Frustratingly Easy Domain Adaptation

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Abstract

We describe an approach to domain adaptation that is appropriate exactly in the case when one has enough "target" data to do slightly better than just using only "source" data. Our approach is incredibly simple, easy to implement as a preprocessing step (10 lines of Perl!) and outperforms state-of-the-art approaches on a range of datasets. Moreover, it is trivially extended to a multi-domain adaptation problem, where one has data from a variety of different domains.

1 Introduction

The task of domain adaptation is to develop learning algorithms that can be easily ported from one domain to another—say, from newswire to biomedical documents. This problem is particularly interesting in NLP because we are often in the situation that we have a large collection of labeled data in one "source" domain (say, newswire) but truly desire a model that performs well in a second "target" domain. The approach we present in this paper is based on the idea of transforming the domain adaptation learning problem into a standard supervised learning problem to which any standard algorithm may be applied (eg., maxent, SVMs, etc.). Our transformation is incredibly simple: we augment the feature space of both the source and target data and use the result as input to a standard learning algorithm.

There are roughly two varieties of the domain adaptation problem that have been addressed in the literature: the fully supervised case and the semi-supervised case. The fully supervised case models the following scenario. We have access to a large, annotated corpus of data from a source domain. In addition, we spend a little money to annotate a small corpus in the target domain. We want to leverage both annotated datasets to obtain a model that performs well on the target domain. The semi-supervised case is similar, but instead of having a small annotated target corpus, we have a large but *unannotated* target corpus. In this paper, we focus exclusively on the fully supervised case.

One particularly nice property of our approach is that it is incredibly easy to implement: the Appendix provides a 10 line, 194 character Perl script for performing the complete transformation (available at `http://hal3.name/easyadapt.pl.gz`). In addition to this simplicity, our algorithm performs as well as (or, in some cases, better than) current state of the art techniques.

2 Problem Formalization and Prior Work

To facilitate discussion, we first introduce some notation. Denote by $\mathcal{X}$ the input space (typically either a real vector or a binary vector), and by $\mathcal{Y}$ the output space. We will write $\mathcal{D}^s$ to denote the distribution over source examples and $\mathcal{D}^t$ to denote the distribution over target examples. We assume access to a samples $D^s \sim \mathcal{D}^s$ of source examples from the source domain, and samples $D^t \sim \mathcal{D}^t$ of target examples from the target domain. We will assume that D^s is a collection of N examples and D^t is a collection of M examples (where, typically, $N \gg M$). Our goal is to learn a function $h : \mathcal{X} \to \mathcal{Y}$ with low expected loss with respect to the target domain.

For the purposes of discussion, we will suppose that $\mathcal{X} = \mathbb{R}^F$ and that $\mathcal{Y} = \{-1, +1\}$. However, most of the techniques described in this section (as well as our own technique) are more general.

There are several "obvious" ways to attack the domain adaptation problem without developing new algorithms. Many of these are presented and evaluated by Daumé III and Marcu (2006).

The SRCONLY baseline ignores the target data and trains a single model, only on the source data.

The TGTONLY baseline trains a single model only on the target data.

The ALL baseline simply trains a standard learning algorithm on the union of the two datasets.

A potential problem with the ALL baseline is that if $N \gg M$, then D^s may "wash out" any affect D^t might have. We will discuss this problem in more detail later, but one potential solution is to re-weight examples from D^s. For instance, if $N = 10 \times M$, we may weight each example from the source domain by 0.1. The next baseline, WEIGHTED, is exactly this approach, with the weight chosen by cross-validation.

The PRED baseline is based on the idea of using the output of the source classifier as a feature in the target classifier. Specifically, we first train a SRCONLY model. Then we run the SRCONLY model on the target data (training, development and test). We use the predictions made by the SRCONLY model as additional features and train a second model on the target data, augmented with this new feature.

In the LININT baseline, we linearly interpolate the predictions of the SRCONLY and the TGTONLY models. The interpolation parameter is adjusted based on target development data.

