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IN THE COMMONWEALTH COURT OF PENNSYLVANIA

CASES CONSOLIDATED

Carol Ann Carter, Monica Parrilla, Rebecca Poyourow, William Tung, Roseanne Milazzo, Burt Siegel, Susan Cassanelli, Lee Cassanelli, Lynn Wachman, Michael Guttman, Maya Fonkeu, Brady Hill, Mary Ellen Balchunis, Tom DeWall, Stephanie McNulty, and Janet Temin,

Petitioners,

v.

Leigh Chapman, in her official capacity as the Acting Secretary of the Commonwealth of Pennsylvania; Jessica Mathis, in her official capacity as Director for the Pennsylvania Bureau of Election Services and Notaries,

Respondents,

No. 464 M.D. 2021

Philip T. Gressman, Ron Y. Donagi, Kristopher R. Tapp, Pamela Gorkin, David P. Marsh, James L. Rosenberger, Amy Myers, Eugene Boman, Gary Gordon, Liz McMahon, Timothy G. Feeman, and Garth Isaak,

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Leigh Chapman, in her official capacity as the Acting Secretary of the Commonwealth of Pennsylvania; Jessica Mathis, in her official capacity as Director for the Pennsylvania Bureau of Election Services and Notaries,

Respondents.

No. 465 M.D. 2021

BRIEF IN SUPPORT OF
GRESSMAN MATH/SCIENCE PETITIONERS' CONGRESSIONAL PLAN

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Pursuant to the Court's January 14, 2022 Order (the "Order"), Petitioners Philip T. Gressman, Ron Y. Donagi, Kristopher R. Tapp, Pamela Gorkin, David P. Marsh, James L. Rosenberger, Amy Myers, Eugene Boman, Gary Gordon, Liz McMahon, Timothy G. Feeman, and Garth Isaak (the "Gressman Math/Science Petitioners" or "Petitioners") respectfully submit the following brief in support of their proposed congressional redistricting plan (the "GMS Plan" or the "Proposed Plan").

INTRODUCTION

The Gressman Math/Science Petitioners are leading professors of mathematics and science at some of Pennsylvania's premier institutes of higher education, including Bryn Mawr College, Bucknell University, Lafayette College, Lehigh University, Penn State University, St. Joseph's University, the University of Pennsylvania, and Villanova University. They have won numerous honors and recognitions from organizations such as the National Science Foundation, the Mathematical Association of America, the American Statistical Association, and the American Mathematical Society. Directly relevant here, their fields of expertise include geometric analysis, spatial statistics, optimization methods, algorithmic techniques, and data science. Besides being experts in academic fields related to redistricting, Petitioners are also registered voters who live in malapportioned congressional districts and care deeply about ensuring that the congressional redistricting process is fair to all Pennsylvanians. As the only nonpartisan party before this Court, Petitioners ask this Court to ensure that the process of selecting a remedial congressional redistricting plan is governed by nonpartisan scientific principles rather than partisan parochial concerns.[1]

Along with this brief, the Gressman Math/Science Petitioners have submitted their proposed congressional redistricting plan, the GMS Plan.[2] Petitioners respectfully submit that their Plan—which was generated through the process of computational redistricting as further explained below—is the proper remedy for the Court to adopt. Adopting the GMS Plan would ensure that Pennsylvania will be able to hold its primary and general elections under a fair and fully legally compliant congressional plan.

Petitioners used the congressional plan adopted by the Pennsylvania Supreme Court in 2018 (the "2018 Plan") as their baseline for what a court-drawn plan should achieve. Because the 2018 Plan was drawn using 2010 Census data and contains 18 rather than 17 congressional districts, a perfect comparison between the 2018 Plan

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[1] For a further description of petitioners, see Brian X. McCrone, *Decision 2022: Fairer Elections in Pa. Could Depend on 12 Mathematicians*, NBC Philadelphia (Jan. 17, 2022), https://www.nbcphiladelphia.com/decision-2022/gerrymandering-redistricting-pennsylvania-mathematicians-fight-congressional-districts-maps/3109820/.

[2] Attached to this brief are a statewide congressional map reflecting the GMS Plan, along with three maps focusing on specific regions of the Commonwealth. To support and explain their Plan, Petitioners also attach an expert report by Professor Daryl DeFord, Ph.D.

and the GMS Plan is not possible. But the 2018 Plan generally provides the baseline for comparison because it reflects the Pennsylvania Supreme Court's instructions for how a remedial congressional redistricting plan should be drawn. *See generally League of Women Voters of Pa. v. Commonwealth*, 178 A.3d 737 (Pa. 2018) [hereinafter "*League of Women Voters I*"].

By taking the Pennsylvania Supreme Court's instructions seriously, the GMS Petitioners offer the Court a remedial plan that performs optimally on all state and federal legal requirements. Key features of the GMS Plan include perfect population equality and contiguity, compact districts that minimally split political boundaries, districts that achieve partisan fairness, and three "majority-minority" districts that give Black and Latino citizens an opportunity to nominate and elect their preferred candidates—a reflection of Pennsylvania's increasingly diverse population. Adopting the GMS Plan would allow this Court to follow the roadmap laid by the Supreme Court just four years ago, thereby ensuring free and fair congressional elections for all Pennsylvanians for the next decade.

In this brief, Petitioners not only explain the features of their own GMS Plan, but also compare it to the congressional plan passed on a party-line vote by the Pennsylvania House on January 12, 2022 (the "House Republican Plan" or "HR Plan"), as well as the congressional plan that Intervenor-Respondent Governor Tom Wolf publicly proposed on January 15, 2022 (the "Governor's Plan"). The results of these comparisons are striking. As explained in the Expert Report of Professor Daryl DeFord filed with this brief, the GMS Plan outperforms its competitors on nearly all metrics, while also scrupulously avoiding the sort of partisan unfairness that rightly troubled the Supreme Court in *League of Women Voters of Pennsylvania v. Commonwealth*, 178 A.3d 737 (Pa. 2018). The latter feature of the GMS Plan is critical here: When a congressional plan is to be drawn by the courts rather than the political branches, it is particularly important that the Court ensure that it is not unwittingly adopting a plan that actually provides one political party with an unfair advantage. *Id.* at 814-17.

A summary chart comparing the GMS Plan's performance to the House Republican Plan and the Governor's Plan, with the 2018 Plan's performance offered as a further comparator, is provided here:

Comparison of the Gressman Math/Science Petitioners' Plan to the the House Republican Plan, and the Governor's Plan, and the 2018 Plan

Redistricting Principle	Metric	GMS Plan	House Repub. Plan	Governor Plan	2018 Plan *(for baseline comparison)*
Population Equality	Maximum Population Deviation	1 person	1 person	1 person	1 person
Contiguity	Non-Contiguous Districts	0	0	0	0
Compactness	*Mean Polsby-Popper*	*0.33*	*0.31*	*0.37*	*0.32*
	Mean Reock	*0.40*	*0.38*	*0.40*	*0.43*
	Mean Convex Hull	*0.80*	*0.78*	*0.81*	*0.79*
	Cut Edges	5,546	5,882	5,154	5,789
Respect for Political Subdivisions*	Split Counties	15	15	16	14
	County Pieces (67 min.)	84	85	86	87
	Split Municipalities	19 (incl. 3 boroughs on cty. lines)	21 (incl. 5 boroughs on cty. lines)	22 (incl. 4 boroughs on cty. lines)	29 (incl. 6 boroughs on cty. lines)
	Municipality Pieces (2,560 min.)	2,577	2,578	2,579	2,584
	Split Wards	15	18	25	29**
	Ward Pieces (4,310 min.)	4,325	4,328	4,335	4,339
Minority Electoral Opportunity	*Majority-Minority Districts (MMDs)*	3	2	2	2
	MMDs with Latino Citizens as the Largest Minority	1	0	0	0
Partisan Fairness	Majority Responsiveness	3 (2 favoring Dems.; 1 favoring GOP)	5 (all favoring GOP)	4 (2 favoring Dems.; 2 favoring GOP)	1 (favoring GOP)
	Average Mean-Median (closer to zero is better)	-1%	-3%	-1%	-2%
	Average Efficiency Gap (closer to zero is better)	1%	-6%	1%	-3%
Incumbent Pairings	Paired Incumbents Seeking Re-Election	0	2	4	N/A

LEGEND:
Italics = larger number is the goal; regular text = smaller number is the goal.
[green] = best score
[yellow] = tied for the best score

* With respect to the "pieces" metrics, if a political subdivision is wholly contained in one district, it has one *piece*; if a political subdivision is divided between two districts, it has two *pieces*; and so on. Dividing a municipality by drawing a district boundary along a county boundary does not create an additional piece.

** This figure comes from materials provided in *League of Women Voters* and is based on ward boundaries as they existed at the time. The ward pieces metric assumes 4,310 wards existed at the time.

BACKGROUND

Pennsylvania's congressional districts must be redrawn to accord with recently released data from the 2020 Census. The new data shows that, over the past decade, Pennsylvania's population has changed in three ways: (1) absolute population, (2) population distribution, and (3) population demographics. *See* Ex. 1, Expert Report of Dr. Daryl DeFord [hereinafter "DeFord Report"] at ¶ 21; U.S. Census Bureau, *Pennsylvania Population Hit 13 Million in 2020*, Pennsylvania: 2020 Census, https://www.census.gov/library/stories/state-by-state/pennsylvania-population-change-between-census-decade.html (last visited Jan. 23, 2022) [hereinafter "Pennsylvania: 2020 Census"].

First, Pennsylvania's population increased to 13,002,700 people. *Id.* ¶ 21. This increase, however, was lower than the nationwide increase, causing Pennsylvania to lose a congressional seat. *See id.*; Pennsylvania: 2020 Census. Thus, Pennsylvania has been apportioned 17 congressional seats. DeFord Report ¶ 21. The ideal district population—13,002,700 people divided by 17 districts—is 764,864.71 persons (though of course it is impossible to include 0.71 of a person in a district). *See id*. In practice, this means Pennsylvania's new congressional map must have exactly five districts with 764,864 persons and 12 districts with 764,865 persons. *Id.*

Second, because Pennsylvania's population growth was not uniform, the Commonwealth's center of population has shifted south and east. *See* Pennsylvania: 2020 Census. Only 23 of the 67 counties in Pennsylvania gained population. *Id.* These counties were largely concentrated in southeastern Pennsylvania; other than Centre County in central Pennsylvania and Butler County in the west, every county with a growth rate at or above the statewide average is in the southeast. *Id.* Conversely, 44 counties spanning seven current congressional districts lost population relative to the 2010 Census. *Id.* These were located largely in western Pennsylvania, central Pennsylvania, and the Northern Tier. *Id.* Collectively, these population shifts require adjustments to the current congressional plan.

Third, Pennsylvania's racial demographics have changed dramatically. In the last decade, the Commonwealth's White population decreased by 5.4%; the Black population stayed relatively stable, increasing by 3.2%; the Latino population increased by 45.8%; and the Asian population increased by 46.3%. *Id.* Most of the counties with a growth rate over 5% saw their Black, Latino, and Asian populations increase at rates well above the statewide average.[3] *Id.* Where Pennsylvania is growing, it is becoming more racially diverse. A new congressional plan must reflect this increased diversity.

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[3] Philadelphia's Latino population, however, grew by 27.0%. *See* Pennsylvania: 2020 Census.

ARGUMENT

Part I of this Brief's argument explains why judicial redistricting of Pennsylvania's existing congressional plan is necessary. Part II describes Petitioners' approach to redistricting and the terminology used in this Brief. Part III provides a detailed explanation of each state and federal legal requirement in the redistricting process and how the GMS Plan satisfies each legal requirement. In Part IV, Petitioners explain how the GMS Plan performs with respect to other redistricting factors that courts often consider in choosing among plans that otherwise fully comply with the legal requirements.

I. THE CURRENT CONGRESSIONAL PLAN CANNOT BE USED IN FUTURE ELECTIONS AND MUST BE REPLACED.

As we expect all parties will stipulate, Pennsylvania's current congressional plan must be redrawn. *See* Resp'ts' Ans. at 4–5 (agreeing that a new plan is required). Pennsylvania's current plan has 18 congressional districts, but the Commonwealth was apportioned only 17 congressional seats after the 2020 Census. *See supra*. Furthermore, because of uneven population growth in the Commonwealth, *see id.*, every congressional district in the Commonwealth is unconstitutionally malapportioned, *see* PA. CONST. art. I, § 1; *id.* art. I, § 5; *id.* art. I, § 20; *id.* art. II, § 16; *id.* art. II, § 26; *League of Women Voters I*, 178 A.3d at 816–17; *see also* Pet. for Rev., *Gressman v. Chapman*, No. 465 M.D. 2021, ¶¶ 3, 34–52 (Pa. Commw. Ct. Dec. 17, 2021).

Although "the primary responsibility and authority for drawing federal congressional legislative districts rests squarely with the state legislature," when "the legislature is unable or chooses not to act, it becomes the judiciary's role to determine the appropriate redistricting plan." *League of Women Voters I*, 178 A.3d at 821–22. This Court set a January 30, 2022 deadline for the General Assembly and Governor to enact a properly apportioned congressional redistricting plan. If the political branches fail to meet this deadline, the Judiciary must adopt a remedial congressional redistricting plan consistent with the instruction of the Pennsylvania Supreme Court in *League of Women Voters I*.

As Petitioners have previously noted, this Court will need to act speedily, and Petitioners appreciate the Court's quick calendaring of this matter. The primary election is scheduled for May 17, 2022. Nomination papers for candidates seeking to appear on the primary ballot can be circulated starting on February 15, 2022, and are due by March 8, 2022. *See* 25 P.S. § 2873. The Gressman Math/Science Petitioners thus urge this Court, following the evidentiary hearing on January 27 and 28, to adopt the GMS Plan no later than January 31, 2022, so that candidates and state and local election administrators will know the district configurations, and the primary can then proceed in an orderly fashion under the current schedule and under the GMS Plan.

II. COMPUTATIONAL REDISTRICTING CAN OPTIMIZE ALL REDISTRICTING REQUIREMENTS SIMULTANEOUSLY.

The GMS Plan was created using a new approach known as "computational redistricting," which draws from advances in the fields of mathematics, statistics, and computer science to apply principles of high-performance computing, algorithmic techniques, and spatial demography to the redistricting process. The fundamental premise of computational redistricting is simple: "Given the number of [redistricting] criteria and the spatial nature of how the criteria operate, it is not easy for humans to find optimal redistricting outcomes on their own.... Put simply, good maps are needles in a haystack of bad or at least worse maps. Enter redistricting algorithms. They are capable of meticulous exploration of the astronomical number of ways in which a state can be partitioned. They can identify possible configurations of districts and zero in on the maps that best meet the redistricting criteria. The algorithms sort through the haystack more efficiently and more systematically so that the needle—the better maps—can be found." Emily Rong Zhang, *Bolstering Faith with Facts: Supporting Independent Redistricting Commissions with Redistricting Algorithms*, 109 CAL. L. REV. 987, 1013 (2021) [hereinafter "*Supporting Independent Redistricting Commissions with Redistricting Algorithms*"].

As the Pennsylvania Supreme Court has recognized, redistricting is a complex process that involves balancing a variety of legal requirements. *See Holt v. 2011 Legislative Reapportionment Comm'n*, 67 A.3d 1211, 1238 (Pa. 2013) [hereinafter "*Holt II*"]; *Holt v. 2011 Legislative Reapportionment Comm'n*, 38 A.3d 711, 759 (Pa. 2012) [hereinafter "*Holt I*"]. Improving compliance with one requirement often creates "downstream consequences" for compliance with other requirements. *See Supporting Independent Redistricting Commissions with Redistricting Algorithms* at 1013. For example, optimizing population equality necessarily requires the splitting of some political subdivisions. And "[d]eciding to keep a county whole instead of splitting it across two districts changes at least the boundaries of all neighboring districts, and could come at the cost of other redistricting criteria, such as making the map as a whole less compact." *Id.* Exploring millions of alternatives by computer sheds light on the tradeoffs between principles, illuminating when improving one objective inevitably comes at the expense of others. Without an intensive, systematic search, one cannot tell whether sacrificing one aim is necessary to achieve others, or instead results from unwarranted fealty to a particular objective, partisan or not, intended or not.

As some of Pennsylvania's leading mathematicians and scientists, Petitioners understand how high-performance computers and cutting-edge algorithmic techniques can thwart gerrymandering, streamline and accelerate the mapmaking process, and promote fair and effective representation for all Pennsylvania residents. As the Pennsylvania Supreme Court itself expressed just four years ago, technology can "aid in the expeditious development of districting maps, the boundaries of which are drawn to scrupulously adhere to neutral criteria." *League of Women Voters I*, 178 A.3d at 817–18. The GMS Plan brings that scrupulous adherence to neutral criteria to this Court.

Before explaining further, some terminology may be helpful. As used in this brief, a *legal requirement* is a redistricting criterion mandated by state or federal law. The Pennsylvania Supreme Court also has referred to the Commonwealth's constitutional redistricting requirements as the "neutral criteria." *League of Women Voters I*, 178 A.3d at 817. In terms of legal requirements, first and foremost, the U.S. Constitution requires that congressional districts be equal in population. *See Karcher v. Daggett*, 462 U.S. 725, 730–44 (1983); *Wesberry v. Sanders*, 376 U.S. 1, 7–8 (1964). That requirement is fundamental to redistricting, as unequally populated congressional districts may be challenged under the "one person, one vote" doctrine. *See Wesberry*, 376 U.S. at 7–8. Next, the Pennsylvania Supreme Court has held that the state constitutional requirements applicable to legislative districts likewise apply to congressional districts, which means that congressional districts "shall be composed of compact and contiguous territory as nearly equal in population as practicable," and that "[u]nless absolutely necessary no county, city, incorporated town, borough, township or ward shall be divided in forming … [a congressional] district."[4] PA. CONST. art. II, § 16; *see League of Women Voters of I*, 178 A.3d at 816–17. These "multiple imperatives in redistricting ... must be balanced." *Holt I*, 38 A.3d at 759. The Pennsylvania Constitution also prohibits partisan gerrymandering and requires that all voters have "equally effective power to select the representative of his or her choice." *League of Women Voters of I*, 178 A.3d at 814, 816, 818. And finally, congressional districts must also comply with the Voting Rights Act, 52 U.S.C. § 10301. All the foregoing are *legal requirements* that must be satisfied when the Court is engaging in redistricting.

A *permissible redistricting factor* is a consideration that, while not legally mandated, may assist the Court in selecting among competing plans that otherwise comply with all legal requirements. *See League of Women Voters I*, 178 A.3d at 817. Permissible redistricting factors for congressional districts include "the

[4] Because the Pennsylvania Constitution's redistricting requirements apply to both legislative and congressional districts, this brief occasionally cites the Pennsylvania Supreme Court's decisions in *Holt I* and *Holt v. 2011 Legislative Reapportionment Comm'n*, 67 A.3d 1211 (Pa. 2013) [hereinafter "*Holt II*"], which addressed a 2012 challenge to the Commonwealth's legislative reapportionment plan. Indeed, in *League of Women Voters I*, the Pennsylvania Supreme Court relied on *Holt*'s discussion of various redistricting factors, *see infra*; *see also League of Women Voters I*, 178 A.3d at 817 (citing *Holt I*, 38 A.3d at 1235). Except for *Holt I*'s approach to the equal- population requirement, which is more flexible than federal law allows for congressional plans, *compare Holt I*, 38 A.3d at 756, 759, *with infra*, the *Holt* decisions' analysis of Pennsylvania's redistricting requirements presumptively applies here.

preservation of prior district lines, protection of incumbents, ... the maintenance of the political balance which existed after the prior reapportionment," *id.*, and the preservation of communities of interest that do not precisely dovetail with political-subdivision lines, *see Holt II*, 67 A.3d at 1241.

