
Balancing information exposure in social networks

Supplementary material

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A Proof of Proposition 1

Proof. To prove the hardness we will use SET COVER. Here, we are given a universe U and family of sets C_1, \dots, C_ℓ , and we are asked to select k sets covering the universe U .

To map this instance to our problem, we first define vertex set V to consist of 3 parts, V_1 , V_2 and V_3 . The first part corresponds to the universe U . The second part consists of k copies of ℓ vertices, i th vertex in j th copy corresponds to C_i . The third part consists of k vertices b_j . The edges are as follows: a vertex v in the j th copy, corresponding to a set C_i is connected to the vertices corresponding to the elements in C_i , furthermore v is connected to b_j . We set $p_1 = p_2 = 1$. The initial seeds are $I_1 = \emptyset$ and $I_2 = V_1 \cup V_3$. We set the budget to $2k$.

Assume that there is a k -cover, C_{i_1}, \dots, C_{i_k} . We set

$$S_1 = S_2 = \{ \text{vertex corresponding to } C_{i_j} \text{ in } j\text{th copy} \}.$$

It is easy to see that the imbalanced vertices in I_2 are exposed to the first campaign. Moreover, S_1 and S_2 do not introduce new imbalanced vertices. This makes the objective equals to 0.

Assume that there exists a solution S_1 and S_2 with a zero cost. We claim that $|S_1 \cap (V_1 \cup V_2)| \leq k$. To prove this, first note that $S_1 \cap V_2 = S_2 \cap V_2$, as otherwise vertices in V_2 are left unbalanced. Let $m = |S_1 \cap V_2|$. Since V_3 must be balanced and each vertex in V_2 has only one edge to a vertex in V_3 , there at least k vertices in $|S_1 \cap \{V_2 \cup V_3\}|$, that is, we must have $|S_1 \cap V_3| \geq k - m$. Let us write $d_{ij} = |S_i \cap V_j|$. The budget constraints guarantee that

$$d_{11} + d_{12} + d_{22} + d_{13} \leq \sum_{ij} d_{ij} \leq 2k,$$

which can be rewritten as

$$d_{11} + d_{12} \leq 2k - d_{22} - d_{13} \leq 2k - m - (k - m) = k.$$

Construct C as follows: for each $S_1 \cap V_2$, select the set that corresponds to the vertex, for each $S_1 \cap V_1$, select any set that contain this vertex (there is always at least one set, otherwise the problem is trivially false). Since V_1 must be balanced, C is a k -cover of U . \square

B Proof of Lemma 2

Before providing the proof, as a technicality, note that submodularity is usually defined for functions with one argument. Namely, given a universe of items U , we consider functions of the type $f : 2^U \rightarrow \mathbb{R}$. However, by taking $U = V \times \{1, 2\}$ we can equivalently write our objectives as functions with one argument, i.e., $\Phi, \Omega, \Psi : 2^U \rightarrow \mathbb{R}$.

Proof. The objective counts 3 types of vertices: (i) vertices covered by both initial seeds, (ii) additional vertices covered by I_1 and S_2 , and (iii) additional vertices covered by I_2 and S_1 . This allows us to decompose the objective as

$$\Omega(S_1, S_2) = \mathbb{E}[|A| + |B| + |C|], \quad \text{where}$$

$$A = r_1(I_1) \cap r_2(I_2), \quad B = (r_1(I_1) \setminus r_2(I_2)) \cap r_2(S_2), \quad C = (r_2(I_2) \setminus r_1(I_1)) \cap r_1(S_1).$$

Note that A does not depend on S_1 and S_2 . B grows in size as we add more vertices to S_2 , and C grows in size as we add more vertices to S_1 . This proves that the objective is monotone.

To prove the submodularity, let us introduce some notation: given a set of edges F , we write $r(S; F)$ to be the set of vertices that can be reached from S via F . This allows us to define

$$\begin{aligned} A(F_1, F_2) &= r(I_1; F_1) \cap r(I_2; F_2), \\ B(F_1, F_2) &= (r(I_1; F_1) \setminus r(I_2; F_2)) \cap r(S_2; F_2), \\ C(F_1, F_2) &= (r(I_2; F_2) \setminus r(I_1; F_1)) \cap r(S_1; F_1). \end{aligned}$$

The score $\Omega(S_1, S_2)$ can be rewritten as

$$\sum_{F_1, F_2} p(F_1, F_2) (|A(F_1, F_2)| + |B(F_1, F_2)| + |C(F_1, F_2)|),$$

where $p(F_1, F_2)$ is the probability of F_1 being the realization of the edges for the first campaign and F_2 being the realization of the edges for the second campaign.