These baselines are actually surprisingly difficult to beat. To date, there are two models that have successfully defeated them on a handful of datasets. The first model, which we shall refer to as the PRIOR model, was first introduced by Chelba and Acero (2004). The idea of this model is to use the SRCONLY model as a *prior* on the weights for a second model, trained on the target data. Chelba and Acero (2004) describe this approach within the context of a maximum entropy classifier, but the idea is more general. In particular, for many learning algorithms (maxent, SVMs, averaged perceptron, naive Bayes, etc.), one *regularizes* the weight vector toward zero. In other words, all of these algorithms contain a regularization term on the weights $\boldsymbol{w}$ of the form $\lambda \, ||\boldsymbol{w}||_2^2$. In the generalized PRIOR model, we simply replace this regularization term with $\lambda \, ||\boldsymbol{w} - \boldsymbol{w}^s||_2^2$, where $\boldsymbol{w}^s$ is the weight vector learned in the SRCONLY model.[1] In this way, the model trained on the target data "prefers" to have weights that are similar to the weights from the SRCONLY model, unless the data demands otherwise. Daumé III and Marcu (2006) provide empirical evidence on four datasets that the PRIOR model outperforms the baseline approaches.

More recently, Daumé III and Marcu (2006) presented an algorithm for domain adaptation for maximum entropy classifiers. The key idea of their approach is to learn *three* separate models. One model captures "source specific" information, one captures "target specific" information and one captures "general" information. The distinction between these three sorts of information is made on a *per-example* basis. In this way, each source example is considered either source specific or general, while each target example is considered either target specific or general. Daumé III and Marcu (2006) present an EM algorithm for training their model. This model consistently outperformed all the baseline approaches as well as the PRIOR model. Unfortunately, despite the empirical success of this algorithm, it is quite complex to implement and is roughly 10 to 15 times slower than training the PRIOR model.

3 Adaptation by Feature Augmentation

In this section, we describe our approach to the domain adaptation problem. Essentially, all we are going to do is take each feature in the original problem and make three versions of it: a general version, a source-specific version and a target-specific version. The augmented source data will contain only general and source-specific versions. The augmented target

[1] For the maximum entropy, SVM and naive Bayes learning algorithms, modifying the regularization term is simple because it appears explicitly. For the perceptron algorithm, one can obtain an equivalent regularization by performing standard perceptron updates, but using $(\boldsymbol{w} + \boldsymbol{w}^s)^\top \boldsymbol{x}$ for making predictions rather than simply $\boldsymbol{w}^\top \boldsymbol{x}$.

data contains general and target-specific versions.

To state this more formally, first recall the notation from Section 2: $\mathcal{X}$ and $\mathcal{Y}$ are the input and output spaces, respectively; D^s is the source domain data set and D^t is the target domain data set. Suppose for simplicity that $\mathcal{X} = \mathbb{R}^F$ for some $F > 0$. We will define our augmented input space by $\breve{\mathcal{X}} = \mathbb{R}^{3F}$. Then, define mappings $\Phi^s, \Phi^t : \mathcal{X} \to \breve{\mathcal{X}}$ for mapping the source and target data respectively. These are defined by Eq (1), where $\mathbf{0} = \langle 0, 0, \dots, 0 \rangle \in \mathbb{R}^F$ is the zero vector.

$$\Phi^s(\boldsymbol{x}) = \langle \boldsymbol{x}, \boldsymbol{x}, \mathbf{0} \rangle, \quad \Phi^t(\boldsymbol{x}) = \langle \boldsymbol{x}, \mathbf{0}, \boldsymbol{x} \rangle \tag{1}$$

Before we proceed with a formal analysis of this transformation, let us consider why it might be expected to work. Suppose our task is part of speech tagging, our source domain is the Wall Street Journal and our target domain is a collection of reviews of computer hardware. Here, a word like "the" should be tagged as a determiner in both cases. However, a word like "monitor" is more likely to be a verb in the WSJ and more likely to be a noun in the hardware corpus. Consider a simple case where $\mathcal{X} = \mathbb{R}^2$, where x_1 indicates if the word is "the" and x_2 indicates if the word is "monitor." Then, in $\breve{\mathcal{X}}$, $\breve{x}_1$ and $\breve{x}_2$ will be "general" versions of the two indicator functions, $\breve{x}_3$ and $\breve{x}_4$ will be source-specific versions, and $\breve{x}_5$ and $\breve{x}_6$ will be target-specific versions.