A *metric* is a precise, quantifiable measure of how well a district, or an entire plan, satisfies a legal requirement or pursues the goal set forth in a permissible redistricting factor. For example, population equality is a legal requirement, and maximum population deviation (the difference between a plan's largest and smallest districts) is a metric. Most of the metrics described below, including the metric for the principle of population equality, are like golf scores: the lower, the better. A few, however, like the metrics used to measure compactness, are like football scores: the higher, the better.

As demonstrated below, the GMS Plan achieves or approaches the best metrics that can be attained on all of Pennsylvania's legal requirements, while appropriately considering the additional permissible redistricting factors.

III. THE GMS PLAN SATISFIES ALL STATE AND FEDERAL LEGAL REQUIREMENTS.

The GMS Plan remedies the malapportionment now present in the 2018 Plan while also optimizing compliance with all state and federal legal requirements. Those legal requirements, and the metrics for how well the GMS Plan achieves them, are set forth below.

A. Equal Population

Chief among the legal requirements for redistricting is the principle of "one person, one vote." Both Pennsylvania and federal constitutional law mandate strict population equality for congressional districting plans. *See* PA. CONST. art. II, § 16 (requiring that districts be "as nearly equal in population as practicable"); *Abrams v. Johnson*, 521 U.S. 74, 98 (1997); *Wesberry*, 376 U.S. at 7–8. Indeed, the command under Article I, Section 2 of the U.S. Constitution "that Representatives be chosen 'by the People of the several States,'" *Wesberry*, 376 U.S. at 7, has been interpreted to require "absolute population equality" in congressional districts, *Karcher*, 462 U.S. at 732. The Pennsylvania Supreme Court has applied the Pennsylvania Constitution's equal-population criterion consistent with federal law: The congressional plan adopted by the Supreme Court in 2018 limited the deviation among congressional districts to a single person. *See League of Women Voters of Pennsylvania v. Commonwealth*, 181 A.3d 1083, 1087 (Pa. 2018) [hereinafter "*League of Women Voters II*"] ("[N]o district has more than a one-person difference in population from any other district, and, therefore, the Remedial Plan achieves the constitutional guarantee of one person, one vote."). To do the same today, Pennsylvania should have five congressional districts with 764,864 residents, and twelve congressional districts with 764,865 residents. DeFord Report ¶ 21.

The GMS Plan does exactly that, and thus has literally the best possible population equality of any congressional plan under the 2020 Census, as shown in Table 2:

TABLE 2: Population Equality	
District Number	**Population**
1	764,865
2	764,865
3	764,864
4	764,864
5	764,865
6	764,865
7	764,865
8	764,865
9	764,865
10	764,865
11	764,865
12	764,865
13	764,865
14	764,864
15	764,865
16	764,864
17	764,864

If any party or *amicus curiae* submits a plan that contains unequally apportioned districts or fails to count all persons that the 2020 Census counted for purposes of apportioning Representatives in Congress, the Court can, and should, easily eliminate that plan from consideration because it would not survive constitutional scrutiny. *See Karcher*, 462 U.S. at 732; *see also Vieth v. Pennsylvania*, 195 F. Supp. 2d 672, 675, 678 (M.D. Pa. 2002) (three-judge court) (invalidating a Pennsylvania congressional redistricting plan because it had a 19-person maximum population deviation).

B. Respect for Political Subdivisions

The Pennsylvania Constitution's requirements for legislative districts, which the Supreme Court has applied to congressional districts, demand that counties, cities, incorporated towns, boroughs, townships, and wards not be split in congressional plans "[u]nless absolutely necessary." PA. CONST. art. II, § 16; *League of Women Voters I*, 178 A.3d at 816–17 (extending Pennsylvania Constitution's political-subdivision requirement to congressional districts). Given the competing demand that congressional districts likewise achieve absolute population equality, "some divisions are inevitable." *Holt I*, 38 A.3d at 758. Accordingly, the Supreme Court has refused "to convey in absolute terms what is an acceptable number of political subdivision splits." *Holt I*, 38 A.3d at 754 n.33.

Consistent with the Supreme Court's instruction that Pennsylvania's redistricting requirements "must be balanced," *id.* at 759, the GMS Plan includes only those political-subdivision splits that are necessary to optimize the Plan's performance on the other redistricting requirements. Balancing respect for political subdivisions with the other legal requirements, however, requires tradeoffs.

Achieving absolute population equality means that subdivisions with populations that exceed the ideal population for a single district ***must*** be split. *See* DeFord Report ¶¶ 29-32. Achieving absolute population equality also means that subdivisions with populations below the ideal will need to be combined in ways that, at times, require subdivisions to be split—a district consisting of a county with a population below the ideal, for instance, may need to include a portion of a neighboring subdivision to reach absolute population equality. *See id.* ¶¶ 29-32, 44. In other words, a plan that achieves absolute population equality without splitting any political subdivisions is not possible. *Id.* ¶ 25.

The constitutionally mandated respect for political subdivisions also cautions against carving up a single political subdivision into too many parts and thus diluting that subdivision's political strength by "cracking" its population among multiple districts. Accordingly, it is important to look not only at the number of political subdivisions that are divided, or split, but also at the number of ***pieces*** into which the subdivisions are split.

On this legal requirement, the GMS Plan outperforms the 2018 Plan as the baseline, as well as the House Republican Plan and the Governor's Plan. Computational redistricting both reduces the number of political subdivisions that are divided (beyond what is necessary to achieve absolute population equality) and reduces the number of pieces into which the subdivisions are divided.

1. Counties

On all county split metrics, the GMS Plan is comparable or superior to the House Republican Plan, the Governor's Plan, and the 2018 Plan. *See* DeFord Report ¶¶ 29-36. Of course, all these plans split the three counties that ***must*** be split because their population exceeds the ideal population size for a district: Philadelphia, Allegheny, and Montgomery Counties. *Id.* From there, the GMS Plan only improves on its competitors. The GMS Plan has one ***fewer*** county split than the Governor's Plan. *Id.* ¶ 36. The GMS Plan contains the same number of county splits as the House Republican Plan, but unlike the House Republican Plan, the GMS Plan contains ***no*** counties split into more than three pieces. *Id.* ¶¶ 34-36. Given its population, Philadelphia County must be split into three pieces, but there is no need to split any county, including Philadelphia, into four pieces.

Table 3 demonstrates how the GMS Plan performs on county integrity compared to the House Republican Plan and the Governor's Plan, and provides the 2018 Plan as a baseline, while recognizing that it is not directly comparable given the different Census numbers and different number of districts (18 rather than 17), *see* DeFord Report ¶¶ 29-36:

TABLE 3: County Integrity				
Metric	**GMS Plan**	**HR Plan**	**Governor Plan**	**2018 Plan**
Total counties split	15	15	16	14

Counties split into 3 or more pieces	2	2	3	4[5]
Counties split into 4 or more pieces	0	1	0	0
Number of county pieces	84	85	86	87

2. Municipalities (Cities, Incorporated Towns, Boroughs, and Townships)

The GMS Plan also respects the boundaries of municipalities—the Commonwealth's cities, incorporated towns, boroughs, and townships—by systematically reducing the number of municipalities that are divided and the number of pieces into which they are divided. *See* PA. CONST. art. II, § 16; *League of Women Voters I*, 178 A.3d at 816–17. The number of splits is calculated by counting the number of municipalities that appear in more than one district. The GMS Plan outperforms the House Republican Plan, the Governor's Plan, and the baseline 2018 Plan on this metric, too. *See* DeFord Report ¶¶ 49-51 & n.5.

Below, the Gressman Math/Science Petitioners include a table that reports the number of split municipalities—defined as the portion of a city, independent town, borough, or township that falls within a single county—in the GMS Plan, House Republican Plan, Governor's Plan, and 2018 Plan. However, a few points on the metrics are worth noting, at the outset.

[5] The 2020 Census geography suggests that the 2018 Plan divides Montgomery County and Philadelphia among four districts each. The Pennsylvania Supreme Court, however, drew the 2018 Plan, based on the 2010 Census, to divide both Montgomery County and Philadelphia among three districts each. Philadelphia and Montgomery are counted here as being split into three pieces in the 2018 Plan.

First, the GMS Plan splits ***ten*** fewer municipalities than the 2018 Plan, ***three*** fewer than the Governor's Plan, and ***two*** fewer than the House Republican Plan. DeFord Report ¶ 51 & n.5.

Second, unlike the Governor's Plan, the ***only*** city the GMS Plan splits is Philadelphia, and Philadelphia must be split because its population exceeds that of a district (in fact, it exceeds the population of two districts). *Id.* ¶¶ 38, 40. While the Governor's Plan splits Pittsburgh, the GMS Plan keeps Pennsylvania's second largest city whole. *Id.*

Third, while the GMS Plan splits Philadelphia into the mathematical minimum number of districts—three—the House Republican Plan splits Philadelphia into ***four*** pieces. *Id.* ¶¶ 38, 39.

Fourth, the GMS Plan outperforms the House Republican Plan, the Governor's Plan, and the 2018 Plan on borough splits: It splits ***half*** the number of boroughs that were split in the 2018 Plan and the House Republican Plan, and one fewer borough than the Governor's Plan splits. *Id.* ¶¶ 42, 46-47. Moreover, as in the 2018 Plan, ***all*** the GMS Plan's borough splits follow county lines. *Id.* ¶ 42. This means that, when faced with the choice of splitting a county or splitting a borough, to achieve absolute population equality, the GMS Plan keeps counties whole. *See id.* ¶ 44 (offering example of Telford Borough, which straddles two counites too large in size to be combined). By contrast, only five of the House Republican Plan's six borough splits follow county lines. *Id.* ¶ 47.

Table 4 summarizes the metrics for municipal integrity, *see id.* ¶¶ 49-51 & n.5:

TABLE 4: Municipal Integrity				
Metric	**GMS Plan**	**HR Plan**	**Governor Plan**	**2018 Plan**
Total Municipalities (Cities, Incorporated Towns, Boroughs, and Townships)				
Total municipalities split	19	21	22	29
Cities				
Total cities split	1	1	2	1
Number of Philadelphia pieces	3	4	3	3[6]
Number of Pittsburgh pieces	1	1	2	1
Number of city pieces	59	60	60	60
Towns				
Total incorporated towns split	0	0	0	0
Boroughs				
Total boroughs split	3	6	4	6
Total boroughs not split on county lines	0	5	0	0
Number of borough pieces	958	961	959	961
Townships				
Total townships split	15	14	16	22
Total township pieces	1,562	1,561	1,563	1,570

[6] The 2020 Census geography suggests that the 2018 Plan divides Philadelphia among four districts. The Pennsylvania Supreme Court, however, drew the 2018 Plan, based on the 2010 Census, to divide Philadelphia among three districts.

3. Wards

A ward is a geographic entity established for representative, administrative, or electoral purposes. *See* 8 Pa. C.S.A. §§ 601–617. Wards do not exist in every part of the Commonwealth.

The GMS Plan respects the boundaries of wards by avoiding unnecessary ward splits, *see* PA. CONST. art. II, § 16, again outperforming the House Republican Plan, the Governor's Plan, and the 2018 Plan. *See* DeFord Report ¶¶ 52-53. The GMS Plan splits ***fourteen*** fewer wards than the 2018 Plan, ***ten*** fewer wards than the Governor's Plan, and ***three*** fewer wards than the House Republican Plan. *Id.* ¶ 53.

Table 5 demonstrates how the GMS Plan performs on ward integrity compared to the House Republican Plan, the Governor's Plan, and the 2018 Plan, *see id.* ¶¶ 52-53:

TABLE 5: Ward Integrity

Metric	GMS Plan	HR Plan	Governor Plan	2018 Plan[7]
Total wards split	15	18	25	29
Number of ward pieces	4,325	4,330	4,335	4,339

* * *

[7] The Supreme Court reported 29 ward splits in connection with its adoption of the 2018 Plan, but that was based on ward boundaries as they existed at the time. The ward "pieces" metric assumes that, at the time of the 2018 Plan, Pennsylvania had 4,310 wards.

By prioritizing respect for the integrity of counties, municipalities, and wards, the GMS Plan fully complies with the Pennsylvania Constitution, as applied to congressional districts in *League of Women Voters I*, and at least matches and often outperforms the House Republican Plan, the Governor's Plan, and the standard set by the Supreme Court in adopting the 2018 Plan.

C. Contiguity

Congressional districts in the Commonwealth must be "composed of ... contiguous territory." PA. CONST. art. II, § 16; *League of Women Voters I*, 178 A.3d at 816–17 (extending Pennsylvania Constitution's contiguity requirement to congressional districts). A contiguous district is "one in which a person can go from any point within the district to any other point (within the district) without leaving the district, or one in which no part of the district is wholly physically separate from any other part." *Commonw. ex rel. Specter v. Levin*, 293 A.2d 15, 17–18 (Pa. 1972) (internal quotation marks omitted), *abrogated on other grounds by Holt I*, 38 A.3d 711.

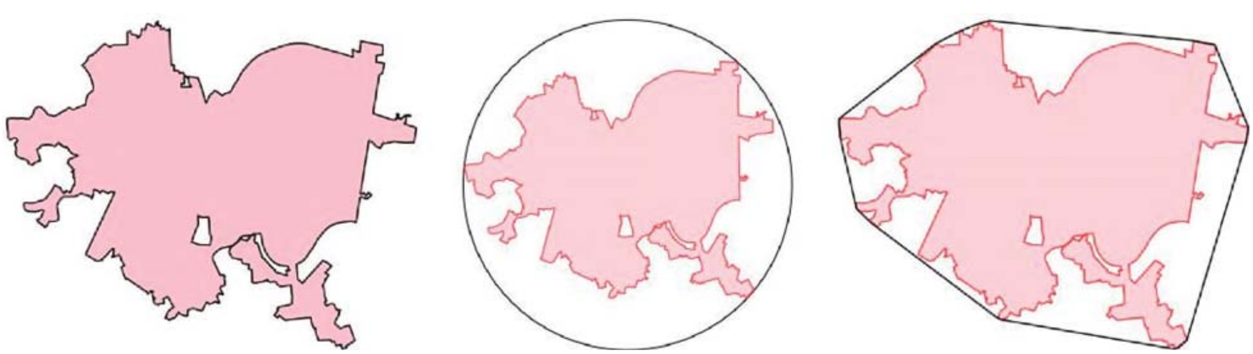
All 17 districts in the GMS Plan are contiguous. DeFord Report ¶ 66. Even the discontiguous portion of Chester County, which the Pennsylvania Supreme Court placed in Delaware County in the 2018 Plan, *see League of Women Voters II*, 181 A.3d at 1087 n.10, is kept within the same contiguous congressional district in the GMS Plan.

D. Compactness

Congressional districts in the Commonwealth must be "composed of compact ... territory." PA. CONST. art. II, § 16; *League of Women Voters I*, 178 A.3d at 816–17 (extending Pennsylvania Constitution's compactness requirement to congressional districts). Compactness "must be evaluated objectively" using "concrete" data. *Specter*, 293 A.2d at 24. In balancing the need for compactness with the other redistricting requirements, however, the Pennsylvania Supreme Court has recognized that achieving "districts of precise mathematical compactness" is impossible, and that "there is a certain degree of unavoidable non-compactness in any apportionment scheme." *Id.* at 19, 23. Thus, any evaluation of compactness must also allow for "the elements of unavoidable noncompactness." *Id.* at 24.

The Pennsylvania Supreme Court considered compactness under a variety of metrics in *League of Women Voters*. *See, e.g.*, *League of Women Voters II*, 181 A.3d at 1087. The Gressman Math/Science Petitioners focus here on four compactness metrics commonly used in redistricting: Polsby-Popper, Reock, Convex Hull, and Cut Edges. *See* DeFord Report ¶ 62. They do so because each metric measures different aspects of what may count as compact for a given district. As Dr. DeFord explains, "taking these measures together provides a more comprehensive view of the district's shape than considering any one measure alone." *Id.* ¶ 57.

For the first three metrics, the Gressman Math/Science Petitioners focus on the mean, or average, compactness score across the 17 districts in any given plan, because using the mean weighs each district equally. Polsby-Popper measures a ratio of perimeter squared to area. *Id.* ¶ 55. Reock measures the ratio of the district's area to that of the smallest possible bounding circle. *Id.* Convex Hull measures the proportion of the area of the smallest convex shape that contains the district. *Id.* All these metrics are scaled to values between 0 and 1, with higher values representing more compact plans. *Id.* ¶ 56. Each is also maximized by the circle (which gets a perfect score of 1), but the Polsby-Popper measure tends to prefer districts with smooth-looking boundaries, the Reock measure tends to prefer districts that are less elongated, and the Convex Hull measure tends to prefer districts that do not contain significant indentations or tendrils. *Id.* The following figure shows how the bounding circle of the Reock compactness measure and the polygon shape of the Convex Hull compactness measure would apply to Pittsburgh's irregular city boundary, *id.* ¶ 58, Fig. 5:



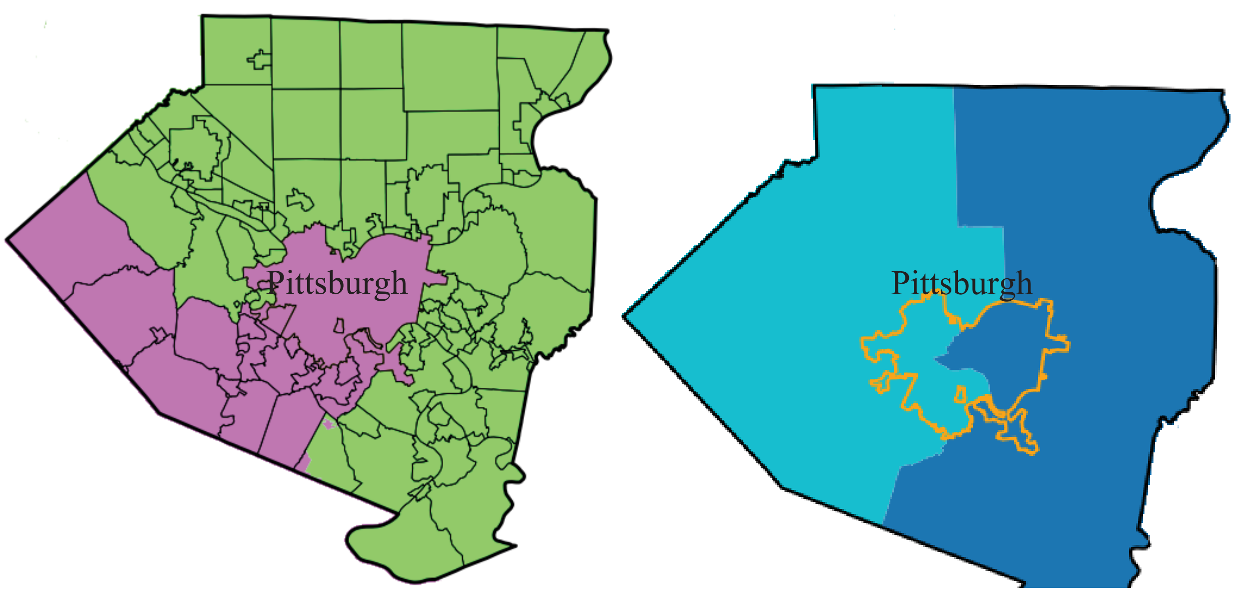
(a) City Boundary (b) Bounding Circle (c) Convex Hull

Cut Edges is a compactness measure that applies not to a single district but rather to a redistricting plan as a whole. *See* DeFord Report ¶ 61. The Cut Edges metric evaluates the perimeters of all the districts and refers to the number of adjacent units, like Census blocks, that are not placed in the same district. *Id*. One could say the Cut Edges metric measures the plan's "scissors" complexity—how much work would have to be done to separate the districts from each other?

