Èdouard Lucas:

The theory of recurrent sequences is an inexhaustible mine which contains all the properties of numbers; by calculating the successive terms of such sequences, decomposing them into their prime factors and seeking out by experimentation the laws of appearance and reproduction of the prime numbers, one can advance in a systematic manner the study of the properties of numbers and their application to all branches of mathematics.

Preview

Hardness results for sampling connected graph partitions with applications to redistricting

Daryl DeFord

MIT – CSAIL
Geometric Data Processing Group

Topology, Geometry and Data Seminar
The Ohio State University
September 26, 2019

Outline

Collaborators

- Prof. Moon Duchin — **Tufts Math**
- Prof. Justin Solomon — **MIT CSAIL**
- Lorenzo Najt — **Wisconsin Math**
- Hugo Lavenant — **Universitè Paris–Sud Math**
- Zachary Schutzman — **UPenn CIS**

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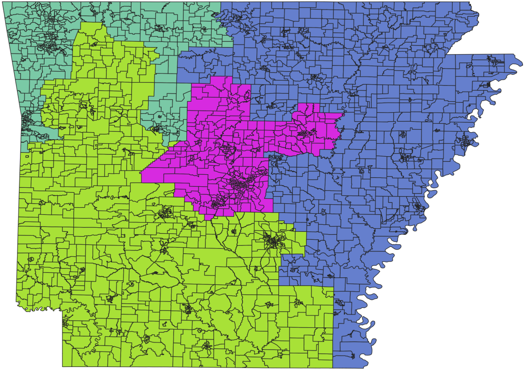
- Hugo Lavenant — **Universitè Paris–Sud Math**
- Zachary Schutzman — **UPenn CIS**

- *Total Variation Isoperimetric Profiles* (with H. Lavenant, Z. Schutzman, and J. Solomon), SIAM Journal on Applied Algebra and Geometry, to appear (2019).
- *Complexity and Geometry of Sampling Connected Graph Partitions* (with L. Najt and J. Solomon), arXiv: 1908.08881.
- *ReCombination: A family of Markov chains for redistricting* (with M. Duchin and J. Solomon), preprint.
- Redistricting Reform in Virginia: Districting Criteria in Context (with M. Duchin), Virginia Policy Review, 12(2), 120-146, (2019).

Additional Materials

- More Related Papers
- Course materials for: Computational Approaches for Political Redistricting
- Interactive Notes on Discrete MCMC (with Scrabble)
- MGGG widgets
- GitHub Source
- VRDI Website
- VRDI materials

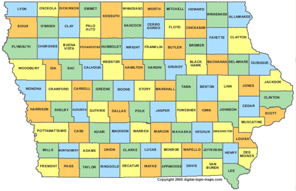
What is a district?

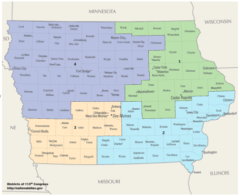


Permissible Districting Plans

- Contiguity
- Population Balance
- Compactness
- Communities of Interest
- Municipal Boundaries
- Competitiveness/Responsiveness
- Incumbency Protection
- ...

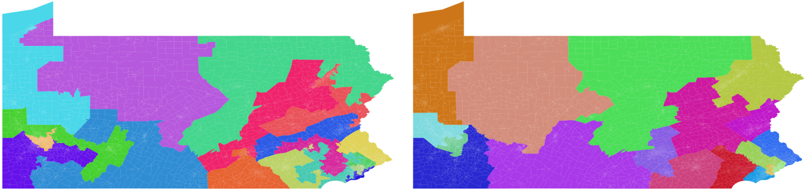
Example: Iowa





- 4 Congressional Districts, 100 House Districts, 50 Senate Districts
- House districts nest into Senate districts
- Congressional districts made out of counties
- Independent committee with legislative approval
- No partisan data allowed

Example: Pennsylvania



- 18 Congressional Districts, 203 House Districts, 50 Senate Districts
- Zero–balanced population
- Legislature draws congressional districts - subcommittee draws legislative districts
- Partisan considerations allowed

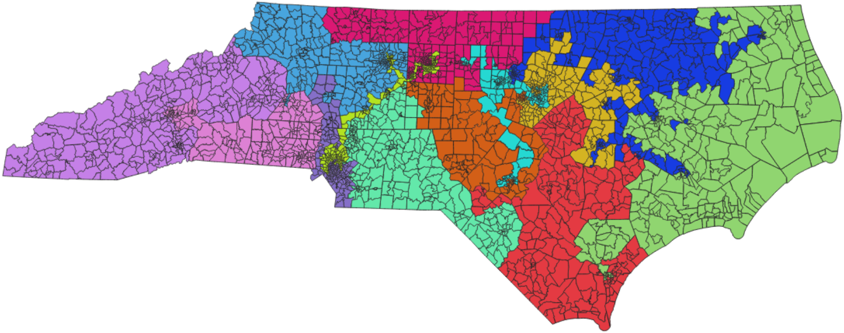
Why analyze?

- Court cases
  - Detecting gerrymandering
  - Evaluating proposed remedies
- Reform Efforts
  - Establishing baselines
  - Potential impacts of new rules
- Commissions and plan evaluation
  - Unintentional gerrymandering [1]
  - Full space of plans

[1] with apologies to J. Chen and J. Rodden, *Unintentional Gerrymandering: Political Geography and Electoral Bias in Legislatures*, Quarterly Journal of Political Science, 8, pp. 239–269, 2013.

Gerrymandering

Ugly Shapes



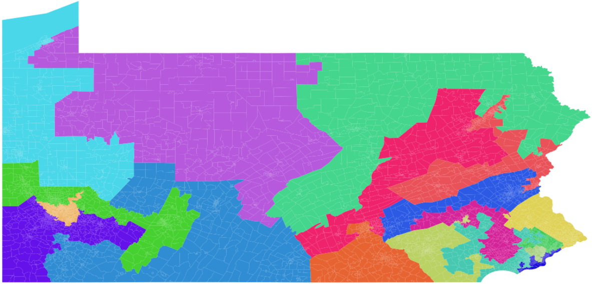
Ugly Shapes

NC12 #1

NC12 #2

NC12 #12

Ugly Shapes



Measurement Problems

Theorem (Bar-Natan, Najt, and Schutzman 2019[1])

There is no local homeomorphism from the globe to the plane that preserves your favorite compactness measure.

Problem (Barnes and Solomon 2018[2])

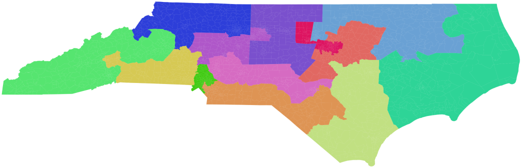
Geographic Compactness scores can be distorted by:

- *Data resolution*
- *Map projection*
- *State borders and coastline*
- *Topography*
- *...*

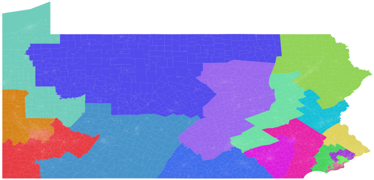
[1] The Gerrymandering Jumble: Map Projections Permute Districts' Compactness Scores, arXiv:1905.03173

[2] Gerrymandering and Compactness: Implementation Flexibility and Abuse, Political Analysis, to appear 2019.