The first term $A(F_1, F_2)$ does not depend on S_1 or S_2 . The second term is submodular as a function of S_2 and does not depend of S_1 . The third term is submodular as a function of S_1 and does not depend of S_2 . Since any linear combination of submodular function weighted by positive coefficients is also submodular, this completes the proof. \square

C Proof of Proposition 3

Proof. Write $c = 1 - 1/e$. Let $\langle S'_1, S'_2 \rangle$ be the optimal solution maximizing Ω . Lemma 2 shows that $\Omega(S_1, S_2) \geq c\Omega(S'_1, S'_2)$.

Note that $\Psi(\emptyset, \emptyset) \geq \Psi(S_1^*, S_2^*)$ as the first term is the average of vertices not affected by the initial seeds. Thus,

$$\begin{aligned} \Phi(S_1^*, S_2^*) &= \Omega(S_1^*, S_2^*) + \Psi(S_1^*, S_2^*) \leq \Omega(S'_1, S'_2) + \Psi(S_1^*, S_2^*) \\ &\leq \Omega(S'_1, S'_2) + \Psi(\emptyset, \emptyset) \leq \Omega(S_1, S_2)/c + \Psi(\emptyset, \emptyset) \\ &\leq \Omega(S_1, S_2)/c + \Psi(\emptyset, \emptyset)/c \\ &\leq (2/c) \max\{\Omega(S_1, S_2), \Psi(\emptyset, \emptyset)\} \\ &\leq (2/c) \max\{\Phi(S_1, S_2), \Phi(\emptyset, \emptyset)\}, \end{aligned}$$

which completes the proof. \square

D Proof of Lemma 4

Proof. As we are dealing with the correlated setting, we can write $r(S) = r_1(S) = r_2(S)$. Our first step is to decompose $\omega = \Phi_C(S_1, S_2)$ into several components. To do so, we partition the vertices based on their reachability from the initial seeds,

$$\begin{aligned} A &= r(I_1) \cap r(I_2), & B &= r(I_1) \setminus r(I_2), \\ C &= r(I_2) \setminus r(I_1), & D &= V \setminus (r(I_1) \cup r(I_2)). \end{aligned}$$

Note that these are all random variables. If $S_1 = S_2 = \emptyset$, then $\Phi_C(S_1, S_2) = \mathbb{E}_C[|A| + |D|]$. More generally, S_1 may balance some vertices in C , and S_2 may balance some vertices in B . We may also introduce new imbalanced vertices in D . To take this into account we define

$$\begin{aligned} B' &= B \cap r(S_2), & C' &= C \cap r(S_1), \\ D' &= D \setminus (r(S_1) \Delta r(S_2)). \end{aligned}$$

We can express the cost of $\Phi_C(S_1, S_2)$ as

$$\omega = \Phi_C(S_1, S_2) = \mathbb{E}_C[|A| + |B'| + |C'| + |D'|].$$

Split $S_1 \cup S_2$ in two equal-size sets, T and Q , and define

$$\omega_1 = \Phi_C(T, T), \quad \omega_2 = \Phi_C(Q, Q).$$

We claim that $\omega \leq \omega_1 + \omega_2$. This proves the proposition, since $\omega_1 + \omega_2 \leq 2 \max\{\omega_1, \omega_2\}$.

To prove the claim let us first split T and Q ,

$$T_1 = T \cap S_1, \quad T_2 = T \cap S_2, \quad Q_1 = Q \cap S_1, \quad Q_2 = Q \cap S_2.$$

Our next step is to decompose ω_1 and ω_2 , similar to ω . To do that, we define

$$\begin{aligned} B_1 &= B \cap r(T_2), & B_2 &= B \cap r(Q_2), \\ C_1 &= C \cap r(T_1), & C_2 &= C \cap r(Q_1). \end{aligned}$$

