Parameterized Complexity of Kemeny Rankings

Nadja Betzler
Friedrich-Schiller-Universität Jena

joint work with

Michael R. Fellows, Jiong Guo, Rolf Niedermeier,
and Frances A. Rosamond

Dagstuhl seminar 09171
April 2009

Applications of voting

Voting scenarios:

- political elections
- committees: decisions about job applicants, grant proposals
- meta search engines, recommender systems
- daily life: choice of restaurant

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Different goals:

- single winner
- set of winners
- ranking of all candidates
- decisions on several (dependent) subjects

Kemeny ranking

Election

Set of votes V, set of candidates C.
A vote is a ranking (total order) over all candidates.

Example: $C = \{a, b, c\}$

vote 1:	a	>	b	>	c
vote 2:	a	>	c	>	b
vote 3:	b	>	c	>	a

How to aggregate the votes into a "consensus ranking"?

KT-distance

KT-distance (between two votes v and w)

$$\text{KT-dist}(v, w) := \sum_{\{c,d\} \subseteq C} d_{v,w}(c, d),$$

where $d_{v,w}(c, d)$ is 0 if v and w rank c and d in the same order, 1 otherwise.

Example:

$$v : a > b > c$$
$$w : c > a > b$$

$$\begin{aligned} \text{KT-dist}(v, w) &= d_{v,w}(a, b) + d_{v,w}(a, c) + d_{v,w}(b, c) \\ &= 0 + 1 + 1 \\ &= 2 \end{aligned}$$

Kemeny Consensus

Kemeny score of a ranking r:

sum of KT-distances between r and all votes

Kemeny consensus r_{con}:

a ranking that minimizes the Kemeny score

v_1 :	$a > b > c$	$\text{KT-dist}(r_{con}, v_1) = 0$
v_2 :	$a > c > b$	$\text{KT-dist}(r_{con}, v_2) = 1$ because of $\{b, c\}$
v_3 :	$b > c > a$	$\text{KT-dist}(r_{con}, v_3) = 2$ because of $\{a, b\}$ and $\{a, c\}$
r_{con} :	$\mathbf{a} > \mathbf{b} > \mathbf{c}$	Kemeny score: $0 + 1 + 2 = 3$

Motivation

Applications:

- ranking of web sites (meta search engines), spam detection
  [Dwork et al., WWW 2001]
- databases
  [Fagin et al., SIGMOD, 2003]
- bioinformatics
  [Jackson et al., IEEE/ACM Transactions on Computational Biology and Bioinformatics 2008]

Kemeny is the only voting system that is

- neutral,
- consistent, and
- Condorcet.

Decision problems

KEMENY SCORE

Input: An election (V, C) and a positive integer k.
Question: Is the Kemeny score of (V, C) at most k?

KEMENY WINNER

Input: An election (V, C) and a distinguished candidate c.
Question: Is there a Kemeny consensus in which c is at the "best" position?

vote 1:	a	>	b	>	c
vote 2:	a	>	c	>	b
vote 3:	b	>	c	>	a
Kemeny consensus:	a	>	b	>	c

Kemeny score = 0+1+2 =3

Kemeny winner: a

Known results

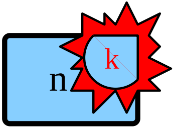
- KEMENY SCORE is NP-complete (even for 4 votes)
  [DWORK ET AL., WWW 2001]
- KEMENY WINNER is $P_{||}^{NP}$-complete
  [E. HEMASPAANDRA ET AL., TCS 2005]

Algorithms:

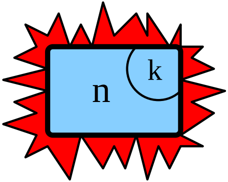
- randomized factor 11/7-approximation
  [AILON ET AL., J. ACM 2008]
- factor 8/5-approximation
  [VAN ZUYLEN AND WILLIAMSON, WAOA 2007]
- PTAS [KENYON-MATHIEU AND SCHUDY, STOC 2007]
- Heuristics; greedy, branch and bound
  [DAVENPORT AND KALAGNANAM, AAAI 2004],
  [CONITZER ET AL. AAAI, 2006]

Parameterized Complexity

Given an NP-hard problem with input size n and a parameter k
Basic idea: Confine the combinatorial explosion to k



instead of



Definition

A problem of size n is called *fixed-parameter tractable* with respect to a parameter k if it can be solved exactly in $f(k) \cdot n^{O(1)}$ time.

