

Prospective Data Fusion for Batch Filtering *

Andrei Anghelescu*, Endre Boros^R, Dmitriy Fradkin*, David Lewis[†], Vladimir Menkov**,
David Neu^R Kwong Bor Ng⁺, Paul Kantor⁼

angheles@cs.rutgers.edu, boros@rutcor.rutgers.edu, dfradkin@paul.rutgers.edu, ddlewis@worldnet.att.net
vmenkov@cs.indiana.edu, neu@rutcor.rutgers.edu,
kbng@scils.rutgers.edu, kantor@scils.rutgers.edu

ABSTRACT

This paper explores the problem of “global” data fusion rules, or combination of evidence. Three rather different schemes for computing the similarity between documents and a set of judged documents are employed. The goal is to learn whether rules for score combination (sometimes called “fusion rules” can be *learned* from a random selection of filtering problems **L** and then applied to another collection of filtering problems **T**. Results are encouraging, and set the stage for further research into “when” (that is, under what conditions) it will be effective to use two or more systems in fusion.

Categories and Subject Descriptors

Information Retrieval [**Filtering of Documents**]: Data Fusion

General Terms

Data Fusion; Linear Classifiers

Keywords

Data Fusion; Filtering; Linear Classifiers; Learning

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1. INTRODUCTION

The work reported here is part of a larger project on identifying interesting messages in large streams of data. Although the results described here are evaluated using a TREC-style metric, the results here are not TREC results and the data submitted here were not necessarily presented at any TREC conference.

The question at issue is whether having multiple systems or schemes for information filtering can lead to better overall system performance. This question can be posed in two ways, which we will call “local” and “global”. The local question asks whether, for a given profile or topic, it is possible to find an excellent rule for combining the scores produced by two systems, so that the combined rule yields higher performance than the individual methods. [1][14] [12] [15] [8] [2] [13] In this setting, the obvious competitor is the best of the two individual methods, which can be presumed known after some period of training. Thus, the question becomes, “can the combined system produce performance better than that of the better system?” There is considerable evidence that for some topics this is true and for others it is not. We consider here the *global* question: If we have information about the performance of two individual systems and their possible combinations on a set of training topics (denoted by **L**), can we form a rule for combination - which can be carried over with confidence - to a completely different set of topics, which we will call the “test topics” (denoted by **T**)?

This global question is obviously of interest to system designers and to those who must purchase or select among multiple systems for message filtering.

In this research, the several schemes used to produce different scores are the result of training exercises to refine the classification rule. For the voting method, the training was done on the TREC2002 Batch filtering task. For the other two methods the training was done on the TREC2002 adaptive filtering task. Thus the results of this work are intended to shed light on the underlying issues of data fusion, and do not represent “post-hoc” claims as to performance achievable in the TREC2002 setting.

2. ACKNOWLEDGMENT.

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3. PRELIMINARIES

In what follows, we will examine only linear rules for the combination of scores. Thus it is not, strictly speaking, necessary to perform any preliminary normalization. However, the discussion and the interpretation of the results are much simpler if we first normalize the raw scores assigned by system i to document d , $S_i^{raw}(d)$, according to the formula:

$$s_i(d) = \frac{S_i^{raw}(d) - \min_d(S_i^{raw}(d))}{\max_d(S_i^{raw}(d)) - \min_d(S_i^{raw}(d))} \quad (1)$$

Note that we have suppressed a topic index, which will be needed in the eventual discussion.

Following the suggestion of [one of the authors], we form the fusion rule for a pair of systems (1 and 2) by a two-step linear discriminant process. For the given topic, all the documents whose relevance judgment is known can be represented by points in the $s_1 - s_2$ plane. The first step is to define the normal vector, β to a candidate separating line. This is defined by minimizing the objective function $M(\beta)$.

$$M(\beta) = \sum_{d \in P} (1 - \beta \cdot \mathbf{s}(d))^2 + \sum_{d \in N} (\beta \cdot \mathbf{s}(d))^2 \quad (2)$$

where $\mathbf{s}(d) = (\mathbf{s}_1(d), \mathbf{s}_2(d))$, and $a \cdot b$ is the Euclidean inner product of a and b in the plane.