As shown in Table 6, the GMS Plan substantially outperforms the House Republican Plan on compactness, outperforms the 2018 Plan on three of the four measures, and achieves compactness scores equal or comparable to those of the Governor's Plan, *see id.* ¶ 65:

TABLE 7: Compactness				
Metric	**GMS Plan**	**HR Plan**	**Governor Plan**	**2018 Plan**
Mean Polsby-Popper (higher is more compact)	0.33	0.31	0.36	0.32
Mean Reock (higher is more compact)	0.40	0.38	0.40	0.43
Mean Convex Hull (higher is more compact)	0.80	0.78	0.81	0.79
Cut Edges (lower is more compact)	5,546	5,882	5,154	5,789

Importantly, respecting political subdivisions presents tradeoffs for compactness. Here, for example, keeping Pittsburgh whole—as the GMS Plan does, but the Governor's Plan does not—can negatively affect a plan's compactness scores under certain metrics. As Dr. DeFord explains, Pittsburgh itself has a poor Polsby-Popper score—a ratio of perimeter squared to area—because a map of the city has many knobs and bumps along the city boundary, thereby increasing the city's perimeter without enclosing significant additional area. *Id.* ¶ 58. Likewise, Pittsburgh has a poor Reock score—which measures the ratio of the district's area to that of the smallest possible bounding circle—a result of the tendrils in the city boundary, which push the district's smallest bounding circle significantly away from the core of the city. *Id.* To illustrate, the following figure shows Allegheny County in the GMS Plan (on the left), keeping Pittsburgh intact and following its boundary for a portion of Districts 14 and 17, compared to Allegheny County in the Governor's Plan (on the right), splitting Pittsburgh into Districts 16 and 17, *see id.* ¶ 64, Fig. 6:



A plan that chooses to divide Pittsburgh therefore can achieve greater compactness scores, at least on these metrics, but at the cost of unnecessarily dividing Pennsylvania's second-largest city. The GMS Plan manages to keep Pittsburgh whole while achieving better compactness scores than the plans that also preserve Pittsburgh (the House Republican Plan and the 2018 Plan), and comparable scores to the plan that splits Pittsburgh (the Governor's Plan)—a strong illustration of the GMS Plan's overall superior compliance with all legal requirements.

E. Partisan Fairness

The Pennsylvania Constitution's Free and Equal Elections Clause "provides the people of this Commonwealth an equally effective power to select the representative of his or her choice, and bars the dilution of the people's power to do so." *League of Women Voters I*, 178 A.3d at 814. When "a congressional districting plan dilutes the potency of an individual's ability to select the congressional representative of his or her choice," that plan "violates the Free and Equal Elections Clause." *Id.* at 816. In particular, when the Pennsylvania Constitution's "neutral criteria have been subordinated, in whole or in part, to extraneous considerations such as gerrymandering for unfair partisan political advantage," that congressional plan is unconstitutional. *Id.* at 817. Such a plan, the Supreme Court explained, "undermines voters' ability to exercise their right to vote in free and 'equal' elections if the term is to be interpreted in any credible way." *Id.* at 821. Furthermore, even a plan that "minimally comport[s] with [the] neutral 'floor' criteria" may "nevertheless operate to unfairly dilute the power of a particular group's vote" on partisan grounds. *Id.* The Court must therefore carefully scrutinize each Proposed Plan for partisan fairness, consistent with the Pennsylvania Constitution.

The GMS Plan demonstrates that balancing population equality and contiguity with the optimal amount of political subdivision splits and compactness can also achieve partisan fairness. As Dr. DeFord explains, the GMS Plan achieves partisan fairness as measured by a variety of metrics commonly used by scholars. DeFord Report ¶¶ 82, 84, 90, 96, 103.

First, ***direct majority responsiveness*** measures the number of times that one political party's candidate won the statewide vote, but the other major political party's candidate carried a majority of congressional districts in the redistricting plan. *Id.* ¶ 73. For example, the Republican candidate won the U.S. Senate seat in Pennsylvania in 2016. For that election, a "majoritarian" outcome under the redistricting plan would be one in which the Republican candidate likewise carried at least half the districts (here, 9 or more, out of 17); and an "antimajoritarian" outcome would be one in which the successful Republican candidate ***lost*** in 9 or more districts. If plans are fairly drawn, then this type of antimajoritarian outcome should be rare.

Using vote totals from 18 statewide general elections conducted between November 2012 and November 2020,[8] Dr. DeFord overlaid those results on the districts in each Proposed Plan (as well as the court-ordered 2018 baseline plan) to determine whether any antimajoritarian outcomes resulted. *Id.* ¶ 29, Table 6. For the GMS Plan, his analysis showed that the party that won the statewide majority of the votes carried a majority of districts in the GMS Plan in 15 of the 18 elections. *Id.* ¶ 82. And, significantly, the three elections that produced antimajoritarian outcomes were divided as evenly as possible, with one election favoring one political party and two favoring the other party. *Id.* ¶ 83. The fact that in over 80% of the elections (15 of 18) the party with the larger vote share was rewarded with the larger seat share, combined with the fact that the few deviations from this majoritarian principle were split between the two parties, suggests that the GMS Plan both allows for effective majority representation and treats voters for each party equally.[9] *See*

[8] In this period, Democrats won 13 of the 18 statewide elections (President of the United States, United States Senator, Attorney General, Auditor General, and State Treasurer in 2012; Governor in 2014; Attorney General, Auditor General, and State Treasurer in 2016; United States Senator and Governor in 2018; and President of the United States and Attorney General in 2020). Republicans won the other 5 statewide elections (President of the United States and United States Senator in 2016; Supreme Court Justice in 2017; and Auditor General and State Treasurer in 2020). DeFord Report ¶ 29, Table 6. Dr. DeFord included the odd-year State Supreme Court election in 2017 in his analysis because that election had a larger margin of victory for the Republican candidate than the other elections in his data set. *Id.* ¶ 68.

[9] This evidence also illustrates how the GMS Plan creates competitive districts in Pennsylvania. Across the 18 statewide elections that Dr. DeFord analyzed, five

also Id. ¶¶ 84, 88 (explaining in further detail the symmetric performance of the GMS Plan).

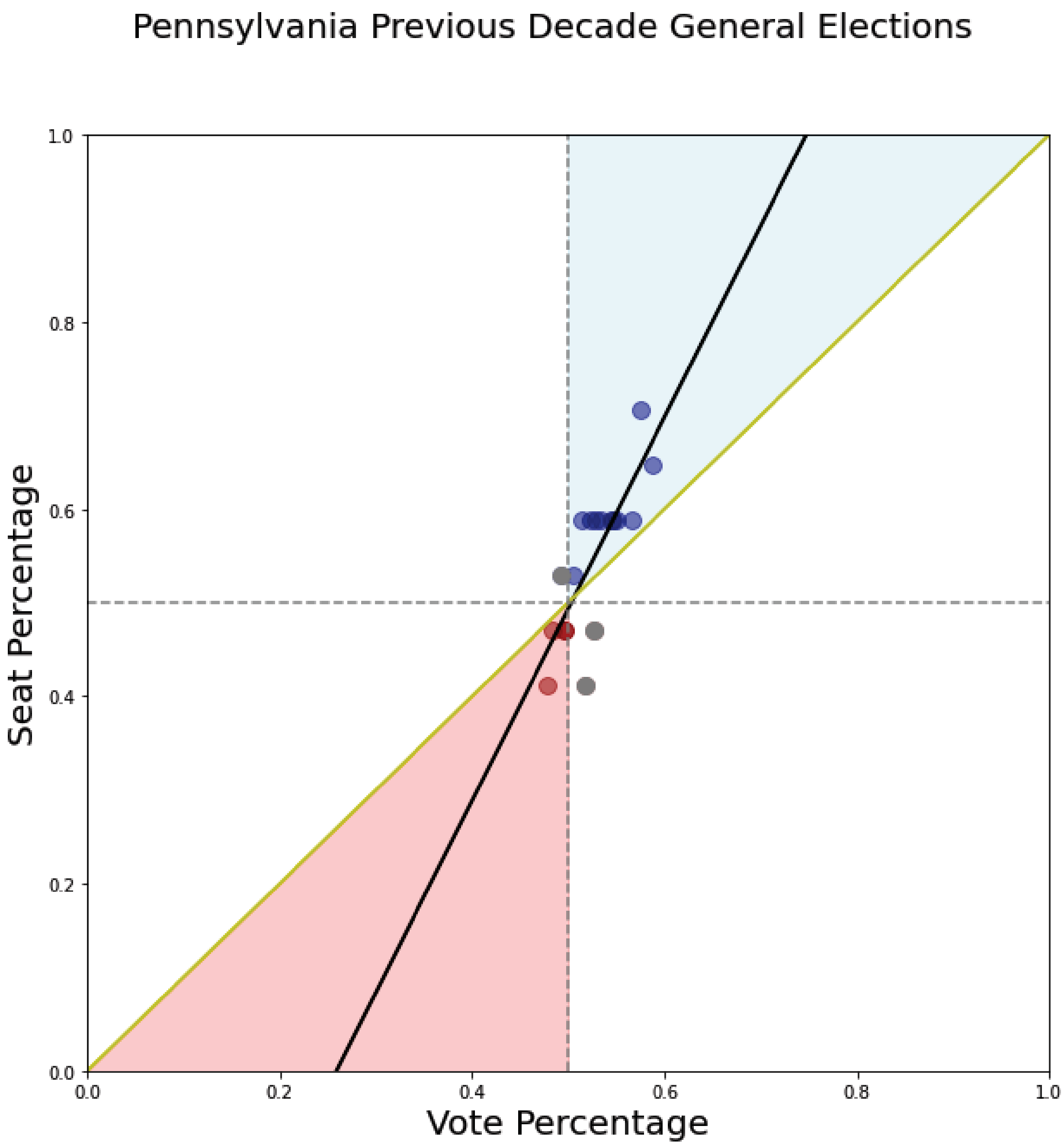
By contrast, the House Republican Plan consistently favors Republicans—under their Plan, the party that won the statewide majority of the votes wins only 13 of the 18 elections Dr. DeFord analyzed, and all five of the antimajoritarian outcomes favored Republicans. *Id.* ¶ 85. The Governor's Plan also underperforms the GMS Plan, with the party that won the statewide vote majority carrying a majority of districts in only 14 of the 18 elections under the Governor's Plan. *Id.* ¶ 86.

The following table shows Dr. DeFord's analysis of majority responsiveness in the GMS Plan, the House Republican Plan, the Governor's Plan, and the 2018 Plan, *see id.* ¶ 87, Table 6. The table displays elections with antimajoritarian outcomes shaded in either red (denoting outcomes favoring Republicans) or blue (denoting outcomes favoring Democrats), *see id.* ¶ 87:

districts were consistently carried by all 18 Democratic candidates, five districts were consistently carried by all 18 Republican candidates, and seven districts were competitive, sometimes being carried by one party's candidate, sometimes by the other's. DeFord Report ¶¶ 91-92. This suggests that the GMS Plan would be responsive to the preferences of both party's voters in actual elections. *Id.* ¶ 92.

Election		Winner	Democratic Vote Share	Share of Democratic Seats			
Office	**Year**			**GMS (seats/17)**	**House (seats/17)**	**Governor (seats/17)**	**2018 (seats/18)**
U.S. President	2012	D	52.7%	58.8% (10)	52.9% (9)	58.8% (10)	50% (9)
U.S. Senator	2012	D	54.6%	58.8% (10)	52.9% (9)	58.8% (10)	55.6% (10)
Attorney General	2012	D	57.5%	70.5% (12)	76.5% (13)	70.5% (12)	66.7% (12)
Auditor General	2012	D	51.7%	**41.2% (7)**	**35.3% (6)**	**47.1% (8)**	38.9% (7)
State Treasurer	2012	D	54.4%	58.8% (10)	47.1% **(8)**	58.8% (10)	55.6% (10)
Governor	2014	D	54.9%	58.8% (10)	52.9% (9)	58.8% (10)	55.6% (10)
U.S. President	2016	R	49.6%	47.1% (8)	41.2% (7)	**52.9% (9)**	44.4% (8)
U.S. Senator	2016	R	49.3%	**52.9% (9)**	29.4% (5)	35.3% (6)	27.8% (5)
Attorney General	2016	D	51.4%	58.8% (10)	**41.2% (7)**	58.8% (10)	55.6% (10)
Auditor General	2016	D	52.6%	**47.1% (8)**	**41.2% (7)**	**47.1% (8)**	50% (9)
State Treasurer	2016	D	53.4%	58.8% (10)	58.8% (10)	58.8% (10)	55.6% (10)
Supreme Court Justice	2017	R	47.7%	41.2% (7)	35.3% (6)	35.3% (6)	33.3% (6)
Governor	2018	D	58.7%	64.7% (11)	58.8% (10)	64.7% (11)	66.7% (12)
U.S. Senator	2018	D	56.7%	58.8% (10)	58.8% (10)	64.7% (11)	61.1% (11)
U.S. President	2020	D	50.6%	52.9% (9)	**47.1% (8)**	52.9% (9)	50% (9)
Attorney General	2020	D	52.3%	58.8% (10)	58.8% (10)	58.8% (10)	55.6% (10)
Auditor General	2020	R	48.4%	47.1% (8)	29.4% (5)	47.1% (8)	38.9% (7)
State Treasurer	2020	R	49.6%	47.1% (8)	41.2% (7)	**52.9% (9)**	50% (9)

Translating these outcomes into a "seats-votes" plot for the GMS Plan shows the symmetric performance of the GMS Plan, which demonstrates that it is treating voters of both parties fairly. *Id.* ¶ 88. In the figure below that shows the GMS Plan's responsiveness to majoritarian outcomes, each dot corresponds to one of the 18 elections described in the table above. *Id.* ¶ 88, Fig. 7. The yellow line marks the values where y=x, which would correspond to strict proportionality, while the black line demonstrates ideal performance on the efficiency gap metric discussed further below. *Id.* ¶ 88. The points colored blue (Democrat) and red (Republican) correspond to the elections where the party that won the majority of the votes also won the majority of the seats, while the three points marked in gray reflect the three elections where this did not occur. *Id.* Overall, as Dr. DeFord concludes, the symmetric performance of the GMS Plan is clear. *Id.*.

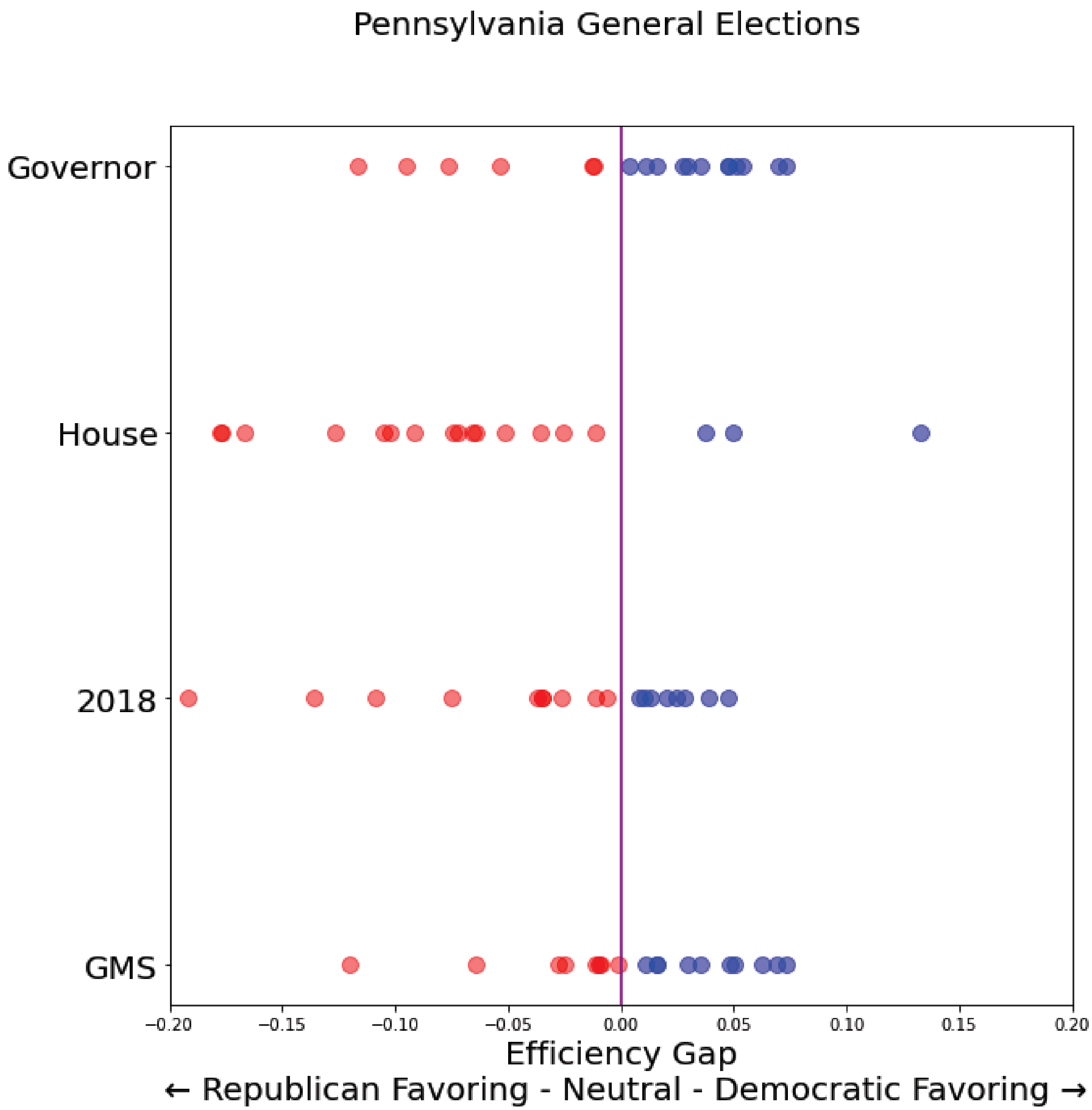


Second, the ***efficiency gap*** is "a formula that measures the number of 'wasted' votes for one party against the number of 'wasted' votes for another party," where "the larger the number, the greater the partisan bias." *League of Women Voters I*, 178 A.3d at 777; *see also* DeFord Report ¶ 80; Nicholas O. Stephanopoulos & Eric

M. McGhee, *Partisan Gerrymandering and the Efficiency Gap*, 82 U. CHI. L. REV. 831, 834 (2015). As Dr. DeFord explains, a vote is considered "wasted" by this measure if it was a vote for the losing candidate in a district or a vote for the winning candidate beyond the number needed to win the district, on the theory that "the most efficient distribution of votes is to carry as many districts as possible by as narrow a margin as possible, while having the opposing party win its districts by large majorities." DeFord Report ¶ 80.