Partisan Imbalance



NC16



PA TS-Proposed

Isoperimetric Profiles

Polsby–Popper

Theorem (Isoperimetry)

Let Ω be a bounded open subset of $\mathbb{R}^2$ with finite perimeter. Then:

$$4\pi A \leq P^2.$$

Definition (Polsby–Popper)

The Polsby–Popper score of a district is:

$$PP(\Omega) = \frac{4\pi A}{P^2}$$

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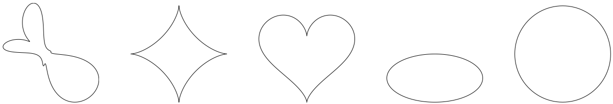
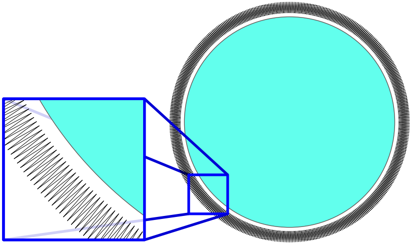
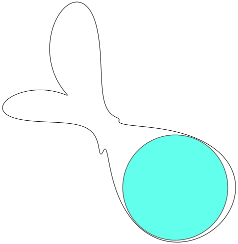


$\frac{4\pi A}{L^2} =$	0.359	0.411	0.680	0.841	1.000

Boundary Perturbation



$$\frac{4\pi A}{L^2} = 0.004$$



$$\frac{4\pi A}{L^2} = 0.359$$

Multiscale Desiderata

- Disambiguate different types of “badness”
- Stability under practical constraints
- Interpolate well–studied single measures
- Continuous and discrete versions
- Internal vs. external

Isoperimetric Profile

Definition (Isoperimetric Inequality)

Let $\Omega \subseteq \mathbb{R}^n$ to be a compact region whose boundary $\partial\Omega \subseteq \Omega$ is an $(n-1)$-dimensional hypersurface in $\mathbb{R}^n$

$$n \cdot \mathrm{vol}(\Omega)^{\frac{(n-1)}{n}} \cdot \mathrm{vol}(B(1, \mathbf{0}))^{\frac{1}{n}} \leq \mathrm{area}(\partial\Omega).$$

Isoperimetric Profile

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$$n \cdot \mathrm{vol}(\Omega)^{\frac{(n-1)}{n}} \cdot \mathrm{vol}(B(1, \mathbf{0}))^{\frac{1}{n}} \leq \mathrm{area}(\partial\Omega).$$

Definition (Isoperimetric Profile)

With Ω as above and $t \in [0, \mathrm{vol}(\Omega)]$ we ask for the smallest surface area needed to enclose volume t completely within Ω:

$$I_\Omega(t) := \min\{\mathrm{area}(\partial\Sigma) : \Sigma \subseteq \Omega \text{ and } \mathrm{vol}(\Sigma) = t\}.$$

Geometric Properties

Theorem (Flores and Nardulli (2016)[1])

Let M^n be a complete smooth Riemannian manifold with $\mathrm{Ric}_M \geq (n-1)k$, with $k \in \mathbb{R}$ and $V(B(p,1)) \geq v_0 > 0$. Then the isoperimetric profile is continuous on $[0, V(M)[$

[1] A. Flores and S. Nardulli: Continuity and differentiability properties of the isoperimetric profile in complete noncompact Riemannian manifolds with bounded geometry, https://arxiv.org/abs/1404.3245.

Geometric Properties

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Question

Identify a polynomial-time algorithm or NP-hardness result for computing isoperimetric profiles. The simplest open problem is computing the isoperimetric profile of a polygon in the plane $\mathbb{R}^2$.

[1] A. Flores and S. Nardulli: Continuity and differentiability properties of the isoperimetric profile in complete noncompact Riemannian manifolds with bounded geometry, https://arxiv.org/abs/1404.3245.

Total Variation

Definition (Three formulations of TV)

$$\mathrm{TV}[f] =$$

1. $$\sup\left\{\int_{\mathbb{R}^n} [f(x)\nabla\cdot\phi(x)]\,dx : \phi \in C_c^1(\mathbb{R}^n \to \mathbb{R}^n) \text{ and } \|\phi\|_\infty \leq 1\right\}$$

2. $$\int_{\mathbb{R}^n} \|\nabla f\|_2\,dx$$

3. $$\int_0^{+\infty} \mathrm{area}(\partial\{f \geq s\})ds$$

Perimeter as Total Variation

Definition

For a region $\Sigma \subseteq \mathbb{R}^n$, denote its *indicator function* $\mathbb{1}_\Sigma$ via

$$\mathbb{1}_\Sigma(x) := \begin{cases} 1 & \text{if } x \in \Sigma \\ 0 & \text{otherwise.} \end{cases} \tag{1}$$

Then, a consequence of the co-area formula is that

$$\text{area}(\partial\Sigma) = \text{TV}[\mathbb{1}_\Sigma]. \tag{2}$$

TV Relaxation

Definition (Isoperimetric Profile)

$$I_\Omega(t) = \begin{cases} \inf_{f \in L^1(\mathbb{R}^n)} & \mathrm{TV}[f] \\ \text{subject to} & \int_{\mathbb{R}^n} f(x)\,dx = t \\ & 0 \leq f \leq \mathbb{1}_\Omega \\ & f(x) \in \{0,1\}\ \forall x \in \mathbb{R}^n. \end{cases}$$

TV Relaxation

Definition (Isoperimetric Profile)

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Definition (TV Profile)

$$I_\Omega^{\mathrm{TV}}(t) := \begin{cases} \min_{f \in L^1(\mathbb{R}^n)} & \mathrm{TV}[f] \\ \text{subject to} & \int_{\mathbb{R}^n} f(x)\,dx = t \\ & 0 \le f \le \mathbb{1}_\Omega. \end{cases}$$

Example: Circle

Proposition

For all (Ω, t), *we have* $I_\Omega^{\mathrm{TV}}(t) \leq I_\Omega(t)$.

Examples (Circle)

Suppose $\Omega \subset \mathbb{R}^2$ *is a circle of radius* R, *and take* $t = \pi r^2$ *for* $r \in (0, R)$. *In this case, by the isoperimetric inequality we know* $I_\Omega(t) = 2\pi r$. *But suppose we take* $f(x) \equiv \dfrac{r^2}{R^2}$. *By the co-area formula*

$$I_\Omega^{\mathrm{TV}}(t) \leq \mathrm{TV}[f] = 2\pi R \cdot \frac{r^2}{R^2} = 2\pi r \cdot \frac{r}{R} < I_\Omega(t).$$

Hence, our relaxation is not tight.

Isoperimetry and Convexity

Proposition (Isoperimetry)

Suppose $B \subset \mathbb{R}^n$ *is a ball whose volume matches* $\mathrm{vol}(\Omega)$*. Then, for all* $t \in [0, \mathrm{vol}(\Omega)]$*, we have* $I_B^{\mathrm{TV}}(t) \le I_\Omega^{\mathrm{TV}}(t)$*, and if the equality holds for some* $t > 0$ *then* Ω *is a ball.*

Proposition (Convexity)

$I_\Omega^{\mathrm{TV}}(t)$ *is a convex function of* t*.*

Proposition (Convex Envelope)

The function I_Ω^{TV} *is the lower convex envelope of* I_Ω*.*

Dual Optimization

Dual Formulation:

$$I_\Omega^{TV}(t) = \begin{cases} \sup_{\phi \in C_c^1(\mathbb{R}^n \to \mathbb{R}^n), \lambda \in \mathbb{R}} & \lambda t - \int_\Omega \max(\lambda - \nabla \cdot \phi(x), 0)\, dx \\ \text{subject to} & \|\phi\|_\infty \leq 1 \end{cases}$$

Proof.

