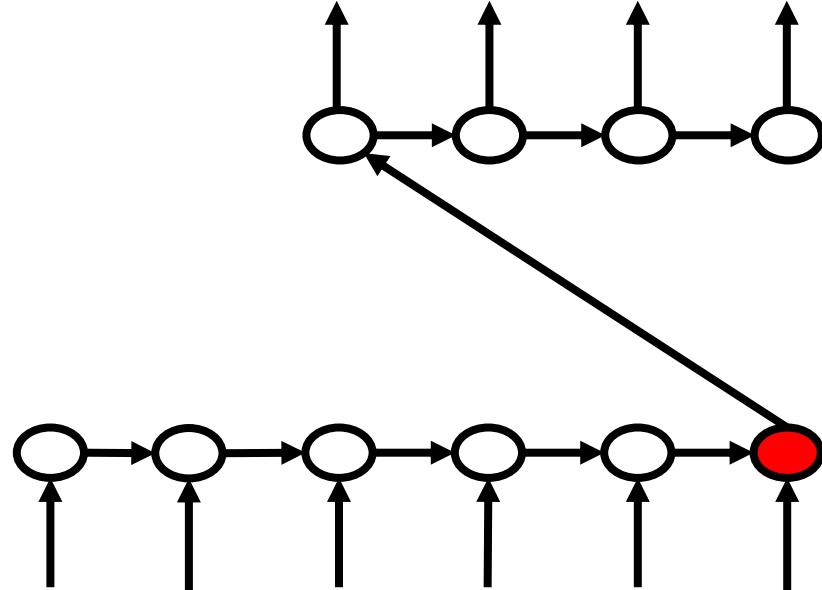
- Another RNN

$$s_i = f(s_{i-1}, y_{i-1}, c_i)$$

- Context vector c_i is dynamic for each output

Regular Machine Translation

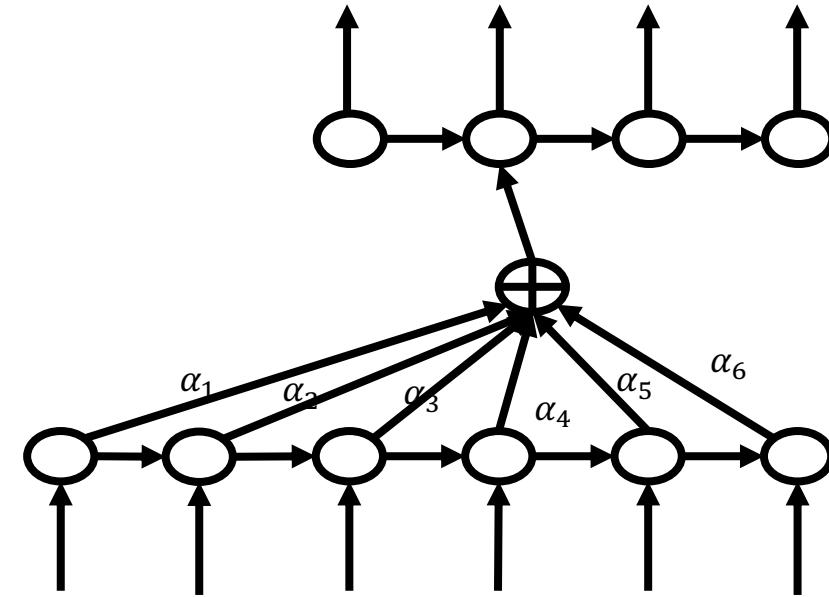
如果你不在乎谁获得了荣誉,
你所能完成的事情是惊人的。



It is amazing what you can accomplish
if you do not care who gets the credit

Neural Attention Mechanism

如果你不在乎谁获得了荣誉,
你所能完成的事情是**惊人的**。



It is **amazing** what you can accomplish
if you do not care who gets the credit

Retain: Interpretable Deep learning model

How to provide interpretability of model

Edward Choi

Taha Bahadori

Andy Schuetz

Buzz Stewart

Jimeng Sun

Choi, Edward, et al. 2016. “RETAIN: An Interpretable Predictive Model for Healthcare Using Reverse Time Attention Mechanism.” In *NIPS*

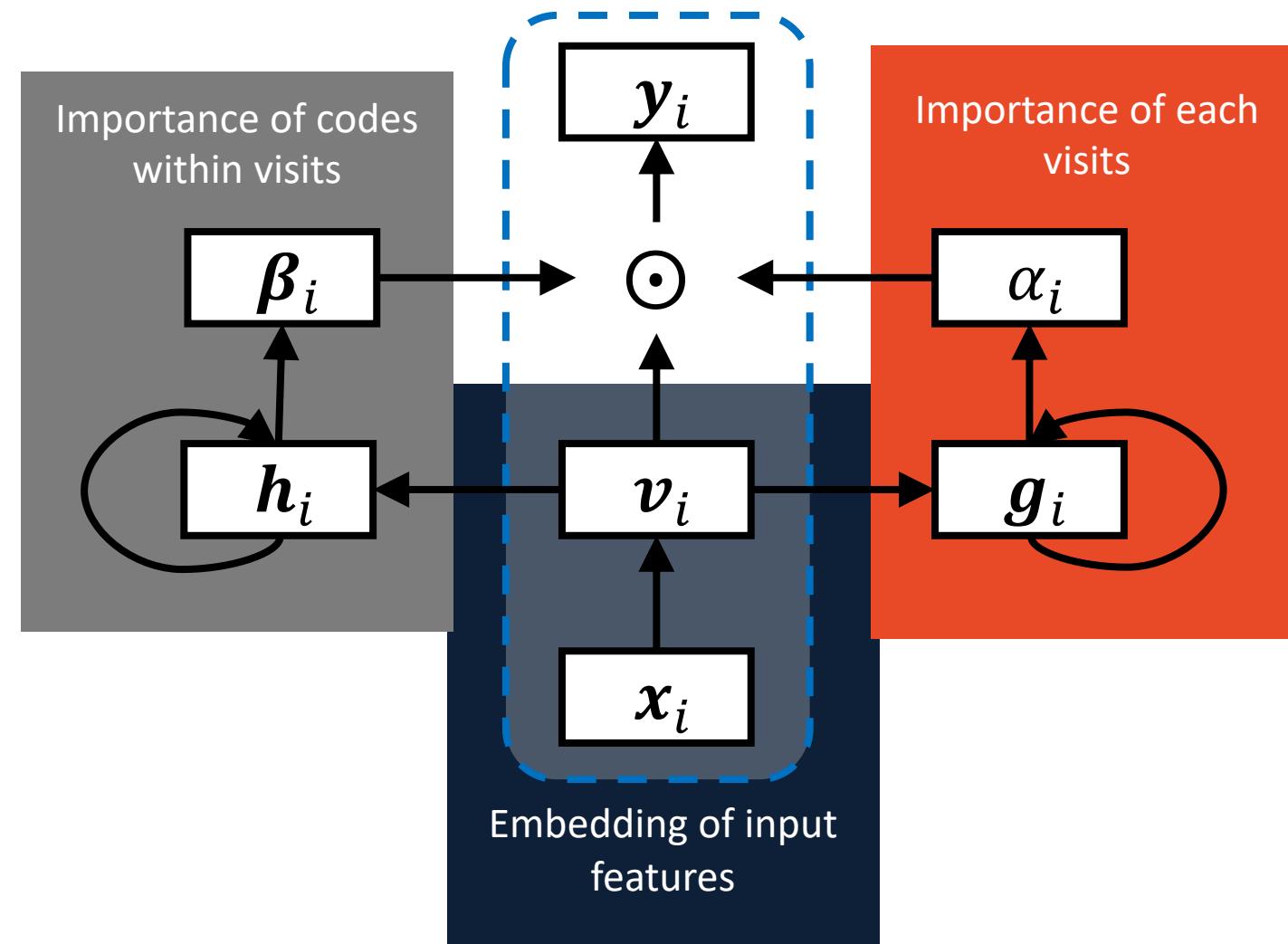
Interpretable Models

What do we mean by interpretability of a model?

Three categories of models:

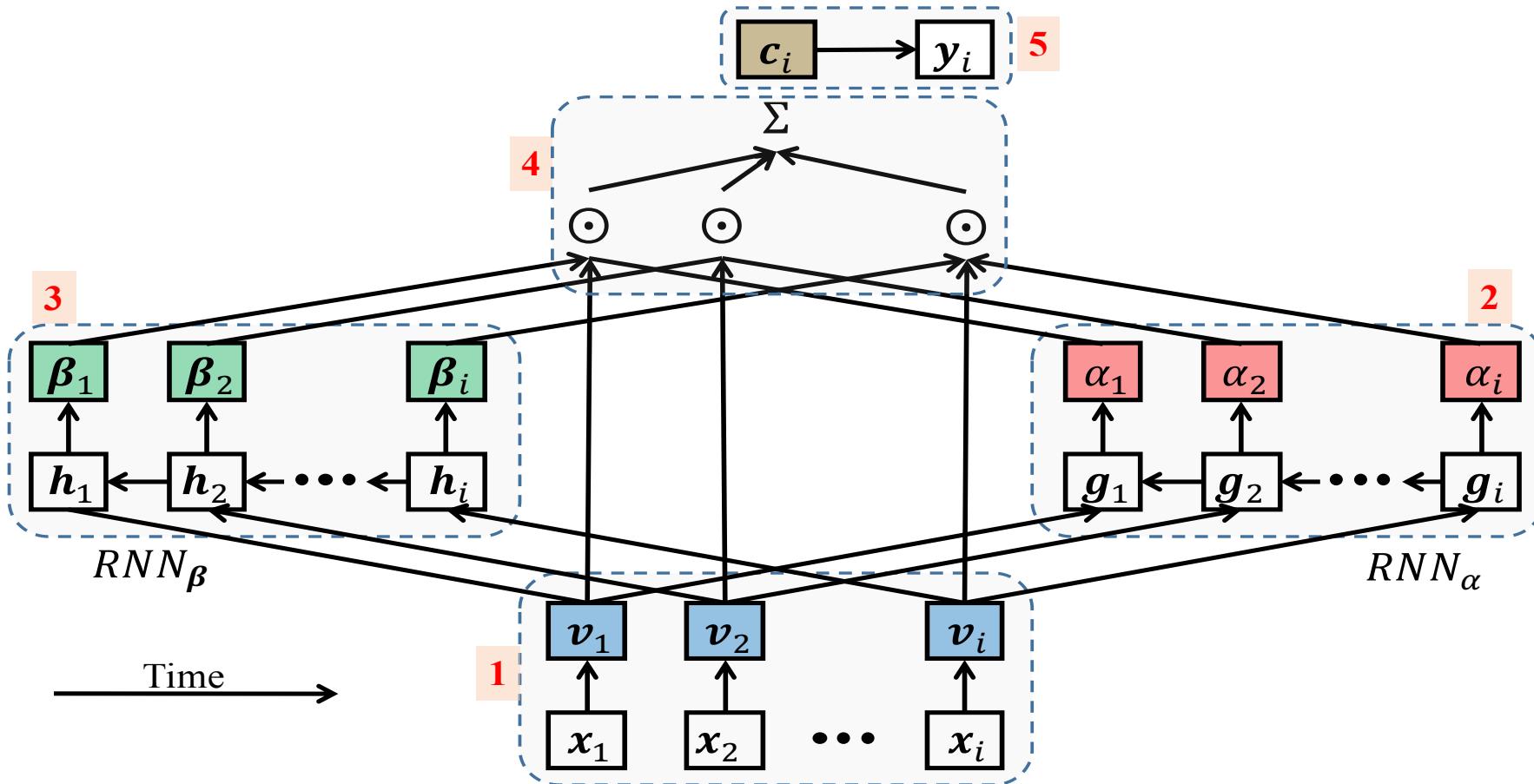
- Rule based: e.g. decision trees
 - Case based: e.g. nearest neighbor methods
 - Risk factor based: e.g. sparse linear regression
-
- Temporal models? Latent variable models

RETAIN: REverse Time Attention model

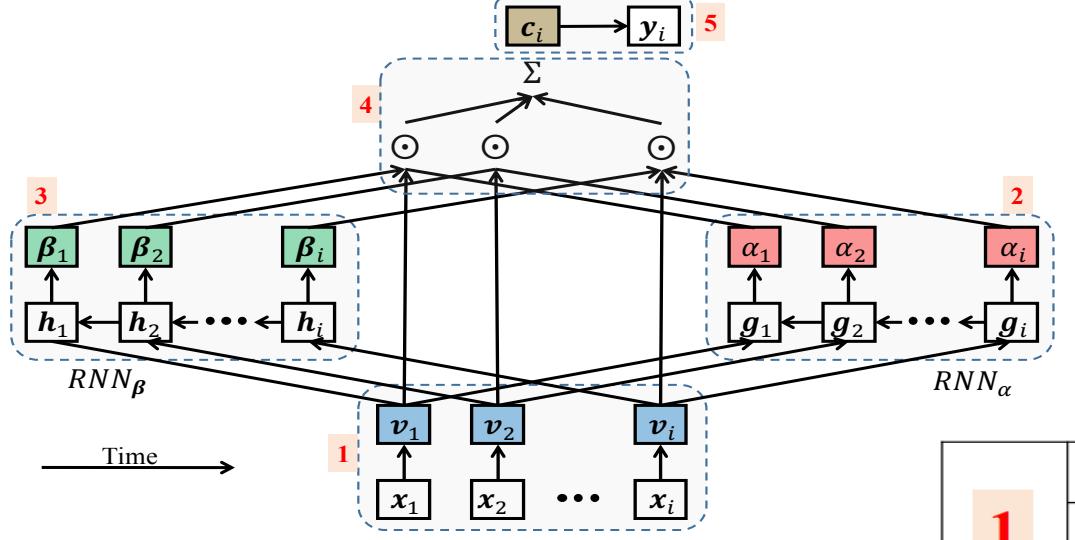


Choi, Edward, et al. 2016. “RETAIN: An Interpretable Predictive Model for Healthcare Using Reverse Time Attention Mechanism.” In *NIPS*