The GMS Plan performs superbly as measured by the efficiency gap: For each of the 18 elections analyzed by Dr. DeFord, the GMS Plan achieves an efficiency gap near zero, meaning that neither political party is heavily favored by the Plan. *Id.* ¶ 97. Overall, the Plan's scores show a very slight pro-Republican tilt, not unlike the 2018 Plan or the Governor's Plan. *Id*. By contrast, the House Republican Plan shows a substantial efficiency gap, and always in the direction favoring Republicans. *Id*. ¶ 98.

The following figure shows the efficiency gap measures for the GMS Plan, House Republican Plan, Governor's Plan, and 2018 Plan, *see id.* ¶ 95, Fig. 9. The points are colored red for values that favor Republican voters and blue for values the favor Democratic voters and the vertical purple line marks the "ideal" zero value. *Id.* ¶ 95. Plans that perform well on this metric will have the majority of their values near zero and will have some elections that favor each party. *Id.*



As this figure demonstrates, the GMS Plan performs extremely well on the efficiency gap metric. *Id.* ¶ 96.

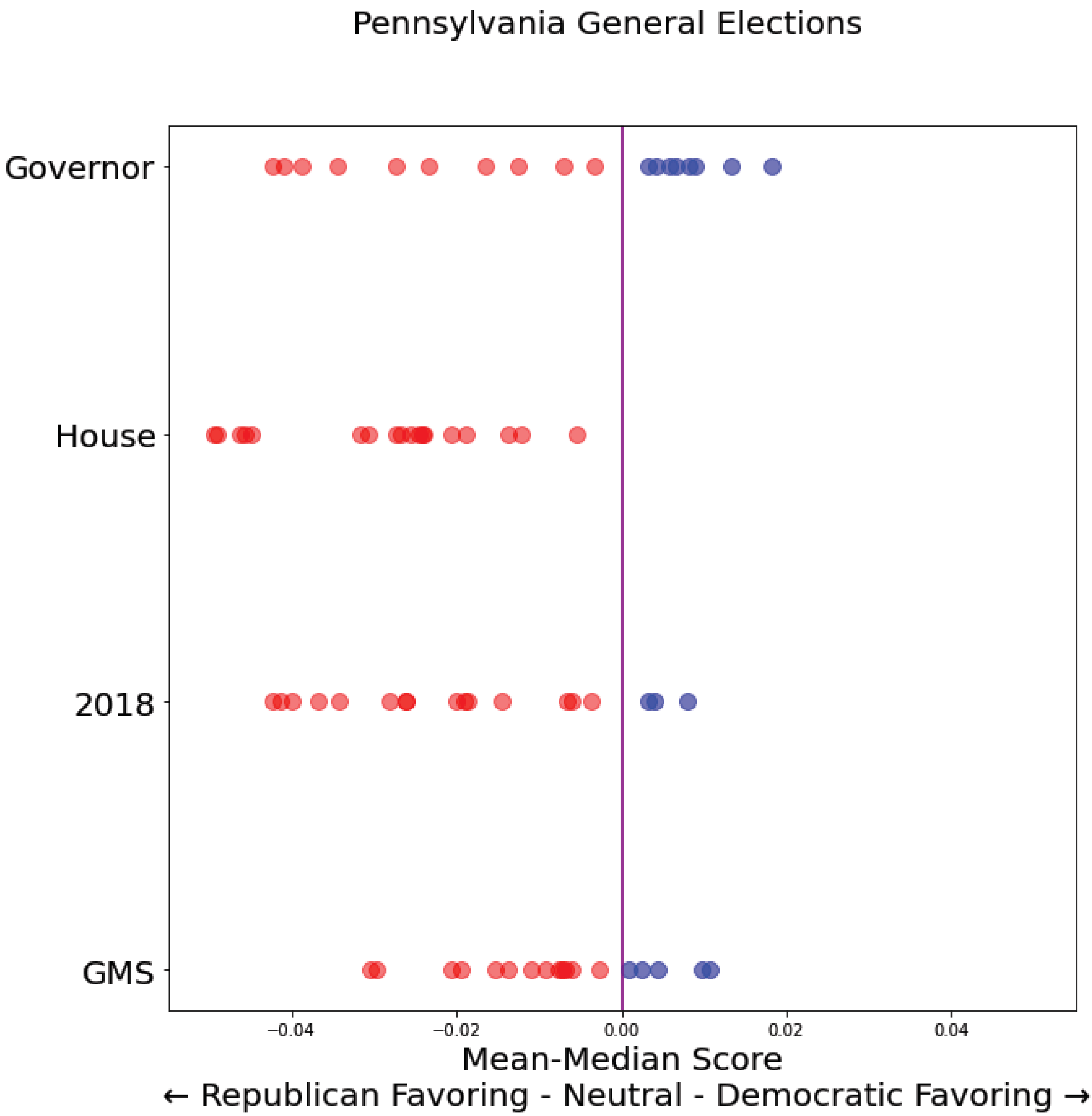
Third, the ***mean-median score*** compares each plan's "median" district—the ninth most Democratic and ninth most Republican district in the 17-district plan—

with the state as a whole. *Id.* ¶¶ 78-79. If the two are similar in their voting behavior, then the plan exhibits a key trait of a fair plan, as about half the districts will usually be more Democratic than the state as a whole and about half the districts will usually be more Republican than the state as a whole. *Id.* Of course, the voters decide how "the state as a whole" votes. But whatever the voters decide, a plan with a low mean-median score will ensure that voters' wishes are respected and that the playing field is not tilted toward one political party or the other. *See id.*; *see generally League of Women Voters I*, 178 A.3d at 820.

Again as measured by the mean-median score, the GMS Plan performs extremely well, scoring very close to zero for all 18 elections in Dr. DeFord's study, while slightly favoring voters for each political party in various different elections. DeFord Report ¶¶ 96-97. This means that the GMS Plan treats voters of both political parties fairly, giving them an equal chance to win a majority of seats in Pennsylvania's congressional delegation. By contrast, the House Republican Plan performs poorly on this metric, just as it performed poorly on the other partisan-fairness metrics—and the unfairness goes in just one direction: Democratic voters. *Id.* ¶ 98.

The following figure shows the mean-median scores for the GMS Plan, House Republican Plan, Governor's Plan, and 2018 Plan, *see id.* ¶ 95, Fig. 8. The points are colored red for values that favor Republican voters and blue for values the favor

Democratic voters and the vertical purple line marks the "ideal" zero value. *Id.* ¶ 95. Plans that perform well on this metric will have the majority of their values near zero and will have some elections that favor each party. *Id.*



* * *

As this figure demonstrates, the GMS Plan also performs extremely well on mean-median scores. *Id.* ¶ 96.

As the Supreme Court said only four years ago, "[i]t is axiomatic that a diluted vote is not an equal vote, as all voters do not have an equal opportunity to translate their votes into representation. This is the antithesis of a healthy representative democracy. Indeed, for our form of government to operate as intended, each and every Pennsylvania voter must have the same free and equal ***opportunity*** to select his or her representatives." *League of Women Voters I*, 178 A.3d at 814 (emphasis in original). The Court should adopt the GMS Plan because it achieves near-optimal partisan fairness by each of these metrics, while also complying with all other constitutional requirements, and thus fulfills Pennsylvania's constitutional imperatives of free, equal, and fair elections.

F. Minority Voting Rights Under Federal Law

Any plan the Court adopts must comply with the Fourteenth Amendment to the U.S. Constitution, which bars the excessive and unjustified use of race and racial data and the intentional dilution of minority voting strength. *See Shaw v. Reno*, 509 U.S. 630, 639–57 (1993); *Rogers v. Lodge*, 458 U.S. 613, 616–28 (1982). Further, the plan must comply with Section 2 of the Voting Rights Act (VRA), 52 U.S.C. § 10301, which prohibits the denial or abridgment of the right to vote on account of race, color, or membership in a language minority group. *See Holt I*, 614 Pa. at 408. The VRA prohibits both intentional and unintentional vote dilution. *Thornburg v. Gingles*, 478 U.S. 30, 43–44 (1986). It provides that, irrespective of discriminatory intent, members of a racial or language-minority group must not "have less opportunity than other members of the electorate" to "nominat[e]" and "elect representatives of their choice," based on "the totality of circumstances." 52 U.S.C. § 10301(b).

In practice, where voting is racially polarized—more specifically, when a bloc-voting majority usually will defeat "candidates supported by a politically cohesive, geographically insular minority group," *Gingles*, 478 U.S. at 49—VRA Section 2 may require replacing one or more districts that elect candidates preferred by the majority group with districts that would nominate and elect candidates preferred by minority voters. *See Johnson v. De Grandy*, 512 U.S. 997, 1008 (1994). To guard against potential liability under Section 2, a redistricting plan must provide effective opportunities for minority-group members to nominate and elect their preferred candidates in a number of districts that is "roughly proportional" to the minority group's share of a state's citizen voting-age population, or "CVAP." *League of United Latin Am. Citizens v. Perry (LULAC)*, 548 U.S. 399, 436–38 (2006); *see De Grandy*, 512 U.S. at 1000.

To that end, a district in which a minority group constitutes less than 50% of the voting-age population but in which the group can still nominate and elect minority-preferred candidates "can … [and] should" count as a minority-effective district for purposes of assessing VRA compliance. *Bartlett v. Strickland*, 556 U.S.

1, 24 (2009) (plurality opinion). Indeed, simply seeking to raise a district's Black voting-age population when there is no showing that this is needed could run afoul of the Fourteenth Amendment. *See Cooper v. Harris*, 137 S. Ct. 1455, 1469–72 (2017) (holding that the VRA did not require the state to "ramp up" the Black percentage in an effective "crossover" district, where Black voters had scored consistent victories despite lacking an arithmetic majority of the voting-age population). In other words, whether a proposed plan complies with the VRA depends on the actual electoral opportunity for minority voters, not on "particular numerical minority percentage[s]." *Ala. Legis. Black Caucus v. Alabama*, 575 U.S. 254, 275 (2015); *see also Cooper*, 137 S. Ct. at 1469; *Bethune-Hill v. Va. State Bd. of Elections*, 137 S. Ct. 788, 799, 801–02 (2017); *Bush v. Vera*, 517 U.S. 952, 969–72 (1996).

In the decade since the 2010 Census, population increases in the Commonwealth have brought with them demographic shifts that must be taken into account under the VRA. As explained above, *see supra*, the Commonwealth's population growth over the past ten years was entirely among people of color, as the White population decreased by almost 6% while the non-White population increased by more than 12%. According to the 2020 Census, Pennsylvania's total population is now more than 26% minority, with African-American residents being by far the largest minority group. With respect to the Commonwealth's adult citizen population (or CVAP), almost 20% is minority, and while most of that group is Black, Latinos now constitute a fast-rising 6% of the Commonwealth's CVAP. In a 17-district plan, because 20% of 17 districts would equal 3.4 districts, the most recent data suggests that, under the VRA's "rough" proportionality principle, Pennsylvania should have at least three congressional districts where minority voters have a realistic opportunity to nominate and then elect their preferred candidates, and then be represented by those candidates in the halls of Congress.

Consistent with the VRA, the GMS Plan contains three districts in which minority-group members constitute 51%, 52%, and 57% of the voting-age population, respectively. DeFord Report ¶ 117. And consistent with Latino population growth in Pennsylvania, the GMS Plan would create, for the first time, a majority-minority congressional district in which the largest group of minority residents—and of minority adult citizens—would be Latino. *Id.* ¶ 141.

All three of the GMS Plan's majority-minority districts—proposed Congressional Districts 2, 3, and 5—contain part of Philadelphia, which, as described above, is too large to fit into two congressional districts. *See supra*. It appears to be impossible to draw a congressional district anywhere else in the state that is majority-minority, reasonably compact, and even minimally respectful of counties, municipalities, and wards. So, when analyzing minority electoral opportunity in a Pennsylvania congressional plan, the focus must be on the Philadelphia area.

In general elections in the Philadelphia area, Black voters and Latino voters consistently and cohesively support the same candidates, usually by landslide margins, as more than 90% of Black voters and more than 60% of Latino voters cast their ballots for Democratic candidates. *See* DeFord Report ¶¶ 9, 119, 140. The key to minority success, then, is having a controlling voice in the selection of Democratic nominees, in Democratic primary elections.

History provides clear evidence about what kind of congressional district can reliably nominate Black-preferred candidates. It is indisputable that Philadelphia has long had a congressional district in which Black voters have successfully both nominated and elected their preferred congressional candidates. This success dates back to 1958, when Robert Nix was elected as Pennsylvania's first Black member of Congress, and has continued up through the current day, with Congressman Dwight Evans representing Congressional District 3 as it is configured in the 2018 Plan.

The GMS Plan's three Philadelphia-area majority-minority congressional districts (Districts 2, 3, and 5) exhibit almost exactly the same voting behavior as the 2018 Plan's indisputably effective Congressional District 3. Dr. DeFord's analysis shows that Democratic candidates carried all four of these districts (the indisputably minority-effective current District 3 and the three majority-minority districts that Petitioners are proposing here) in 18 out of 18 recent statewide general elections. *Id.* ¶¶ 118-19, 128, 135. And these four districts *also* voted for the same candidate in 8 out of 10 recent statewide Democratic primary elections.[10] DeFord Report ¶¶ 47, Table 1; 48, Table 2; 52, Table 3; 55, Table 4. So, it is clear that all three proposed majority-minority districts would be effective, just like the current District 3 is.

The GMS Plan's District 2 would have the added benefit of being, Petitioners believe, the first majority-minority congressional district in Pennsylvania history to have more Latino than Black adult citizen residents. Dr. DeFord's analysis demonstrates that this district has been carried by Latino-preferred candidates in 18 of 18 recent statewide general elections and in 7 of 10 recent statewide Democratic primaries (and the three exceptions were all more than five years ago). *See id.* ¶ 55, Table 4. The percentage of proposed District 2's adult citizen population that is Latino is increasing by about a half percentage point a year. And a glimpse of the promising future for Latino voters in this proposed district can be found in the May 2021 Democratic primary election for Philadelphia's District Attorney, in which Latino candidate Carlos Vega, who managed to win only 33% of the vote citywide,

[10] Dr. DeFord also found that proposed District 3 and current District 3, both of which are located wholly within Philadelphia, voted for the same candidate in every single citywide Democratic primary since 2015 that involved candidates from more than one racial or language minority group. *See* DeFord Report ¶ 48, Table 2.

nonetheless easily carried the Philadelphia portion of this proposed district with a remarkable 64% of the vote.[11] *Id.* ¶ 140..

In sum, with its three majority-minority districts, the GMS Plan reflects the demographic changes to the Commonwealth and thus fully complies with Section 2 of the Voting Rights Act, while also complying with the Fourteenth Amendment to the Federal Constitution.

IV. THE GMS PLAN APPROPRIATELY CONSIDERS AND ADDRESSES OTHER PERMISSIBLE REDISTRICTING FACTORS.

Although a congressional plan must adhere to the legal requirements described above, federal and state law of course permit mapmakers to consider additional legitimate redistricting objectives. Indeed, the Pennsylvania Supreme Court has recognized that additional redistricting factors can help create a plan that reflects the realities of the Commonwealth's population and voters' priorities. *See League of Women Voters I*, 178 A.3d at 817. By adhering to a neutral, scientific approach to redistricting, the Gressman Math/Science Petitioners have offered a plan that ***also*** appropriately accounts for certain accepted redistricting factors without compromising the plan's compliance with any legal requirements.

[11] About 20% of proposed District 2 is located outside of Philadelphia.

A. Paired Incumbents

The Pennsylvania Constitution neither requires nor precludes consideration of whether a congressional district plan pairs incumbents. *See League of Women Voters I*, 178 A.3d at 817 ("We recognize that other factors have historically played a role in the drawing of legislative districts, such as the … . protection of incumbents…. However, we view these factors to be wholly subordinate to the neutral criteria . . . . (citation omitted)); *Holt II*, 67 A.3d at 1235 (noting that avoiding pairing incumbents is neither constitutionally required nor prohibited). The GMS Plan pairs ***zero*** congressional incumbents who are seeking reelection in 2022,[12] while the Governor's Plan pairs two sets of incumbents seeking reelection (Representatives Madeleine Dean and Mary Gay Scanlon in District 5, and Representatives Fred Keller and John Joyce in District 12), and the House Republican Plan pairs one set (Representatives Daniel Meuser and Matt Cartwright).

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[12] The GMS Plan's District 14 pairs Representative Guy Reschenthaler with Representative Conor Lamb, who is not seeking reelection. DeFord Report ¶ 145; *see* Deirdre Walsh et. al., *House retirement tracker: Senior Democrats exit as the GOP is confident of a Takeover*, NPR (Jan. 13, 2022), https://www.npr.org/2021/12/09/1061182786/house-retirement-tracker-2022-congress-republicans-democrats. The House Republican Plan's District 15 pairs Representative Lamb with Representative Mike Doyle. DeFord Report ¶ 145.

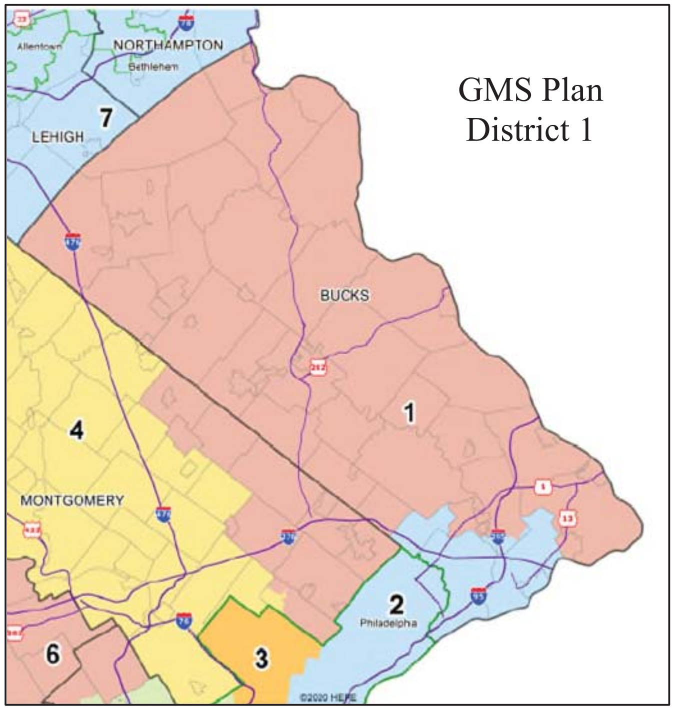
DeFord Report ¶ 145. To the extent the Court prefers not to pair incumbents, the GMS Plan is superior.