Note that, the pair $\langle T, T \rangle$ does not introduce new imbalanced nodes. This leads to

$$\omega_1 = \Phi_C(T, T) = \mathbb{E}_C[|A| + |B_1| + |C_1| + |D|],$$

and similarly,

$$\omega_2 = \Phi_C(Q, Q) = \mathbb{E}_C[|A| + |B_2| + |C_2| + |D|].$$

To prove $\omega \leq \omega_1 + \omega_2$, note that $|D'| \leq |D|$. In addition,

$$\begin{aligned} |B'| &= |B \cap (r(T_2) \cup r(Q_2))| \\ &\leq |B \cap r(T_2)| + |B \cap r(Q_2)| = |B_1| + |B_2| \end{aligned}$$

and

$$\begin{aligned} |C'| &= |C \cap (r(T_1) \cup r(Q_1))| \\ &\leq |C \cap r(T_1)| + |C \cap r(Q_1)| = |C_1| + |C_2|. \end{aligned}$$

Combining these inequalities proves the proposition. \square

E Proof of Proposition 5

To prove the proposition, we need the following technical lemma, which is a twist of a standard technique for proving the approximation ratio of the greedy algorithm on submodular functions.

Lemma 1. *Assume a universe U . Let $f : 2^U \rightarrow \mathbb{R}$ be a positive function. Let $T \subseteq U$ be a set with k elements. Let $C_0 \subseteq \dots \subseteq C_k$ be a sequence of subsets of U . Assume that $f(C_i) \geq \max_{t \in T} f(C_{i-1} \cup \{t\})$.*

Assume further that for each $i = 1, \dots, k$, we can decompose f as $f = g_i + h_i$ such that

1. g_i is submodular and monotonically increasing function,
2. $h_i(W) = h_i(C_{i-1})$, for any $W \subseteq T \cup C_{i-1}$.

Then $f(C_k) \geq (1 - 1/e)f(T)$.

Proof. The assumptions of the propositions imply

$$\begin{aligned}
f(T) &= g_i(T) + h_i(T) \\
&= g_i(T) + h_i(C_{i-1}) \\
&\leq g_i(C_{i-1}) + h_i(C_{i-1}) + \sum_{t \in T} g_i(C_{i-1} \cup \{t\}) - g_i(C_{i-1}) \\
&= f(C_{i-1}) + \sum_{t \in T} h_i(C_{i-1}) + g_i(C_{i-1} \cup \{t\}) - g_i(C_{i-1}) - h_i(C_{i-1}) \\
&= f(C_{i-1}) + \sum_{t \in T} h_i(C_{i-1} \cup \{t\}) + g_i(C_{i-1} \cup \{t\}) - g_i(C_{i-1}) - h_i(C_{i-1}) \\
&= f(C_{i-1}) + \sum_{t \in T} f(C_{i-1} \cup \{t\}) - f(C_{i-1}) \\
&\leq f(C_{i-1}) + k(f(C_i) - f(C_{i-1})),
\end{aligned}$$

where the first inequality is due to the submodularity of g_i , and is a standard trick to prove the approximation ratio for the greedy algorithm.

We can rewrite the above inequality as

$$kf(T) + (1 - k)f(T) = f(T) \leq f(C_{i-1}) + k(f(C_i) - f(C_{i-1})).$$

Rearranging the terms leads to

$$\frac{k-1}{k}(f(C_{i-1}) - f(T)) \leq f(C_i) - f(T) \quad .$$

Applying induction over i , yields

$$f(C_k) - f(T) \geq \left(\frac{k-1}{k}\right)^k (f(C_0) - f(T)) \geq \frac{1}{e}(f(C_0) - f(T)) \geq -f(T)/e,$$

leading to $f(C_k) \geq (1 - 1/e)f(T)$. □

We can now prove the main claim. Note that since we are using the correlated model, we have $r_1 = r_2$. For notational simplicity, we will write $r = r_1 = r_2$.

Proof of Proposition 5. Let OPT be the cost of the optimal solution. Let D be the solution maximizing $\Phi_C(D, D)$ with $|D| \leq k/2$. Lemma 4 guarantees that $OPT/2 \leq \Phi_C(D, D)$.

In order to apply Lemma 6, we first define the universe U as

$$U = \{\langle u, v \rangle \mid u, v \in V\} \cup \{\langle v, \emptyset \rangle \mid v \in V\} \cup \{\langle \emptyset, v \rangle \mid v \in V\}.$$

The sets are defined as

$$C_i = \{\langle v, \emptyset \rangle \mid v \in S_1^i\} \cup \{\langle \emptyset, v \rangle \mid v \in S_2^i\}.$$

Given a set $C \subseteq U$, let us define $\pi_1(C) = \{v \mid \langle v, u \rangle \in C, v \neq \emptyset\}$ to be the union of the first entries in C . Similarly, define $\pi_2(C) = \{v \mid \langle u, v \rangle \in C, v \neq \emptyset\}$.