The selected normal vector is represented as β^* .

$$\beta^* = \operatorname{argmin}_{\beta} (M(\beta)). \quad (3)$$

Since β is a pair of numbers but contains only one piece of information, we replace it by a single number α defined so that

$$\alpha/(1 - \alpha) = \beta_1/\beta_2 \quad (4)$$

In addition, the system must select a threshold value τ which will define the classification rule applied to incoming documents. Specifically, a document will be sent for evaluation if and only if $\alpha s_1 + (1 - \alpha)s_2 \geq \tau$. The result is that some number $P(\alpha, \tau)$ of positive (relevant) documents will be selected, and some number $N(\alpha, \tau)$ of negative (not relevant) documents will be selected. We use the ‘‘TREC-like’’ utility function $U_{11} = 2P - N$. We define the optimal value of τ as $\tau^* = \operatorname{argmax}_{\tau} (U_{11}(\tau))$.

In reality, this process is done separately for each topic, and each pair of systems, resulting in a pair of parameters: α, τ (we suppress the asterisk at this point).

We note at the outset that our approach is not totally optimal because, in the results to be shown later in the paper, we actually use a peculiar modified TREC score, which was introduced to avoid embarrassment to competitors, and is bounded from below. Results would presumably be somewhat different if this objective were also used to define α^*, τ^* .

4. THE SPECIFIC METHODS

The three different methods that we will describe are a simple Rocchio-type classifier **R** [11]; a classifier that uses the centroid of a positive (or relevant documents), the centroid of the negative cases, and the origin in the docu-

ment vector space, which we call the ratio classifier (represented by **C**) and finally a complex scoring and representation scheme which selects terms based on their ability to resolve positive and negative documents. Since this scheme lets 5 different methods for computing resolving power **Vote** on the term selection, we denote it by **V**.

In general, we represent documents in terms of the frequency with which specific stemmed (Porter stemmer) non-stop (SMART stop words) tokens appear. If $f(d, i)$ is the frequency with which the i -th term appears in document d then components of the vector representing d are given by $d_i = 1 + \log(f(i))$ with the value 0 if $f(i) = 0$. The weighting of terms is given by an ‘‘inverse document frequency’’ or IDF metric $\rho(t, t') = \delta_{t,t'} \log \frac{1+C}{1+C(t)}$. Here $C(t)$ is the number of documents in which the term t appears at least once, and C is the total number of documents in the corpus. $\delta_{t,t'}$ is the Kronecker delta, which vanishes unless the indices are equal, where it takes the value 1. Inner products are defined in terms of this metric tensor by the equation $(d, d') = \sum_{t,t'} f(d, t) \rho(t, t') f(d', t')$.

The Rocchio method is modified in that at each step the 30 terms having greatest weight in the updated classification vector (or query vector) are retained and all the others are dropped. This introduces some non-linearity in the learning process.

The specific algorithm is given in pseudocode as

Algorithm 1 Query term selection

Require: query vector Q , k

```

1: for  $t \in Q$  do
2:   if  $t < 0$  then
3:      $t = 0$ 
4:   end if
5: end for
6:  $S = \text{reverse}(\text{sort}(Q))$ 
```

Ensure: $S[1 : \min(|S|, k)]$, the top k positive components of Q

Each of these three systems has been developed (and certain parameters fixed once for all) in experiments conducted for the TREC2002 conference. These parameters have not been optimized for the present experiments, but simply represent a possible starting point for the investigations on fusion.

