Random Indexing Re-Hashed

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Outline

1. Review random indexing for dimensionality reduction.
2. Review the notion of universal families of hash functions.
3. Show how $1 + 2 = \text{hashed random indexing.}$
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2. Review the notion of universal families of hash functions.
3. Show how $1 + 2 = $ hashed random indexing.
4. Caveats.
5. Pilot experiments.
6. Summing up.
Random Indexing: Some History

- Initially intended as a **compact** way of modeling the semantic similarity of words in **word-by-document vector spaces** by Kanerva et al. (2000).

- Much work on RI-based **semantic spaces** has later followed (e.g. Karlsgren & Sahlgren, 2001; Sahlgren, 2005).

- Many previous NODALIDA papers on RI;
  - Sahlgren and Swanberg (2001), Gambäck et al. (2003), Sahlgren (2003), Holmlund et al. (2005), Kann and Rosell (2005), Hassel and Sjöbergh (2007),...
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- Velldal (2010) applied RI for SVM-based uncertainty classification.
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- Velldal (2010) applied RI for **SVM-based uncertainty classification**.

- **Note**: While *not* here assuming any particular type of data or application, we will assume a **vector space model** for representation:
  - Given *n* examples and *d* features, the feature vectors can be thought of as rows in a matrix $F \in \mathbb{R}^{n \times d}$. 
Random Indexing

Goal

- Instead of using the original $n \times d$ feature matrix $F$, we will construct an $n \times k$ matrix $G$, where $k \ll d$.

Two Simple Steps

- As a new feature is instantiated, it is assigned a randomly generated index vector: A vector with a fixed dimensionality $k$, consisting of a small number of $-1$s and $+1$s, with the remaining elements set to 0.
- The vector representing a given training example (a row in $G$) is given by simply summing the random index vectors of its features.

Parameters

- The number of non-zeros ($\epsilon$) and the dimensionality ($k$).
Constructing Feature Vectors: the Standard Approach

Features:

Feature activations:

Feature vector $f(x)$:

Dimensions:
Constructing Feature Vectors: the Standard Approach

Features: $f_1, f_2, f_3, f_4, f_5, \ldots, f_d$

Feature activations: $+1, +1, +1$

Feature vector $f(x)$:

Dimensions: 1 2 3 4 5 ... d
Constructing Feature Vectors: the Standard Approach

Features: $f_1, f_2, f_3, f_4, f_5, ...$

Feature activations: $\downarrow 1 \downarrow 1 \downarrow 1$

Feature vector $f(x)$:

Dimensions: $1, 2, 3, 4, 5, ...$

As many dimensions as there are features.

Each feature $f_i$ maps to one dimension $i$. 
Constructing Feature Vectors: the Standard Approach

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- The mappings correspond to orthogonal vectors.

Feature activations:
- As many dimensions as there are features.

Feature vector $f(x)$:
- The feature vector of a given example $f(x)$ is simply the sum of its active features.

Dimensions:
Constructing Feature Vectors: the RI Approach

Features:

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Feature vector $f(x)$:

Dimensions:
Constructing Feature Vectors: the RI Approach

Each feature $f_i$ is randomly mapped to several dimensions, valued -1 or +1.

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The dimensionality is lower than the number of features.
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Features:

Feature activations:

The dimensionality is lower than the number of features.

$f(x) = \text{the sum of the index vectors of } x$'s features.
RI—an example of Random Projections

- For $F \in \mathbb{R}^{n \times d}$ and a random matrix $R \in \mathbb{R}^{d \times k}$, where $k \ll d$:

  $$FR = G \in \mathbb{R}^{n \times k}$$

- The pairwise distances in $F$ can be preserved in $G$ with high probability (the Johnson-Lindenstrauss lemma).

- The rand. index of the $i$th feature corresponds to the $i$th row of $R$. 
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A particular advantage of RI

- Constructs $G$ by *incrementally* accumulating the index vectors.
  - Means that $F$ does not need to be explicitly computed.
  - Constructs $G$ directly (dimension reduction only implicit).
  - Can easily add more data without recomputing $R$ and $G$.
  - Suitable for parallelization and stream processing.
Rethinking the Random Index Representation

- Storage is fairly cheap: For each index vector we only need to keep track of the signs and the positions of the non-zeros.
- Still, for hundreds of thousands or millions of features, it adds up...
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  - Hashed-based data structure for compactly representing set membership.
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- Still, for hundreds of thousands or millions of features, it adds up . . .
- Taking a step back, the index vectors are reminiscent of probabilistic data structures like Bloom Filters . . .
  - Hashed-based data structure for compactly representing set membership.
- Idea: We can save resources by having a set of hash functions compute and represent the index vectors.
  - Eliminates the need for storing $R$. 
Hashing

- For some set of hash keys $U = \{x_1, \ldots, x_k\}$, a hash function $h$ maps each $x_i$ into some smaller set of hash codes $I = \{i_1, \ldots, i_l\}$.
  - $h : U \rightarrow I$ with $|U| \geq |I|$.