Details of RETAIN



RETAIN Algorithm

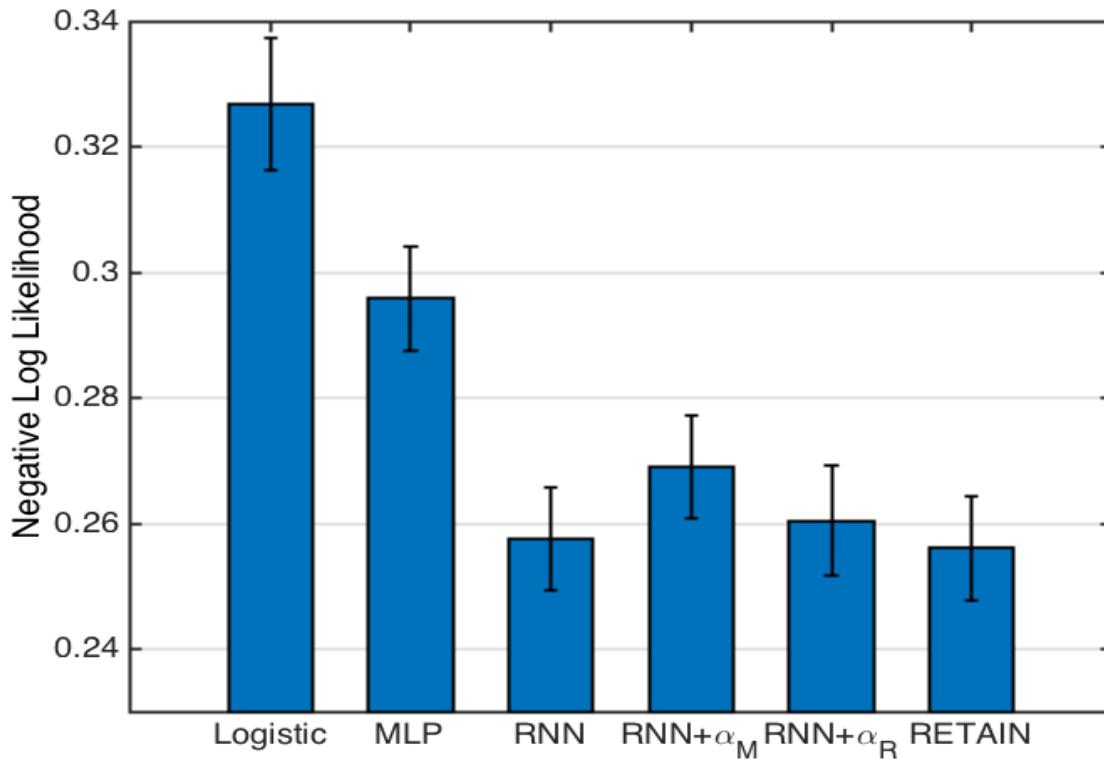


1	$\mathbf{v}_i = \mathbf{E}\mathbf{x}_i$
2	$\mathbf{g}_i, \mathbf{g}_{i-1}, \dots, \mathbf{g}_1 = RNN_\alpha(\mathbf{v}_i, \mathbf{v}_{i-1}, \dots, \mathbf{v}_1),$ $\alpha_1, \alpha_2, \dots, \alpha_i = \text{Softmax}(\mathbf{w}_\alpha^\top [\mathbf{g}_1, \mathbf{g}_2, \dots, \mathbf{g}_i] + b_\alpha)$
3	$\mathbf{h}_i, \mathbf{h}_{i-1}, \dots, \mathbf{h}_1 = RNN_\beta(\mathbf{v}_i, \mathbf{v}_{i-1}, \dots, \mathbf{v}_1)$ $\beta_j = \tanh(\mathbf{W}_\beta \mathbf{h}_j + \mathbf{b}_\beta) \quad \text{for } j = 1, \dots, i$
4	$\mathbf{c}_i = \sum_{j=1}^i \alpha_j \beta_j \odot \mathbf{v}_j$ The attention weights α_i and β_i are combined with the visit representation \mathbf{v}_i to obtain the context vector \mathbf{c}_i .
5	$\hat{\mathbf{y}}_i = \text{Softmax}(\mathbf{W}\mathbf{c}_i + \mathbf{b})$ Using the context vector \mathbf{c}_i , we make the final prediction.

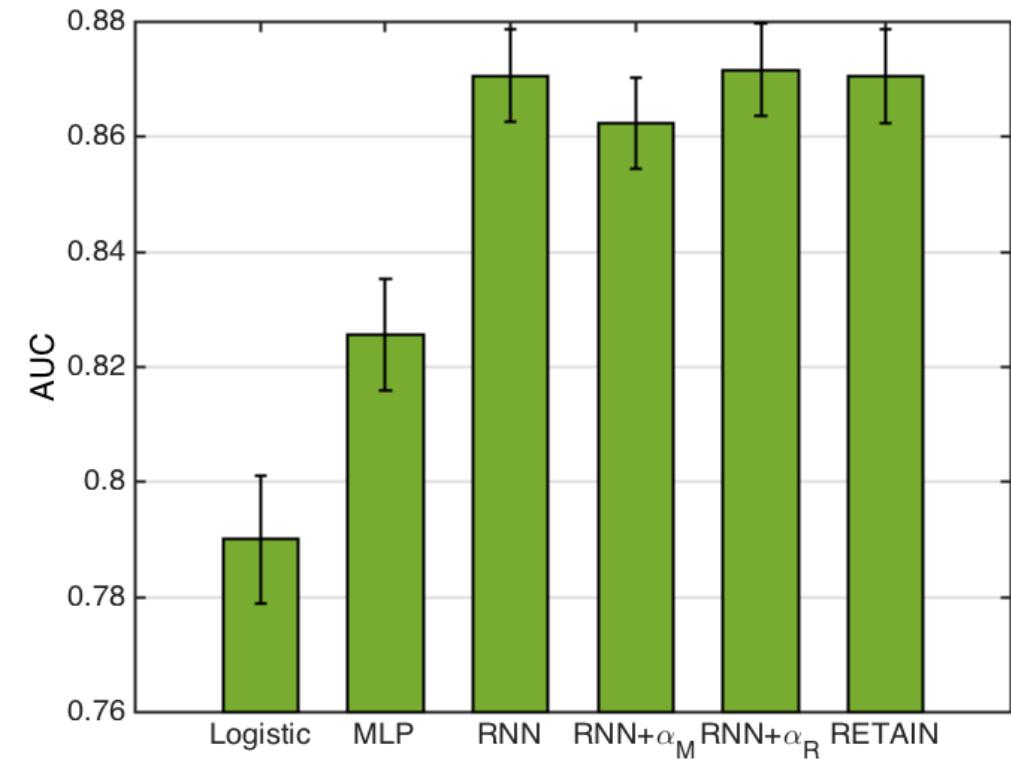
Heart Failure Results



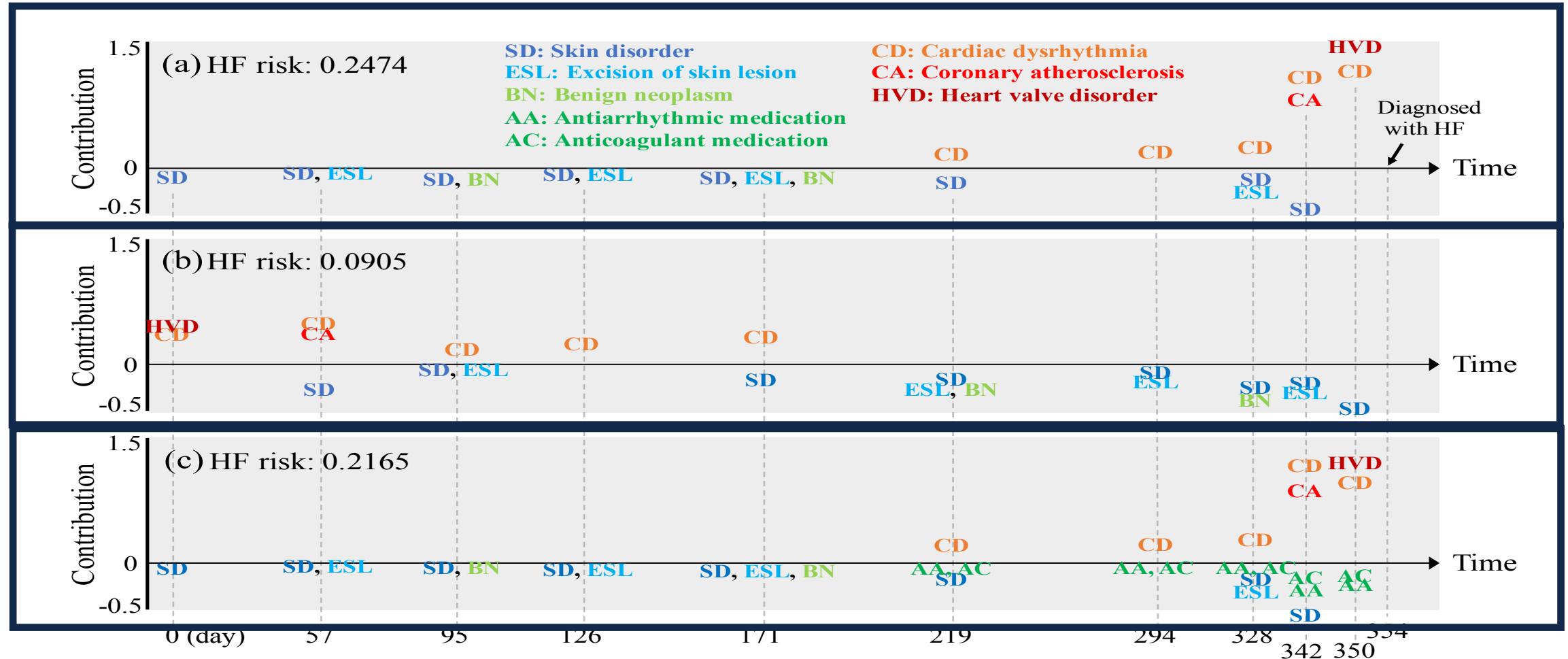
- Negative Log Likelihood on Test Set



- Classification AUC



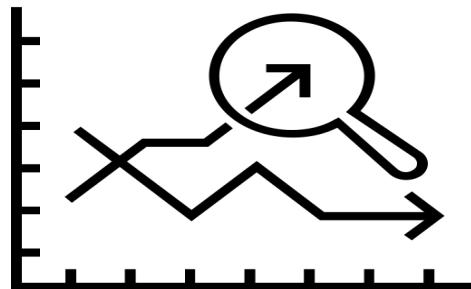
Interpretation of RETAIN model



Retain: Interpretable Deep learning model



- Challenge: Deep learning models are often difficult to interpret



- RETAIN is a temporal attention model on electronic health records
 - Great predictive power
 - Good interpretation

Choi, Edward, et al. 2016. "RETAIN: An Interpretable Predictive Model for Healthcare Using Reverse Time Attention Mechanism." In *NIPS*

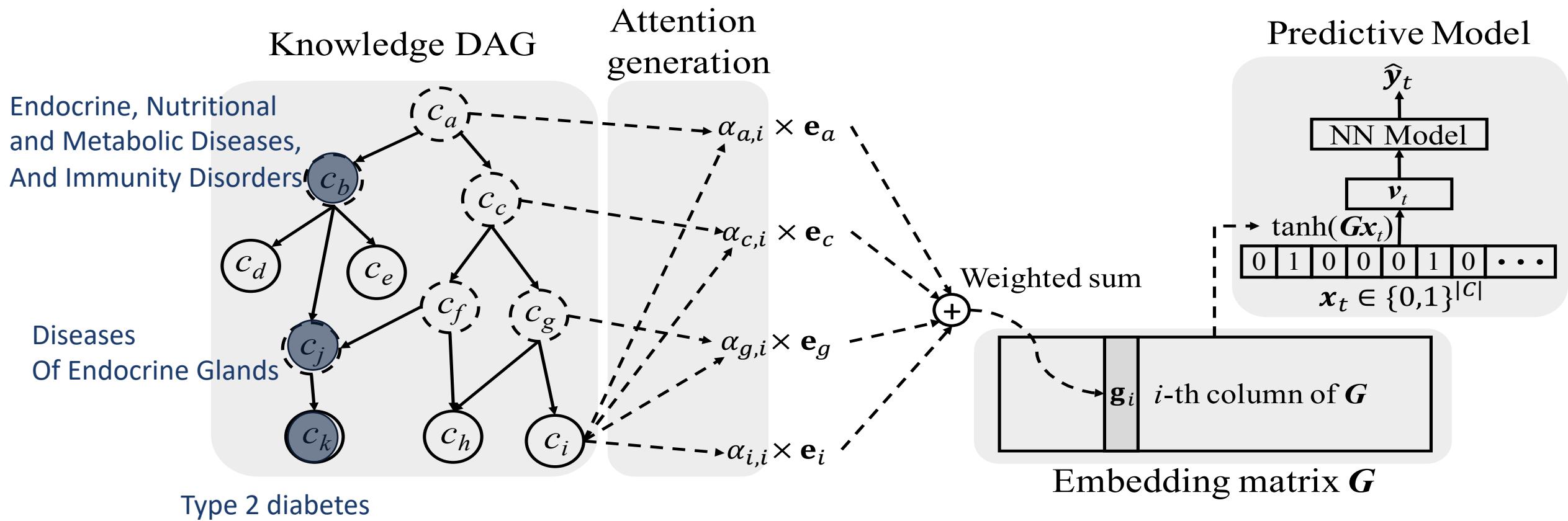
GRAM: Graph-based Attention Model for Healthcare Representation Learning