With the dual in hand, the convexity results follow from constructing an auxilliary function:

$$h(\lambda) = \inf_{\|\phi\|_\infty \leq 1} \int_\Omega \max(\lambda - \nabla \cdot \phi(x), 0)\, dx.$$

and computing some Legendre transforms. □

Minimizer Structure

Proposition (Distinguished Solutions)

There exists a family $(f_t)_{t\in[0,1]}$ *such that:*

- *For any* $t \in [0,1]$, *the function* $f_t \in L^1(\mathbb{R}^n)$ *satisfies* $0 \le f_t \le \mathbb{1}_\Omega$, $\int_{\mathbb{R}^n} f_t(x)\,dx = t$ *and* $\mathrm{TV}(f_t) = I_\Omega^{\mathrm{TV}}(t)$.
- *For any* $t \in [0,1]$, *there exist* $v_t \in (0,1)$ *such that* f_t *takes its values in* $\{0, v_t, 1\}$.
- *For a.e.* $x \in \Omega$, *the function* $t \to f_t(x)$ *is increasing.*

NC 12 # 9

NC 12 # 2

NC 12 # 12

Cheeger Sets

Definition (Cheeger Constant)

The Cheeger constant of Ω, denoted by $h_1(\Omega)$, is defined as

$$h_1(\Omega) := \inf_{\tilde{\Sigma} \subseteq \Omega} \frac{\operatorname{area}(\partial \tilde{\Sigma})}{\operatorname{vol}(\tilde{\Sigma})},$$

and a subset $\Sigma \subseteq \Omega$ such that $h_1(\Omega) = \frac{\operatorname{area}(\partial \Sigma)}{\operatorname{vol}(\Sigma)}$ is known as a Cheeger set of Ω.

Proposition (Small t)

Let Ω be compact, let $h_1(\Omega)$ be the Cheeger constant of Ω, and let Σ be a Cheeger set of Ω. Then for any $t \leq \operatorname{vol}(\Sigma)$, we have $I_\Omega^{\mathrm{TV}}(t) = h_1(\Omega)t$, and a solution f is given by $f := \frac{t}{\operatorname{vol}(\Sigma)} \cdot \mathbb{1}_\Sigma$.

Cheeger Proof

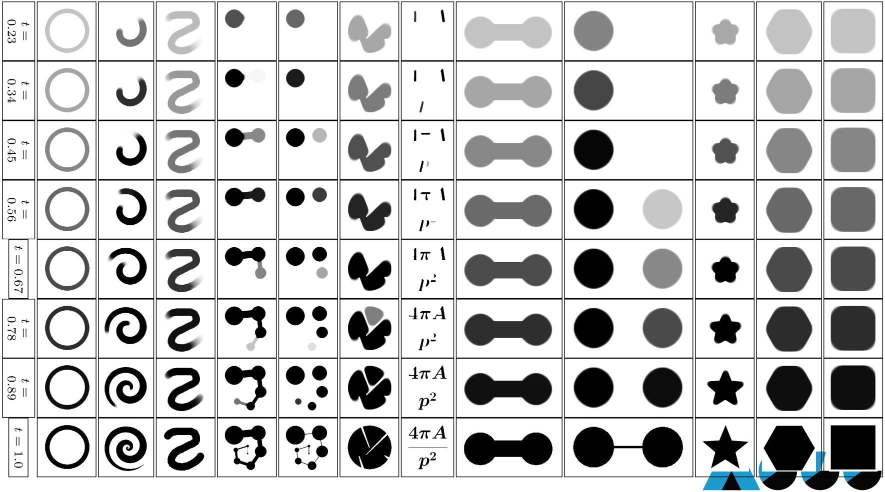
Proof.

We start with $\hat{f} = \frac{t}{\mathrm{vol}(\Sigma)} \cdot \mathbb{1}_\Sigma$ which satisfies the constraints of the problem defining $I_\Omega^{\mathrm{TV}}(t)$ as soon as $t \leq \mathrm{vol}(\Sigma)$, which ensures $0 \leq \hat{f} \leq \mathbb{1}_\Sigma \leq \mathbb{1}_\Omega$. Hence, $I_\Omega^{\mathrm{TV}}(t) \leq h_1(\Omega)t$. On the other hand, using the co-area formula, if f is any competitor then

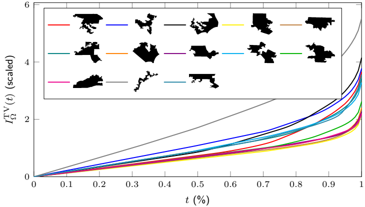
$$
\begin{aligned}
\mathrm{TV}(f) &= \int_0^{+\infty} \mathrm{area}(\partial\{f \geq s\}) ds \\
&= \int_0^{+\infty} \mathrm{vol}(\{f \geq s\}) \cdot \underbrace{\frac{\mathrm{area}(\partial\{f \geq s\})}{\mathrm{vol}(\{f \geq s\})}}_{\geq h_1(\Omega) \text{ by definition}} ds \\
&\geq h_1(\Omega) \int_0^{+\infty} \mathrm{vol}(\{f \geq s\}) ds = h_1(\Omega) \int_{\mathbb{R}^d} f(x) dx = h_1(\Omega)t.
\end{aligned}
$$

Hence, for $t \leq \mathrm{vol}(C)$, we have $I_\Omega^{\mathrm{TV}}(t) = h_1(\Omega)t$. □