- We can use hashing to implement the compression of RI;
  - The keys $U$ are dimensions in the original space.
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- Collisions; multiple keys may be mapped to the same hash code.
  - Need to distribute codes as evenly as possible to reduce the noise.

- RI uses one-to-many mappings, so we need multiple hash functions.
Universal Families of Hash Functions

- Introduced by Carter and Wegman (1979).
- A method for randomly generating hash functions $h_i : U \to I$ from a family of functions $H$ that guarantees that the probability of a collision for any two distinct keys is bounded by $1/|I|$.
- On demand, we can randomly select deterministic functions from $H$ that maps the data to indices/codes as if at random.
- There exists several ways of implementing such universal classes...
Multiplicative Universal Hashing (Dietzfelbinger et al., 1997)

- A particularly simple class of mappings from \(k\)-bit keys to \(l\)-bit indices.
  - Let \(U = \{0, \ldots, 2^k - 1\}\) and \(I = \{0, \ldots, 2^l - 1\}\).
  - Let \(A = \{a \mid 0 < a < 2^k \text{ and } a \text{ is odd}\}\).
  - Now \(H_{k,l} = \{h_a \mid a \in A\}\) defines a 2-universal family where
    \[
    h_a(x) = (ax \mod 2^k) \div 2^{k-l} \quad \text{for } 0 \leq x < 2^k
    \]
  - For two distinct keys \(x\) and \(y\) in \(U\), \(h_a\) obeys
    \[
    \text{Prob}(h_a(x) = h_a(y)) \leq \frac{1}{2^{m-1}}
    \]
  - By randomly picking a number \(a \in A\) we generate a new hash function \(h_a\) from the set of \(2^{k-1}\) distinct hash functions in \(H_{k,l}\).
  - Efficient bit-level implementation of modulo and integer division.
Any set of random index vectors with \( \epsilon \) non-zeros in each can now be implicitly represented by a set of \( \epsilon \) functions \( \{h_{\alpha^1}, \ldots, h_{\alpha^\epsilon}\} \subset H_{k,l} \).

Half of the functions indicate \(-1\)s and the other \(+1\)s.
Hashed Random Indexing

- Any set of random index vectors with $\epsilon$ non-zeros in each can now be implicitly represented by a set of $\epsilon$ functions $\{h_{a1}, \ldots, h_{a\epsilon}\} \subset H_{k,l}$.
- Half of the functions indicate $-1$s and the other $+1$s.
- Eliminates the $R \in \mathbb{R}^{d \times k}$ random matrix:
  - Store $\epsilon$ integers instead of the $d\epsilon$ signed positions minimally required otherwise.
- Can compute $FR = G$ without explicitly representing neither $F$ or $R$. 
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- Can compute $FR = G$ without explicitly representing neither $F$ or $R$.
- Better support for parallelization:
  - The only knowledge that needs to be shared is the seed numbers.
Caveats

- Random projection methods (such as RI) are often applied for reducing memory load and computational cost...

- However, if your original space $F$ is very sparse, the dimensionality reduction might give you the opposite effect.
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- However, if your original space $F$ is very sparse, the dimensionality reduction might give you the opposite effect.

- Why?
  - Because the reduced space $G$ will then be much more dense than $F$,
  - and the cost of storage and standard vector operations depend not on dimensionality alone, but on the number of non-zero elements.
  - Zero-valued elements can be ignored.
Pilot Experiments with Applying HRI

- Joint work with Lilja Øvrelid (University of Oslo) and Fredrik Jørgensen (Meltwater News).
- Two SVM-based classification tasks with large feature spaces:
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- Two SVM-based classification tasks with large feature spaces:
  - Stacked dependency parsing (Maltparser) on the Tiger treebank:
    - Features: 500,000 → 16,384 ($\epsilon = 4$)
    - UAS: 90.15 → 90.00
    - LAS: 87.83 → 87.65
  - Uncertainty detection on the CoNLL-2010 shared task data:
    - Feature reduction: 670,000 → 8,192 ($\epsilon = 4$)
    - Sentence-level F$_1$: 86.78 → 86.91
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- Feature space reduced by up to two orders of magnitude without statistically significant differences in classifier accuracy!
Summing up:

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- **Hashed Random Indexing:**
  - Efficient reformulation of RI.
  - No need to explicitly represent the random vectors.
  - Rely on universal hashing instead.
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- Hashing—an emerging trend in NLP!
  - Several recent studies the use of hashing for scaling up models.
  - Locality sensitive hashing, sketching, generalized bloom filters, hash-kernels, the hashing-trick, random feature mixing.
  - The relation to HRI further discussed in Velldal (2011).
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