Edward Choi, Mohammad Taha Bahadori, Le Song, Walter F. Stewart, Jimeng Sun

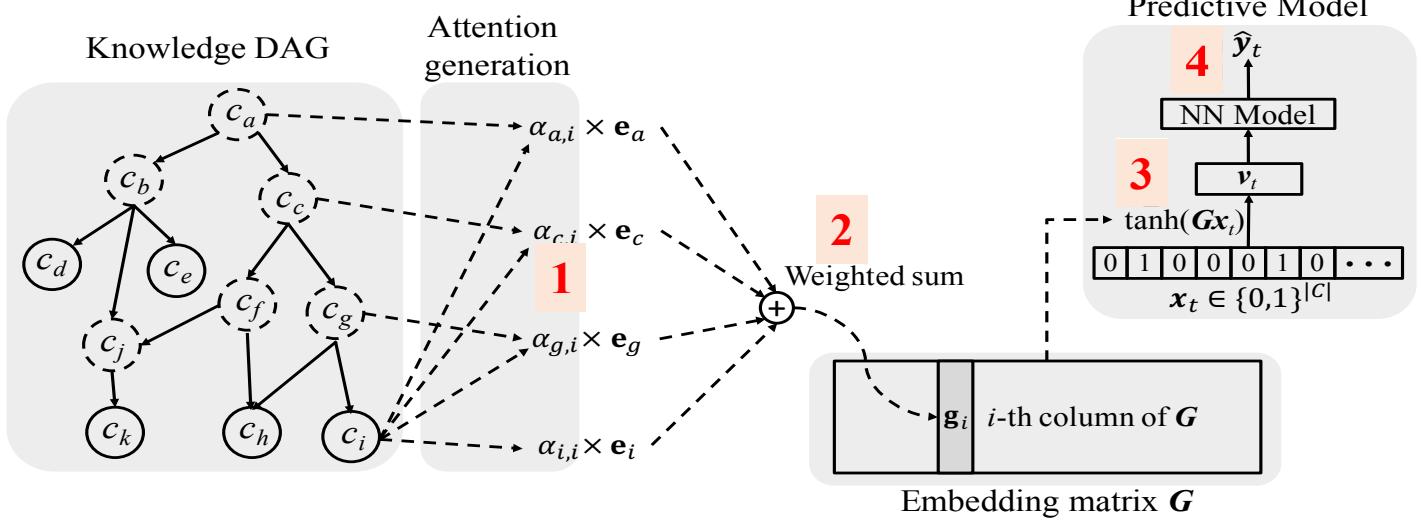
KDD' 17

GRAM: Learn representations of medical codes leveraging medical ontologies

Method: Generate a medical code representation vector by combining the representation vectors of its ancestors using the attention mechanism



GRAM: Algorithm



1
$$\alpha_{ij} = \frac{\exp(f(\mathbf{e}_i, \mathbf{e}_j))}{\sum_{k \in \mathcal{A}(i)} \exp(f(\mathbf{e}_i, \mathbf{e}_k))} \quad \text{where} \quad f(\mathbf{e}_i, \mathbf{e}_j) = \mathbf{u}_a^\top \tanh(\mathbf{W}_a \begin{bmatrix} \mathbf{e}_i \\ \mathbf{e}_j \end{bmatrix} + \mathbf{b}_a)$$

Attention weights are generated for all pairs of basic embeddings and its ancestors .

2
$$\mathbf{g}_i = \sum_{j \in \mathcal{A}(i)} \alpha_{ij} \mathbf{e}_j,$$

Final representation is the weighted sum of attention weights and basic embeddings.

3
$$\mathbf{v}_1, \mathbf{v}_2, \dots, \mathbf{v}_t = \tanh(\mathbf{G}[\mathbf{x}_1, \mathbf{x}_2, \dots, \mathbf{x}_t])$$

Sequence of visit representations are obtained using the Embedding matrix \mathbf{G} .

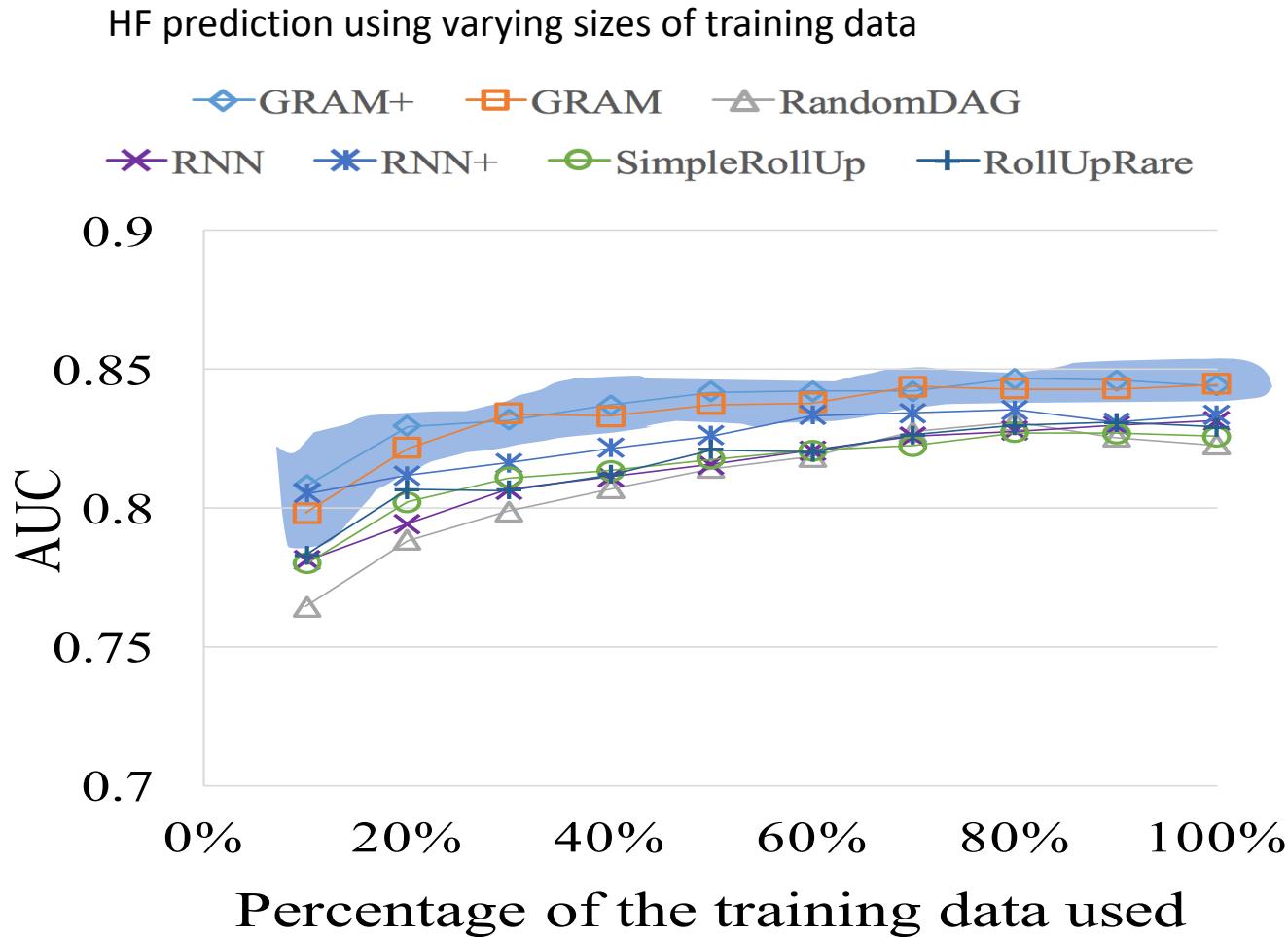
4
$$\mathbf{h}_1, \mathbf{h}_2, \dots, \mathbf{h}_t = \text{RNN}(\mathbf{v}_1, \mathbf{v}_2, \dots, \mathbf{v}_t, \theta_r),$$

$$\hat{y}_t = \hat{\mathbf{x}}_{t+1} = \text{Softmax}(\mathbf{W}\mathbf{h}_t + \mathbf{b}),$$

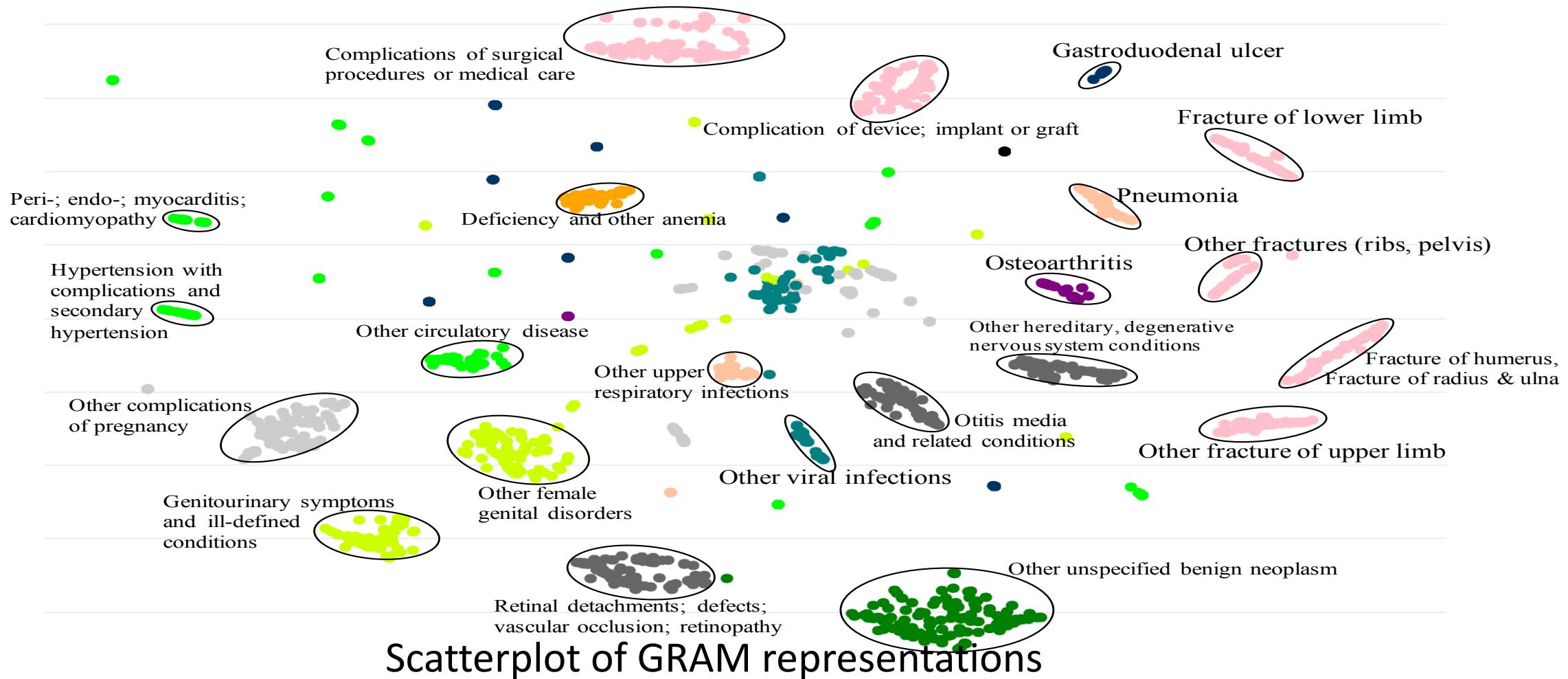
Performing sequential diagnoses prediction, outcomes are generated by RNN and Softmax.

GRAM provides accurate prediction

GRAM shows better predictive performance under data constraints



GRAM learns representations well aligned with knowledge ontology



GRAM: Summary

Medical
ontology

GRAM

Electronic
health records

- Robust representation against **data insufficiency**
- Interpretable: Well aligned with medical knowledge

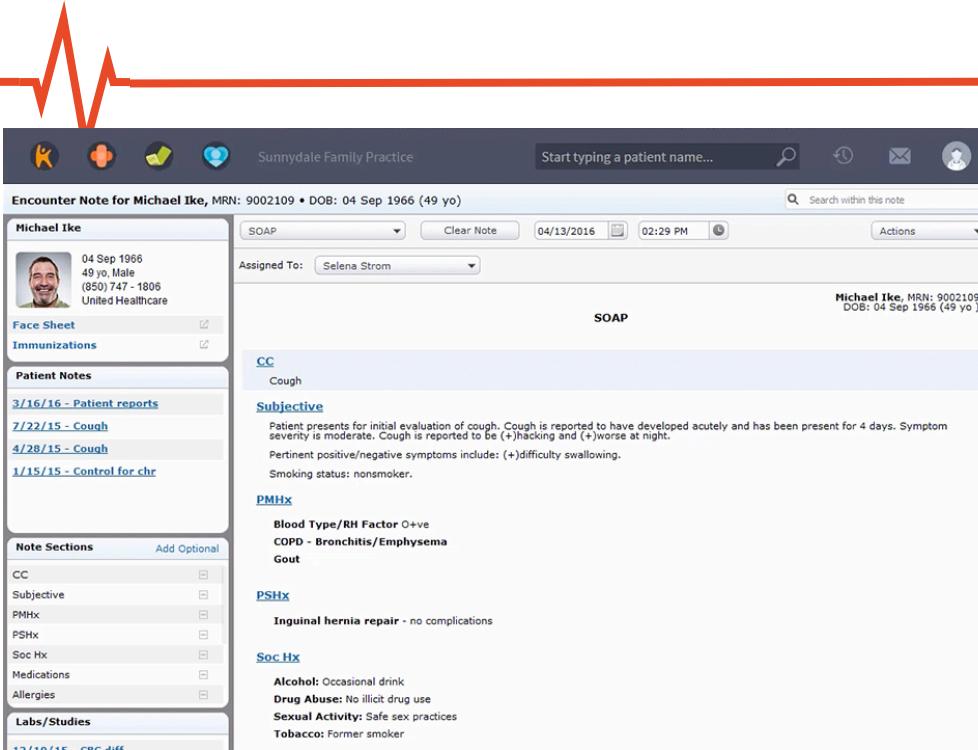
Choi, Edward, et al."GRAM: Graph-based Attention Model for Healthcare Representation Learning." KDD, 2017.