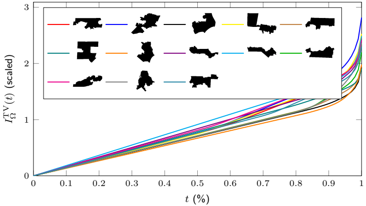
Synthetic Examples



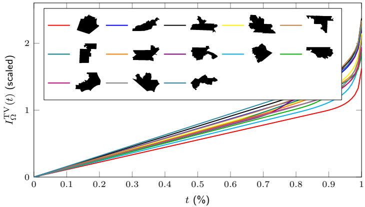
North Carolina



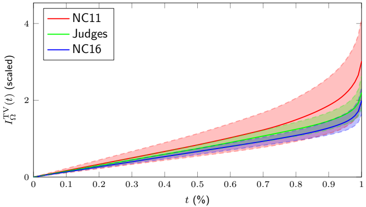
(a) 2011 districts



(b) 2016 districts

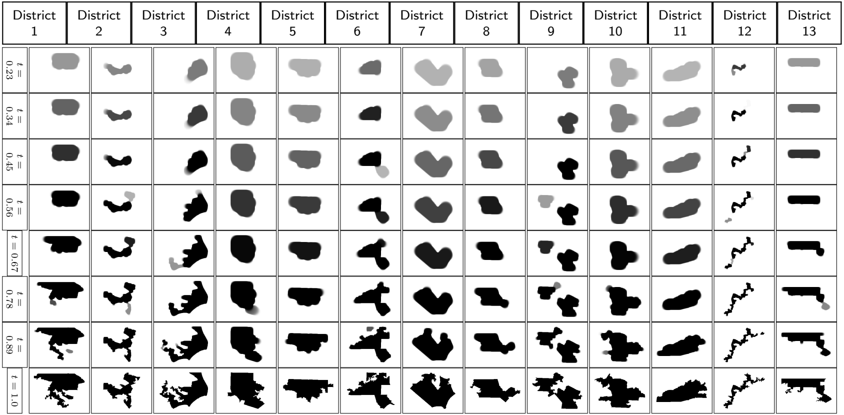


(c) Judges plan

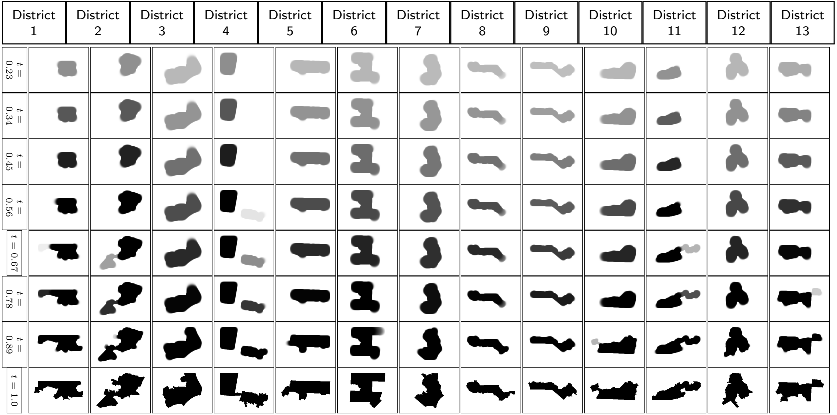


(d) Comparison

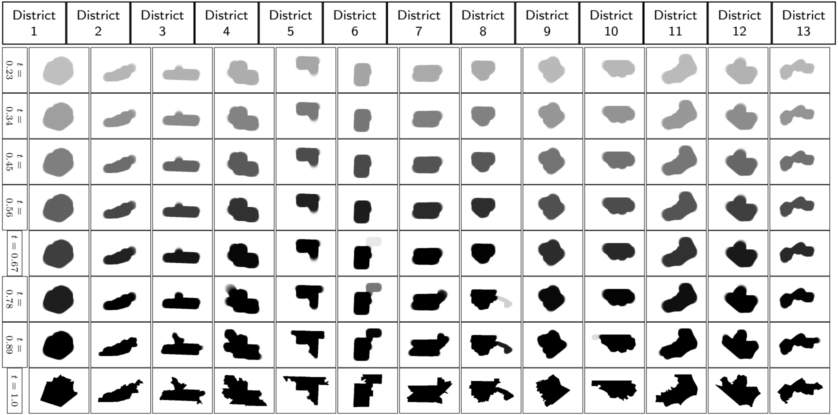
NC 2011 Districts



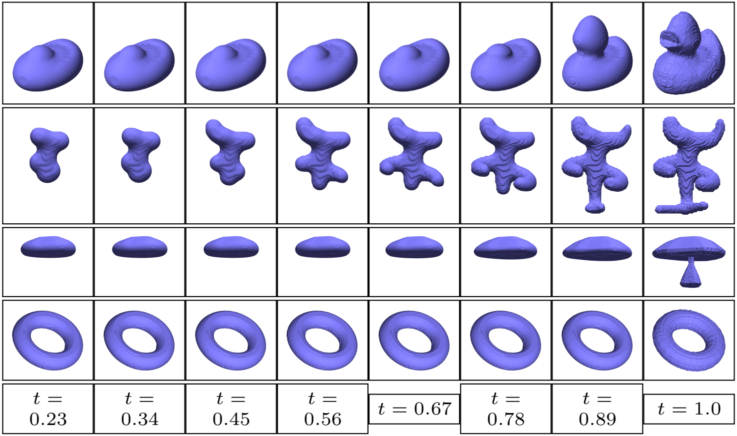
NC 2016 Districts



Judge's Plan


District 1
District 2
District 3
District 4
District 5
District 6
District 7
District 8
District 9
District 10
District 11
District 12
District 13
t = 0.23
t = 0.34
t = 0.45
t = 0.56
t = 0.67
t = 0.78
t = 0.89
t = 1.0

Higher Dimensions



Other Formulations

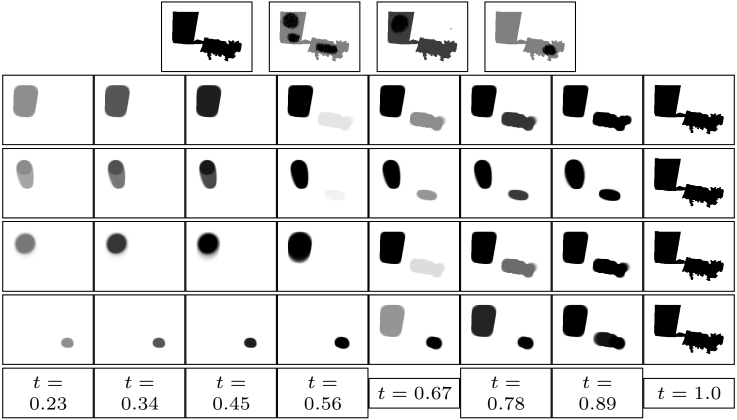
Definition (Population Measure)

$$I^{\mathrm{TV}}_{\Omega,\rho}(t) := \begin{cases} \min_{f \in L^1(\mathbb{R}^n)} & \mathrm{TV}[f] \\ \text{subject to} & \int_{\mathbb{R}^n} f(x)\, d\rho(x) = t \\ & 0 \le f \le \mathbb{1}_\Omega. \end{cases}$$

Definition (Discrete)

$$I^{\mathrm{TV}}_{V_0}(t) := \begin{cases} \min_{f \in \mathbb{R}^V} & \sum_{(v,w)\in E} |f(v) - f(w)| \\ \text{subject to} & \sum_{v \in V_0} f(v) = t|V_0| \\ & f(v) = 0 \ \forall v \notin V_0 \\ & f(v) \in [0,1] \ \forall v \in V. \end{cases}$$

Synthetic Cities



Discrete Animation

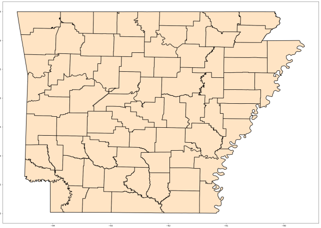
Multiscale Wrapup

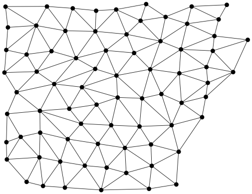
Open questions:

- How much can we learn about the full profile from the relaxed version?
- Can the medial axis be computed from the TV-Profile?
- What is the right way to compare regions of the profiles?

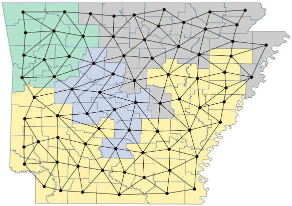
- Spectral Versions (i.e. how to make the heat kernel useful)
- Random walk versions (absorbing boundary nodes)
- Distance based measures
- ...

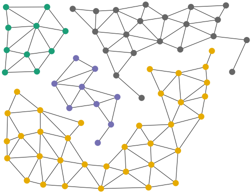
Discrete Partitioning





Discrete Partitioning





Permissible Districting Plans

We want to partition a given geography (graph), at a given scale, into k pieces, satisfying some constraints:

- **Contiguity**
- **Population Balance**
- Compactness
- Communities of Interest
- Municipal Boundaries
- Competitiveness/Responsiveness
- Incumbency Protection
- ...

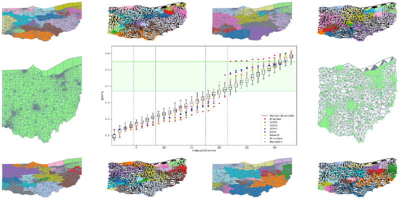
Mathematical Formulation

Given a (connected, planar) graph $G = (V, E)$:

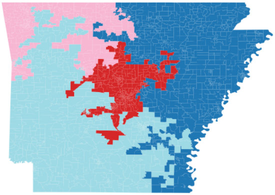
- A k-**partition** $P = \{V_1, V_2, \ldots, V_k\}$ of G is a collection of disjoint subsets $V_i \subseteq V$ whose union is V.
- A partition P is **connected** if the subgraph induced by V_i is connected for all i.
- The **cut edges** of P are the edges (u, w) for which $u \in V_i$, $w \in V_j$, and $i \neq j$
- A partition P is ε-**balanced** if $\mu(1-\varepsilon) \leq |V_i| \leq \mu(1+\varepsilon)$ for all i where μ is the mean of the $|V_i|$'s
- An **equi–partition** is a 0-balanced partition

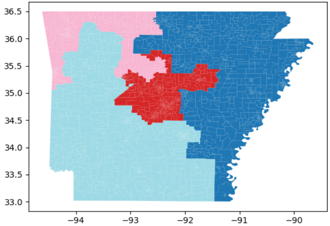
Ensemble Analysis

- The wide variety in rules applied to districting problems (even in the same state) means that any single measure of gerrymandering will be insufficient/exploitable
- Instead we want to compare to large ensembles of other feasible plans.
- This allows us to understand the impacts of the underlying political and demographic geography on a wide collection of metrics.



Which ensembles?