Now, consider what a learning algorithm could do to capture the fact that the appropriate tag for "the" remains constant across the domains, and the tag for "monitor" changes. In this case, the model can set the "determiner" weight vector to something like $\langle 1, 0, 0, 0, 0, 0 \rangle$. This places high weight on the common version of "the" and indicates that "the" is most likely a determiner, regardless of the domain. On the other hand, the weight vector for "noun" might look something like $\langle 0, 0, 0, 0, 0, 1 \rangle$, indicating that the word "monitor" is a noun *only* in the target domain. Similar, the weight vector for "verb" might look like $\langle 0, 0, 0, 1, 0, 0 \rangle$, indicating the "monitor" is a verb *only* in the source domain.

Note that this expansion is actually redundant. We could equally well use $\Phi^s(\boldsymbol{x}) = \langle \boldsymbol{x}, \boldsymbol{x} \rangle$ and $\Phi^t(\boldsymbol{x}) = \langle \boldsymbol{x}, \mathbf{0} \rangle$. However, it turns out that it is easier to analyze the first case, so we will stick with that. Moreover, the first case has the nice property that it is straightforward to generalize it to the multi-domain adaptation problem: when there are more than two domains. In general, for K domains, the augmented feature space will consist of $K+1$ copies of the original feature space.

3.1 A Kernelized Version

It is straightforward to derive a kernelized version of the above approach. We do not exploit this property in our experiments—all are conducted with a simple linear kernel. However, by deriving the kernelized version, we gain some insight into the method. For this reason, we sketch the derivation here.

Suppose that the data points x are drawn from a reproducing kernel Hilbert space $\mathcal{X}$ with kernel $K : \mathcal{X} \times \mathcal{X} \to \mathcal{R}$, with K positive semi-definite. Then, K can be written as the dot product (in $\mathcal{X}$) of two (perhaps infinite-dimensional) vectors: $K(x, x') = \langle \Phi(x), \Phi(x') \rangle_{\mathcal{X}}$. Define Φ^s and Φ^t in terms of Φ, as:

$$\begin{aligned} \Phi^s(x) &= \langle \Phi(x), \Phi(x), \mathbf{0} \rangle \\ \Phi^t(x) &= \langle \Phi(x), \mathbf{0}, \Phi(x) \rangle \end{aligned} \tag{2}$$

Now, we can compute the kernel product between Φ^s and Φ^t in the expanded RKHS by making use of the original kernel K. We denote the expanded kernel by $\breve{K}(x, x')$. It is simplest to first describe $\breve{K}(x, x')$ when x and x' are from the same domain, then analyze the case when the domain differs. When the domain is the same, we get: $\breve{K}(x, x') = \langle \Phi(x), \Phi(x') \rangle_{\mathcal{X}} + \langle \Phi(x), \Phi(x') \rangle_{\mathcal{X}} = 2K(x, x')$. When they are from different domains, we get: $\breve{K}(x, x') = \langle \Phi(x), \Phi(x') \rangle_{\mathcal{X}} = K(x, x')$. Putting this together, we have:

$$\breve{K}(x, x') = \begin{cases} 2K(x, x') & \text{same domain} \\ K(x, x') & \text{diff. domain} \end{cases} \tag{3}$$

This is an intuitively pleasing result. What it says is that—considering the kernel as a measure of similarity—data points from the same domain are "by default" twice as similar as those from different domains. Loosely speaking, this means that data points from the target domain have twice as much influence as source points when making predictions about test target data.