Explainable Prediction of Medical Codes from Clinical Text

James Mullenbach, Sarah Wiegreffe, Jon Duke, Jacob Eisenstein

NAACL'18

Clinical Coding Problem



Electronic Health Records
contain rich clinical texts



Features	ICD-9
Possible Codes	14,000
Characters	3–5



ICD: taxonomy of diagnoses &
procedures

Human coding laborious, error-prone [Birman-Deych et al., 2005]

Clinical Coding Problem, as a CS researcher



- Highly multi-label classification
 - 14K ICD9, 68K ICD10 labels
- Testbed for document representations
- Documents are long and loosely structured





Prior approaches

- Predict a subset of labels
- Sub-domain focus, e.g. radiology
- Private datasets

This work

- Predict all labels
- General ICU setting
- Open-access data

The dataset



- Open-access, de-identified
- 47k admissions -> 47k documents for training

<https://mimic.physionet.org/>

The dataset



- Open-access, de-identified
- 47k admissions -> 47k documents for training
- **Loosely structured:**

Admission Date: [**2118-6-2**]

Discharge Date: [**2118-6-14**]

Date of Birth:

Sex: F

Service: MICU and then to [**Doctor Last Name **] Medicine

HISTORY OF PRESENT ILLNESS: This is an 81-year-old female with a history of emphysema (not on home O2), who presents...

The dataset



- Open-access, de-identified
- 47k admissions -> 47k documents for training
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Admission Date: [**2118-6-2**]

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HISTORY OF PRESENT ILLNESS: This is an 81-year-old female with a history of emphysema (not on home O2), who presents...

Long: Median post-processed document length: 1,341

The dataset



- Open-access, de-identified
- 47k admissions -> 47k documents for training
- **Loosely structured:**

Many labels:

Admission Date: [**2118-6-2**]

Discharge Date: [**2118-6-14**]

519.1: 'Other disease...'

Date of Birth:

Sex: F

491.21: 'Obstructive ...'

Service: MICU and then to [**Doctor Last Name **] Medicine

518.81: 'Acute respir...'

HISTORY OF PRESENT ILLNESS: This is an 81-year-old female
with a history of emphysema (not on home O2), who presents...

486: 'Pneumonia, organ...'

276.1: 'Hyposmolality...'

244.9: 'Unspecified h...'

31.99: 'Other operati...'

Long: Median post-processed document length: 1,341

The dataset



- Open-access, de-identified
- 47k admissions -> 47k documents for training
- **Loosely structured:**

Median # labels: 14
Many labels:

Admission Date: [**2118-6-2**]

Discharge Date: [**2118-6-14**]

Date of Birth:

Sex: F

Service: MICU and then to [**Doctor Last Name **] Medicine

HISTORY OF PRESENT ILLNESS: This is an 81-year-old female with a history of emphysema (not on home O2), who presents...



519.1: 'Other disease...'
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244.9: 'Unspecified h...'
31.99: 'Other operati...'
. . .

Long: Median post-processed document length: 1,341

Modeling consideration



- Focus on the parts that matter

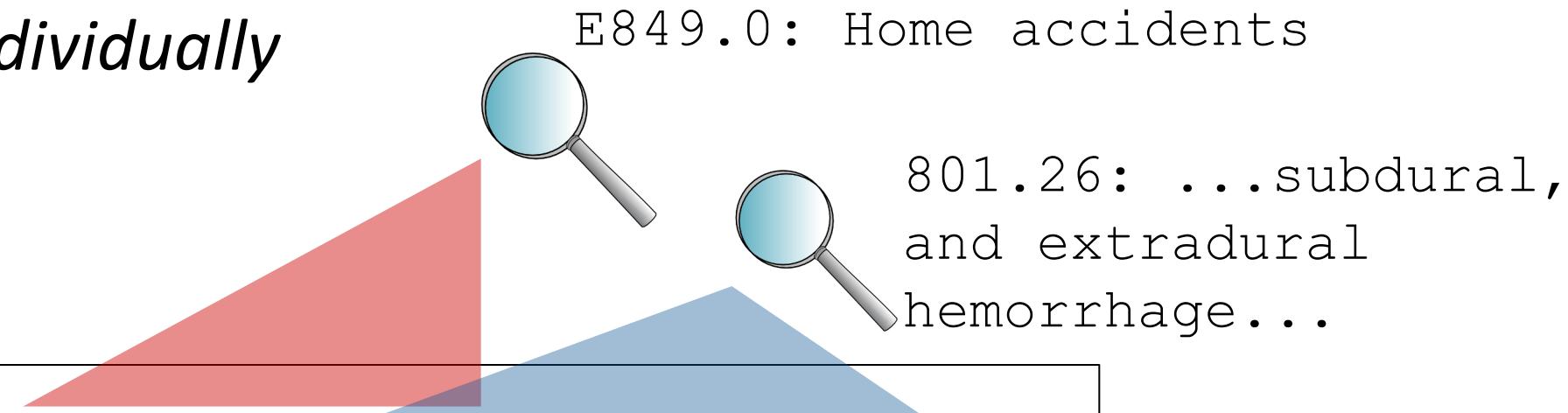
...who sustained a fall at home she was found to have a large acute on **chronic subdural hematoma** with extensive midline shift...



Modeling consideration



- Focus on the parts that matter
- Treat labels *individually*

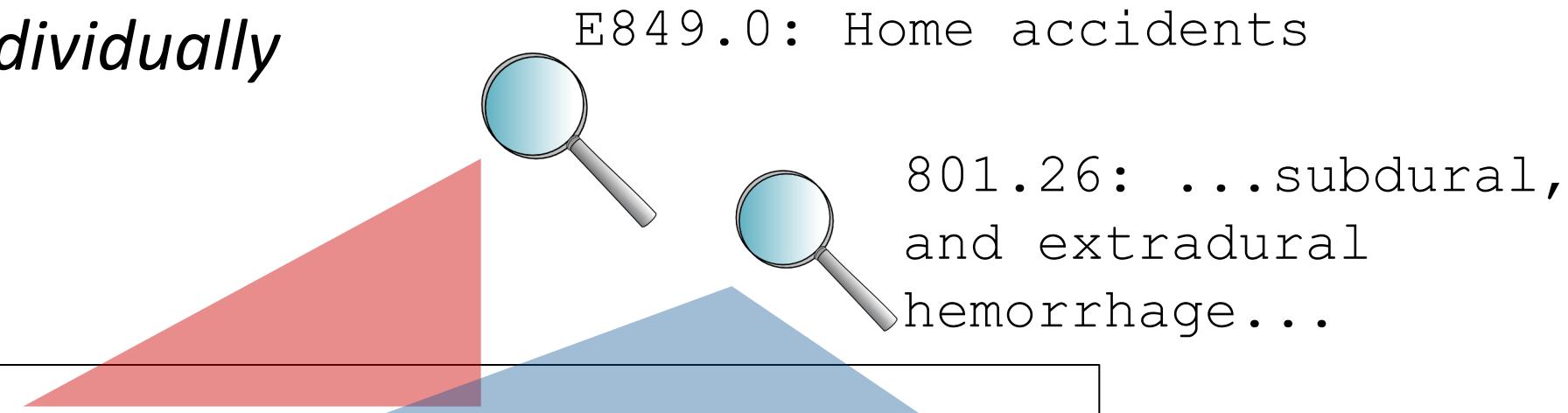


...who sustained **a fall at home** she was found to have a large acute on **chronic subdural hematoma** with extensive midline shift...

Modeling consideration

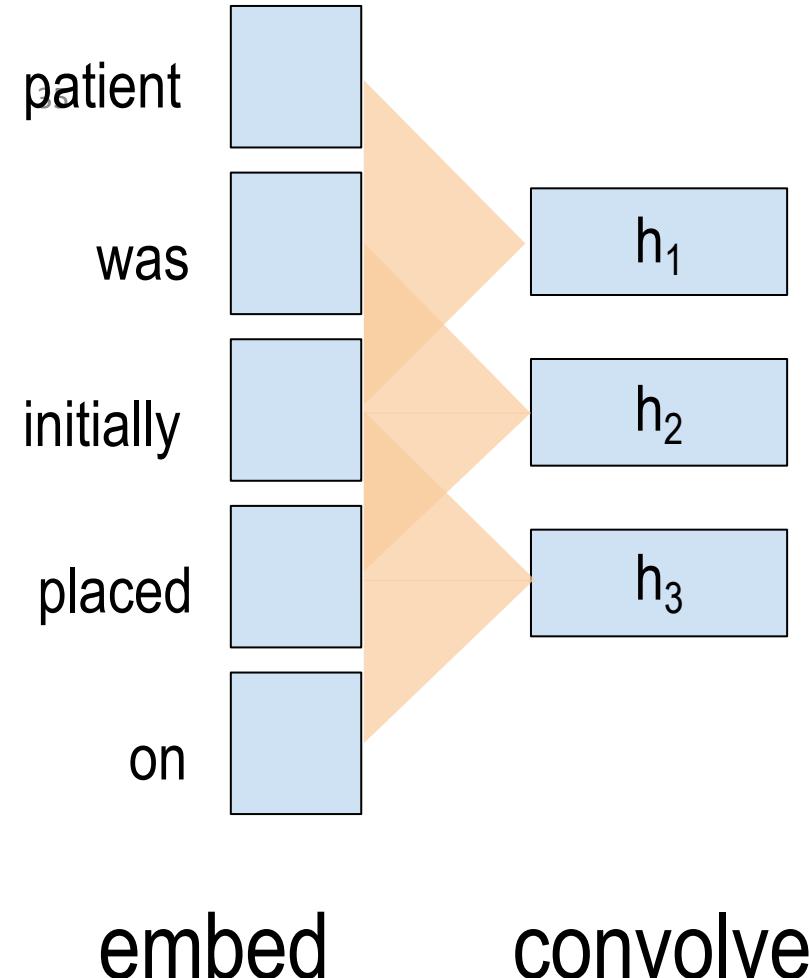


- Focus on the parts that matter
- Treat labels *individually*
- Be fast!

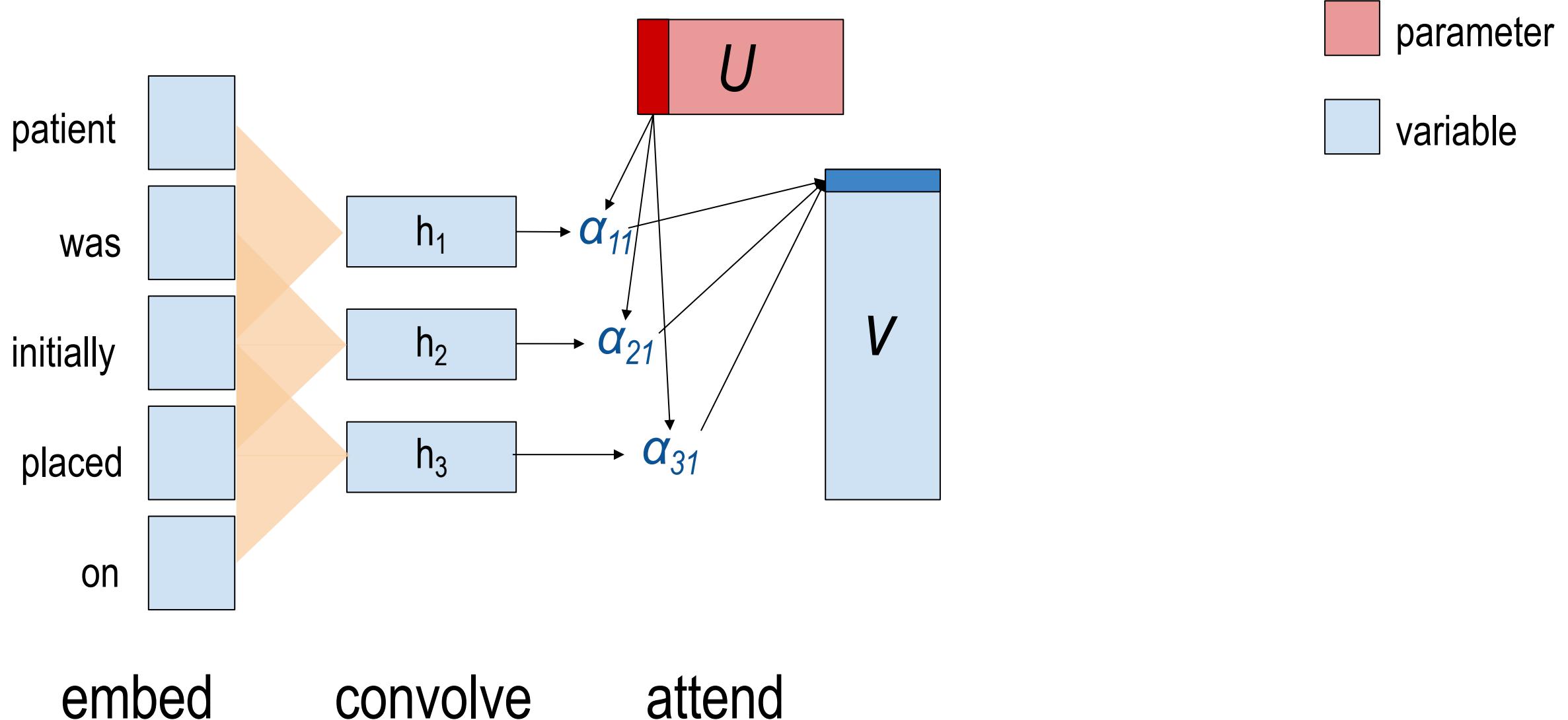


...who sustained **a fall at home** she was found to have a large acute on **chronic subdural hematoma** with extensive midline shift...