The Rocchio and Centroid methods used for their training materials a complex set of information: (1) an original topic or query statement (2) a set of 3 judged relevant documents (3) a set of pseudo-judged documents. All materials are drawn from the the RCV1 corpus, i.e. Reuters newswire stories from August 20, 1996 through August 19, 1997. They are separated into a training set of 83,650 documents (20-Aug-1996 to 30-Sep-1996) and a test set of 723,141 documents (1-Oct-1996 to 19-Aug-1997) Both methods were implemented using the Lemur toolkit [16].

4.1 Details of the Rocchio Algorithm

The training stage of the algorithm consists of the following steps:

1. set Q_0 as the encoding of the query description
2. update Q with the labeled training examples (all are positive)

$$Q_{up} = \alpha \cdot Q_0 + \beta \cdot \sum_{d \in \text{Train}} d$$

3. order all documents in the training set by their scores relative to Q_{up}
4. define the top $p\%$ as pseudo-positives, the remaining as pseudo-negatives
5. uniformly sample n_+ documents from the pseudo-positives (let the selected set be PP)
6. uniformly sample n_- documents from the pseudo-negatives (let the selected set be PN)
7. update Q with

$$Q_{up} = \alpha \cdot Q_0 + \beta \cdot \sum_{d \in PP} w_+ \cdot d - \gamma \cdot \sum_{d \in PN} w_- \cdot d,$$

where w_+, w_- are weights assigned to pseudo-positive and pseudo-negative documents, respectively.

8. calculate the threshold, τ_0 , that maximizes the U_{11} score, given Q and the set of training documents.

We determined experimentally that the following values of parameters work better than the others that we tried:

α	1
β	1
γ	0.125
n_+	20
w_+	0.1
n_-	100
w_-	0.05

These parameters were used to produce the document scores which are identified as $S_{\mathbf{R}}(d)$ in what follows.

4.2 Details of the Centroid Algorithm

The centroid algorithm orders documents by a measure of the ratio of their similarities to the centroids of the positive and negative examples. Thus it builds on the relevance feedback information available to Rocchio, with a key difference. Scores are calculated using the (regularized) ratio of distances between normalized vectors. Specifically, if $\mathbf{p}, \mathbf{n}$ are the unit vectors corresponding to the centroids of the positive and negative examples, and $\mathbf{d}$ is the unit vector corresponding to the document being scored, then

$$s_{\mathbf{C}}(d) = \frac{1 - (\mathbf{n}, \mathbf{d})}{1 - (\mathbf{p}, \mathbf{d})} \quad (5)$$

If the denominator vanishes, the value 10^6 is used as a default.

4.3 The Voting Method

In this method each of five different schemes for assessing the “discriminatory power” of a term is computed. Each of these schemes then “casts one vote” for each of the terms to which it gives a score in the top 50. We then retain the top 50 terms, ranked by the number of votes that they have received. This method currently uses a Boolean formulation of the bag-of-words model.

For each of the $n > 0$ distinct terms in the document collection we associate an index in $V\{1, 2, \dots, n\}$. Letting $\mathbb{B} = \{0, 1\}$, we represent each document in the collection as an n -dimensional *Boolean* vector $\mathbf{x} \in \mathbb{B}^V$. Each component of $\mathbf{x}$ corresponds one of the distinct terms in the document collection, with $x_i = 1$ if the i^{th} term is present in the document and $x_i = 0$ if the i^{th} term is absent from the document.

4.3.1 Ranking Functions

For each $i \in V$, each of the ranking functions presented here utilizes the following four values

- $a_i \equiv$ the number of relevant documents containing the i^{th} term
- $b_i \equiv$ the number of irrelevant documents containing the i^{th} term
- $c_i \equiv$ the number of relevant documents which do not contain the i^{th} term
- $d_i \equiv$ the number of irrelevant documents which do not contain the i^{th} term

For each $i \in V$, the relationship between a_i, b_i, c_i and d_i and the document collection is given by the following 2×2 contingency table