We can now define f as $f(C) = \Phi_C(\pi_1(C), \pi_2(C))$. To decompose f , let us first write

$$X_i = r(I_1 \cup \pi_1(C_{i-1})) \cup r(I_2 \cup \pi_2(C_{i-1})) = r(I_1 \cup S_1^{i-1}) \cup r(I_2 \cup S_2^{i-1}), \quad Y_i = V \setminus X_i.$$

and set

$$\begin{aligned}
g_i(C) &= \mathbb{E}[|X_i \setminus (r(I_1 \cup \pi_1(C)) \Delta r(I_2 \cup \pi_2(C)))|], \\
h_i(C) &= \mathbb{E}[|Y_i \setminus (r(I_1 \cup \pi_1(C)) \Delta r(I_2 \cup \pi_2(C)))|].
\end{aligned}$$

Finally, we set $T = \{\langle d, d \rangle \mid d \in D\}$.

First note that $f = g_i + h_i$ since $X_i \cap Y_i = \emptyset$. The proof of Lemma 2 shows that g_i is monotonically increasing and submodular.

Let $C \subseteq C_{i-1} \cup T$. If there is a vertex v in $r(I_1 \cup \pi_1(C))$ but not in X_i , then this means v was influenced by $d \in D$. Since $d \in \pi_2(C)$, we have $v \in r(I_2 \cup \pi_2(C))$. That is,

$$r(I_1 \cup \pi_1(C)) \setminus X_i = r(I_2 \cup \pi_2(C)) \setminus X_i.$$

Since Y_i and X_i are disjoint, this gives us

$$\begin{aligned} h_i(C) &= \mathbb{E}[|Y_i \setminus (r(I_1 \cup \pi_1(C)) \Delta r(I_2 \cup \pi_2(C)))|] \\ &= \mathbb{E}[|Y_i \setminus ((r(I_1 \cup \pi_1(C)) \setminus X_i) \Delta (r(I_2 \cup \pi_2(C)) \setminus X_i))|] \\ &= \mathbb{E}[|Y_i|]. \end{aligned}$$

That is, $h_i(C)$ is constant for any $C \subseteq C_{i-1} \cup T$. Thus, $h_i(C) = h_i(C_{i-1})$.

Finally, the assumption of the proposition guarantees that $f(C_i) \geq f(C_{i-1} \cup \{t\})$, for $t \in T$.

Thus, these definitions meet all the prerequisites of Lemma 6, guaranteeing that

$$(1 - 1/e)\Phi_C(D, D) \leq \Phi_C(S_1^{k/2}, S_2^{k/2}) \leq \Phi_C(S_1^k, S_2^k).$$

Since $OPT/2 \leq \Phi_C(D, D)$, the result follows. □

F Additional tables and figures related to the experimental evaluation

Table 1: Dataset descriptions, as well as tags and retweets that were used to collect the data.

USElections: Tweets containing hashtags and keywords identifying the USElections, such as #uselections, #trump2016, #hillary2016, etc. Collected using Twitter 1% sample for 2 weeks in September 2016

Pro-Hillary

RT @hillaryclinton, #hillary2016, #clin-tonkaine2016, #imwithher

Pro-Trump

RT @realdonaldtrump, #makeamericagreatagain, #trump Pence16, #trump2016

Brexit: Tweets containing hashtags #brexit, #voterremain, #voteleave, #eureferendum for all of June 2016, from the 1% Twitter sample.

Pro-Remain

#voterremain, #strongerin, #remain, #re-main, #votein

Pro-Leave

#voteleave, #strongerout, #leaveeu, #takecontrol, #leave, #voteout

Abortion: Tweets containing hashtags #abortion, #prolife, #prochoice, #anti-abortion, #pro-abortion, #plannedparenthood from Oct 2011 to Aug 2016.

Pro-Choice

RT @thinkprogress, RT @komenforthe-cure, RT @mentalabortions, #waronwomen, #nbprochoice, #prochoice, #standwithpp, #reprorights

Pro-Life

RT @stevenertelt, RT @lifenewshq, #pray, #prolifeyouth, #prolife, #defundpp, #unbornlivesmatter

Obamacare: Tweets containing hashtags #obamacare, and #aca from Oct 2011 to Aug 2016.