3.2 Analysis

We first note an obvious property of the feature-augmentation approach. Namely, it does not make learning harder, in a minimum Bayes error sense. A more interesting statement would be that it makes learning *easier*, along the lines of the result of (Ben-David et al., 2006) — note, however, that their results are for the "semi-supervised" domain adaptation problem and so do not apply directly. As yet, we do not know a proper formalism in which to analyze the fully supervised case.

It turns out that the feature-augmentation method is remarkably similar to the PRIOR model[2]. Suppose we learn feature-augmented weights in a classifier regularized by an ℓ_2 norm (eg., SVMs, maximum entropy). We can denote by w_s the sum of the "source" and "general" components of the learned weight vector, and by w_t the sum of the "target" and "general" components, so that w_s and w_t are the predictive weights for each task. Then, the regularization condition on the entire weight vector is approximately $||w_g||^2 + ||w_s - w_g||^2 + ||w_t - w_g||^2$, with free parameter w_g which can be chosen to minimize this sum. This leads to a regularizer proportional to $||w_s - w_t||^2$, akin to the PRIOR model.

Given this similarity between the feature-augmentation method and the PRIOR model, one might wonder why we expect our approach to do better. Our belief is that this occurs because we optimize w_s and w_t *jointly*, not sequentially. First, this means that we do not need to cross-validate to estimate good hyperparameters for each task (though in our experiments, we do not use any hyperparameters). Second, and more importantly, this means that the single supervised learning algorithm that is run is allowed to regulate the trade-off between source/target and general weights. In the PRIOR model, we are forced to use the prior variance on in the target learning scenario to do this ourselves.

3.3 Multi-domain adaptation

Our formulation is agnostic to the number of "source" domains. In particular, it may be the case that the source data actually falls into a variety of more specific domains. This is simple to account for in our model. In the two-domain case, we expanded the feature space from $\mathbb{R}^F$ to $\mathbb{R}^{3F}$. For a K-domain problem, we simply expand the feature space to $\mathbb{R}^{(K+1)F}$ in the obvious way (the "$+1$" corresponds to the "general domain" while each of the other $1 \dots K$ correspond to a single task).

4 Results

In this section we describe experimental results on a wide variety of domains. First we describe the tasks, then we present experimental results, and finally we look more closely at a few of the experiments.

4.1 Tasks

All tasks we consider are sequence labeling tasks (either named-entity recognition, shallow parsing or part-of-speech tagging) on the following datasets:

ACE-NER. We use data from the 2005 Automatic Content Extraction task, restricting ourselves to the named-entity recognition task. The 2005 ACE data comes from 5 domains: Broadcast News (bn), Broadcast Conversations (bc), Newswire (nw), Weblog (wl), Usenet (un) and Converstaional Telephone Speech (cts).

CoNLL-NE. Similar to ACE-NER, a named-entity recognition task. The difference is: we use the 2006 ACE data as the source domain and the CoNLL 2003 NER data as the target domain.

PubMed-POS. A part-of-speech tagging problem on PubMed abstracts introduced by Blitzer et al. (2006). There are two domains: the source domain is the WSJ portion of the Penn Treebank and the target domain is PubMed.

CNN-Recap. This is a recapitalization task introduced by Chelba and Acero (2004) and also used by Daumé III and Marcu (2006). The source domain is newswire and the target domain is the output of an ASR system.

Treebank-Chunk. This is a shallow parsing task based on the data from the Penn Treebank. This data comes from a variety of domains: the standard WSJ domain (we use the same data as for CoNLL 2000), the ATIS switchboard domain, and the Brown corpus (which is, itself, assembled from six subdomains).

Treebank-Brown. This is identical to the Treebank-Chunk task, except that we consider all of the Brown corpus to be a single domain.

[2] Thanks an anonymous reviewer for pointing this out!