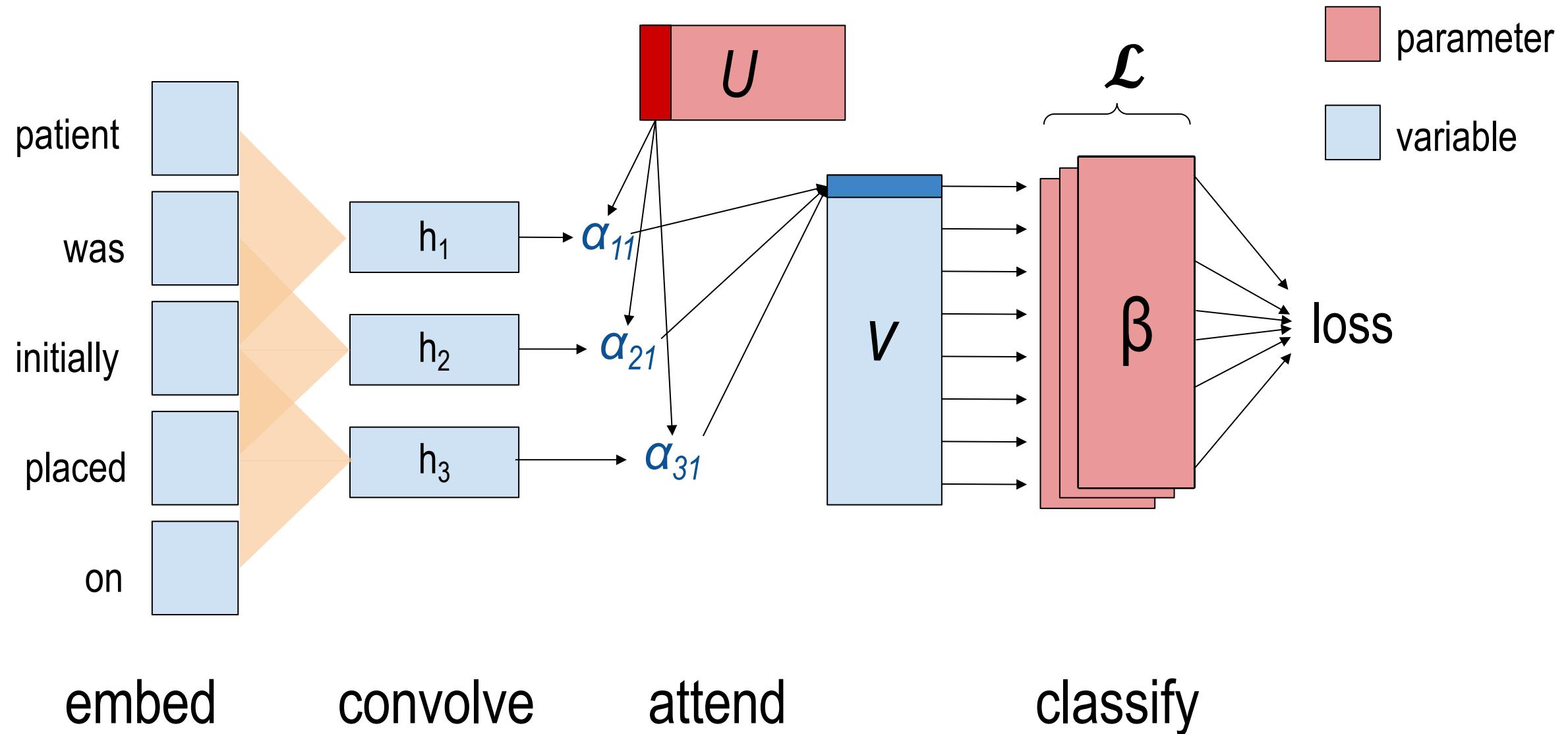
Convolution



Convolution + Attention



Convolution + Attention = CAML model



Dealing with the long tail

- Huge label space (nearly 9,000 total)

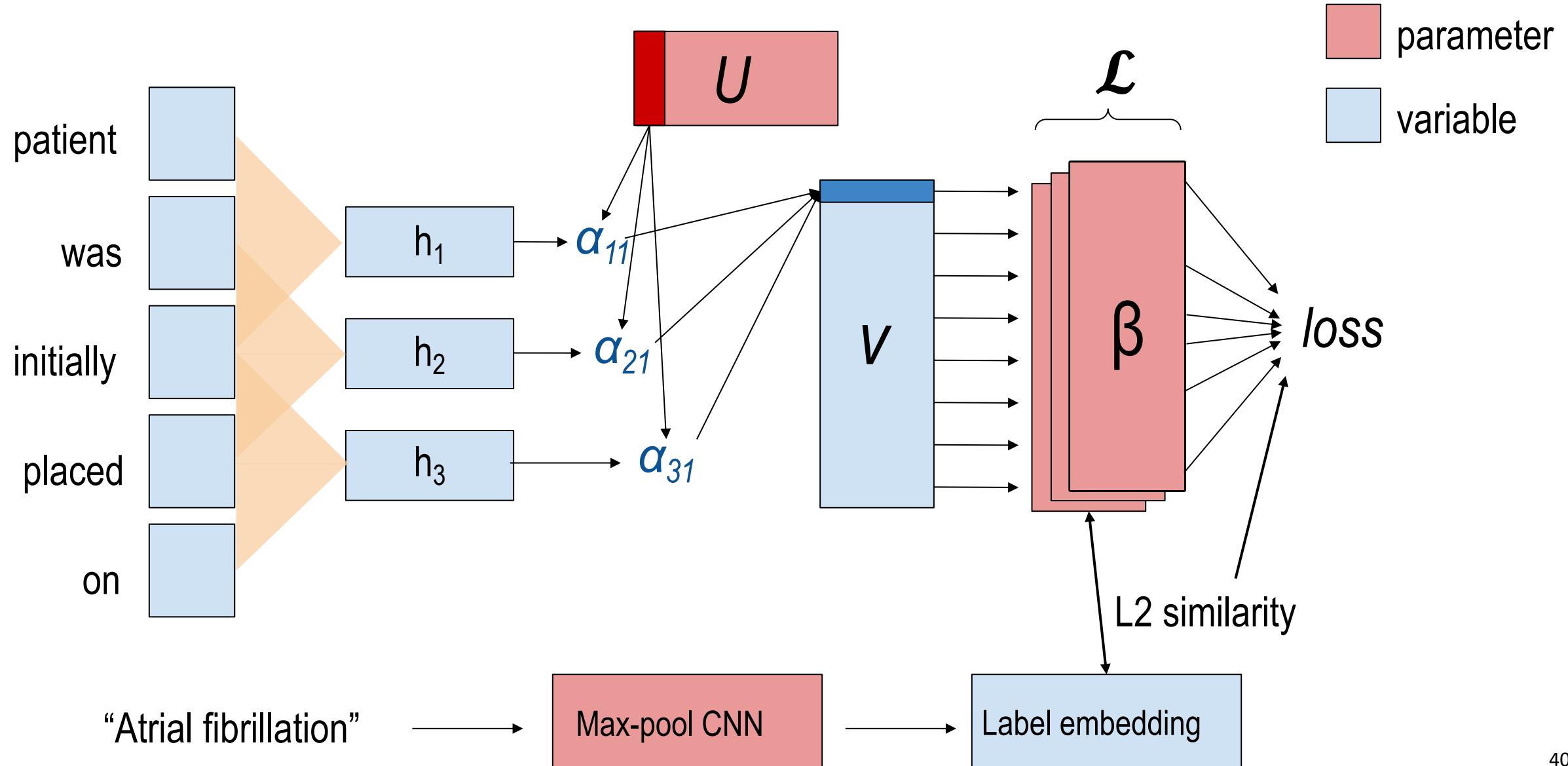
Dealing with the long tail

- Huge label space (nearly 9,000 total)
- Many labels are similar

250.00: "Diabetes mellitus without mention of complication, type II or unspecified type, not stated as uncontrolled"

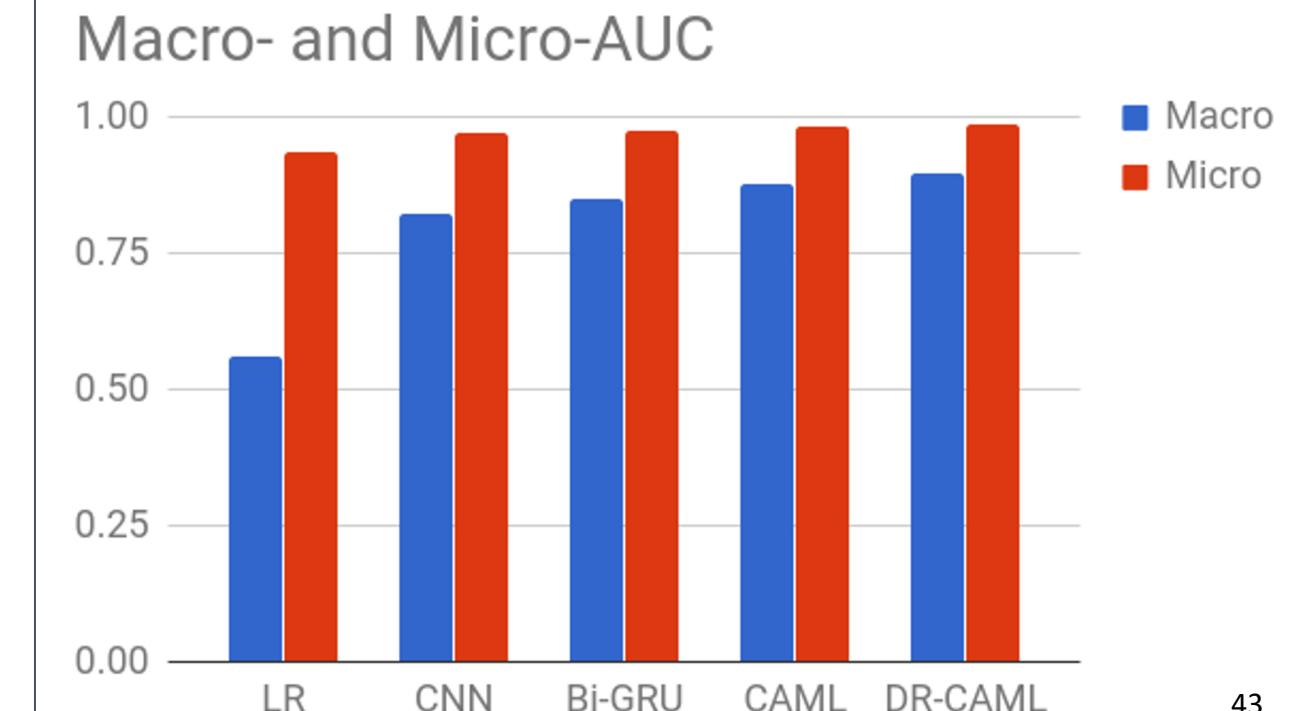
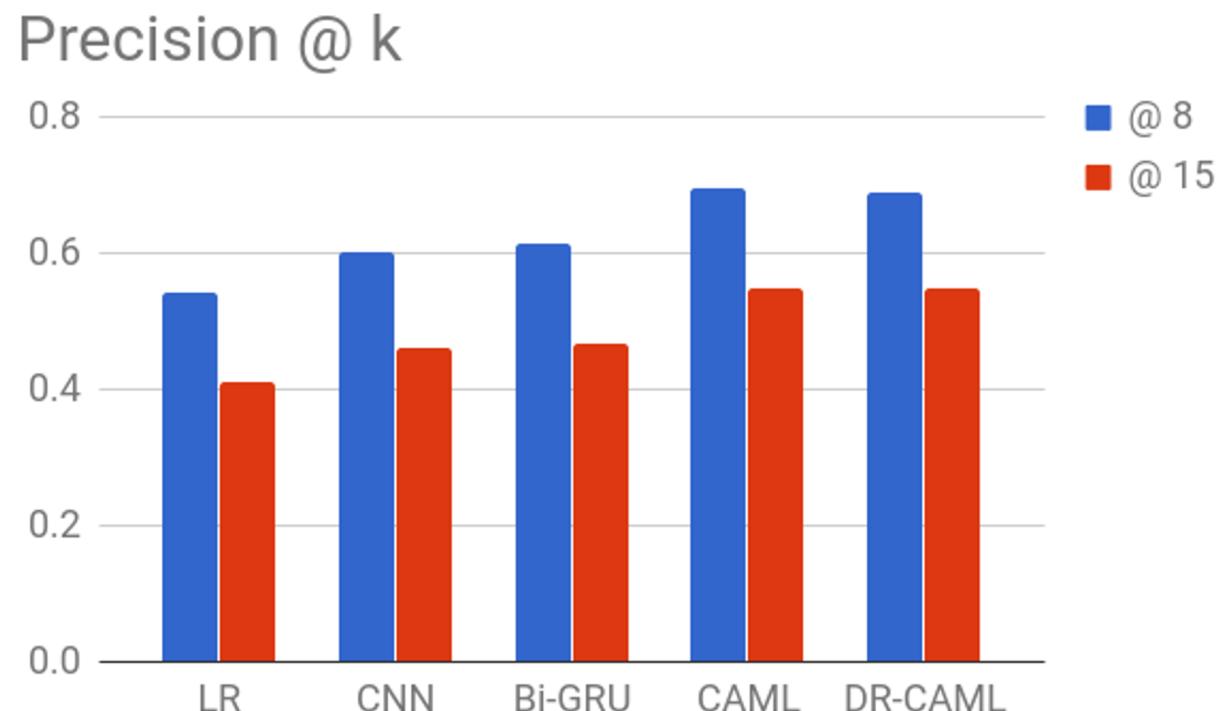
250.02: "Diabetes mellitus without mention of complication, type II or unspecified type, uncontrolled"

Dealing with the long tail: DR-CAML



Experiment results

- Enable future comparison
- Precision @ k: decision support use-case



But, is the model really interpretable?