	$y \in P$	$y \in N$	
$x_i = 1$	a_i	b_i	$a_i + b_i = \theta_i$
$x_i = 0$	c_i	d_i	$c_i + d_i = \bar{\theta}_i$
	$a_i + c_i = P $	$b_i + d_i = N $	m

where the marginals θ and $\bar{\theta}_i$ represent the number of documents containing the i^{th} term and the number of documents which do not contain the i^{th} term respectively, and $y \in \mathbb{B}$ is defined as

$$y = \begin{cases} 1 & \text{if } x \in P, \\ 0 & \text{otherwise.} \end{cases}$$

Obviously, the marginals $|P|$ and $|N|$ are constant for all terms while the marginals θ_i and $\bar{\theta}_i$ vary for each term. The total number of documents in the collection is $C = a_i + b_i + c_i + d_i$ which is obviously also a constant.

For the simplicity of notations, we shall view all ranking functions as functions of the four parameters a, b, c and d , though clearly there are only two independent values among these.

In [4] we analyzed and compared a number of possible ranking functions, and based on that study, we selected 5 such functions for this TREC experiment:

Function α

$$\alpha = \left| \frac{a}{a+c} - \frac{b}{b+d} \right| = \frac{|ad-bc|}{|P||N|} \quad (6)$$

is the absolute value of the difference between the number of relevant-irrelevant document pairs in the training collection

which provide evidence that the i^{th} term is a good classifier of relevant documents and the number of relevant-irrelevant document pairs which provide evidence that the i^{th} term is a good classifier of irrelevant documents, normalized by the total number (i.e. both correctly distinguished and incorrectly distinguished) of relevant-irrelevant document pairs.

Function β

$$\beta = \frac{ad + bc}{(a + c)(b + d)} = \frac{ad + bc}{ab + ad + bc + cd} = \frac{ad + bc}{|P||N|} \quad (7)$$

is the total number of relevant-irrelevant document pairs correctly distinguished by the i^{th} term, normalized by the total number of relevant-irrelevant document pairs in the training collection.

Function γ

$$\gamma = \frac{ad}{(a + c)(b + d)} = \frac{ad}{|P||N|}$$

is an obvious variant of both α and β .

Function δ

$$\delta = \frac{|ad - bc|}{\sqrt{(a + b)(c + d)(a + c)(b + d)}} = \frac{ad - bc}{\sqrt{\theta\bar{\theta}}|P||N|} \quad (8)$$

is the absolute value of the *Pearson Product Moment Correlation* coefficient or simply the *correlation coefficient* for the Boolean variables x_i and y as defined above. It measures the degree to which these two variables have a linear relationship.

Function ρ

$$\rho = \frac{(a + b + c + d)(ad - bc)^2}{(a + b)(c + d)(a + c)(b + d)} = \frac{m(ad - bc)^2}{\theta\bar{\theta}|P||N|} \quad (9)$$

is the χ^2 statistic for the Boolean variables x_i and y as defined above and provides another measure of association for these two variables. We recognize that ρ and δ are monotone functions of each other for fixed collection size. Effectively, in what follows, the measure that they represent has been allowed to “vote twice”.

4.3.2 Training the Classifier

This section describes the feature selection method and the simple classifier used in the batch filtering sub-task of the filtering track.

The set of unique terms in the training set $P \cup N$ was ranked by each of the five ranking functions $\alpha, \beta, \gamma, \delta, \rho$ described in §4.3.1. Five intermediate feature sets, $S_\alpha, S_\beta, S_\gamma, S_\delta, S_\rho$, were constructed using the top ranking $K = 50$ terms of the corresponding ranking functions. Letting

$$\tilde{S} = S_\alpha \cup S_\beta \cup S_\gamma \cup S_\delta \cup S_\rho$$

we assigned a score $\psi \in \{1, \dots, 5\}$ to each of the terms in $\tilde{S}$, defined as the number of sets $S_\xi, \xi \in \{\alpha, \beta, \gamma, \delta, \rho\}$ in which the term appeared. The final feature set S was constructed by selecting the $K = 50$ terms with the highest ψ scores.