Pro-Obamacare

RT @barackobama, RT @lolgop, RT @charlespgarcia, RT @defendobamacare, RT @thinkprogress, #obamacares, #enoughal-ready, #uniteblue

Anti-Obamacare

RT @sentedcruz, RT @realdonaldtrump, RT @mittromney, RT @breitbartnews, RT @tedcruz, #defundobamacare, #makedclisten, #fullrepeal, #dontfundit

Fracking: Tweets containing hashtags and keywords #fracking, 'hydraulic fracturing', 'shale', 'horizontal drilling', from Oct 2011 to Aug 2016.

Pro-Fracking

RT @shalemarkets, RT @energyindepth, RT @shalefacts, #fracknation, #frackingez, #oi-landgas, #greatgasgala, #shalegas

Anti-Fracking

RT @greenpeaceuk, RT @greenpeace, RT @ecowatch, #environment, #banfracking, #keepitintheground, #dontfrack, #globalfrackdown, #stopthefrackattack

iPhone vs. Samsung: Tweets containing hashtags #iphone, and #samsung from April (release of Samsung Galaxy S7), and September 2015 (release of iPhone 7).

Pro-iPhone

#iphone

Pro-Samsung

#samsung

Table 2: Dataset statistics. The column $|C|$ refers to the average number of edges in a randomly generated cascade in the correlated case, while $|C_1|$ and $|C_2|$ refer to average number of edges generated in a cascade of the campaigns 1 and 2, respectively, in the heterogeneous case.

Dataset	# Nodes	# Edges	$ C $	$ C_1 $	$ C_2 $
Abortion	279 505	671 144	2 105	326	1 801
Brexit	22 745	48 830	476	113	390
Fracking	374 403	1 377 085	4 156	1 595	3 103
iPhone	36 742	49 248	4 776	339	4 478
ObamaCare	334 617	1 511 670	6 614	2 404	4 527
US-elections	80 544	921 368	4 697	3 097	12 044

Table 3: Detailed values of the data presented in Figure 2. The data correspond to the absolute value expected symmetric difference $n - \Phi$ of Hedge and the baselines for $k = 20$ across all datasets. Low values are better.

Heterogeneous setting						
Dataset	Hedge	BBLO	Inters.	Union	HighDeg.	Random
Abortion	1436.090	1447.710	1571.180	1655.580	3414.310	4253.220
Brexit	17.907	17.765	31.850	27.770	54.131	87.341
Fracking	3411.810	3420.700	3651.230	3825.360	5197.060	7449.350
iPhone	421.411	865.126	839.119	1048.090	1189.650	631.543
ObamaCare	1768.560	1828.900	1998.250	1846.750	3315.570	4032.140
US-elections	515.347	516.587	1030.640	685.089	1474.330	5988.160
Homogeneous setting						
Dataset	Hedge	BBLO	Inters.	Union	HighDeg.	Random
Abortion	144.898	185.569	446.462	444.766	2368.610	1279.100
Brexit	1.232	1.615	9.643	9.374	28.850	34.283
Fracking	275.143	269.404	1423.870	781.994	2529.570	2960.720
iPhone	14.624	19.893	79.854	80.279	895.353	759.629
ObamaCare	97.319	95.062	1314.830	360.103	2253.050	2484.330
US-elections	64.870	103.318	128.586	104.911	1979.79	5325.130