Task	Dom	# Tr	# De	# Te	# Ft
ACE-NER	bn	52,998	6,625	6,626	80k
	bc	38,073	4,759	4,761	109k
	nw	44,364	5,546	5,547	113k
	wl	35,883	4,485	4,487	109k
	un	35,083	4,385	4,387	96k
	cts	39,677	4,960	4,961	54k
CoNLL-NER	src	256,145	-	-	368k
	tgt	29,791	5,258	8,806	88k
PubMed-POS	src	950,028	-	-	571k
	tgt	11,264	1,987	14,554	39k
CNN-Recap	src	2,000,000	-	-	368k
	tgt	39,684	7,003	8,075	88k
Tree bank-Chunk	wsj	191,209	29,455	38,440	94k
	swbd3	45,282	5,596	41,840	55k
	br-cf	58,201	8,307	7,607	144k
	br-cg	67,429	9,444	6,897	149k
	br-ck	51,379	6,061	9,451	121k
	br-cl	47,382	5,101	5,880	95k
	br-cm	11,696	1,324	1,594	51k
	br-cn	56,057	6,751	7,847	115k
	br-cp	55,318	7,477	5,977	112k
	br-cr	16,742	2,522	2,712	65k

Table 1: Task statistics; columns are task, domain, size of the training, development and test sets, and the number of unique features in the training set.

In all cases (except for CNN-Recap), we use roughly the same feature set, which has become somewhat standardized: lexical information (words, stems, capitalization, prefixes and suffixes), membership on gazetteers, etc. For the CNN-Recap task, we use identical feature to those used by both Chelba and Acero (2004) and Daumé III and Marcu (2006): the current, previous and next word, and 1-3 letter prefixes and suffixes.

Statistics on the tasks and datasets are in Table 1.

In all cases, we use the Searn algorithm for solving the sequence labeling problem (Daumé III et al., 2007) with an underlying averaged perceptron classifier; implementation due to (Daumé III, 2004). For structural features, we make a second-order Markov assumption and only place a bias feature on the transitions. For simplicity, we optimize and report only on label accuracy (but require that our outputs be parsimonious: we do not allow "I-NP" to follow "B-PP," for instance). We do this for three reasons. First, our focus in this work is on building better learning algorithms and introducing a more complicated measure only serves to mask these effects. Second, it is arguable that a measure like F_1 is inappropriate for chunking tasks (Manning, 2006). Third, we can easily compute statistical significance over accuracies using McNemar's test.

4.2 Experimental Results

The full—somewhat daunting—table of results is presented in Table 2. The first two columns specify the task and domain. For the tasks with only a single source and target, we simply report results on the target. For the multi-domain adaptation tasks, we report results for each setting of the target (where all other data-sets are used as different "source" domains). The next set of eight columns are the *error rates* for the task, using one of the different techniques ("Augment" is our proposed technique). For each row, the error rate of the best performing technique is bolded (as are all techniques whose performance is not statistically significantly different at the 95% level). The "T<S" column is contains a "+" whenever TgtOnly outperforms SrcOnly (this will become important shortly). The final column indicates when Augment comes in first.[3]

There are several trends to note in the results. Excluding for a moment the "br-*" domains on the Treebank-Chunk task, our technique always performs best. Still excluding "br-*", the clear second-place contestant is the Prior model, a finding consistent with prior research. When we repeat the Treebank-Chunk task, but lumping all of the "br-*" data together into a single "brown" domain, the story reverts to what we expected before: our algorithm performs best, followed by the Prior method.

Importantly, this simple story breaks down on the Treebank-Chunk task for the eight sections of the Brown corpus. For these, our Augment technique performs rather poorly. Moreover, there is no clear winning approach on this task. Our hypothesis is that the common feature of these examples is that these are exactly the tasks for which SrcOnly outperforms TgtOnly (with one exception: CoNLL). This seems like a plausible explanation, since it implies that the source and target domains may not be that different. If the domains are so similar that a large amount of source data outperforms a small amount of target data, then it is unlikely that blow-

[3] One advantage of using the averaged perceptron for all experiments is that the only tunable hyperparameter is the number of iterations. In all cases, we run 20 iterations and choose the one with the lowest error on development data.