Parameterizations of Kemeny Score

Number of votes n [Dwork et al. WWW 2001]	NP-c for $n = 4$
Number of candidates m	$O^*(2^m)$
Kemeny score k	$O^*(1.53^k)$

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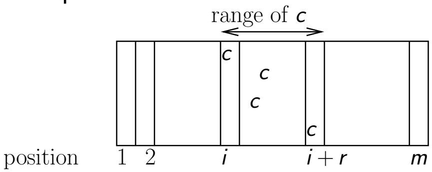
Further "structural" parameters:



Maximum range $r_m := \max_{c \in C} \text{range}(c)$	$O^*(32^{r_m})$
Average range r_a	NP-c for $r_a \geq 2$

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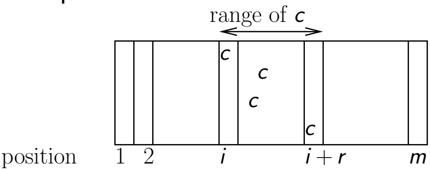

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Average KT-distance

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Recall: The KT-distance between two votes is the number of inversions or "conflict pairs".

Definition

For an election (V, C) the average KT-distance d_a is defined as

$$d_a := \frac{1}{n(n-1)} \cdot \sum_{\{u,v\} \in V, u \neq v} \text{KT-dist}(u, v).$$

In the following, we show that Kemeny Score is fixed-parameter tractable with respect to the "average KT-distance".

Complementarity of parameterizations

- Number of candidates m: $O^*(2^m)$
- Maximum range r of candidate positions in the input votes: $O^*(32^r)$
- Average distance of the input votes: $O^*(16^{d_a})$

($m \geq r$, but corresponding algorithm has a better running time)

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Example 1: small range, large number of candidates and average distance

a	$>$	c	$>$	b	$>$	e	$>$	d	$>$	f	$\ldots$
b	$>$	a	$>$	c	$>$	d	$>$	e	$>$	f	$\ldots$
b	$>$	c	$>$	a	$>$	e	$>$	f	$>$	d	$\ldots$

Example 2: small average distance, large number of candidates and range

a	$>$	b	$>$	c	$>$	d	$>$	e	$>$	f		$\ldots$
b	$>$	c	$>$	d	$>$	e	$>$	f	$>$	$\ldots$		a
a	$>$	b	$>$	c	$>$	d	$>$	e	$>$	f		$\ldots$

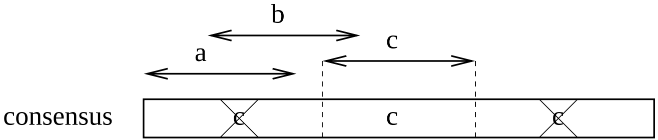
$\Rightarrow$ check size of parameter and then use appropriate strategy

Basic idea

Average distance d_a.

Crucial observation

In every Kemeny consensus every candidate can only assume a number of consecutive positions that is bounded by $2 \cdot d_a$.



Dynamic programming

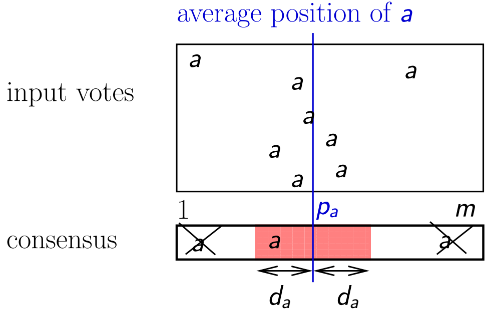
making use of the fact that every candidate can be “forgotten” or “inserted” at a certain position.

