

# Contents

|          |                                                                                          |           |
|----------|------------------------------------------------------------------------------------------|-----------|
|          | <b>Preface</b> .....                                                                     | <b>xi</b> |
| <b>1</b> | <b>Introduction</b> .....                                                                | <b>1</b>  |
| <b>2</b> | <b>Monolingual Word Embedding Models</b> .....                                           | <b>9</b>  |
| <b>3</b> | <b>Cross-Lingual Word Embedding Models: Typology</b> .....                               | <b>13</b> |
| <b>4</b> | <b>A Brief History of Cross-Lingual Word Representations</b> .....                       | <b>21</b> |
| 4.1      | Cross-Lingual Word Representations using Bilingual Lexicons .....                        | 24        |
| 4.2      | Cross-Lingual Word Embeddings and Word Alignments .....                                  | 27        |
| 4.3      | Representations Based on Latent and Explicit Cross-Lingual Concepts .....                | 29        |
| 4.4      | Summary .....                                                                            | 32        |
| <b>5</b> | <b>Word-Level Alignment Models</b> .....                                                 | <b>33</b> |
| 5.1      | Word-level Alignment Methods with Parallel Data .....                                    | 33        |
| 5.1.1    | Mapping-Based Approaches .....                                                           | 34        |
| 5.1.2    | Pseudo-Mixing Approaches .....                                                           | 41        |
| 5.1.3    | Joint Approaches .....                                                                   | 42        |
| 5.1.4    | Sometimes Mapping, Joint, and Pseudo-Bilingual Approaches are<br>Equivalent .....        | 44        |
| 5.2      | Word-Level Alignment Methods with Comparable Data .....                                  | 46        |
| <b>6</b> | <b>Sentence-Level Alignment Methods</b> .....                                            | <b>49</b> |
| 6.1      | Sentence-Level Methods with Parallel Data .....                                          | 49        |
| 6.2      | Sentence Alignment with Comparable Data .....                                            | 53        |
| <b>7</b> | <b>Document-Level Alignment Models</b> .....                                             | <b>55</b> |
| 7.1      | Document Alignment with Comparable Data .....                                            | 55        |
| <b>8</b> | <b>From Bilingual to Multilingual Training</b> .....                                     | <b>59</b> |
| 8.1      | Multilingual Word Embeddings from Word-Level Information .....                           | 60        |
| 8.2      | Multilingual Word Embeddings from Sentence-Level and<br>Document-Level Information ..... | 64        |

|           |                                                                     |            |
|-----------|---------------------------------------------------------------------|------------|
| <b>9</b>  | <b>Unsupervised Learning of Cross-Lingual Word Embeddings</b> ..... | <b>67</b>  |
| 9.1       | Seed Dictionary Induction .....                                     | 68         |
| 9.2       | Refinement and Heuristics .....                                     | 72         |
| 9.3       | Limitations of Unsupervised Approaches .....                        | 74         |
| <b>10</b> | <b>Applications and Evaluation</b> .....                            | <b>75</b>  |
| 10.1      | Intrinsic Evaluation .....                                          | 75         |
| 10.2      | Extrinsic Evaluation Through Cross-Lingual Transfer .....           | 76         |
| 10.3      | Multi-Modal and Cognitive Approaches to Evaluation .....            | 80         |
| <b>11</b> | <b>Useful Data and Software</b> .....                               | <b>83</b>  |
| 11.1      | Monolingual Resources .....                                         | 83         |
| 11.2      | Cross-Lingual Data .....                                            | 84         |
| 11.3      | Cross-Lingual Word Embedding Models .....                           | 84         |
| 11.4      | Evaluation and Application .....                                    | 86         |
| <b>12</b> | <b>General Challenges and Future Directions</b> .....               | <b>89</b>  |
|           | <b>Bibliography</b> .....                                           | <b>93</b>  |
|           | <b>Authors' Biographies</b> .....                                   | <b>119</b> |