- Physician evaluation: select the text snippet(s) that explain the code
- Informative and Highly Informative
- 100 random label-document samples
- Baselines: LogReg, CNN, cosine similarity



Physician evaluation example*

Code: 575.4

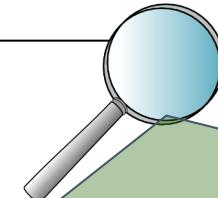
Full descriptions: Perforation of gallbladder

". . . in the setting of gallbladder perforation secondary to acute acalculous cholecystitis after
inhalation hospital1 times a day metronidazole mg tablet sig
one tablet po tid times to have an infection in
your gallbladder requiring iv antibiotics and tube placement
for"

*not exact format used

Physician evaluation example*

Code: 575.4



CAML

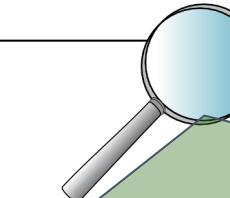
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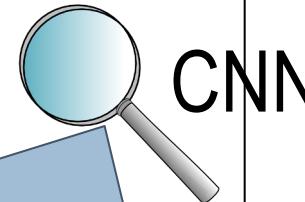
Physician evaluation example*

Code: 575.4



CAML

Full descriptions: Perforation of gallbladder



“. . . in the setting **of gallbladder perforation secondary** to acute acalculous cholecystitis after inhalation hospital 1 times a day **metronidazole mg tablet sig** one tablet po tid times to have an infection in your gallbladder requiring iv antibiotics and tube placement for”

*not exact format used

Physician evaluation example*

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Physician evaluation example*

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Full descriptions: Perforation of gallbladder

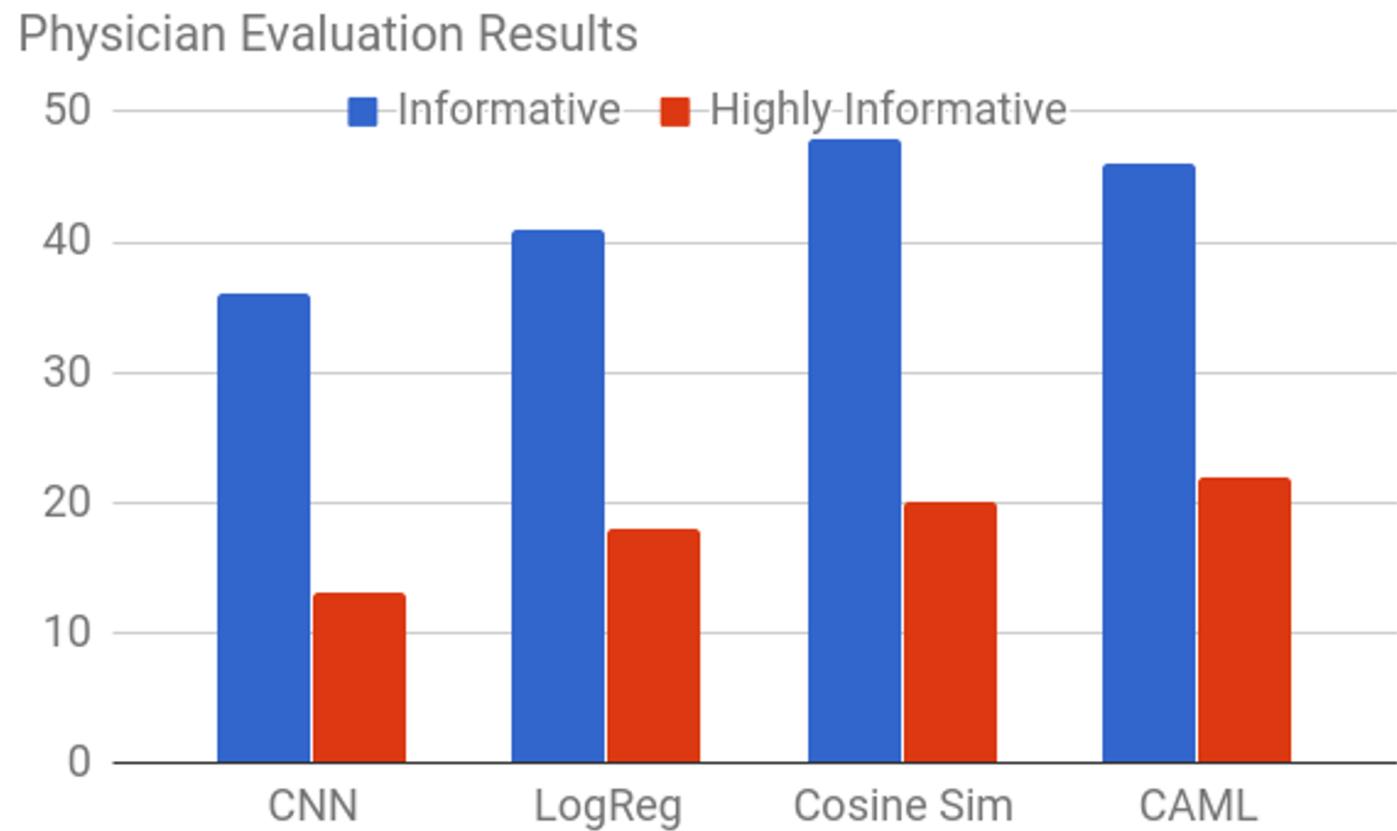
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LogReg

*not exact format used

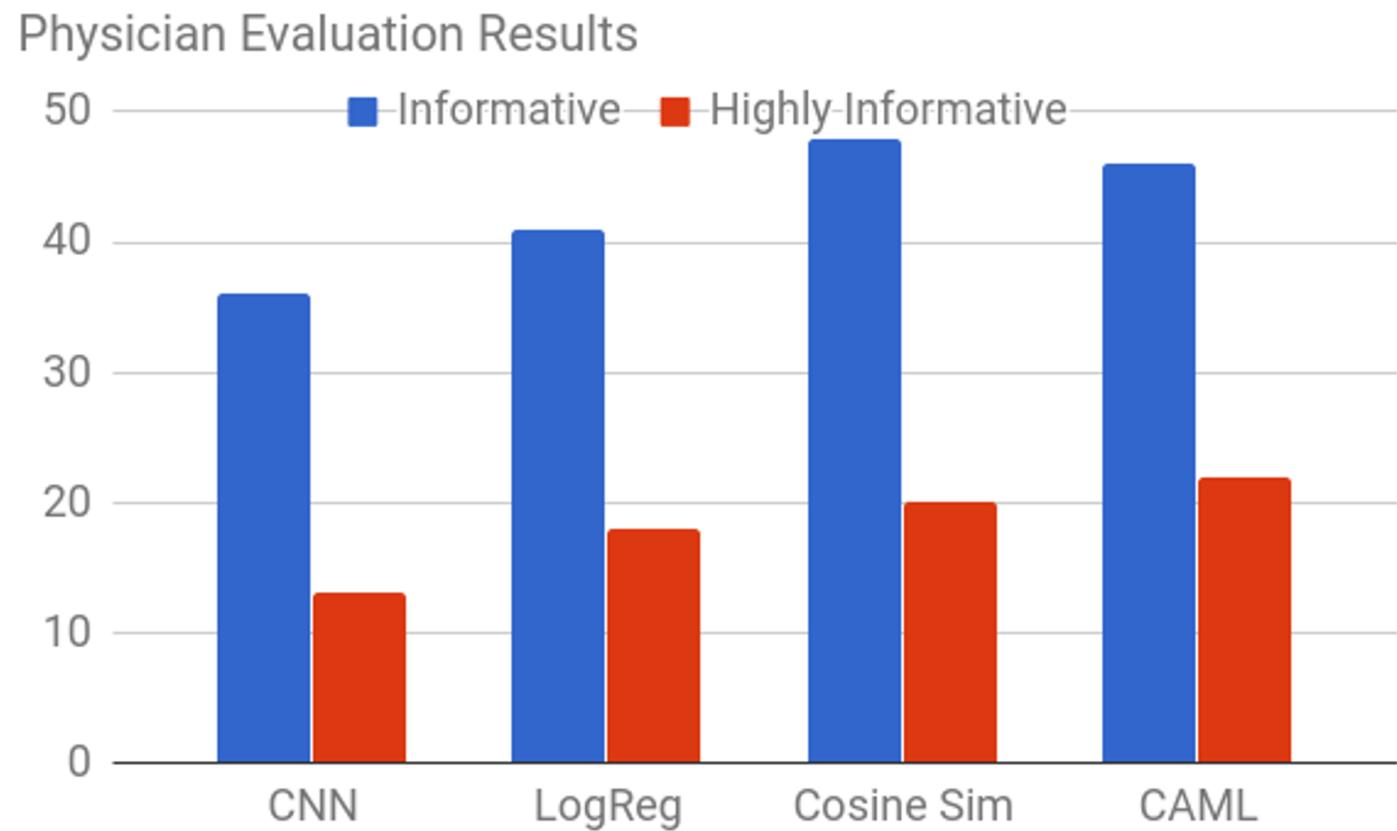
Physician evaluation results

- Improves upon CNN, LogReg



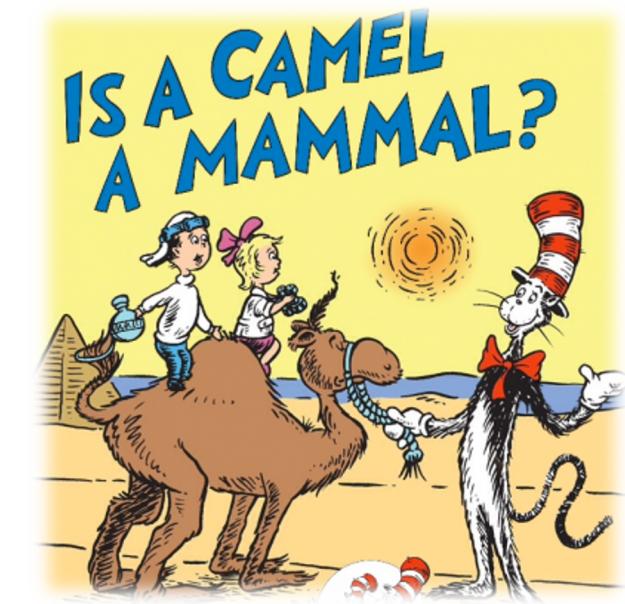
Physician evaluation results

- Improves upon CNN, LogReg
- More experts needed!



CAML: Explainable Prediction of Medical Codes from Clinical Text

- ICD coding is valuable and challenging
- Convolution + attention works well
- Attention can explain the predictions

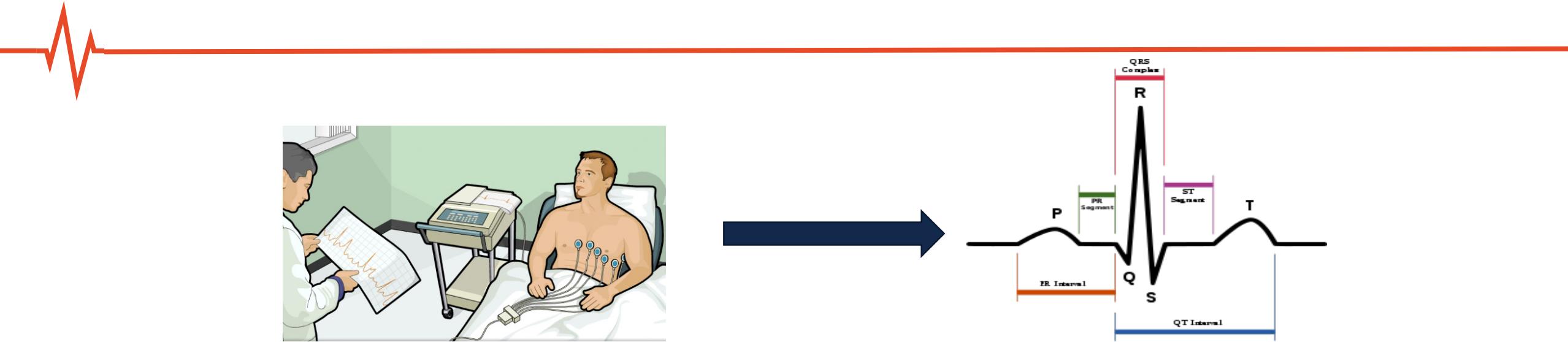


MINA: Multilevel Knowledge-Guided Attention for Modeling Electrocardiography Signals

Shenda Hong, Cao Xiao, Tengfei Ma, Hongyan Li, Jimeng Sun

ICJAI'19

Motivation



Electrocardiography (ECG) is a commonly used non-invasive diagnostic tool for heart diseases

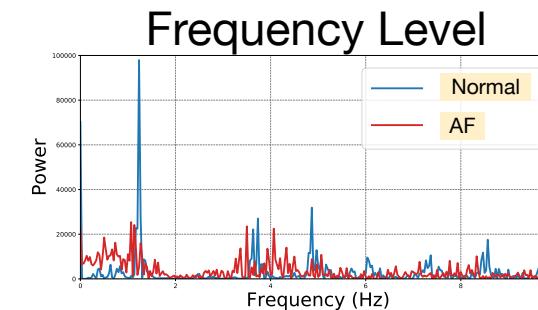
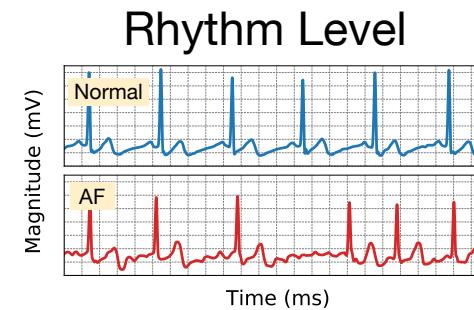
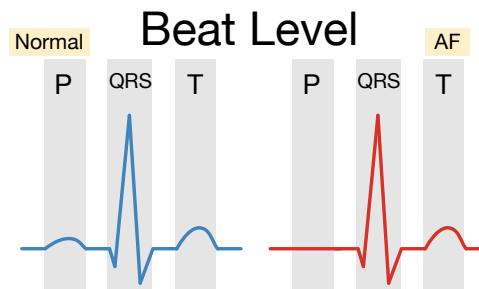
Deep learning models showed initial success in modeling ECG