Next, to each term in $i \in S$ we assigned the weight

$$\omega(i) = \frac{\frac{a_i + 0.5}{a_i + c_i + 1}}{\frac{b_i + 0.5}{b_i + d_i + 1}}$$

which can be thought of as a Yule-adjusted Bayesian weight of evidence, and to each document $y \in T[S] \cup F[S]$ we as-

signed the score

$$\Omega(y) = \sum_{j \in S} \log(\omega(i))y_j.$$

That is, each document projected onto the selected feature set S is assigned a score equal to the sum of the logarithms of the Bayesian weights of evidence for the terms it contains.

The batch filtering task requires the definition of a static classification rule which specifies whether each document in the test set should be considered relevant and retrieved, or irrelevant and ignored. The rule we utilized specifies that $y \in P[S] \cup N[S]$ will be retrieved if and only if $\Omega(y) \geq \tau$ for some $\tau \in \mathbb{R}$. The threshold τ was selected so as to optimize the utility measure U_{11} over the training set.

5. THE EXPERIMENTS

We considered 50 TREC topics that are called “Assessor” topics, for which judgments were produced by human analysts, and another set of topics called “Intersection” topics where judgments were produced on artificial sets formed by the intersection of previously classified sets. We treat these separately because the experience at TREC 2002 suggested that systems perform quite differently on them.

For each category, we did 25 replications of the following process: Randomly select 25 topics to be the training topics. Compute the average parameters by either of two methods described below. Test those parameters on the remaining 25 topics. Repeat this process with the two subsets interchanged.

Thus there were, for each type of topic, a total of 50 tests run.

The distinction between the two methods has to do with the selection of the fusion parameters (α, τ) . We define $\bar{\alpha}$ to be the average alpha for all the topics in the learning set. Under method M1, for each topic in the test set, we separately find the best threshold for that topic using its own best value of α . Then the values of α and τ are averaged separately to produce the values used in testing. Method 2 uses the computed value of $\bar{\alpha}$ and recomputes a new threshold is determined for each topic in the training set, based on the average value of alpha. The average of those thresholds, $\bar{\tau}$ is then used to complete the specification of method M2.

6. THE RESULTS

The results of repeating this approach for all 3 possible combinations of filtering methods, for both the “assessor” and the “intersection” topics, and for both methods M1 (the hybrid method) and M2 (using means of the weight parameter and the threshold, are shown in the Tables and graphs that follow. [16]

7. THE CONCLUSIONS

As these results show, for each of the possible pairings, and for each of the specific methods and problem sets, there is a very good probability to do better than an oracle. (The oracle is presumed to know in advance which system will work better on each topic, and apply that system to the topic.) This probability, averaged over all 25 testing topics, is simply the fraction of the upper rectangle, in each graph, that is included in the bars above the axis. A detailed table (a portion is shown in Table 2) shows that there are a number of topics for which the fusion or combination that

we propose here is consistently (actually, 25 times out of 25) better than using an oracle.

We note that because we use a technique of repeated split half testing and training, our conclusions have a stochastic character. For example, Table 2 shows that for topic 105, the combination of Rocchio and Centroid schemes beats the performance of an oracle 100% of the time. This means that for each of the 25 different training sets that we chose (from the 49 available) the resulting average fusion rule was highly effective for topic 105. For topic 104, this occurred in only 20 of the training cases, and so forth. Thus the our method of studying the problem produces probabilistic estimates of the effectiveness of fusion, for a given problem. We take the average of these probabilities as a single measure of effectiveness of the entire approach. This is the number summarized in Table 1, under the heading “best”. When one has a rule that is effective about 50% of the time, it is clearly important to understand better which half of the cases it will work for.