Task	**Dom**	SRCONLY	TGTONLY	ALL	WEIGHT	PRED	LININT	PRIOR	AUGMENT	T<S	**Win**
ACE-NER	bn	4.98	2.37	2.29	2.23	2.11	2.21	2.06	**1.98**	+	+
	bc	4.54	4.07	3.55	3.53	3.89	4.01	**3.47**	**3.47**	+	+
	nw	4.78	3.71	3.86	3.65	3.56	3.79	3.68	**3.39**	+	+
	wl	2.45	2.45	**2.12**	**2.12**	2.45	2.33	2.41	**2.12**	=	+
	un	3.67	2.46	2.48	2.40	2.18	2.10	2.03	**1.91**	+	+
	cts	2.08	0.46	0.40	0.40	0.46	0.44	**0.34**	**0.32**	+	+
CoNLL	tgt	2.49	2.95	1.80	**1.75**	2.13	**1.77**	1.89	**1.76**		+
PubMed	tgt	12.02	4.15	5.43	4.15	4.14	3.95	3.99	**3.61**	+	+
CNN	tgt	10.29	3.82	3.67	3.45	3.46	3.44	**3.35**	**3.37**	+	+
Treebank-Chunk	wsj	6.63	4.35	4.33	4.30	4.32	4.32	4.27	**4.11**	+	+
	swbd3	15.90	4.15	4.50	4.10	4.13	4.09	3.60	**3.51**	+	+
	br-cf	5.16	6.27	4.85	4.80	4.78	**4.72**	5.22	5.15		
	br-cg	4.32	5.36	**4.16**	**4.15**	4.27	4.30	4.25	4.90		
	br-ck	5.05	6.32	5.05	4.98	**5.01**	**5.05**	5.27	5.41		
	br-cl	5.66	6.60	5.42	**5.39**	**5.39**	5.53	5.99	5.73		
	br-cm	3.57	6.59	**3.14**	**3.11**	3.15	3.31	4.08	4.89		
	br-cn	4.60	5.56	4.27	4.22	**4.20**	**4.19**	4.48	4.42		
	br-cp	4.82	5.62	4.63	**4.57**	**4.55**	**4.55**	4.87	4.78		
	br-cr	5.78	9.13	5.71	5.19	5.20	**5.15**	6.71	6.30		
Treebank-brown		6.35	5.75	4.80	4.75	4.81	4.72	4.72	**4.65**	+	+

Table 2: Task results.

ing up the feature space will help.

We additionally ran the MEGAM model (Daumé III and Marcu, 2006) on these data (though not in the multi-conditional case; for this, we considered the single source as the union of all sources). The results are not displayed in Table 2 to save space. For the majority of results, MEGAM performed roughly comparably to the best of the systems in the table. In particular, it was not statistically significantly different that AUGMENT on: ACE-NER, CoNLL, PubMed, Treebank-chunk-wsj, Treebank-chunk-swbd3, CNN and Treebank-brown. It did outperform AUGMENT on the Treebank-chunk on the Treebank-chunk-br-* data sets, but only outperformed the best other model on these data sets for br-cg, br-cm and br-cp. However, despite its advantages on these data sets, it was quite significantly slower to train: a single run required about ten times longer than any of the other models (including AUGMENT), and also required five-to-ten iterations of cross-validation to tune its hyperparameters so as to achieve these results.

4.3 Model Introspection

One explanation of our model's improved performance is simply that by augmenting the feature space, we are creating a more powerful model. While this may be a partial explanation, here we show that what the model learns about the various domains actually makes some plausible sense.