Ensembles in Practice

- The appeal of an ensemble method is that you get to control the input data very carefully
- However, just because a particular type of data was not considered doesn't mean that the outcome is necessarily "fair"
- There are lots of "random" methods for constructing districting plans
- Most don't offer any control over the distribution that you are drawing from

MCMC on partitions

1. Set constraints to define the state space
2. Start with an initial plan
3. Propose a modification
4. Verify that the modification satisfies the constraints
5. Accept using MH criterion
6. Repeat

MCMC on partitions

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Why?

MCMC on partitions

1. Set constraints to define the state space
2. Start with an initial plan
3. Propose a modification
4. Verify that the modification satisfies the constraints
5. Accept using MH criterion
6. Repeat

Why?

- Control over sampling distribution and input data
- Possibility of local sampling
- Ergodic Theorem

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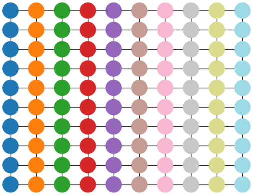
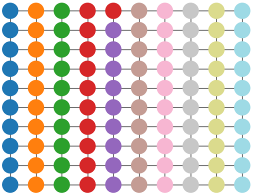
Single Edge Flip Proposals

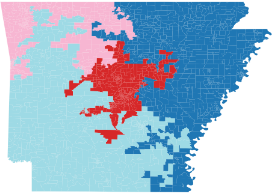
1. Uniformly choose a cut edge
2. Change one of the incident node assignments to the other

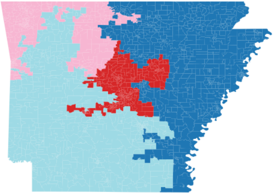




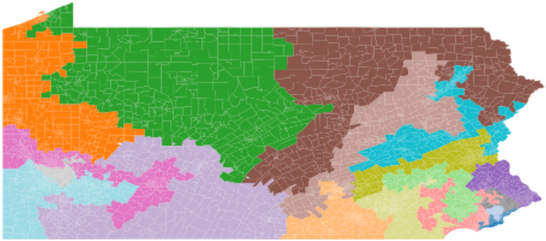
- Mattingly et al. (2017, 2018) Court cases in NC and WI.
- Pegden et al. Assessing significance in a Markov chain without mixing, PNAS, (2017). Court case in PA.

Single Edge Ensembles

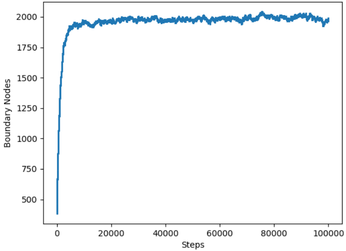


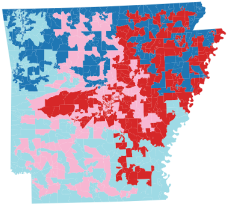


PA Single Edge Flip

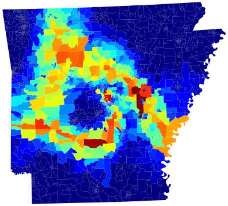


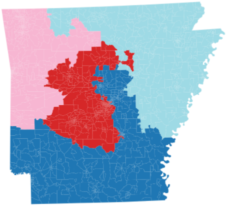
Unconstrained Flip



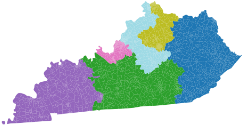


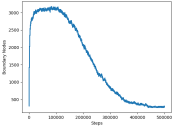
Constrained Flip

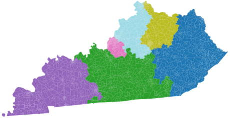




Annealing




Boundary Nodes
3000
2500
2000
1500
1000
500
0
100000
200000
300000
400000
500000
Steps



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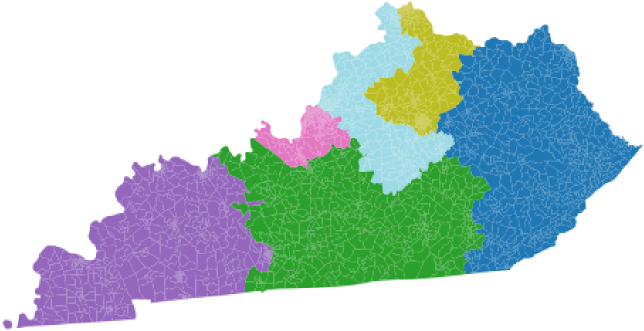

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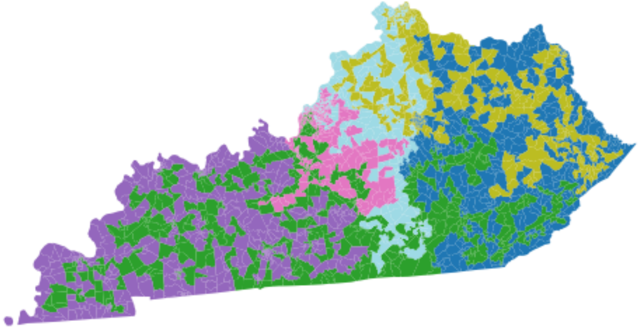

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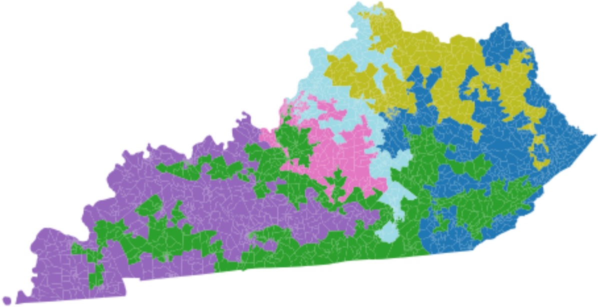

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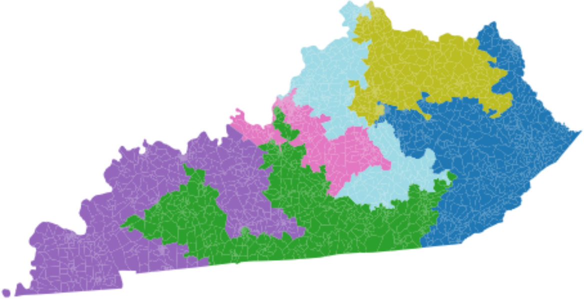

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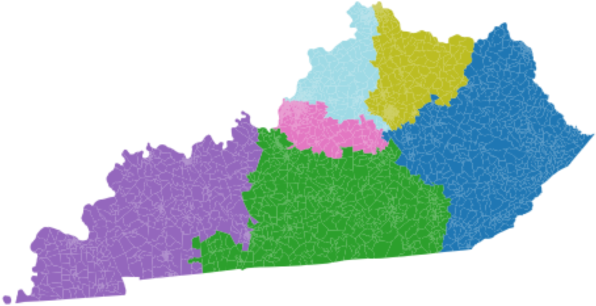
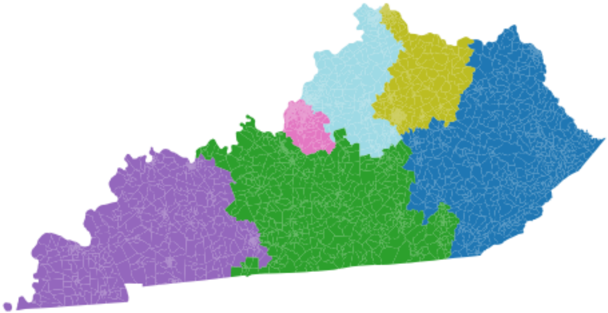


Annealing



Uniform Sampling of Contiguous Partitions

Theorem (Najt, D., and Solomon 2019)

Suppose that $\mathscr{C}$ is the class of connected planar graphs and $k \geq 2$. If there is a polynomial time algorithm to sample uniformly from:

- *the connected k-partitions of graphs in $\mathscr{C}$,*
- *or the connected, 0-balanced k-partitions of graphs in $\mathscr{C}$.*

then $RP = NP$.