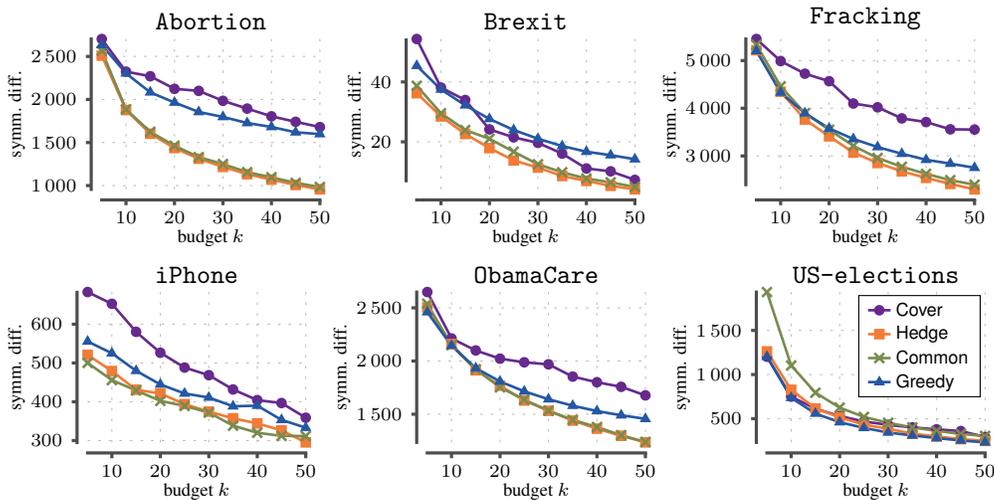


Figure 1: Expected symmetric difference $n - \Phi_H$ as a function of the budget k . Heterogeneous model. Low values are better.

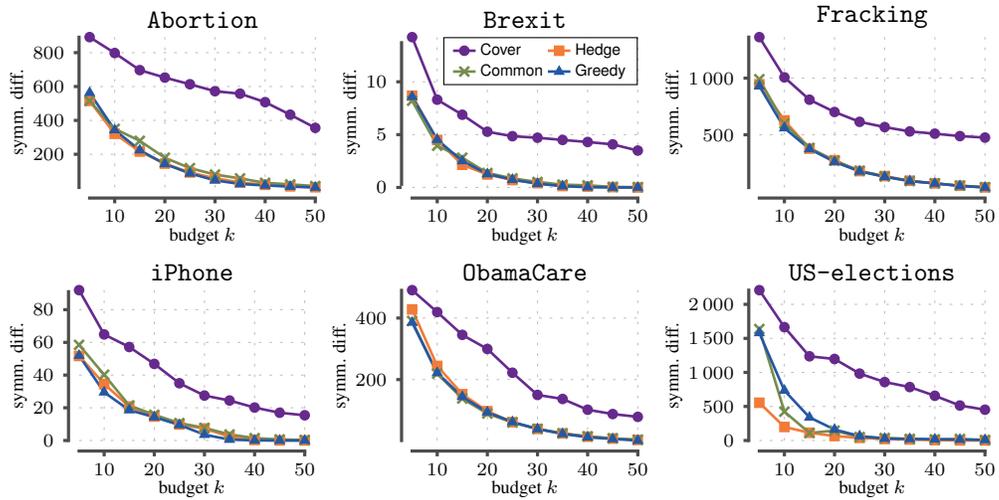


Figure 2: Expected symmetric difference $n - \Phi_C$ as a function of the budget k . Correlated model. Low values are better.

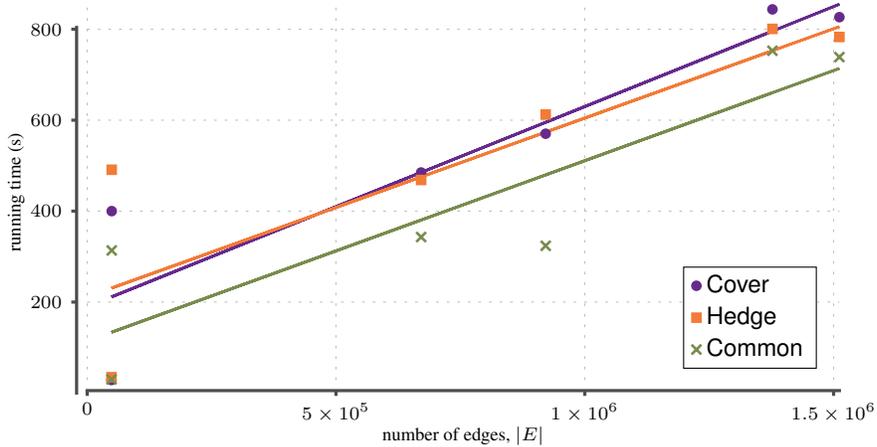
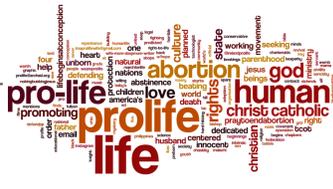


Figure 3: Running time as a function of number of edges. Correlated model with $k = 20$.

Side 1
Pro-Choice



Side 2
Pro-Life



Hedge



Pro-Remain



Pro-Leave



Pro-Fracking



Anti-Fracking



Pro-iPhone



Pro-Samsung



Pro-Obamacare



Anti-Obamacare



Pro-Hillary



Pro-Trump



Figure 4: Word clouds of the profiles for the initial seeds, and profiles selected by Hedge.