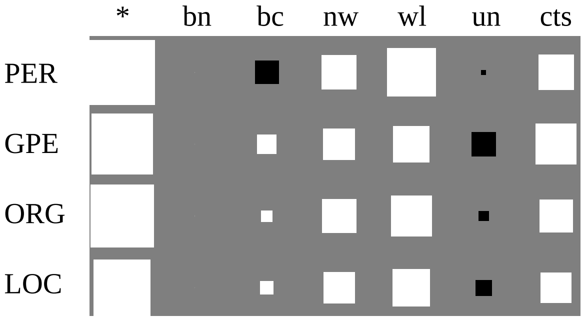

Figure 1: Hinton diagram for feature /Aa+/ at current position.

We perform this analysis only on the ACE-NER data by looking specifically at the learned weights. That is, for any given feature f, there will be seven versions of f: one corresponding to the "cross-domain" f and seven corresponding to each domain. We visualize these weights, using Hinton diagrams, to see how the weights vary across domains.

For example, consider the feature "current word has an initial capital letter and is then followed by one or more lower-case letters." This feature is presumably useless for data that lacks capitalization information, but potentially quite useful for other domains. In Figure 1 we shown a Hinton diagram for this figure. Each column in this figure correspond to a domain (the top row is the "general domain").

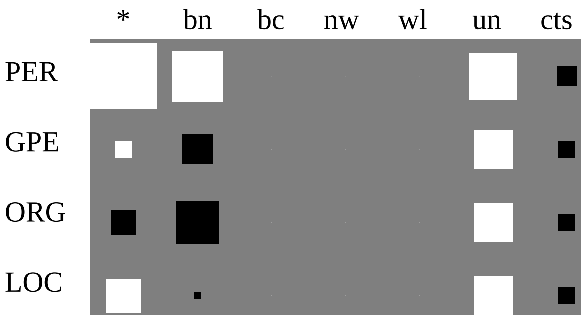

Figure 2: Hinton diagram for feature /bush/ at current position.

Each row corresponds to a class.[4] Black boxes correspond to negative weights and white boxes correspond to positive weights. The size of the box depicts the absolute value of the weight.

As we can see from Figure 1, the /Aa+/ feature is a very good indicator of entity-hood (it's value is strongly positive for all four entity classes), regardless of domain (i.e., for the "*" domain). The lack of boxes in the "bn" column means that, beyond the settings in "*", the broadcast news is agnostic with respect to this feature. This makes sense: there is no capitalization in broadcast news domain, so there would be no sense is setting these weights to anything by zero. The usenet column is filled with negative weights. While this may seem strange, it is due to the fact that many email addresses and URLs match this pattern, but are not entities.

Figure 2 depicts a similar figure for the feature "word is 'bush' at the current position" (this figure is case sensitive).[5] These weights are somewhat harder to interpret. What is happening is that "by default" the word "bush" is going to be a person—this is because it rarely appears referring to a plant and so even in the capitalized domains like broadcast conversations, if it appears at all, it is a person. The exception is that in the conversations data, people *do* actually talk about bushes as plants, and so the weights are set accordingly. The weights are high in the usenet domain because people tend to talk about the president without capitalizing his name.

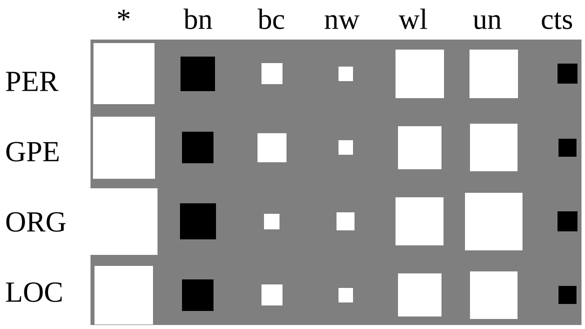

Figure 3: Hinton diagram for feature /the/ at current position.

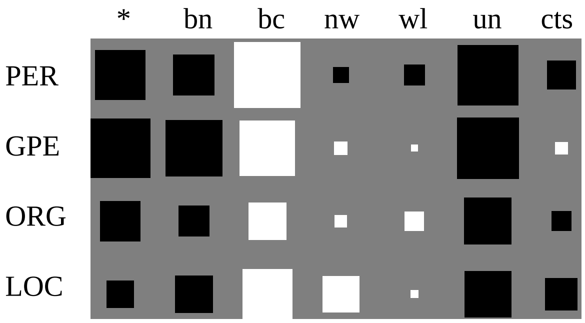

Figure 4: Hinton diagram for feature /the/ at previous position.