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then $RP = NP$.

Remark

This theorem has various interesting extensions, including:

- *Connectivity constraints on $\mathscr{C}$*
- *Degree bounds*
- *Distributions proportional to cut length*
- *TV distribution approximation*

Stronger Version Example

Theorem (Najt, D., and Solomon 2019)

Let $\mathscr{C}$ be the class of cubic, planar 3-connected graphs, with face degree bounded by $C = 60$. Let $\mu_x(G)$ be the probability measure on $P_k(G)$ such that a partition P is drawn with probability proportional to $x^{cut(P)}$. Fix some $x > 1/\sqrt{2}$, $\epsilon > 0$ and $\alpha < 1$. Suppose that there was an algorithm to sample from $P_2^\epsilon(G)$ according to a distribution $\nu(G)$, such that $||\nu_G - \mu_x(G)||_{TV} < \alpha$, which runs polynomial time on all $G \in \mathscr{C}$. Then $RP = NP$.

Proof Outline Sketch

Following technique of Jerrum, Valiant, and Vazirani[1].

1. Show that uniformly sampling simple cycles is hard on some class $\mathscr{C}$
    1. Choose a gadget that respects $\mathscr{C}$ and allows us to concentrate probability on long cycles
    2. Count the proportion of cycles as a function of length
    3. Reduce to Hamiltonian path on the graph class
2. Show closure of class under planar dual
3. Identify partitions with cut edges $\mapsto$ simple cycles (via planar duality)
4. Conclude that sampling partitions would allow you to sample from cycles which would allow you to find Hamiltonian cycles

□

[1] M. Jerrum, L. Valiant, and V. Vazirani, Random generation of combinatorial structures from a uniform distribution, Theoretical Computer Science, 43 (1986), 169–188.

Proof Sketch – Planar 2–Partitions

Still following technique of Jerrum, Valiant, and Vazirani.

1. Let $\mathscr{C}$ be the planar connected graphs
   1. Replace the edges with chains of dipoles
   2. Hamiltonian hardness for $\mathscr{C}$ given by [1]
2. $\mathscr{C}$ closed under planar duals
3. Identify partitions with cut edges (via planar duality)

$\square$

[1] M. Garey, D. Johnson, and R. Tarjan, The Planar Hamiltonian Circuit Problem is NP-Complete, SIAM Journal on Computing, 5, (1976), 704–714.

Slowly Mixing Graph Families

Theorem (Najt, D., and Solomon 2019)

Let G be any connected graph. Then let $G^{(d)}$ be the graph obtained by replacing each edge by a doubled d-star. Then the flip walk on partitions of family of graphs $G^{(d)}_{d \geq 1}$ is slowly mixing, in the sense the Cheeger constant is decaying exponentially fast. More specifically:

$$H(Partition\ Graph(G^{(d)}) = O(2^{-d})$$

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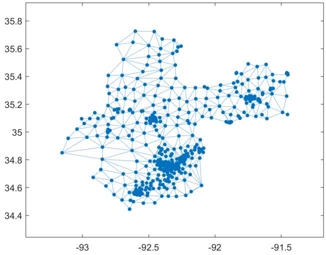
Remark

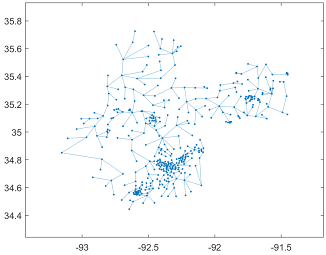
There are many similar constructions that give rise to equivalent mixing results.

Slow Mixing Example

Tree based methods

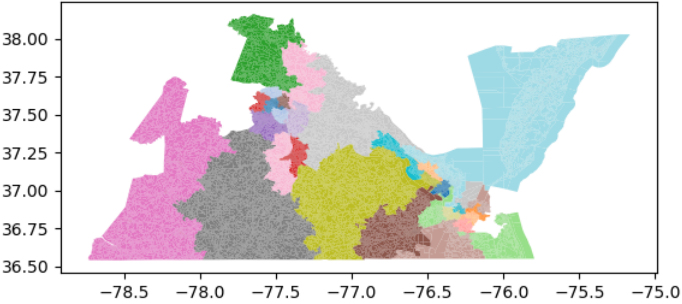


District



Spanning Tree

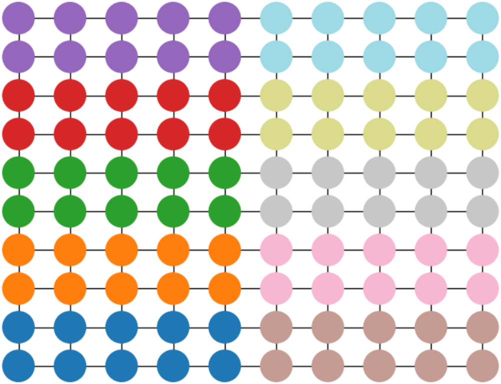
Tree Seeds Ensemble



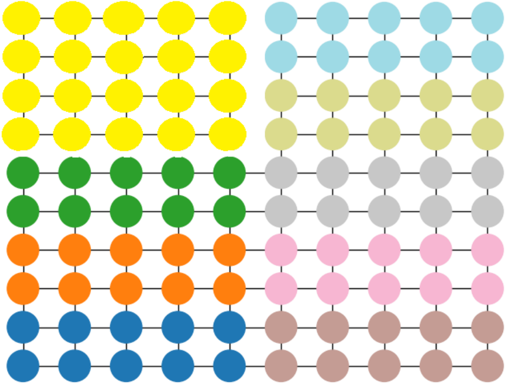
Recombination Steps

1. At each step, select two adjacent **districts**
2. Merge the subunits of those two districts
3. Draw a spanning tree for the new super–district
4. Delete an edge leaving two population balanced districts
5. Repeat

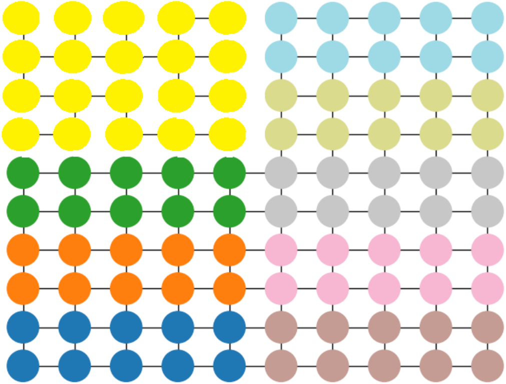
Recombination Step Example



Recombination Step Example



Recombination Step Example



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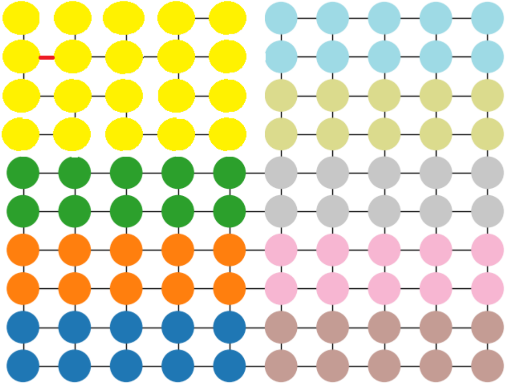
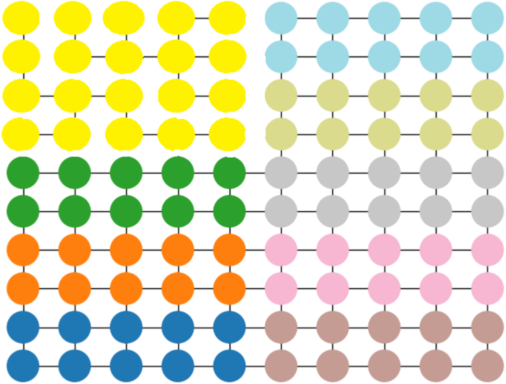
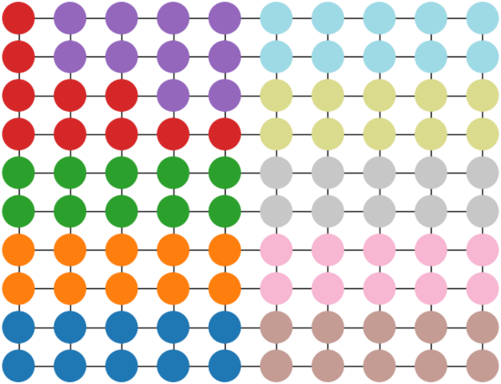