B. Respect for Communities of Interest

"Communities of interest" refer to distinct geographic areas whose residents share common social, cultural, economic, or policy interests. *See Mellow*, 530 Pa. at 76–77. The Pennsylvania Supreme Court has recognized as an appropriate factor in redistricting the preservation of communities of interest defined by, among other things, their "common economic base," "circulation arteries," shared "schools of higher education," and shared "news media." *Mellow*, 530 Pa. at 76–77; *see id.* at 53; *Holt II*, 67 A.3d at 1241; *see also Abrams*, 521 U.S. at 100).

A district-by-district overview of the GMS Plan demonstrates how the GMS Plan substantially preserves communities of interest throughout the Commonwealth[13]:

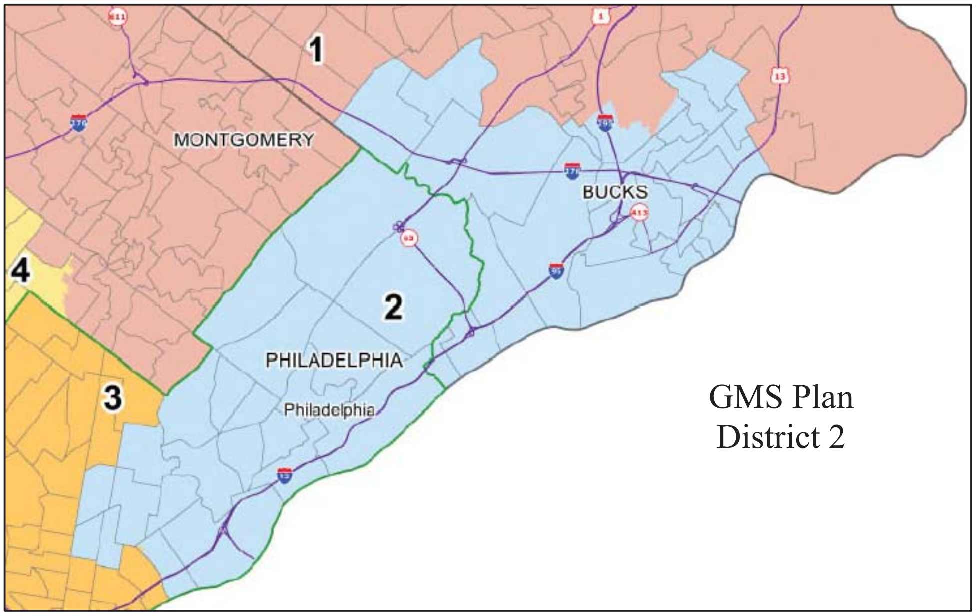
[13] Each of the insets of the GMS Plan's districts outlines counties in black and cities in green. For most insets, boroughs and townships (along with Pennsylvania's sole incorporated town) are outlined in gray. For the districts in the Philadelphia area, the gray lines show ward boundaries.



District 1: District 1 joins all the communities of Bucks County other than those closest to Northeast Philadelphia with similar communities along the Montgomery County/Bucks County border. The communities of Bucks and Montgomery Counties are so closely aligned that the local newspaper, the Bucks County Courier Times, reports about snowstorm closures and other local news in both counties together.[14] This area has also experienced notable population growth

[14] *See, e.g.*, *Bucks County weather: How much snow fell in area's 1st winter storm?*, Bucks Cty. Courier Times (Jan. 7, 2022), https://www.buckscountycouriertimes.com/story/news/2022/01/07/bucks-county-weather-snow-totals-first-snowfall-school-closures/9128118002/; Nick Siano, *Snow storm closures: See what's closed, delayed in Bucks and Montgomery counties*, Bucks Cty. Courier Times (Dec. 17, 2020), https://www.buckscountycouriertimes.com/story/news/2020/12/16/bucks-montgomery-county-closures-see-whats-closed-thursday-pa-storm/3933497001/;

over the past decade, fueled in part by the rapid expansion of biotechnology in both Bucks County and Montgomery County.[15]

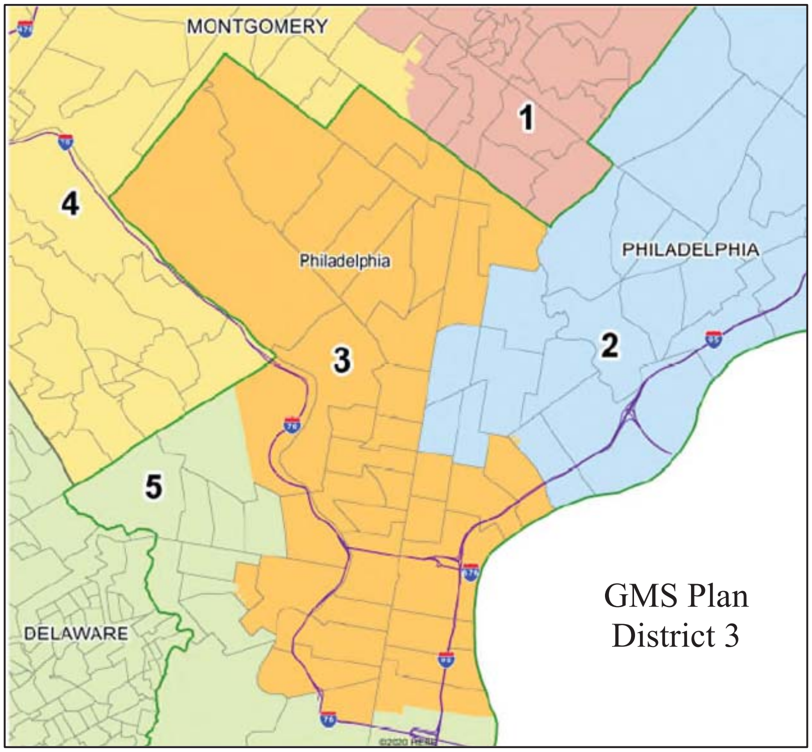


District 2: District 2 connects Northeast Philadelphia with similar suburban communities in the southernmost part of Bucks County. District 2 includes greater Northeast Philadelphia and the communities of Bucks County that adjoin Philadelphia and share economic interests more akin to their Northeast Philadelphia neighbors than to the more rural communities in the northernmost parts of Bucks

Christopher Dornblaser, *Deed scam targeting Montgomery County homeowners*, Bucks Cty. Courier Times (Sept. 10, 2020), https://www.buckscountycouriertimes.com/story/news/2020/09/10/deed-scam-targeting-montgomery-county-homeowners/3460196001/.

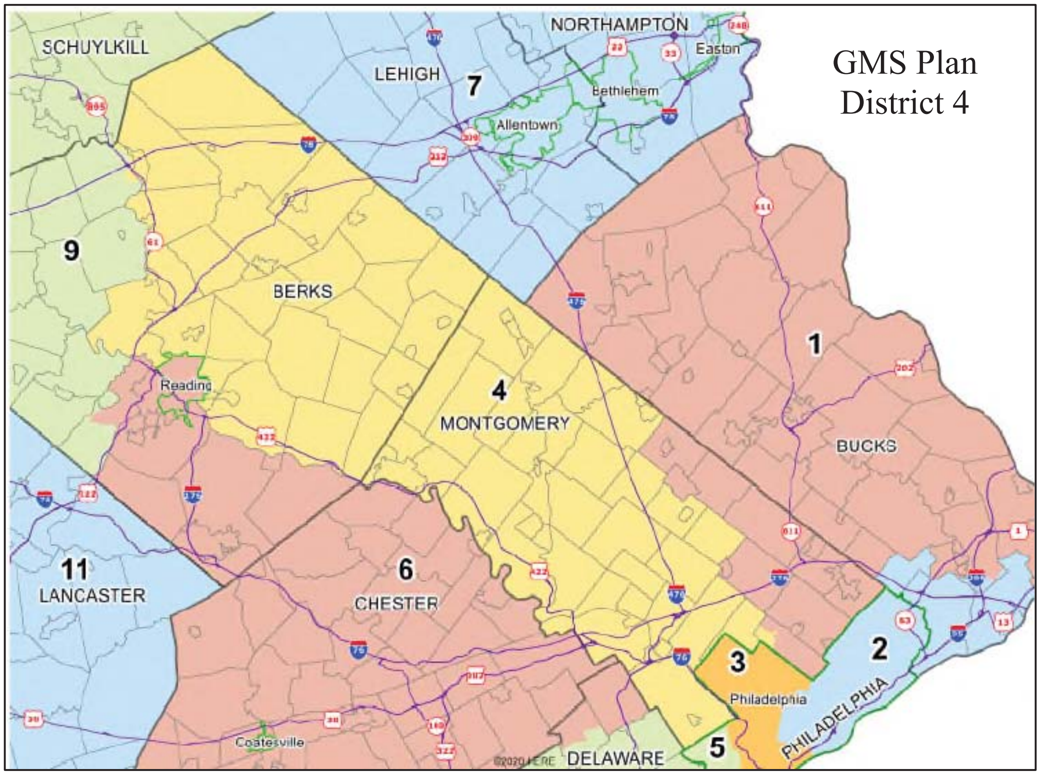
15 *See* Christine Tarlecki, *Montgomery County Makes List of Top 10 Biopharma Clusters Nationwide*, MontCo.Today, (Mar. 23, 2021), https://montco.today/2021/03/montgomery-county-makes-list-of-top-10-biopharma-clusters-nationwide/.

County. Moreover, as discussed above, District 2 is a majority-minority district that could provide historic opportunities to Pennsylvania's growing Latino communities.

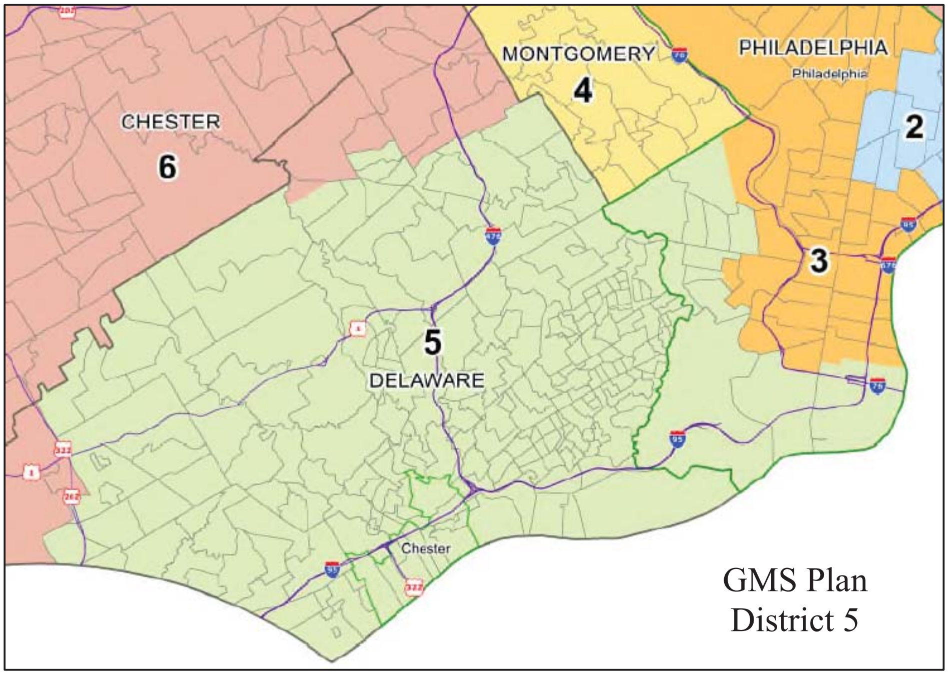


GMS Plan
District 3

District 3: District 3 consists entirely of communities within Philadelphia city limits, joining Northwest Philadelphia, Center City, and parts of both West and South Philadelphia. It maintains the core of the former district while accounting for significant population growth in certain Philadelphia neighborhoods since 2010. Moreover, as discussed above, District 3 is a minority opportunity district with a track record of strongly supporting the same Black-preferred candidates that current District 3 supports.

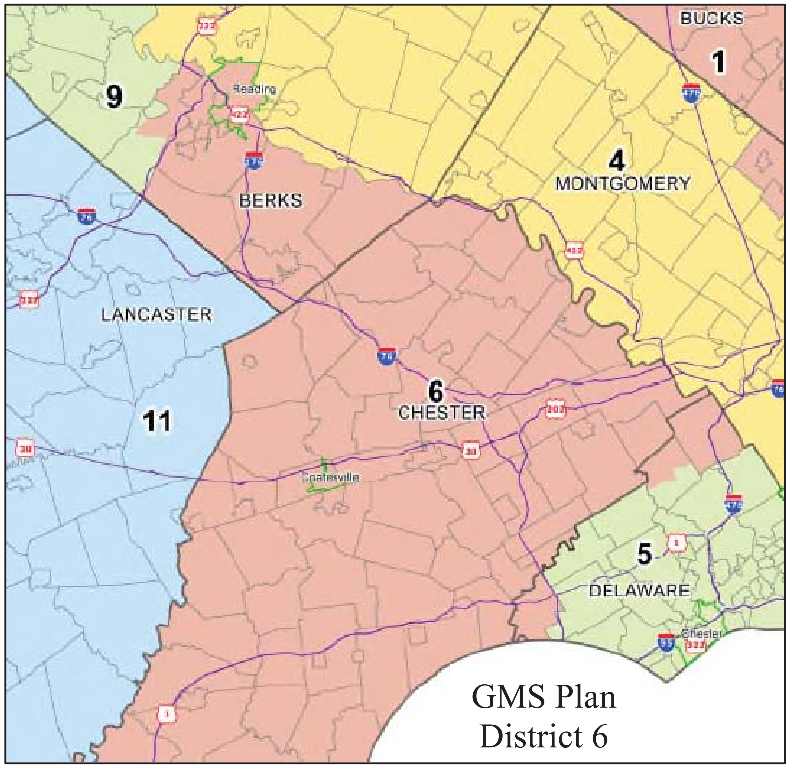


District 4: District 4 unites most of rapidly growing Montgomery County with the neighboring communities of Berks County. It follows the northern end of Pottsville Pike (PA-61 N) to the Schuylkill County Border, keeping together small communities such as Leesport and Hamburg in northern Berks County.

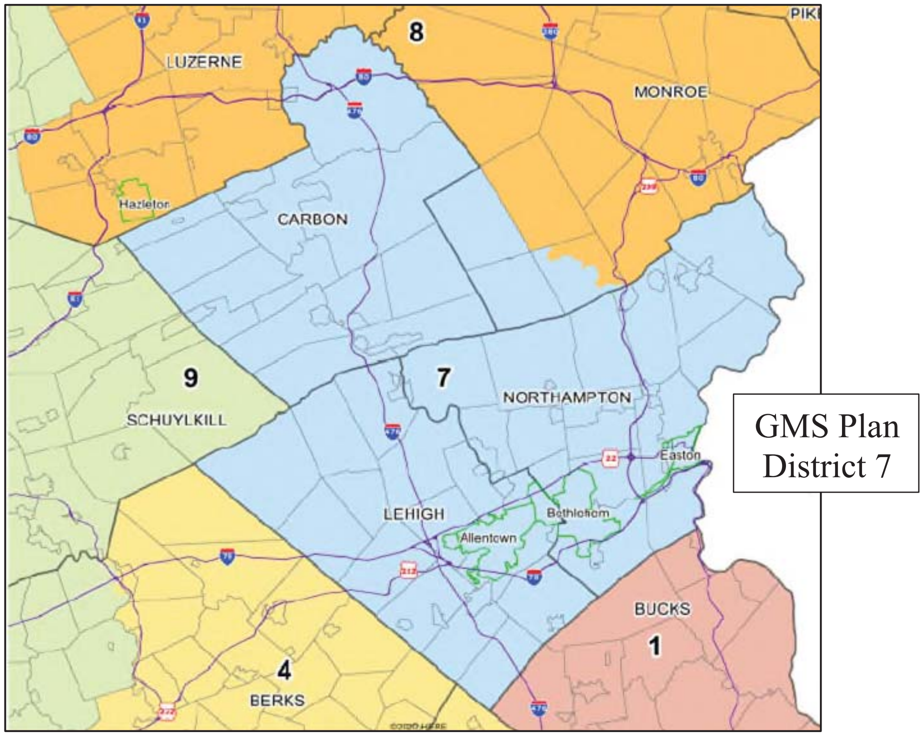


GMS Plan
District 5

District 5: District 5 contains most of Delaware County, linked with parts of West and South Philadelphia. These neighboring communities include the Philadelphia International Airport, which is located at the county border, as well as the industrial areas in Southwest Philadelphia and along the Delaware River. Moreover, as discussed above, District 5 is also a minority opportunity district with a track record of strongly supporting the same Black-preferred candidates that current District 3 supports.



District 6: Similar to the 2018 Plan, District 6 keeps Chester County intact and links it with portions of Delaware County and Berks County, including all of Reading, Pennsylvania's fourth largest city with a growing Latino population. These counties share strong population growth and increasing diversity.



District 7: District 7 joins all of Lehigh, Northampton, and Carbon Counties and thus preserves the core of the Lehigh Valley, keeping the Allentown-Bethlehem-Easton metropolitan statistical area ("MSA")[16] intact. It also includes the southwest portion of Monroe County that sits between Carbon and Northampton Counties. The communities in this District are connected via the Northeast Extension of the Pennsylvania Turnpike (I-476) and its arteries.