However, taken together, these results suggests that in some sense the “correct fusion rule” is characteristic of the two systems being combined, and not entirely conditioned on the specific filtering task. This opens the door to many avenues of investigation. Among the most promising are (1) application of other methods for learning the rule of combination in the two dimensional space defined by the scores [such as nonlinear methods, Support Vector Machines, etc.] (2) extension of the entire formalism to sets of three or more systems (3) a renewed look at the question of whether examination of other characteristics of systems (besides the scores that they assign to relevant and not relevant documents) can form a basis for either (a) specification of a fusion rule or (b) specification of whether any linear fusion rule is likely to be effective. This question has been raised by Ng in [2], and has been addressed also by Vogt and Cottrell in [15] but has not, to our knowledge, been satisfactorily resolved as yet. It appears that it is relatively easy to predict how well a fusion scheme will score overall, but it is far more difficult to predict whether that overall performance will compare favorably to that of an oracle.

Fusion	Score 1	Score 2	Method1			Method2		
			Fusion Score	Beats Best	Beats Stronger	Fusion Score	Beats Best	Beats Stronger
r-c-ass:	0.442	0.500	0.531	0.482	0.546	0.528	0.426	0.527
r-c-int:	0.462	0.384	0.474	0.377	0.609	0.478	0.377	0.627
r-v-ass:	0.441	0.369	0.443	0.309	0.380	0.440	0.246	0.344
r-v-int:	0.462	0.419	0.430	0.218	0.378	0.449	0.273	0.494
c-v-ass:	0.500	0.369	0.505	0.396	0.457	0.505	0.410	0.470
c-v-int:	0.384	0.419	0.443	0.366	0.636	0.445	0.341	0.636

Table 1: contains trec-style scores averaged over all topics and runs (separately for assessor and intersection topics). The column “Beats Best” shows the fraction of runs where the combination performed better than either one of the classifiers. The column headed “Beats Stronger” shows the fraction of runs where the fusion beats the simple rule of picking the best of the two systems for the training split and using it for all the test cases.

tID	Sb-r	Sb-c	Sb-comb	S-r	S-c	S-comb	Best	Just Beats Average
101	0.916	0.922	0.923	0.745	0.843	0.890	1.000	0.000
102	0.843	0.698	0.843	0.728	0.489	0.821	1.000	0.000
103	0.634	0.678	0.738	0.600	0.621	0.734	1.000	0.000
104	0.699	0.709	0.738	0.683	0.629	0.708	0.800	0.200
105	0.793	0.793	0.800	0.602	0.726	0.828	1.000	0.000
106	0.333	0.484	0.495	0.222	0.437	0.373	0.080	0.680
107	0.468	0.631	0.658	0.310	0.335	0.190	0.000	0.160
108	0.644	0.622	0.800	0.618	0.504	0.725	1.000	0.000
109	0.464	0.635	0.477	0.367	0.435	0.373	0.160	0.080
110	0.495	0.753	0.753	0.000	0.716	0.512	0.160	0.600
...	...	...	...	...	...	...	...	...
141	0.484	0.642	0.626	0.378	0.443	0.443	0.480	0.520
142	0.431	0.333	0.597	0.000	0.000	0.000	0.000	1.000
143	0.406	0.348	0.391	0.024	0.000	0.000	0.000	0.720
144	0.782	0.848	0.788	0.523	0.578	0.742	1.000	0.000
145	0.333	0.630	0.556	0.000	0.483	0.237	0.040	0.400
146	0.730	0.910	0.916	0.665	0.778	0.834	0.960	0.040
147	0.608	0.657	0.676	0.567	0.415	0.552	0.400	0.440
148	0.908	0.925	0.950	0.661	0.724	0.806	0.960	0.040
149	0.468	0.345	0.503	0.386	0.345	0.456	0.840	0.120
150	0.420	0.654	0.642	0.210	0.552	0.480	0.120	0.760
Av:	0.584	0.657	0.688	0.442	0.500	0.531	0.482	0.320