- Convolutional neural networks (CNN)
- Recurrent neural networks (RNN)
- Attention mechanism

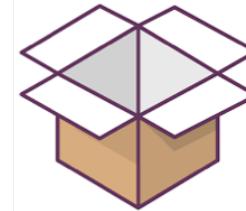
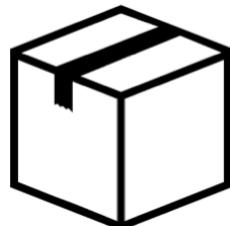
Challenges



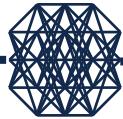
Incorporate **knowledge** across different levels



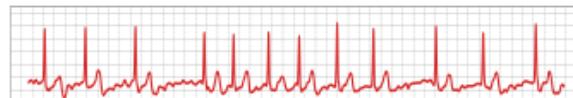
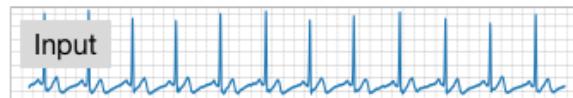
Provide **interpretable** results



Multilevel Deep Neural Network



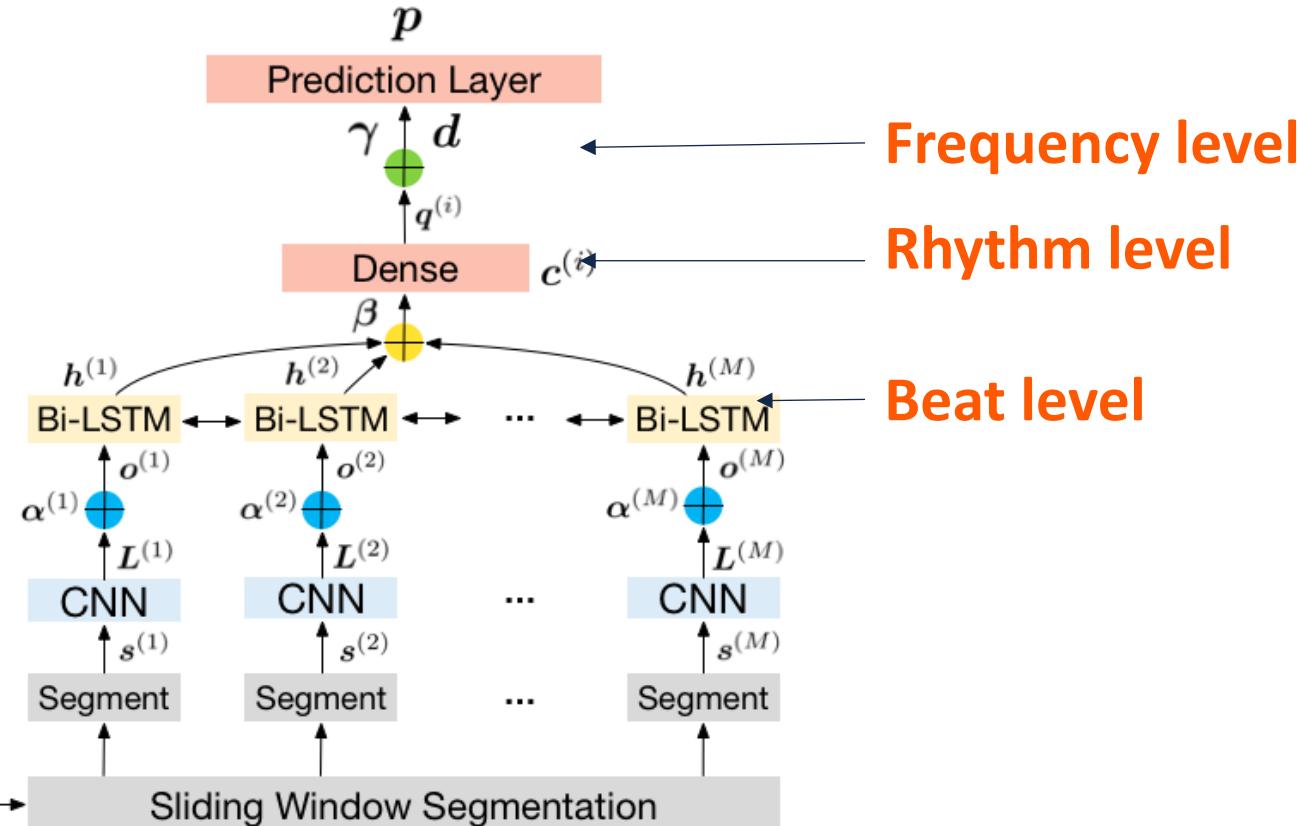
- Frequency Attention
- Rhythm Attention
- Beat Attention

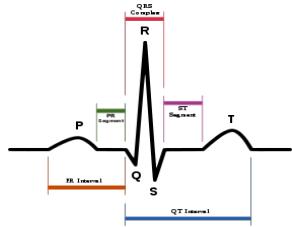


x

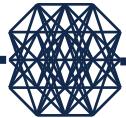
Frequency Transformation Layer

X

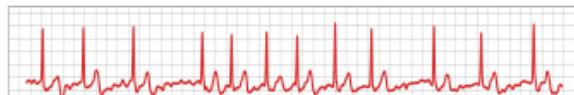
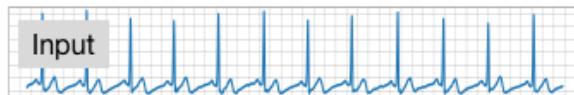




Beat-level attention



- Frequency Attention
- Rhythm Attention
- Beat Attention

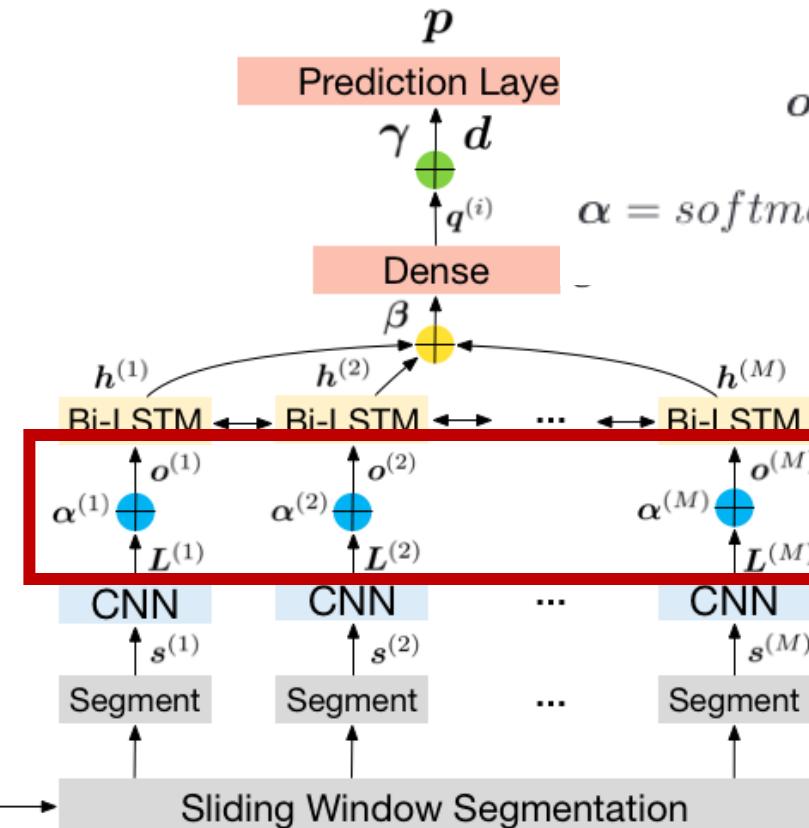


x

Frequency Transformation Layer

X

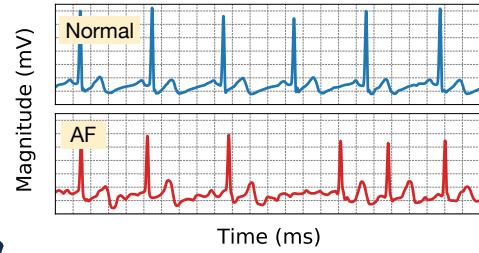
Sliding Window Segmentation



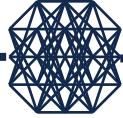
$$o = \sum_{j=1}^N \alpha_j l^{(j)}$$

$$\alpha = softmax(\mathbf{V}_\alpha^T (\mathbf{W}_\alpha^T \begin{bmatrix} \mathbf{L} \\ \mathbf{K}_\alpha \end{bmatrix} \oplus \mathbf{b}_\alpha))$$

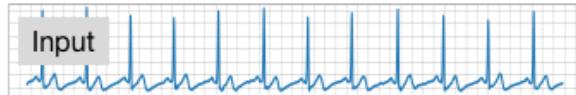
External knowledge:
abnormal wave shapes,
sharp change points



Rhythm level attention



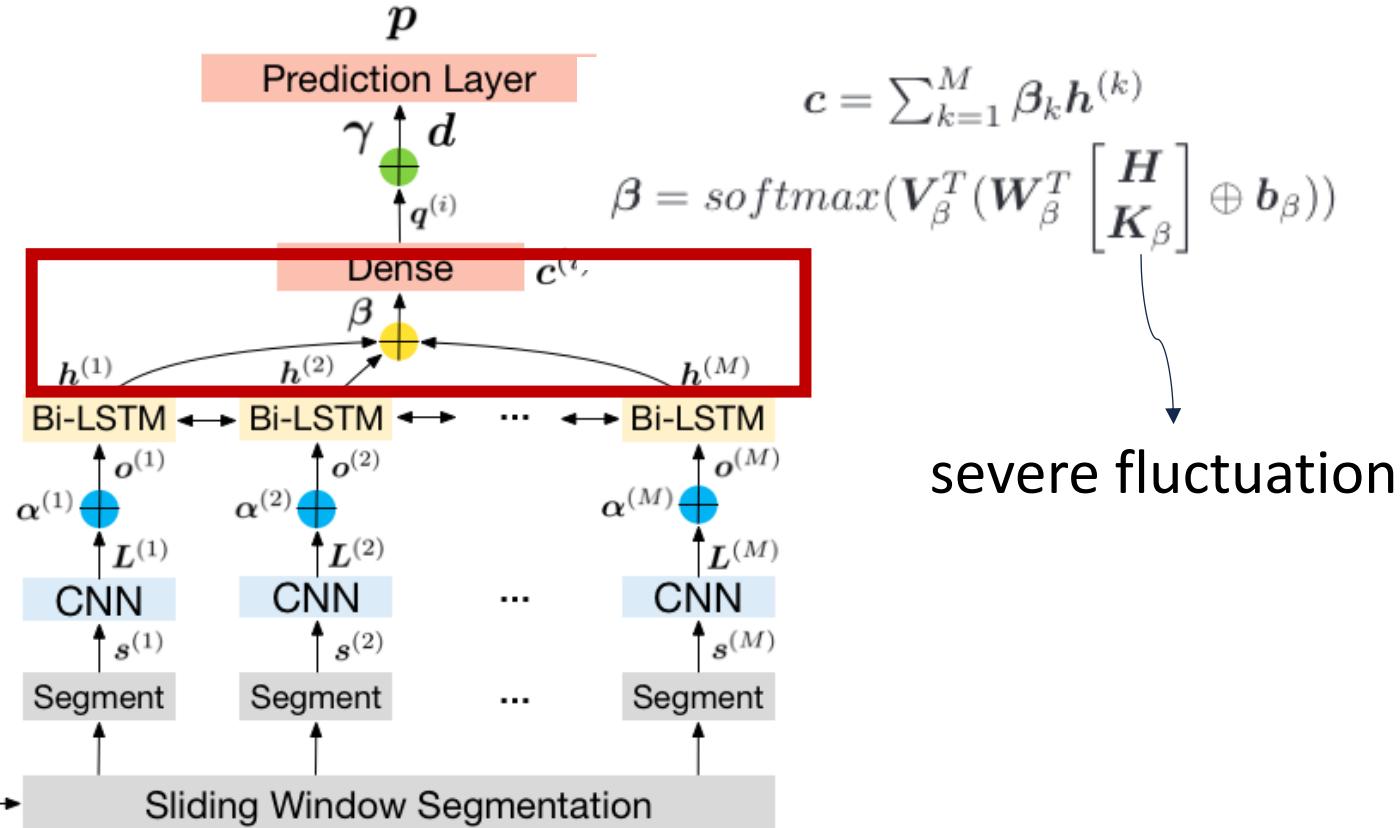
- Frequency Attention
- Rhythm Attention
- Beat Attention