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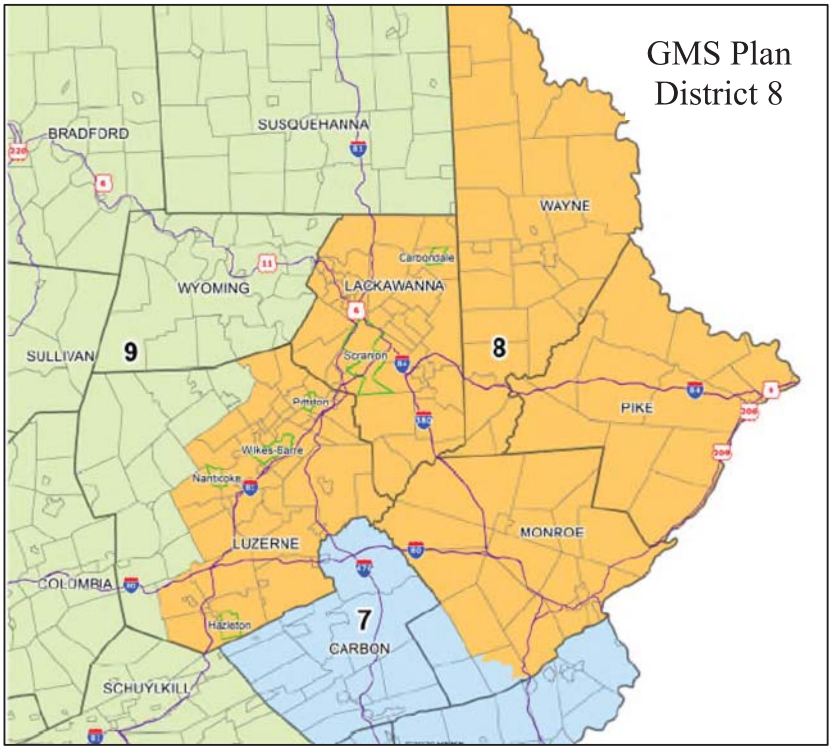
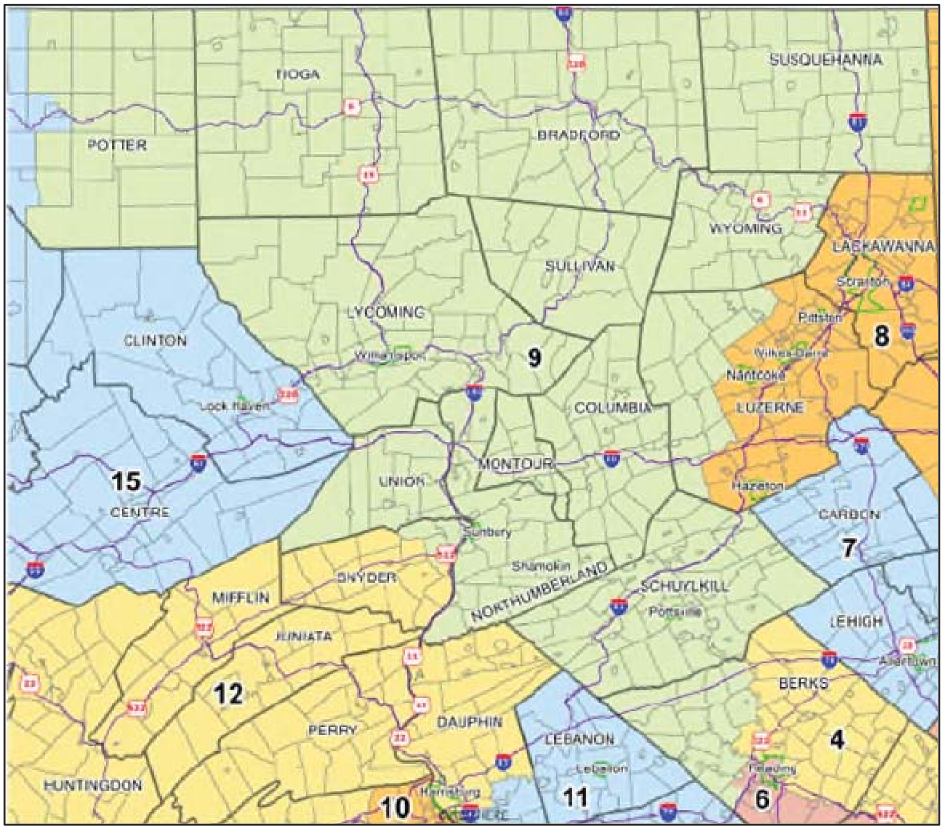
[16] The United States Office of Management and Budget delineates MSAs and Combined Statistical Areas ("CSA"). An MSA is "a core area containing a substantial population nucleus, together with adjacent communities having a high degree of economic and social integration with that core." https://www.census.gov/programs-surveys/metro-micro/about.html. CSAs combine MSAs or adjacent micropolitan statistical areas.

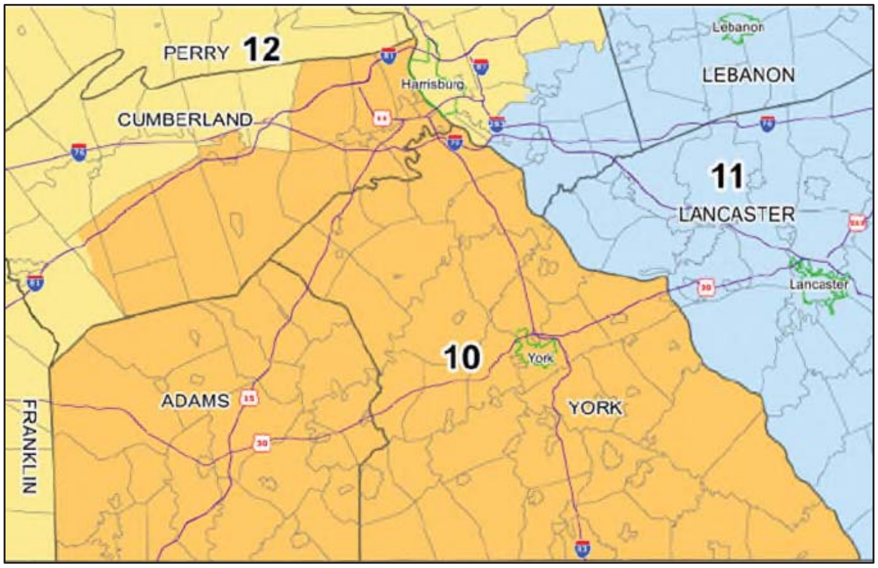


District 8: District 8 keeps whole Wayne, Pike, and Lackawanna Counties, and joins these with the majority of Monroe and Luzerne Counties. This District is anchored by the cities of Scranton, Wilkes-Barre, and Hazleton, joining those cities with geographically similar communities in the Poconos.



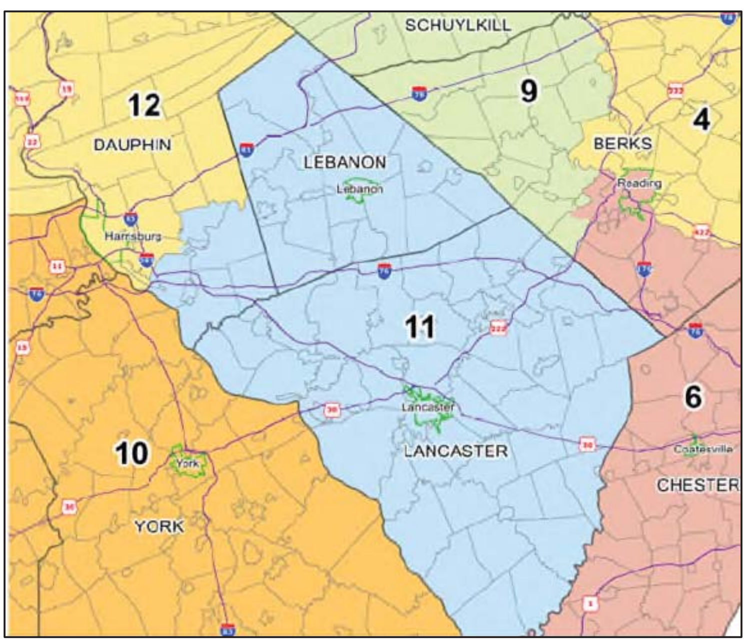
GMS Plan
District 9

District 9: This District groups the northern tier counties of Susquehanna, Bradford, Tioga, and most of Potter with adjoining counties to the south. This portion of the state is experiencing slow population growth, and this district keeps these communities together while preserving eleven counties intact.



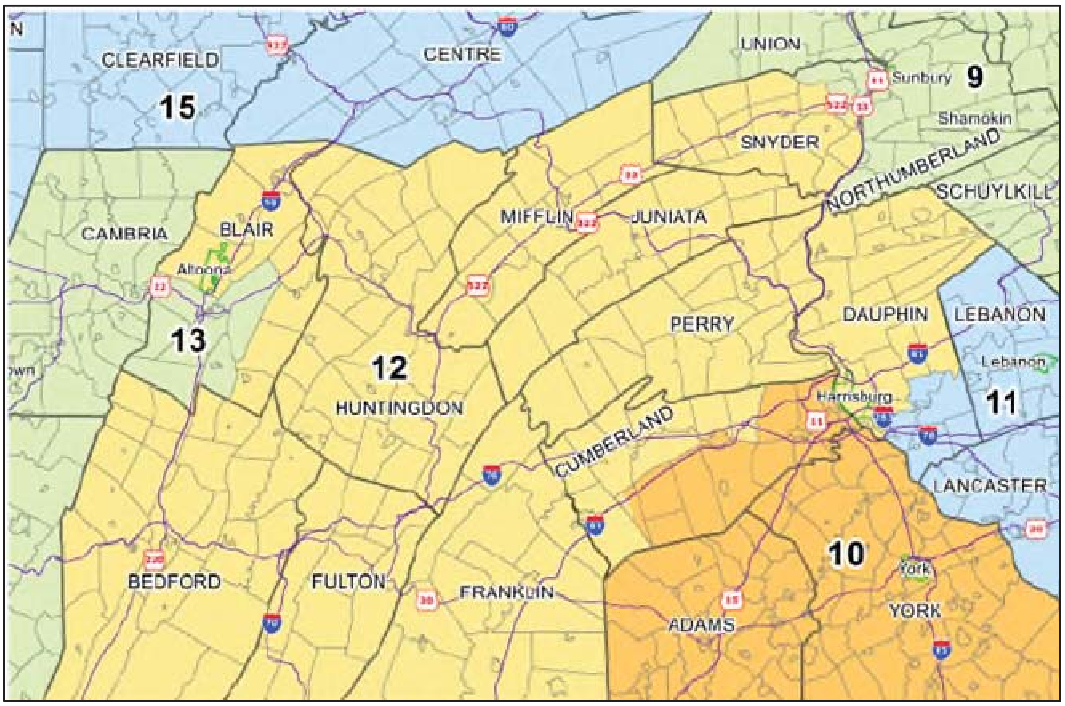
GMS Plan
District 10

District 10: This District joins all of Adams County and York County—keeping intact the York-Hanover and Gettysburg MSAs—with adjoining communities in Cumberland County, including the county seat of Carlisle. This rapidly growing and diversifying area shares economic anchors, is home to many colleges and universities, and is connected by major transportation arteries.



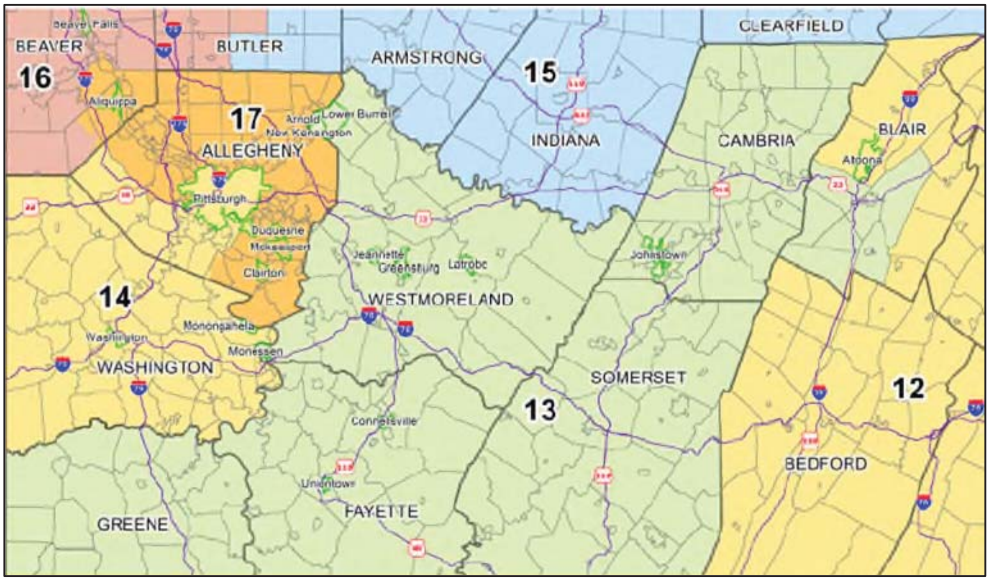
GMS Plan
District 11

District 11: This District keeps all of Lebanon and Lancaster Counties intact, as well as the Lebanon and Lancaster MSAs, along with similarly fast-growing and increasingly diverse neighboring communities in Dauphin County. This District also includes Hershey and Middletown.



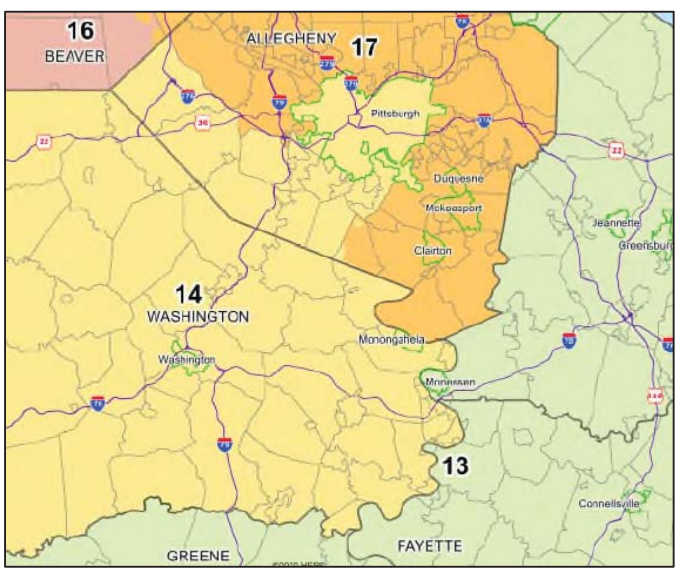
GMS Plan District 12

District 12: District 12 keeps intact seven whole counties—Bedford, Franklin, Fulton, Huntington, Juniata, Mifflin, and Perry—as well as the Chambersburg-Waynesboro MSA. It groups these counties with parts of Blair, Cumberland, Dauphin, and Snyder Counties that contain the mountainous and rural region of south-central Pennsylvania. This district is anchored by the city of Harrisburg, which also is kept intact.



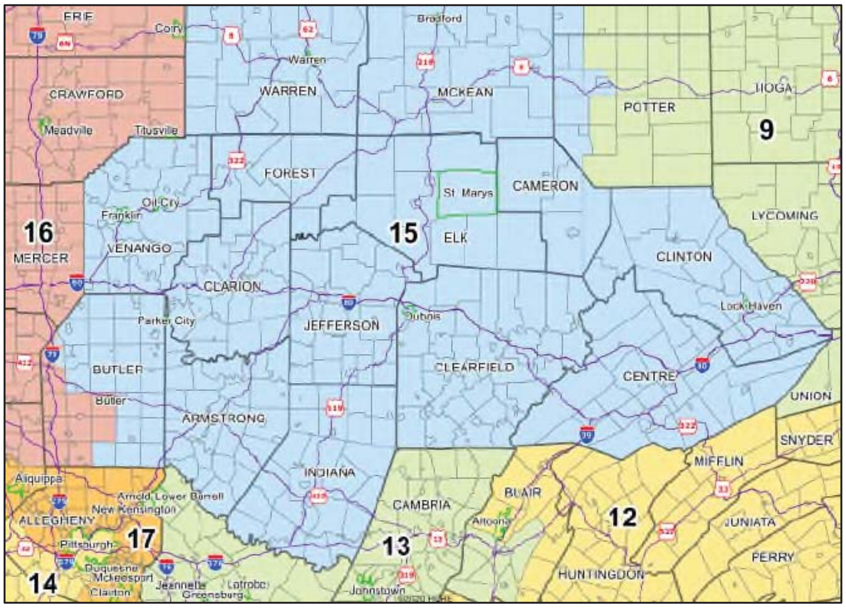
GMS Plan District 13

District 13: District 13 joins all the Laurel Highlands—Westmoreland, Somerset, and Fayette Counties—with Cambria County, Greene County, and parts of Blair County. This District allows for six intact counties and unites communities with similar economic characteristics and interests in this mountainous area that has historically been a source of energy production.



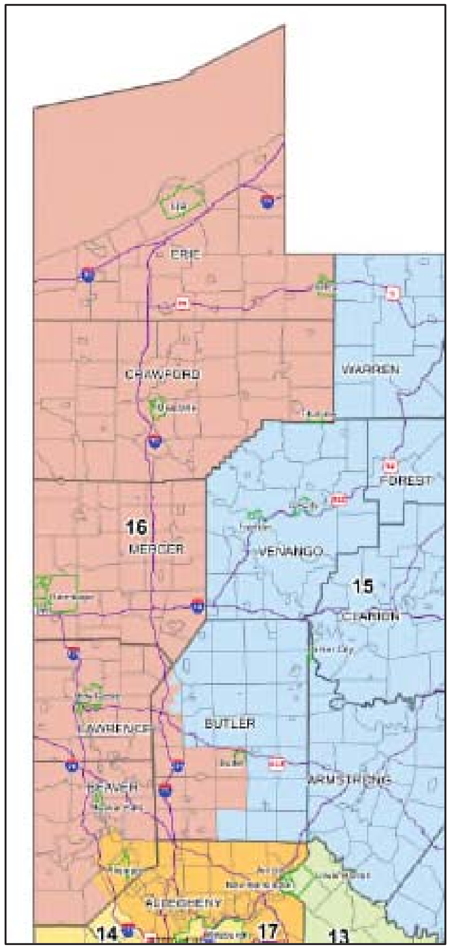
GMS Plan District 14

District 14: District 14 centers on Pittsburgh, Pennsylvania's second-largest city, which is kept fully intact. It pairs Pittsburgh with its southwest Allegheny County suburbs and with all of neighboring Washington County.



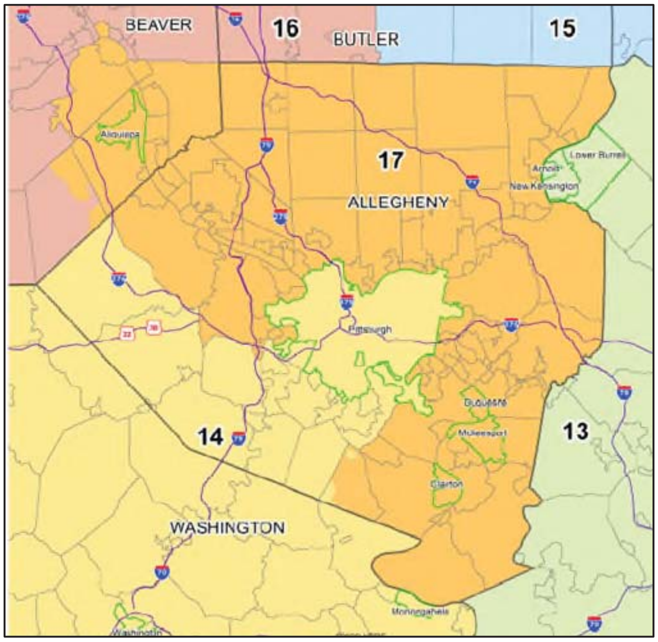
GMS Plan
District 15

District 15: District 15 gathers much of the Pennsylvania Wilds in one district, keeping thirteen counties whole, as well as the State College-Dubois Combined Statistical Area ("CSA"). District 13 brings together communities that share geographic characteristics and economic interests in tourism, outdoor recreational opportunities, and energy production, and is also the home of Punxsutawney Phil.



GMS Plan
District 16

District 16: District 16 includes most of Pennsylvania's western border counties and is anchored by Erie County in the northwest, linking it with other industrial and rural counties to its south: all of Crawford, Mercer, and Lawrence, and parts of Beaver and Butler Counties. It joins, among other areas, the Erie-Meadville CSA and the Pennsylvania portion of the Youngstown-Warren CSA



GMS Plan
District 17

District 17: District 17 connects most of the non-Pittsburgh portions of Allegheny County, including the northern and eastern suburbs and exurbs of Pittsburgh, along with neighboring communities in Beaver County. This keeps the smaller towns and cities that make up Pittsburgh's North and East Hills together, along with similarly sized former industrial towns in eastern Beaver County.