Crucial observation

Let the average position of a candidate c be $p_a(c)$.

Lemma

Let d_a be the average KT-distance of an election (V, C). Then, in every optimal Kemeny consensus r_{con}, for every candidate $c \in C$ we have $p_a(c) - d_a < r_{con}(c) < p_a(c) + d_a$.



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Idea of proof:

1. "The Kemeny score of (V, C) is smaller than $d_a \cdot |V|$."
   We show that one of the input votes has this Kemeny score.
2. Contradiction: Assume a candidate has a position outside the given range. Then, we can show that the Kemeny score is greater than $d_a \cdot |V|$, a contradiction.

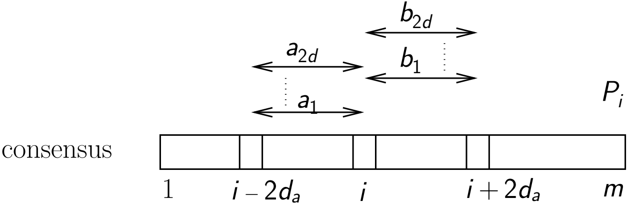
Number of candidates per position

For a position i, let P_i denote the set of candidates that can assume i in an optimal consensus.

Lemma

Let d_a be the average KT-distance of an election (V, C). For a position i, we have $|P_i| \leq 4 \cdot d_a$.

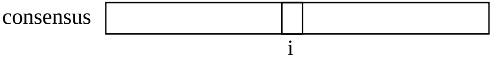
Proof: Position "range" of every candidate is at most $2 \cdot d_a$.



$$P_i = \{a_1, .., a_{2d}, b_1, .., b_{2d}\}$$

Every candidate of P_i must have a position smaller than $i + 2d_a$ and greater than $i - 2d_a$.

Dynamic programming



$P_i = \{a, b, c, d, e, f\}$

Observation:

For any position i and a subset P_i of candidates that can assume i:

- One candidate of P_i must assume position i in a consensus.
- Every other candidate of P_i must be either left or right of i.

Dynamic programming table

Position i, a candidate $c \in P_i$, a subset of candidates $P'_i \subseteq P_i \setminus \{c\}$

Definition

$T(i, c, P'_i) :=$ optimal partial Kemeny score if c has position i and all candidates of P'_i have positions smaller than i

$P_i = \{a, b, c, d, e, f\}$

$P'_i = \{a, b\}$

consensus	{a,b}	c	{d,e,f}
		i	

Computation of partial Kemeny scores:

- Overall Kemeny score can be decomposed (just a sum over all votes and pairs of candidates)
- Relative orders between c and all other candidates are already fixed

Running time

n votes

m candidates

$P_i = \{a, b, c, d, e, f\}$

consensus	$\{a, b\}$	c	$\{d, e, f\}$
		i	

We have $|P_i| \leq 4d_a$, thus there are at most 2^{4d_a} subsets of P_i.

$\Rightarrow$ Table size is bounded by $16^{d_a} \cdot \text{poly}(n, m)$.

Theorem

Kemeny Score can be solved in $O(n^2 \cdot m \log m + 16^d \cdot (16d^2 \cdot m + 4d \cdot m^2 \log m \cdot n))$ time with average KT-distance d_a and $d := \lceil d_a \rceil$.

Overview of parameterized complexity

	Kemeny Score
Number of votes n [Dwork et al. WWW 2001]	NP-c for $n = 4$
Kemeny score k	$O^*(1.53^k)$
Number of candidates m	$O^*(2^m)$
Maximum range of candidate positions r	$O^*(32^r)$
Average range of candidate positions r_a	NP-c for $r_a \geq 2$
Average KT-distance d_a	$O^*(16^{d_a})$

Outlook

- Average distance: investigate typical values.
- Improve the running time for the parameterizations "average distance" and "maximum candidate range".
- Implementation of the algorithms is under way.
- Consider generalizations like incomplete votes and ties.
- NP-completeness of KEMENY SCORE with 3 votes?