Table 2: Averaged results of 25 2-fold cross-validation runs, combining Rocchio and Centroid-Ratio methods (a number of rows were left out to save space) Columns “Sb-*” contain the best scores achievable using the specified method. Columns “S-*” contain the average of the scores achieved on cross-validation runs. Column “Best” shows the fraction of times that the combination was better than either of the single classifiers. Column “Beats Average” shows the fraction of times that the combination was better than the average of the two single classifiers but worse than the best. The last row is the average of scores over all topics (i.e. of all the rows in the table, including those left out)

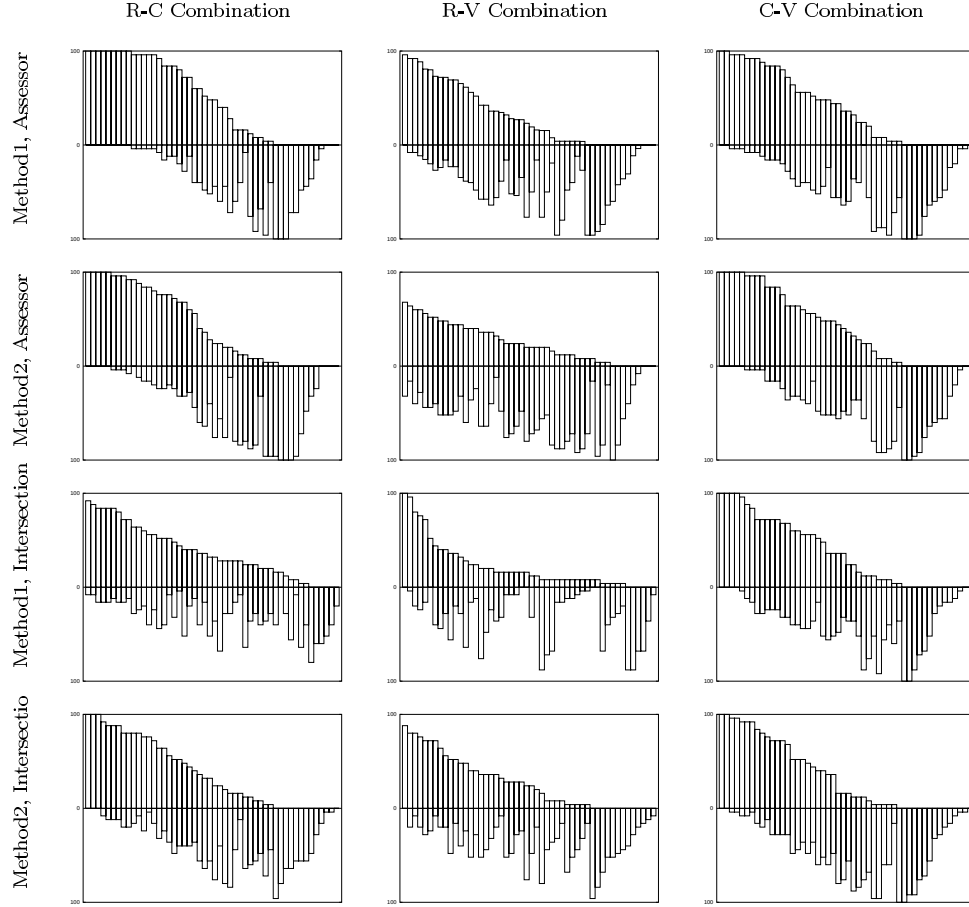


Table 3: Bars above the horizontal axis, indicate, for each topic, the percentage of runs where the combination performed better than the best of the two single classifiers. Bars below the horizontal axis, indicate the percentage of runs where the combination performed worse than the best classifier but better than the average of the two classifiers. Topics are sorted by the “top” value, so the meaning of the horizontal axis is different in each of the twelve figures. The total height of the bar indicates the chance that the combination performs better than the average for the given topic.

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