* * *

Importantly, the GMS Plan substantially preserves these communities of interest without sacrificing performance on any of the legal requirements.

CONCLUSION

This Court should adopt the GMS Plan because the GMS Plan fully complies with all state and federal legal requirements, outperforms its competitor plans on nearly every metric, expands opportunities for minority voters, preserves numerous communities of interest, pairs no incumbents, and is fundamentally fair.

Dated: January 24, 2022

Respectfully submitted,

By: /s/ Kim M. Watterson

Kim M. Watterson (PA 63552)
Devin M. Misour (PA 311892)
REED SMITH LLP
225 Fifth Avenue, Ste. 1200
Pittsburgh, PA 15222
(412) 288-3131
kwatterson@reedsmith.com
dmisour@reedsmith.com

Shannon E. McClure (PA 164502)
REED SMITH LLP
Three Logan Square
1717 Arch Street, Ste. 3100
Philadelphia, PA 19103
(215) 851-8100
smcclure@reedsmith.com

Sam Hirsch (PHV)
Jessica Ring Amunson (PHV)
Lindsay C. Harrison (PHV)
Tassity S. Johnson (PHV)
Claire M. Lally (PHV)
JENNER & BLOCK LLP
1099 New York Avenue, NW, Ste. 900
Washington, DC 20001
(202) 639-6000
SHirsch@jenner.com
JAmunson@jenner.com
TJohnson@jenner.com
LHarrison@jenner.com
CLally@jenner.com

April A. Otterberg (PHV)
JENNER & BLOCK LLP
353 North Clark Street
Chicago, IL 60654-3456
(312) 222-9350
AOtterberg@jenner.com

Counsel for Petitioners

CERTIFICATE OF COMPLIANCE

I certify that this filing complies with the provisions of the *Case Records Public Access Policy of the Unified Judicial System of Pennsylvania* that require filing confidential information and documents differently than non-confidential information and documents.

Submitted by: Kim M. Watterson

Signature: /s/ Kim M. Watterson

Name: Kim M. Watterson

Attorney No. PA 63552_________

PROOF OF SERVICE

On January 24, 2022, I caused a copy of the foregoing to be served on all counsel of record via the electronic filing system, PACFile:

/s/ Kim M. Watterson
Kim M. Watterson (PA 63552)
REED SMITH LLP
225 Fifth Avenue, Ste. 1200
Pittsburgh, PA 15222
(412) 288-3131
kwatterson@reedsmith.com

EXHIBIT 1

Expert Report of Professor Daryl R. DeFord on behalf of the Gressman Math/Science Petitioners

Monday, January 24, 2022

I Qualifications

¶ 1 I am an Assistant Professor of Data Analytics in the Department of Mathematics and Statistics at Washington State University. I earned A.M. and Ph.D. degrees in Mathematics at Dartmouth College and also hold a B.S. in Theoretical Mathematics from Washington State University. From 2018 to 2020, I was a postdoctoral associate in the Geometric Data Processing Group in the Computer Science and Artificial Intelligence Laboratory ats the Massachusetts Institute of Technology and affiliated with the Metric Geometry and Gerrymandering Group in the Jonathan M. Tisch College of Civic Life at Tufts University with a full-time focus on computational redistricting research.

¶ 2 My mathematical work focuses on applications of combinatorial and algebraic techniques to the analysis of social data and particularly includes the study of statistical sampling techniques for political redistricting problems. This work includes both theoretical design and analysis of algorithms as well as empirical projects modeling the interactions between districting criteria. My redistricting work has been published in the *Harvard Data Science Review*, *Political Analysis*, *Statistics and Public Policy*, *Journal of Computational Social Science*, *Mathematical Association of America's Math Horizons*, *Physical Review E*, and *Society of Industrial and Applied Mathematics Journal on Applied Algebra and Geometry*. I have given dozens of presentations on computational redistricting and designed an Independent Activity Period course at MIT on the topic. As a postdoc, I helped supervise the Voting Rights Data Institute summer program in 2018 and 2019, and in Summer 2021, I supervised a team of research fellows through the University of Washington's Data Science for Social Good program, applying computational redistricting to initial stages of the map-making process.

¶ 3 During the current redistricting cycle, Dr. Jeanne Clelland, Dr. Beth Malmskog, Dr. Flavia Sancier-Barbosa, and I provided reports and analysis for the 2021 Colorado Independent Legislative Redistricting Commission. Our work was cited by the commission in their final report supporting their maps, and the Colorado Supreme Court cited our work as evidence that the commission complied with the legislative requirement to optimize for the number of competitive districts. In 2019, I performed computational work and served as a collaborator on an Amicus brief to the United States Supreme Court for *Rucho v. Common Cause*. I have not previously testified as an expert witness or been deposed in any legal proceeding. I have recently submitted expert reports on behalf of certain intervenors in *Johnson v. Wisconsin Elections Commission*, Case No. 2021AP001450 OA, a redistricting matter pending in the Supreme Court of Wisconsin.

¶ 4 A full copy of my CV, which also contains a list of my publications in the last 10 years, is included in Appendix A. For my work on this matter, I am being compensated at a rate of $300 per hour. This compensation does not depend in any way on the results of my analysis, the conclusions that I draw, or the eventual outcome of the litigation.

II Executive Summary

¶ 5 I analyzed the congressional redistricting plan proposed by a group of Pennsylvania voters, referred to here as the Gressman Math/Science Petitioners ("GMS"), by selecting metrics that are responsive to the relevant legal criteria. My analysis shows that, as applied to the 2020 Census data for Pennsylvania, this map obtains excellent scores across all of the criteria and outperforms the 2018 map adopted by the Supreme Court of Pennsylvania on many of them. The values of the 2018 map serve as an effective baseline, as the Supreme Court adopted that map after a detailed analysis. Particularly distinctive features of the GMS Plan are its performance on preserving political-subdivision boundaries, its evenhanded treatment of voters from both major political parties, and the creation of three majority-minority districts. A full description of my methodology and findings concerning the GMS Plan is presented in Section V.

¶ 6 As an initial threshold, the GMS Plan satisfies the binary requirements of population balance and contiguity. The GMS Plan achieves the tightest possible population deviation of a one-person difference between the largest and smallest districts in the plan, and each district is contiguous. The plan is also compact, improving on the compactness of the 2018 plan on several commonly accepted shape-based measures.

¶ 7 The GMS Plan also performs very well at preserving the boundaries of political subdivisions, splitting only 12 counties beyond those required for population balance and splitting fewer counties into three pieces than the 2018 map. Additionally, the GMS Plan keeps intact well over 99% of the municipalities and wards in the state.

¶ 8 The GMS Plan demonstrates excellent performance on measurements of majoritarian responsiveness and partisan symmetry as applied to a broad class of elections that occurred in the state over the previous decade, including elections won by nominees from both major political parties. The plan is particularly effective at allowing voters from both parties to convert even a small statewide vote majority into a majority of the seats in the plan, and the plan also achieves strong, balanced values on standard measures of partisan symmetry. Simply put, the GMS Plan is fair to voters of both major political parties.

¶ 9 Finally, the GMS Plan contains three majority-minority voting age population districts in the Philadelphia area that are likely to both nominate (in Democratic primaries) and elect (in general elections) candidates preferred by minority voters and thus serve the interests of the Commonwealth's largest Black and Latino communities.

¶ 10 Taken together, these properties demonstrate the strong performance of the GMS Plan, on metrics related to compliance with federal and state law, adherence to traditional redistricting criteria, and attention to Pennsylvania-specific geography and constraints. Overall, the GMS Plan equals or outperforms the 2018 plan on these factors.

¶ 11 I also have analyzed the map passed by the Pennsylvania House of Representatives on January 12, 2022 (the "House Plan"); and the map proposed by Governor Wolf on January 15, 2022 (the "Governor's Plan") as comparators to the GMS Plan. The GMS Plan outperforms both plans on preserving political boundaries, and it significantly outperforms the House plan on measures of partisan fairness. On each of the criteria I analyzed, the GMS Plan performs comparably or better to the comparator plans and demonstrates that while there may be some tradeoffs necessary between the relevant constraints, it is possible to create a map that performs very successfully on all criteria.

III Assignment

¶ 12 Counsel for a group of Pennsylvania voters ("the Gressman Math/Science Petitioners" or "GMS") asked me to evaluate their proposed redistricting plan for Pennsylvania's Congressional districts. Specifically, I was asked to evaluate how the GMS Plan performs on redistricting criteria that are mandated by federal law, such as equal population and compliance with the federal Voting Rights Act ("VRA"). I was also asked to evaluate the GMS Plan with respect to Pennsylvania's neutral redistricting requirements, listed in the Commonwealth's Constitution, as well as partisan fairness, mandated by the Free and Equal Elections Clause of the Pennsylvania Constitution. Additionally, I was asked to compare the performance of the proposed plan to the properties of the 2018 Plan and the properties of the House Plan and the Governor's Plan. The 2018 map was drawn by a special master in connection with the *League of Women Voters* litigation before the Pennsylvania Supreme Court. This map was extensively vetted and analyzed according to legal and traditional districting criteria, and thus its performance on metrics evaluating these criteria can serve as a starting point or baseline for identifying potentially reasonable values for plans created during this redistricting cycle based on the 2020 Census data.

¶ 13 To carry out my evaluation, I measured the properties of the GMS Plan, the 2018 Plan, the House Plan, and the Governor's Plan according to several different metrics corresponding to the legal criteria. For the VRA aspects of my analysis, I was assisted by Professors John Alford and Randolph Stevenson at Rice University, who were compensated at the rate of $400 per hour.

¶ 14 In measuring the properties of the GMS Plan, the 2018 Plan, the House Plan, and the Governor's Plan, I relied on Pennsylvania population and geographic data obtained from the Pennsylvania Legislative Reapportionment Commission and the U.S. Census Bureau, as well as data released by the individual parties. Further description of this data, and a list of all materials that I relied upon in preparing this Report, is provided in Appendix B, attached to this report.

IV Data and Methodology

¶ 15 The data used in this report is described in Appendix B. The starting point for my quantitative analysis of the GMS Plan was the Pennsylvania block-level shapefile, which contains population values and subcategories derived from the Census data release, without prisoner reallocation. A block equivalence file provided by counsel was used to associate the GMS Plan to the Census block geographies and a similar equivalence file I downloaded from Dave's Redistricting App was used to analyze the Governor's Plan. I used the MAUP package to attach the current, enacted 2018 Plan and the House Plan to the same units.

¶ 16 The geometries representing the Census blocks included overlapping boundaries. When attempting to measure the compactness of the districts, these overlaps had the potential to include extraneous perimeter, so I restricted my attention to the boundary of the dissolved units. As discussed in the *League of Women Voters* order, there are many modeling choices that can impact the measurement of compactness measures. The values reported here reflect a single set of decisions, but I have performed tests with other projections, aggregation techniques, and measurements, and my results are consistent across these choices.

¶ 17 For the vote total computations that are necessary to evaluate district performance for partisan fairness, I have used the voting district-level geographic data provided in the Legislative Redistricting Commission 1b data release, and supplemented that data with vote totals for 18 statewide general elections provided by counsel for the Gressman Math/Science Petitioners. Because all the plans were constructed from blocks, I associated the votes with these smaller units using the MAUP package to prorate vote totals from the voting district level according to voting-age population.

¶ 18 In order to evaluate effectiveness of the plans for VRA analysis, I used additional voting data provided by Counsel, beyond the 18 general elections used for partisan fairness analysis. This additional dataset consisted of statewide vote totals at the voting district level for 10 Democratic primary elections, as well as data for six local elections in Philadelphia. To associate the plans under consideration with the voting districts, mapping files were provided by Counsel, along with proportional counts of population that were split for district boundaries that did not neatly nest into the voting districts. A description of the methodology I used for my evaluation of the proposed plans for compliance with the VRA is provided in Section V.F.2 below.

V Redistricting Criteria, Metrics, and Analyses

¶ 19 To evaluate the GMS Plan, as well as to compare it to the 2018 Plan, the House Plan, and the Governor's Plan, I analyzed performance on several redistricting criteria identified by counsel. These include population equality; respect for political-subdivision boundaries; district compactness; contiguity; partisan fairness; and opportunities for minorities to nominate and elect their preferred candidates. In this section, I set out the quantitative metrics used to evaluate performance under these criteria and provide my conclusions on each.

V.A Population Equality

¶ 20 Population equality for purposes of redistricting is usually formulated as an optimization constraint where plans with smaller top-to-bottom deviations in population are regarded more favorably. This value, obtained by subtracting the smallest district population from the largest, is known as the "maximum deviation" and is a common measure of a map's overall population balance. For Congressional districts, I have been instructed that federal law requires absolute population equality. This is frequently referred to as "zero-balancing," in that there should be a maximum deviation of one person when comparing the largest and smallest district populations.

¶ 21 Pennsylvania has been allocated 17 Congressional seats instead of its current 18 after the 2020 Census. According to the Census, the Commonwealth's total population is 13,002,700. As a result of losing a seat, the size of an ideal congressional district in Pennsylvania has grown by 8.4 percent to 764,865 in 2020, compared to 705,688 in 2010. Thus, to achieve zero-balancing, a Pennsylvania Congressional map based on the 2020 Census data should have exactly five districts containing 764,864 persons and twelve districts containing 764,865 persons.

¶ 22 The GMS Plan achieves this optimal value. The populations for each of the proposed districts are recorded in Table 1 below. I have confirmed that the House Plan and the Governor's Plan also reflect one-person maximum population deviation.

District #	Population
1	764,865
2	764,865
3	764,864
4	764,864
5	764,865
6	764,865
7	764,865
8	764,865
9	764,865
10	764,865
11	764,865
12	764,865
13	764,865
14	764,864
15	764,865
16	764,864
17	764,864

Table 1: Population Totals for the Proposed Congressional Districts in the GMS Plan

V.B Respect for Political Subdivision Boundaries

V.B.1 Criteria and Metrics

¶ 23 The Pennsylvania Constitution requires that state legislative districts preserve county, city, incorporated town, borough, township, and ward boundaries "unless absolutely necessary" [PA State Constitution, article II, section 16]. In 2018, in *League of Women Voters of Pa. vs. Pennsylvania*, the Supreme Court of Pennsylvania ruled that these measures are also appropriate for evaluating "whether a congressional redistricting plan violates the Free and Equal Elections Clause of the Pennsylvania Constitution." [178 A.3d 737]

¶ 24 To evaluate how the GMS Plan performs on the criterion addressing respect for political subdivision boundaries, I analyze the frequency with which the map traverses these boundaries. Counties "tile" the state, meaning that every Pennsylvania resident's home, indeed every square inch of Pennsylvania, falls in one and only one county. Similarly, the Census category "Minor Civil Divisions" (MCDs) consist of the Commonwealth's cities, its sole incorporated town, its boroughs, and its townships—in other words, its municipalities. These MCD or municipality units also tile the state. Wards are further subdivisions of some but not all of the municipalities throughout the state. Wards do not cover the entire state. So, every Census block in the state is located in one county and in one MCD, but only some Census blocks are located in one ward.

¶ 25 In evaluating how a proposed map performs on the criterion addressing respect for political subdivision boundaries, it is important to remember that it is not possible to construct districts that have perfect population equality, like the GMS Plan, and also preserve all county boundaries (or, for that matter, all municipality boundaries). The metrics that I describe below include variants that account for this reality.

¶ 26 I use several different metrics to measure performance on this criterion. I will discuss these measurements using counties as an example:

- First, it is possible to measure the number of counties that are split by district lines. A county is split if it intersects multiple districts in the plan under consideration.

- Second, it is possible to measure the number of times that counties are divided by district lines—in other words, the number of pieces into which each county is split. For example, a county that is split once will consist of two pieces (one in one district and the other in another district), while a county that is split twice will have three pieces, each of which falls in a different district.

- Third, it is possible to evaluate whether and to what extent specific counties must be split because their population exceeds the population of an ideal congressional district. Under the 2020 Census data, Pennsylvania's three largest counties (Allegheny, Montgomery, and Philadelphia) must be split because each has a population that exceeds that of a congressional district (and Philadelphia's population exceeds that of two districts). Counting splits of political subdivisions, such as counties, that are dictated by population numbers can overstate the count of splits that were made at the discretion of the line-drawer or created as a tradeoff to satisfy other districting priorities. Thus, I also compute the number of splits and pieces above those that are strictly necessary to comply with the population-equality requirement.[1] A political subdivision such as a county that is split into the minimal number of pieces as determined by this measure will be called "intact," even if it intersects multiple districts.

[1] To obtain this value, I divide the political-subdivision population by the ideal district population and then round up to the next integer.

¶ 27 I follow a similar approach for each of the other categories of boundaries that I analyze in this report (each type of municipality and wards). Although I report the number of political subdivisions that are split, for each of these boundary types and each of three measurements described above, a smaller number of splits or pieces and, equivalently, a larger number of intact or non-split political subdivisions, corresponds to better performance on the boundary preservation metric. Additionally, some of the smaller municipalities do not nest neatly within county boundaries, as demonstrated for boroughs below. When a political subdivision, such as a borough, is split in order to preserve a county boundary, as with units that are necessarily split due to their large population, I still regard the unit as "intact."

V.B.2 Counties Analysis

¶ 28 I start my analysis with counties as the most fundamental political unit.

Performance of the GMS Plan

¶ 29 There are 15 counties that intersect multiple districts in the GMS Plan, but three of these are Allegheny, Philadelphia, and Montgomery Counties, which are each larger than a Congressional district and must be split in any population-balanced plan.

¶ 30 For example, Allegheny County has a population of 1,250,578 persons. This population total means Allegheny County must be split into at least two districts to achieve zero balancing. As shown in Figure 1, in the GMS Plan, Allegheny County is split into exactly two districts, while the city of Pittsburgh and its irregular boundaries, together with the boundaries of every other municipality in the county (except South Park township), are preserved. As a result, I count Allegheny County as an "intact" county in the GMS Plan. That makes sense because it literally could not intersect fewer congressional districts.

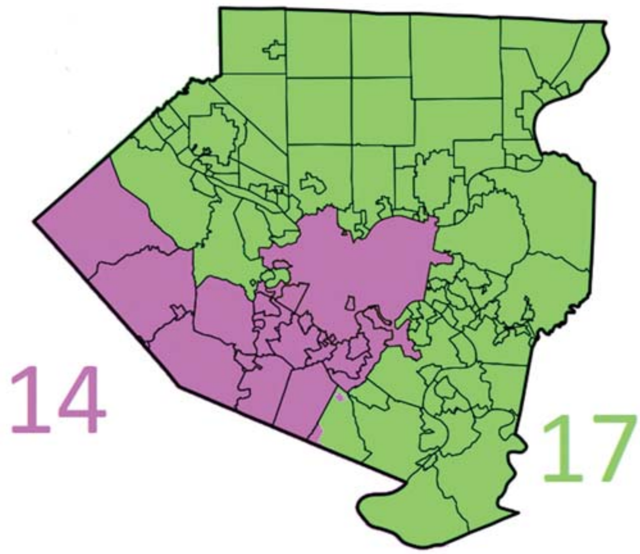


Figure 1: Allegheny County in Districts 14 and 17 in the GMS Plan, with its municipal boundaries

¶ 31 Similarly, under the 2020 Census data, the county and city of Philadelphia have a population of 1,603,797, or approximately 2.1 Congressional districts. Thus, to achieve zero-balancing of population, at least three districts must contain portions of Philadelphia. In the GMS Plan, exactly three districts intersect Philadelphia, so I do not count this "splitting" against the map, and record Philadelphia as an intact county and the city of Philadelphia as an intact city.

