

# PA1 Report

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## Part 1: DAN

## Part 2: BPE

## Part 3: Skip-Gram

### Q1

3a) We are given the skip-gram model defined as:

$$P(\text{context} = y | \text{word} = x) = \frac{\exp(\mathbf{v}_x \cdot \mathbf{c}_y)}{\sum_{y'} \exp(\mathbf{v}_x \cdot \mathbf{c}_{y'})}$$

where  $x$  is the "center word",  $y$  is a "context word" being predicted, and  $\mathbf{v}_x$  and  $\mathbf{c}_y$  are  $d$ -dimensional vectors corresponding to words and contexts respectively. Each word has independent vectors for each, thus each word has two embeddings.

Given the sentences:

the dog  
the cat  
a dog

window size of  $k = 1$ , we get the training examples:  $(x = \text{the}, y = \text{dog})$ ,  $(x = \text{dog}, y = \text{the})$ . Consequently, the skip-gram objective, log-likelihood is  $\sum_{(x,y)} \log P(y|x)$ . With word and context embeddings of dimension  $d = 2$ , the context embedding vectors  $w$  for *dog* and *cat* are both  $(0, 1)$ , and the embeddings vectors  $w$  for *a* and *the* are  $(1, 0)$ . Thus, the set of probabilities  $P(y|\text{the})$  that maximize the log-likelihood are:

$$P(y|\text{the}) = \begin{cases} \frac{1}{2} & y = \text{dog} \\ \frac{1}{2} & y = \text{cat} \\ 0 & y = \text{a} \\ 0 & y = \text{the} \end{cases}$$

- 3b) We want a setting  $\mathbf{v}_{\text{the}}$  where  $P(\text{dog}|\text{the}) \approx 0.5$ ,  $P(\text{cat}|\text{the}) \approx 0.5$ , and  $P(\text{a}|\text{the}), P(\text{the}|\text{the}) \approx 0$ . We know we can calculate  $P(y|\text{the})$  as:

$$P(y|\text{the}) = \frac{\exp(\mathbf{v}_{\text{the}} \cdot \mathbf{c}_y)}{\sum_{y'} \exp(\mathbf{v}_{\text{the}} \cdot \mathbf{c}_{y'})}$$

$$= \frac{\exp(\mathbf{v}_{\text{the}} \cdot \mathbf{c}_y)}{\exp(\mathbf{v}_{\text{the}} \cdot \mathbf{c}_{\text{dog}}) + \exp(\mathbf{v}_{\text{the}} \cdot \mathbf{c}_{\text{cat}}) + \exp(\mathbf{v}_{\text{the}} \cdot \mathbf{c}_{\text{a}}) + \exp(\mathbf{v}_{\text{the}} \cdot \mathbf{c}_{\text{the}})}$$

We know that  $\mathbf{c}_{\text{dog}} = \mathbf{c}_{\text{cat}} = (0, 1)$  and  $\mathbf{c}_{\text{a}} = \mathbf{c}_{\text{the}} = (1, 0)$ . Thus, we want the dot products of cat and dog to be very large and positive, while minimizing the dot products of a and the. Therefore, we can look for settings of  $\mathbf{v}_{\text{the}}$  in a  $(-C, C)$  format. We search for such values using a Python script `part3.py` by iterating through values from 1 upwards and calculating the probabilities until we find that a nearly optimal vector within 0.01 of the optimum, which is  $\mathbf{v}_{\text{the}} = (-2, 2)$ . Increasing the values further brings the probabilities closer to the target.

## Q2

- 3c) With a word embedding space  $d = 2$ , the training examples derived from the sentences:

```
the dog
the cat
a dog
a cat
```

with window size  $k = 1$  are:

$$(x = \text{the}, y = \text{dog})$$

$$(x = \text{dog}, y = \text{the})$$

$$(x = \text{the}, y = \text{cat})$$

$$(x = \text{cat}, y = \text{the})$$

$$(x = \text{a}, y = \text{dog})$$

$$(x = \text{dog}, y = \text{a})$$

$$(x = \text{a}, y = \text{cat})$$

$$(x = \text{cat}, y = \text{a})$$

- 3c) We see that each center word appears equally often with each context word. Thus, the optimal probabilities for each context word given a

center word are:

$$\begin{aligned} P(\text{the}|\text{dog}) &= P(\text{a}|\text{dog}) = 0.5 \\ P(\text{the}|\text{cat}) &= P(\text{a}|\text{cat}) = 0.5 \\ P(\text{dog}|\text{the}) &= P(\text{cat}|\text{the}) = 0.5 \\ P(\text{dog}|\text{a}) &= P(\text{cat}|\text{a}) = 0.5 \end{aligned}$$

and all other context words have probability 0. With context vectors:

$$\begin{aligned} \mathbf{c}_{\text{dog}} &= \mathbf{c}_{\text{cat}} = (0, 1) \\ \mathbf{c}_{\text{a}} &= \mathbf{c}_{\text{the}} = (1, 0) \end{aligned}$$

we can find nearly optimal word vectors  $\mathbf{v}_w$  for each word  $w$  using similar logic as in 3b. However, we also need to ensure that  $\mathbf{v}_{\text{dog}}$  and  $\mathbf{v}_{\text{cat}}$  this time give equal probabilities, and thus should follow  $(C, -C)$  format instead. From our value in 3b, we then obtain the following vectors:

$$\begin{aligned} \mathbf{v}_{\text{the}} &= (-2, 2) \\ \mathbf{v}_{\text{a}} &= (-2, 2) \\ \mathbf{v}_{\text{dog}} &= (2, -2) \\ \mathbf{v}_{\text{cat}} &= (2, -2) \end{aligned}$$

Running `part3.py` confirms that these vectors yield probabilities within 0.01 of the optimum.