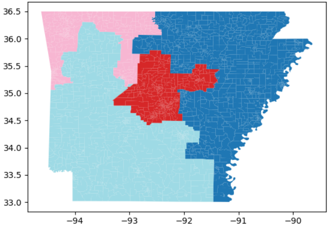
Recombination Step Example

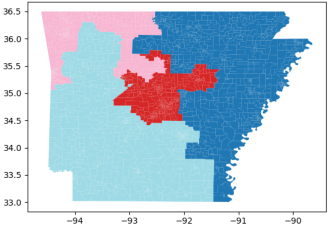


Recombination Step Example



AR Ensembles





PA Recombination Steps

Tree Partitioning Questions

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- How bad is the best cut?
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- Criteria for determining when all spanning trees of a graph are ε cuttable?
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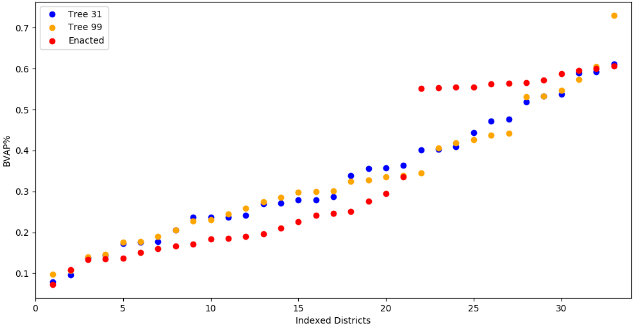
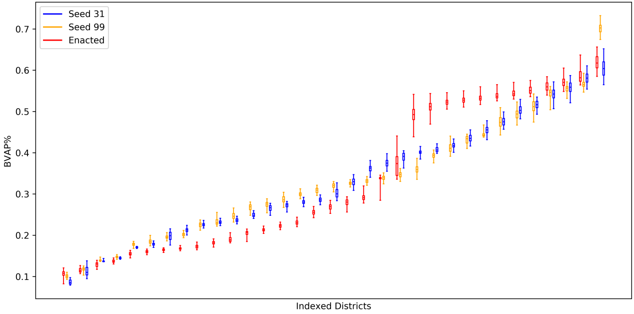
Initial Seeds



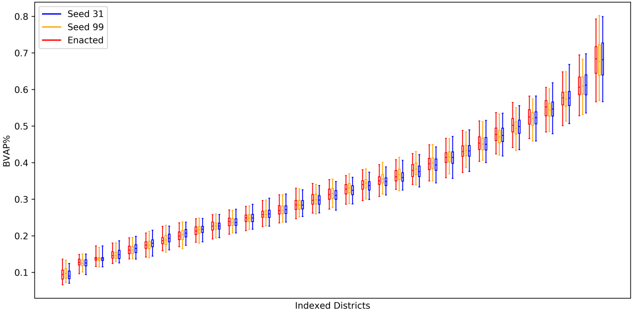
Initial

Boundary Flip Mixing – Seeds



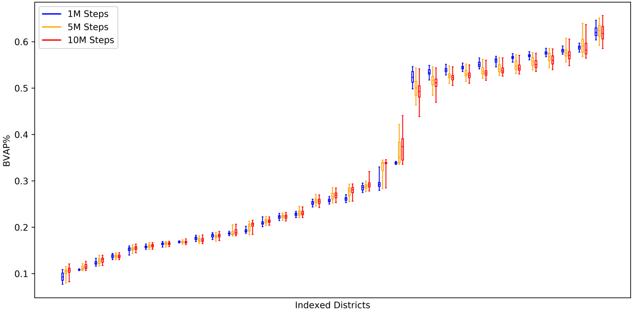
10,000,000 Flip Steps

Recombination Mixing – Seeds

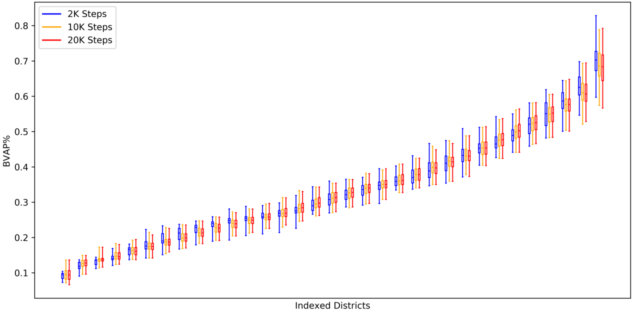


20,000 Recombination Steps

Boundary Flip Mixing – Length



Recombination Mixing – Length



20,000 Recombination Steps

Try it at home!

- Draw your own districts with **Districtr**
  - https://districtr.org
  - Easy to generate complete districting plans in browser or on a tablet
  - Measures district demographics and expected partisan performance
  - Identifies communities of interest
- Generate your own ensembles with **GerryChain**[1]
  - https://github.com/mggg/gerrychain
  - Flexible, modular software for sampling graph partitions
  - Handles the geodata processing as well as the MCMC sampling
  - Current support for a
  - Successfully applied in VA, NC, PA, etc.
- Data is available for your favorite state!
  - Census dual graphs with demographic information:
  - https://people.csail.mit.edu/ddeford/dual_graphs
  - Precincts with electoral results
  - https://github.com/mggg-states

[1] Originally RunDMCMC

Applications

Nos. 18-422, 18-726

IN THE
Supreme Court of the United States

ROBERT A. RUCHO, ET AL.,
Appellants,
v.
COMMON CAUSE, ET AL.,
Appellees.

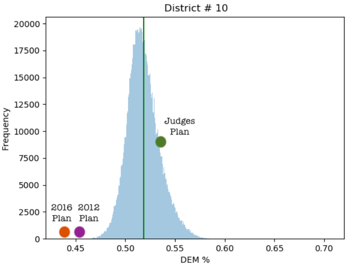
On Appeal from the United States District Court for the Middle District of North Carolina

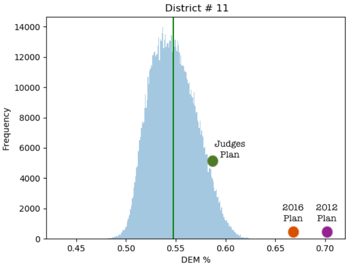
LINDA H. LAMONE, ET AL.,
Appellants,
v.
O. JOHN BENISEK, ET AL.,
Appellees.