Figure 3 presents the Hinton diagram for the feature "word at the current position is 'the"' (again, case-sensitive). In general, it appears, "the" is a common word in entities in all domain except for broadcast news and conversations. The exceptions are broadcast news and conversations. These exceptions crop up because of the capitalization issue.

In Figure 4, we show the diagram for the feature "previous word is 'the'." The only domain for which this is a good feature of entity-hood is broadcast conversations (to a much lesser extent, newswire). This occurs because of four phrases very common in the broadcast conversations and rare elsewhere: "the Iraqi people" ("Iraqi" is a GPE), "the Pentagon" (an ORG), "the Bush (cabinet|advisors|. . .)" (PER), and "the South" (LOC).

Finally, Figure 5 shows the Hinton diagram for the feature "the current word is on a list of common names" (this feature is case-*in*sensitive). All around, this is a good feature for picking out people and nothing else. The two exceptions are: it is also a good feature for other entity types for broadcast

[4] Technically there are many more classes than are shown here. We do not depict the smallest classes, and have merged the "Begin-*" and "In-*" weights for each entity type.

[5] The scale of weights across features is *not* comparable, so do not try to compare Figure 1 with Figure 2.

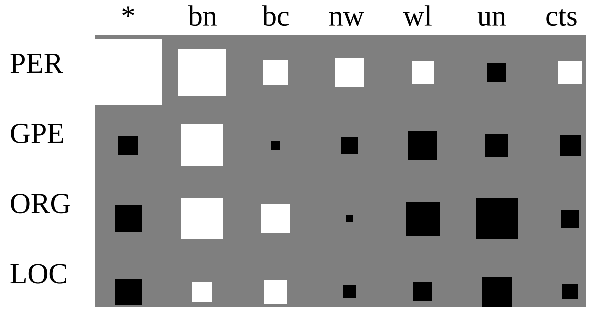

Figure 5: Hinton diagram for membership on a list of names at current position.

news and it is not quite so good for people in usenet. The first is easily explained: in broadcast news, it is very common to refer to countries and organizations by the name of their respective leaders. This is essentially a metonymy issue, but as the data is annotated, these are marked by their true referent. For usenet, it is because the list of names comes from news data, but usenet names are more diverse.

In general, the weights depicte for these features make some intuitive sense (in as much as weights for any learned algorithm make intuitive sense). It is particularly interesting to note that while there are some regularities to the patterns in the five diagrams, it is definitely *not* the case that there are, eg., two domains that behave identically across all features. This supports the hypothesis that the reason our algorithm works so well on this data is because the domains are actually quite well separated.

5 Discussion

In this paper we have described an *incredibly* simple approach to domain adaptation that—under a common and easy-to-verify condition—outperforms previous approaches. While it is somewhat frustrating that something so simple does so well, it is perhaps not surprising. By augmenting the feature space, we are essentially forcing the learning algorithm to do the adaptation for us. Good supervised learning algorithms have been developed over decades, and so we are essentially just leveraging all that previous work. Our hope is that this approach is so simple that it can be used for many more real-world tasks than we have presented here with little effort. Finally, it is very interesting to note that using our method, shallow parsing error rate on the CoNLL section of the treebank improves from 5.35 to 5.11. While this improvement is small, it is real, and may carry over to full parsing. The most important avenue of future work is to develop a formal framework under which we can analyze this (and other supervised domain adaptation models) theoretically. Currently our results only state that this augmentation procedure doesn't make the learning harder — we would like to know that it actually makes it easier. An additional future direction is to explore the kernelization interpretation further: why should we use 2 as the "similarity" between domains—we could introduce a hyperparamter α that indicates the similarity between domains and could be tuned via cross-validation.

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