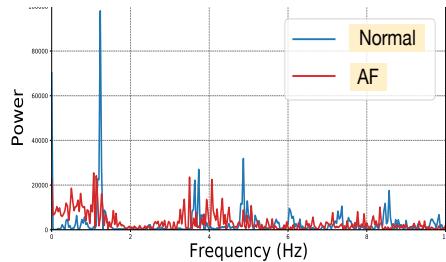


x

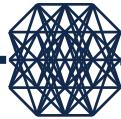
Frequency Transformation Layer

X

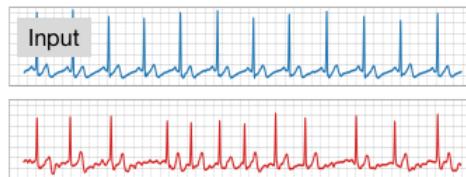




Frequency level attention



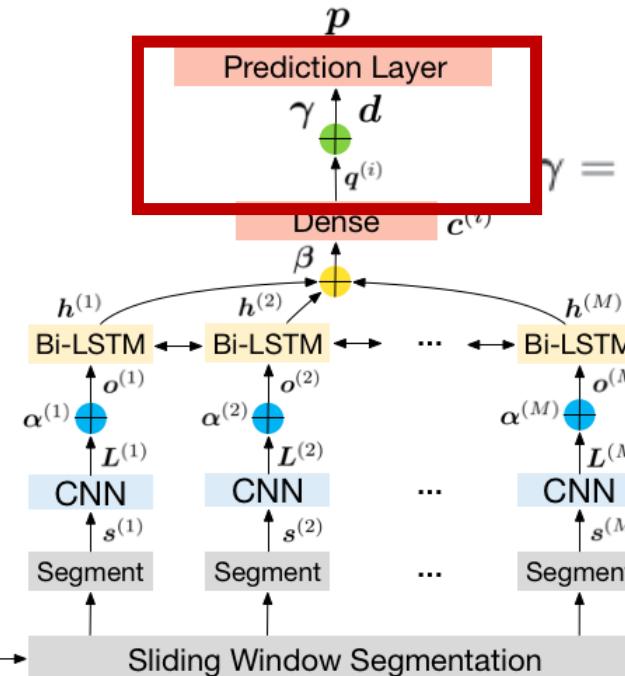
- Frequency Attention
- Rhythm Attention
- Beat Attention



x

Frequency Transformation Layer

X



$$d = \sum_{i=1}^F \gamma_i q^{(i)}$$

$$\gamma = \text{softmax}(V_\gamma^T \begin{bmatrix} Q \\ K_\gamma \end{bmatrix} \oplus b_\gamma))$$

power spectral density

Experiments



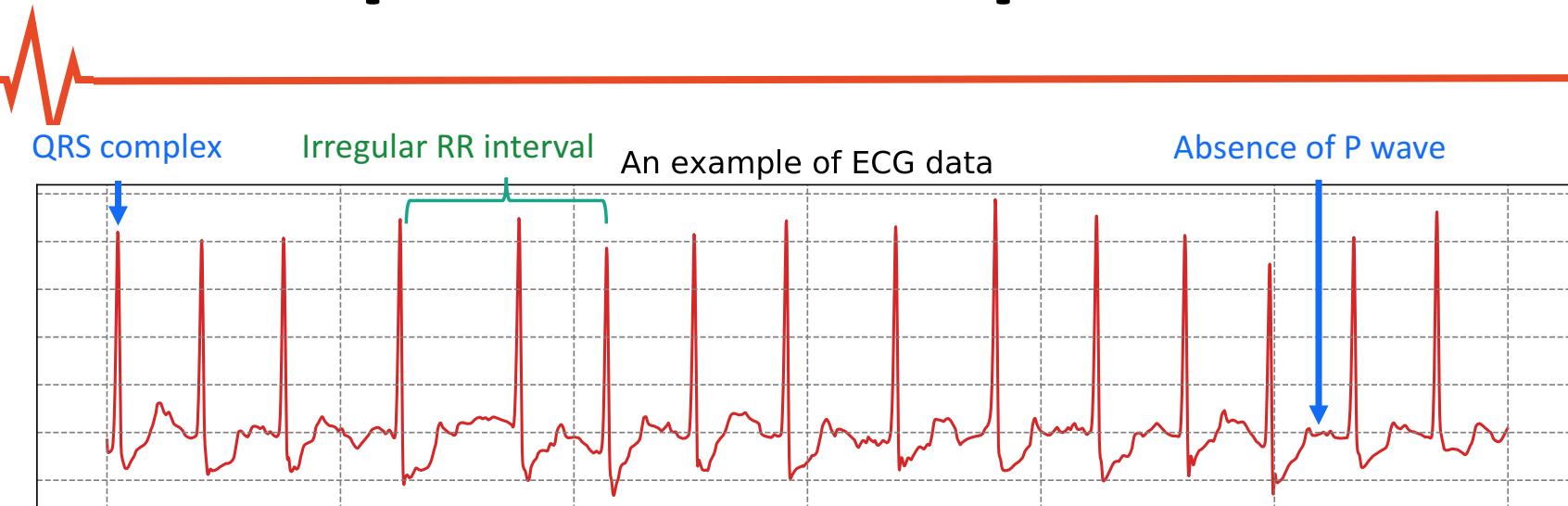
PhysioNet Challenge 2017 databases

- ECG recordings lasting from 9s to just over 60s and sampled at 300Hz by the AliveCor device
- 738 from AF patients and 7790 from controls as predefined by the challenge

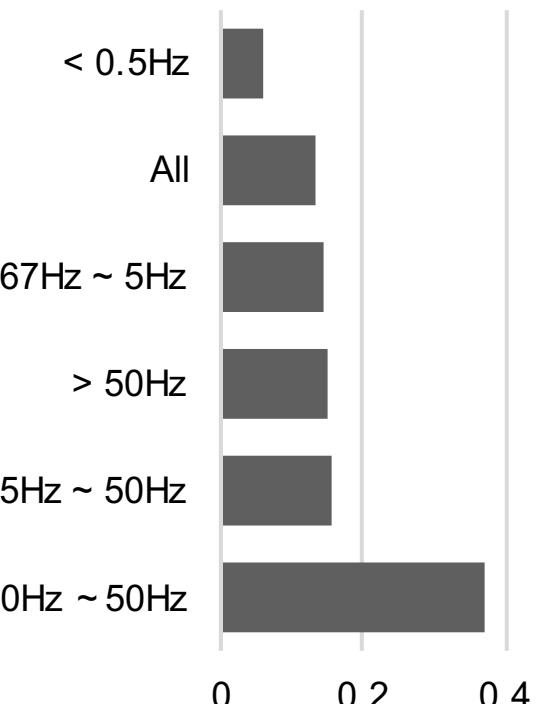
Discriminate records of AF patients from those of controls

	ROC-AUC	PR-AUC	F1
ExpertLR	0.9350 ± 0.0000	0.8730 ± 0.0000	0.8023 ± 0.0000
ExpertRF	0.9394 ± 0.0000	0.8816 ± 0.0000	0.8180 ± 0.0000
CNN	0.8711 ± 0.0036	0.8669 ± 0.0068	0.7914 ± 0.0090
CRNN	0.9040 ± 0.0115	0.8943 ± 0.0111	0.8262 ± 0.0215
ACRNN	0.9072 ± 0.0047	0.8935 ± 0.0087	0.8248 ± 0.0229
MINA	0.9488 ± 0.0081	0.9436 ± 0.0082	0.8342 ± 0.0352

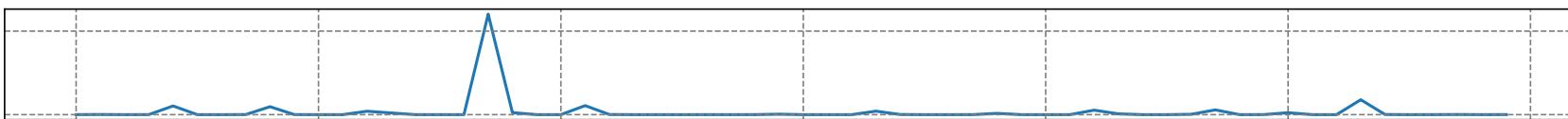
MINA provides interpretable results



Frequency level attention
shows QRS complex is dominant
between 10Hz ~ 50 Hz.

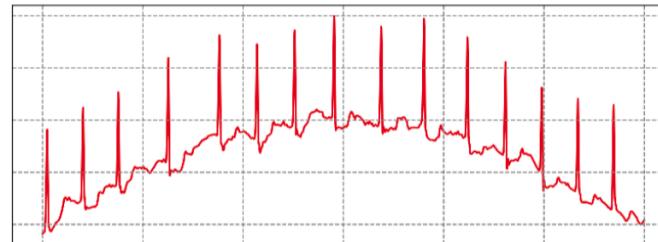


Beat level attention points the location of QRS complex and absent P waves.

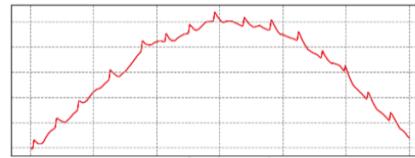


Rhythm level attention shows the location of abnormal RR interval.

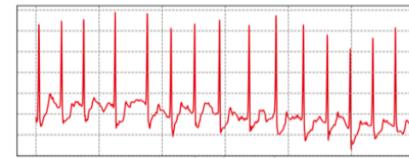
Experiment: MINA handles well low frequency noise



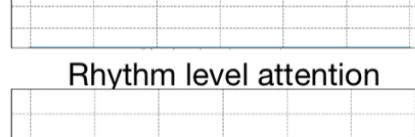
(a) Baseline wandering distortion ECG signal



Beat level attention

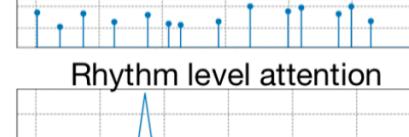


Rhythm level attention

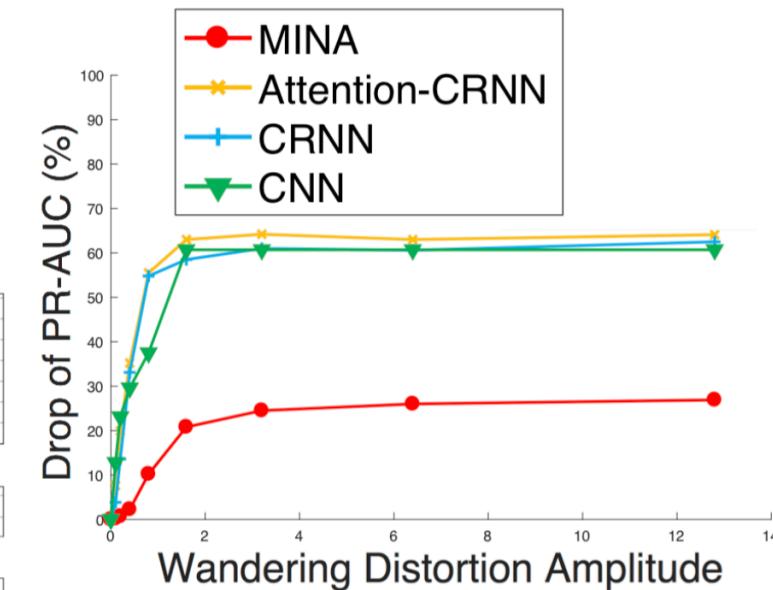


Rhythm level attention

(b) Channel 1

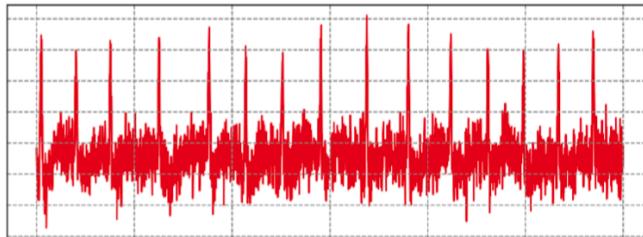


(c) Channel 2

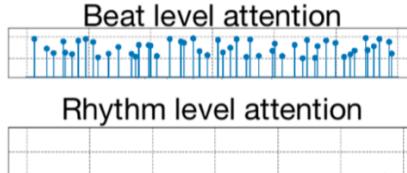
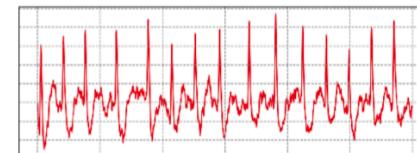
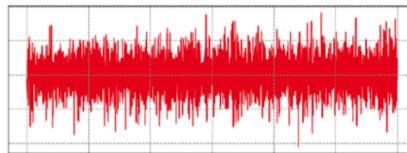


(d) Performance drop comparison

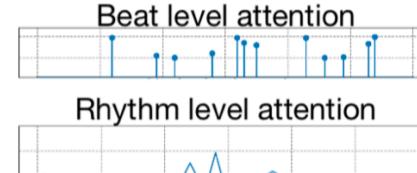
Experiment: MINA handles well high frequency noise



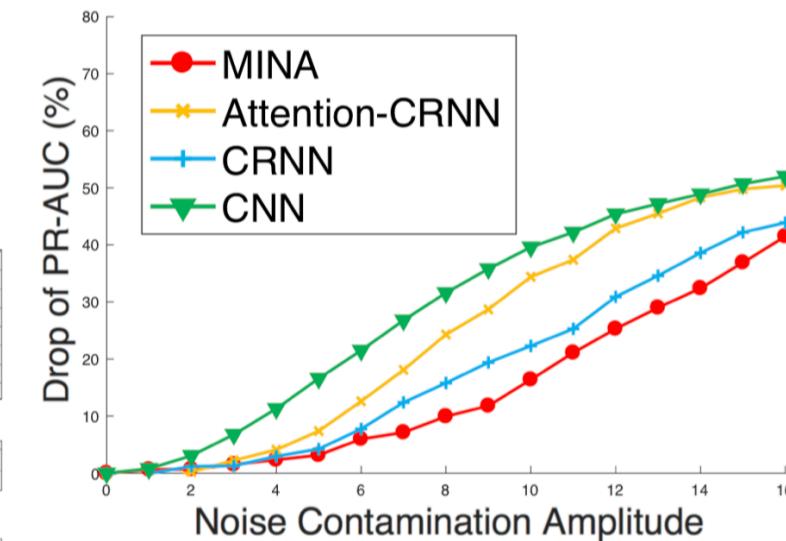
(a) Noise contamination ECG signal



(b) Channel 3



(c) Channel 2



(d) Performance drop comparison