On Appeal from the United States District Court for the District of Maryland

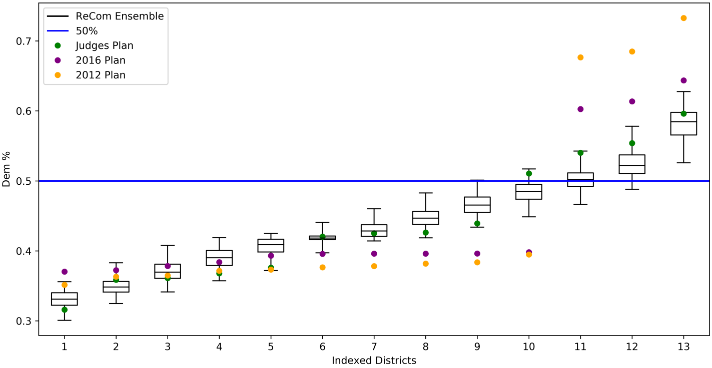
AMICUS BRIEF OF MATHEMATICIANS, LAW PROFESSORS, AND STUDENTS IN SUPPORT OF APPELLEES AND AFFIRMANCE

Outlier Example: NC

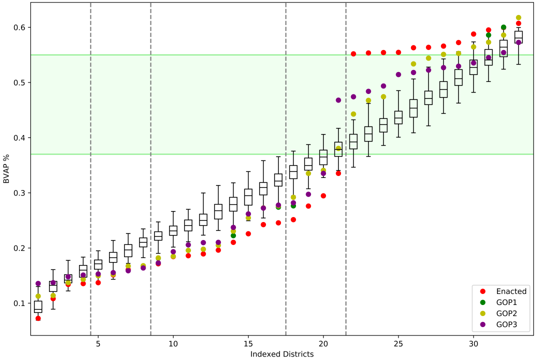




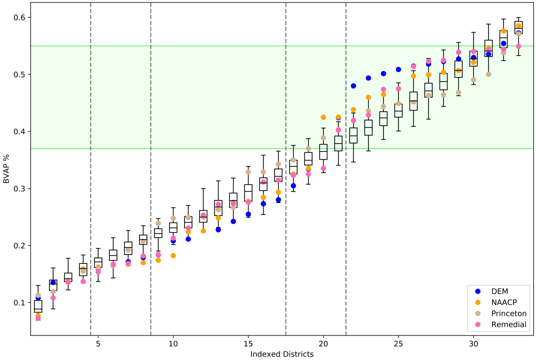
Outlier Example: NC



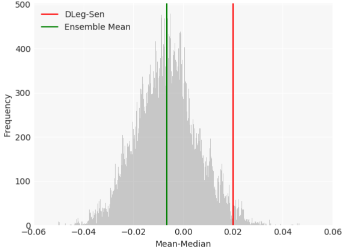
Outlier Example: VA



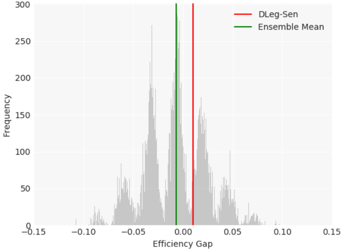
Outlier Example: VA



Baseline Example: VA

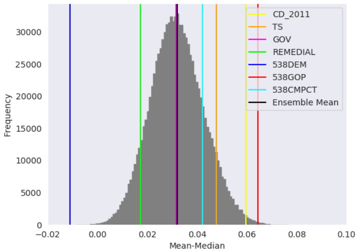


Mean–Median

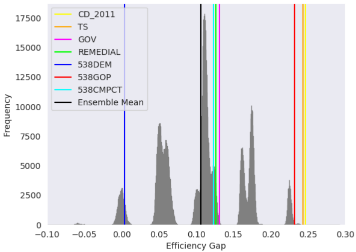


Efficiency Gap

Baseline Example: PA

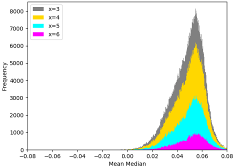


Mean–Median

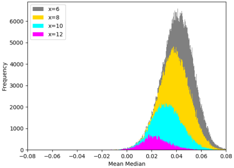


Efficiency Gap

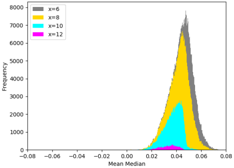
Reform Example: Competitiveness



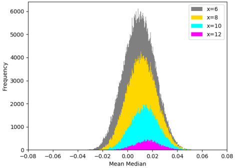
UT



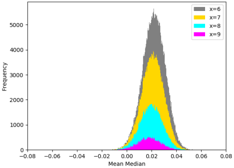
GA



WI



VA



MA

The End

Thanks!

General Tree Proposals

1. Form the induced subgraph on the complement of the cut edges
2. Add some subset of the cut edges
3. Uniformly select a maximal spanning forest
4. Apply a Markov chain on trees
5. Partition the spanning forest into k population balanced pieces

Special Cases

- Uniform Trees: Add all cut edges
- k–edges: Uniformly add k cut edges
- Recombination: Add all cut edges between one pair of districts.
- Super-Recombination: Take a maximal matching on the dual graph to the districts and add all cut edges between matched districts.
- Bounce Walk: Add a single cut edge between enough pairs of districts to make a tree in the dual graph of districts.

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Question

What are the steady state distributions (and mixing times) of these walks?

Tree Partitioning Questions

- Characterizing the distribution on partitions defined by cutting trees!
- How bad is the best cut?
- Criteria for determining when a tree is ε cuttable?
- Criteria for determining when all spanning trees of a graph are ε cuttable?
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General Merge Proposals

1. At each step, select two adjacent **districts**
2. Merge the subunits of those two districts
3. Bipartition the new super–district
4. Repeat
5. (Optional) Mix with single edge flips

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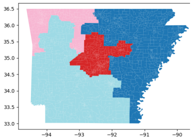
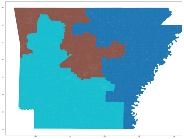
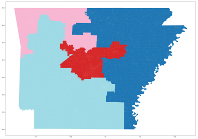


Before



During



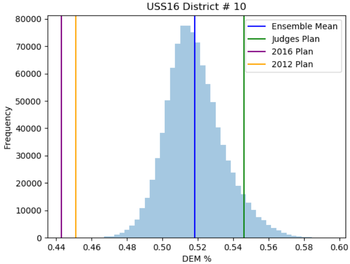
After

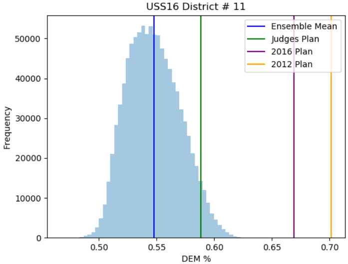
Bipartitioning Methods

- Trees!
- Flood Fills
- Path Fills
- Agglomerative/Hierarchical
- Spectral
- Min Cut

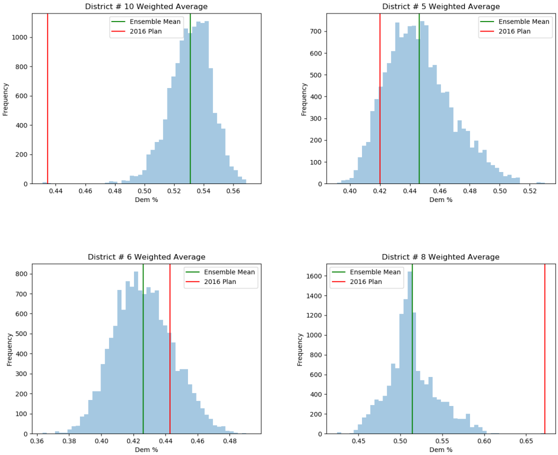
More details (and colorful figures) at:
`https://www.overleaf.com/read/zpmyzqmpvmnx`

Ensemble Example: NC

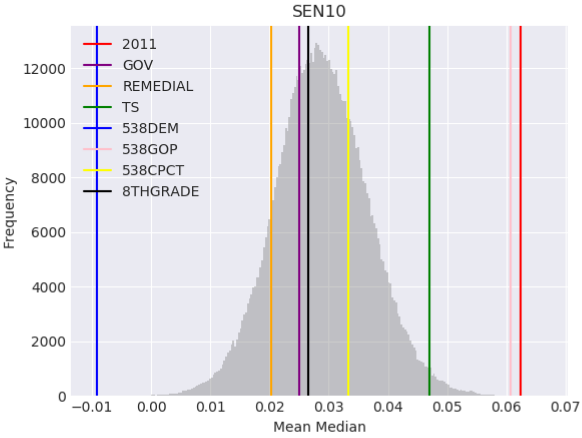




Ensemble Example: NC



Ensemble Example: PA



Ensemble Example: PA