¶ 32 As with Allegheny County, the GMS Plan also splits Montgomery County into two pieces, the minimum number of pieces required to obtain zero-balancing of the population.

¶ 33 As such, I count Allegheny, Philadelphia, and Montgomery as "intact," and conclude that the GMS Plan splits only 12 counties above the number that must be split to satisfy the population requirement. As a result, 55 of Pennsylvania's 67 counties are considered intact in the GMS Plan. This can be seen in Figure 2 below.

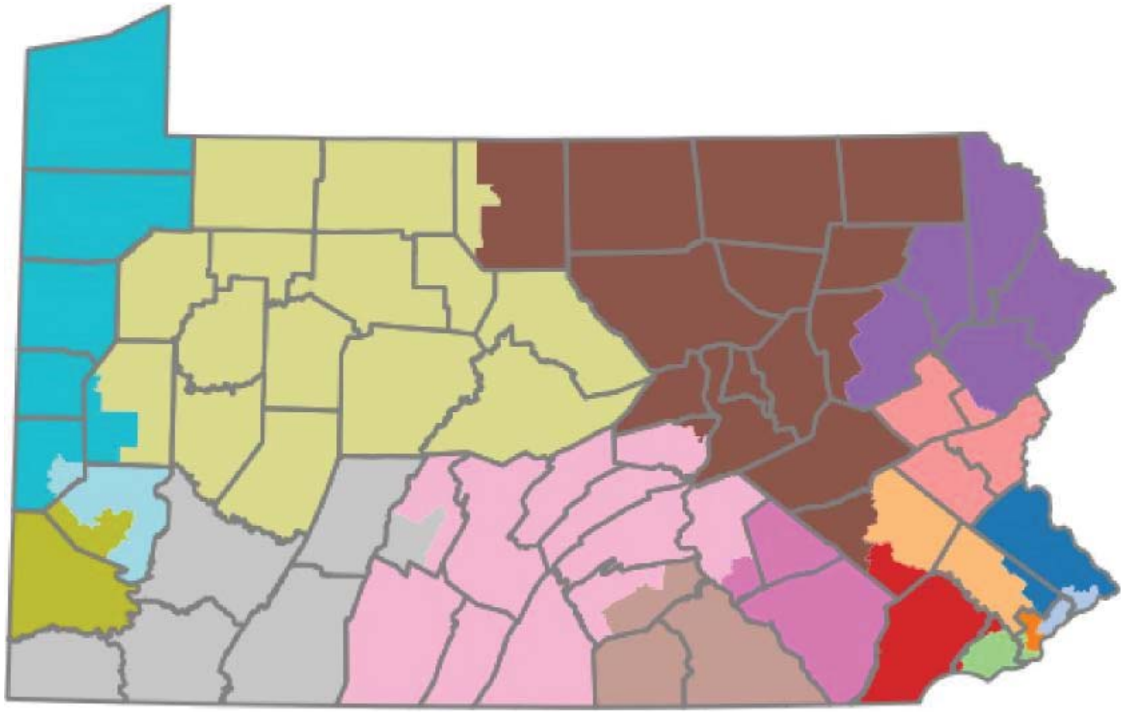


Figure 2: The GMS Plan Overlayed on Pennsylvania County Boundaries

¶ 34 In addition, just two counties, Philadelphia and Berks, are split into three pieces in the GMS Plan, and the three pieces in Philadelphia are the minimum number required for population equality. This improves on the four counties that were split into three pieces in the 2018 Plan.[2] No county is split into more than three pieces in the GMS Plan. Accordingly, the GMS Plan contains 84 county pieces, which is 13 pieces beyond those 71 pieces required by the populations of the counties. For comparison, in the 2018 Plan, 14 counties in total were split, and 11 of those were split more times than required by population. Including the split of Chester County,[3] the 2018 Plan also contained 87 total county pieces.

[2] The Pennsylvania Supreme Court drew the 2018 Plan, based on the 2010 Census, to divide both Montgomery County and Philadelphia among three districts each. The 2020 Census geography suggests, however, that the 2018 Map divides Montgomery County and Philadelphia among four districts each. For purposes of the Tables in this Report, I have assumed that the former numbers were correct.

[3] The 2018 Plan split 14 counties, according to GIS analysis, but one of the splits was of a discontiguous portion of Chester County. For this reason, as discussed in footnote 10 of the *League of Women Voters* order, the Court opted to report 13 county splits instead of 14. The GMS Plan does not split Chester County at all.

Fourteen county pieces were beyond those that were strictly required by the populations of the counties, one more than occurs in the GMS Plan.

Performance of the House Plan and the Governor's Plan

¶ 35 I also analyzed the number of county splits and pieces in the House Plan and in the Governor's Plan. The House Plan splits 15 total counties, including the three counties that must be split for population-balancing. However, it splits Philadelphia County into four pieces, instead of the three pieces required by its population. As such, I do not count Philadelphia as "intact" in the House Plan. And the House Plan splits Dauphin County into three pieces, when no splits are required for population reasons. As such, the House Plan has a total of 85 pieces, 14 of which are beyond those required for population reasons. The Governor's Plan splits 16 total counties (including the three required for population reasons), and two counties (Berks and Montgomery) are split into three pieces, although neither has a population larger than two Congressional districts. As such, I count 14 non-intact counties in the Governor's Plan. This creates a total of 86 pieces in the Governor's Plan, 15 of which are beyond those required for population reasons.

¶ 36 My comparison of the proposed redistricting plans on the principle of respect for county boundaries can be summarized as follows:

	GMS	**House**	**Governor**
Number of non-"intact" counties	12	13	14
Number of county pieces beyond those required by population	13	14	15

Table 2: Summary of County Splits Across Proposed Plans

V.B.3 Municipalities Analysis

¶ 37 Next, I turn to the municipalities in the order they are listed in the Constitution. The Commonwealth's municipality boundaries are shown in Figure 3.

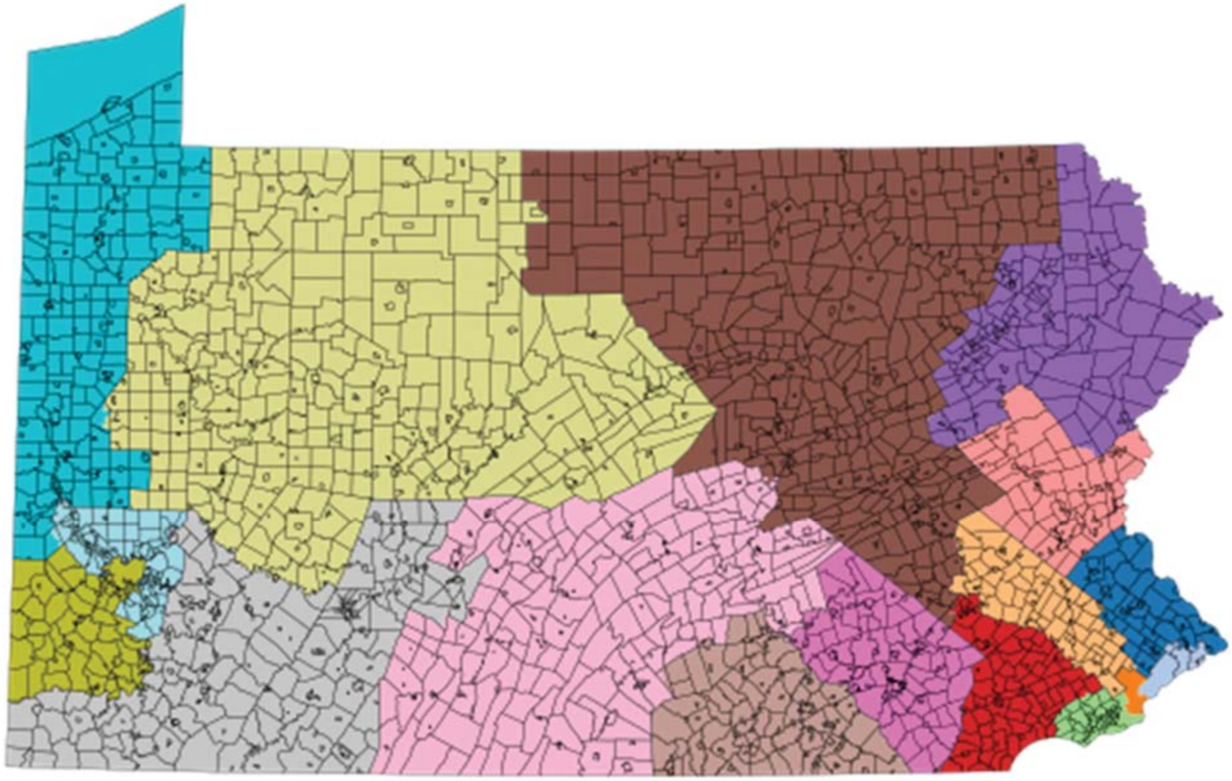


Figure 3: The GMS Plan overlayed on Pennsylvania municipality boundaries

Cities

¶ 38 Of the 57 cities in Pennsylvania, the GMS Plan splits only Philadelphia, and Philadelphia must be split into three pieces because of its large population. The GMS Plan splits Philadelphia into precisely three pieces, as was the case with the 2018 Plan.[4] Because the GMS Plan splits Philadelphia into only the minimum required number of pieces, I count Philadelphia as an intact city in the GMS Plan. As such, all cities are intact in the GMS Plan.

¶ 39 By contrast, although the House Plan also splits no cities other than Philadelphia, it splits that city into four pieces, one more than required for population purposes. As such, I do not count Philadelphia as an "intact" city in the House

[4] The city of Philadelphia and the county of Philadelphia share the same boundary. As such, the clarification regarding the Philadelphia County boundary set forth in footnote 2, above, also applies to the city of Philadelphia, as the 2020 Census boundaries suggest that the city of Philadelphia is split into four pieces instead of three in the 2018 Plan.

Plan. The House Plan thus has 60 city pieces, one more than required for population reasons.

¶ 40 The Governor's Plan splits two cities—Philadelphia (into the population-mandated three pieces) and Pittsburgh. The split of Pittsburgh is not required by its total population, so I do not count Pittsburgh as "intact" in the Governor's Plan. The Governor's Plan thus has 60 city pieces, one more than required for population reasons.

Incorporated Town

¶ 41 There is only one incorporated town in Pennsylvania (Bloomsburg, in Columbia County), and it is not split in the GMS Plan or any of the other plans I analyzed.

Boroughs

¶ 42 Of the 955 boroughs in the state, three are split by the GMS Plan, but each of these splits falls precisely along a county boundary that is preserved in the map. This follows the example of the 2018 Plan, which splits 6 boroughs, also to preserve county boundaries.

¶ 43 Splitting a municipality along county lines has the effect of preserving county boundaries. As noted, some counties and municipalities that do not themselves exceed the required district population size must be split to achieve a zero-balanced plan. Where municipalities such as boroughs cross county lines and the counties it connects cannot be kept together, the mapmaker can either split the municipality along the county line or keep the municipality whole but split one of the two counties in which the municipality sits.

¶ 44 Figure 4 shows an example of a borough split along county lines in the GMS Plan. Telford Borough lies partially in Bucks County and partially in Montgomery County. To keep Telford Borough whole and avoid an additional county split, one would have to combine Bucks County and Montgomery County in the same district. That is not possible because those two counties together far exceed the maximum population of a congressional district.

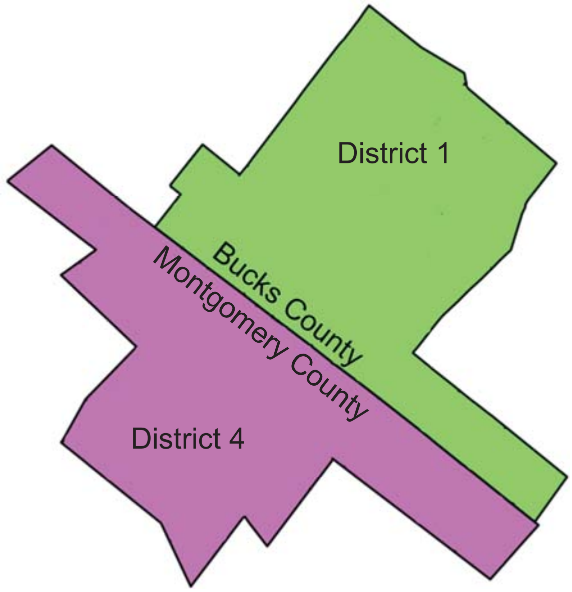


Figure 4: Telford Borough, which is divided between Bucks and Montgomery counties

¶ 45 Because I understand that counties are considered to be a more fundamental political unit than boroughs, I do not count against the GMS Plan its three borough splits that occur along county lines. In other words, I count all boroughs as intact in the GMS Plan. As such, I conclude there are 955 borough pieces in the GMS Plan, just as there was in the 2018 Plan.

¶ 46 The Governor's Plan splits four boroughs, and all of these splits are along county lines. I count these boroughs as intact in the Governor's Plan. Accordingly, I also concluded there are 955 borough pieces in the Governor's Plan.

¶ 47 By contrast, the House Plan splits six boroughs, but only five of these are along county lines. Accordingly, I count the House Plan as having one borough split and thus 956 borough pieces.

Townships

¶ 48 Finally, the GMS Plan splits 15, or less than 1%, of the Commonwealth's 1,547 townships. This is fewer than the 22 that are split in the 2018 Plan when overlayed on the 2020 Census data. This is one more township than is split in the House Plan but one fewer township than is split in the Governor's Plan.

Summary

¶ 49 Together, this means that the GMS Plan divides only 19 of Pennsylvania's 2,560 municipalities, and four of those are "intact" municipalities, as these four divisions were made to preserve either population balance (the split of Philadelphia) or county boundaries (the three borough splits). In other words, 99.4% of municipalities can be considered intact in the GMS Plan.

¶ 50 By comparison, the House Plan divides 21 municipalities, of which five may be considered "intact." The Governor's Plan divides 22 municipalities, of which five may be considered "intact."

¶ 51 The comparison among the three proposed plans can be summarized as follows[5]:

	GMS	House	Governor
Total municipalities split	**19**	**21**	**22**
Population-required splits	1	1	1
Number of municipalities split along county lines	3	5	4
Number of non-"intact" municipalities	**15**	**15**	**17**

Table 3: Summary of municipality splits among the proposed plans

V.B.4 Wards Analysis

¶ 52 As with the 2018 Plan, the GMS Plan follows ward boundaries in Philadelphia to the extent possible. The GMS Plan splits only 5 wards inside the city.[6] Keeping the ward splits so low is difficult given the size of the wards and the need for zero-balancing. The GMS Plan also splits only 10 wards in the remainder of the

[5] The 2018 Plan split a total of 29 municipalities, including one city split (Philadelphia) for population reasons and six boroughs split on county lines.

[6] The 2018 Plan was premised on ward boundaries as they existed at the time. Materials accompanying the 2018 Plan suggests there were 29 wards split in that plan. Ward boundaries have changed over the last decade, however.

state, for a total of 15 splits out of 4,310 total wards in the Commonwealth. In other words, in the GMS Plan, 99.7% of wards are kept intact.

¶ 53 By contrast, the House Plan splits 18 wards (3 more than in the GMS Plan), and the Governor's Plan splits 25 wards (10 more than in the GMS Plan).

V.C Compactness

V.C.1 Criteria and Metrics

¶ 54 Compactness is a measure of geographic or geometric regularity of a district or districting plan. The Supreme Court of Pennsylvania evaluated compactness in *League of Women Voters* in 2018, applying the compactness requirement of Pennsylvania's Constitution to congressional maps. The Court discussed the performance of the 2018 maps with respect to Reock, Schwartzberg,[7] Polsby–Popper, Population Polygon, and Minimum Convex Polygon (referred to in this report as the Convex Hull Ratio). In this report, I apply several of these measures of compactness, computed using Python libraries [geocompactness, gerrychain] in the epsg:4269 projection.[8]

¶ 55 Three commonly applied measures for evaluating compactness of individual districts based on area and perimeter are (1) Polsby-Popper, which measures a ratio of perimeter squared to area; (2) Reock, which measures the ratio of the district's area to that of the smallest possible bounding circle; and (3) the Convex Hull Ratio, which measures what proportion of the area of the smallest convex shape containing the district is filled by the district.

¶ 56 All three measures are scaled to values between 0 and 1, with higher values representing more compact plans. Each is also maximized by the circle (which would achieve a perfect score of 1), but the Polsby-Popper measure when applied

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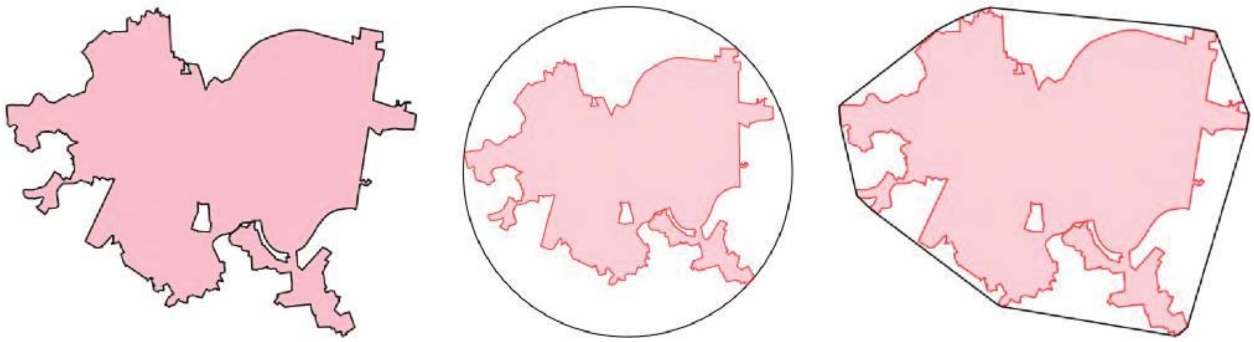
[7] This score can be derived as the reciprocal of the square root of the Polsby-Popper score and hence does not provide any additional information that is not already provided by the Polsby-Popper measure [Duchin and Tenner 2018].

[8] This is the projection that the data provided by the Pennsylvania LRC uses. Due to irregularities and overlaps in the block-level boundaries, I do not report on measures derived from reprojecting the data in my summary analysis. The fact that projections can change the values reported by compactness measures is well-known and is only one potential source of small deviations in geographic measurements [Bar-Natan–Najt–Schutzmann 2020, Solomon and Barnes 2021]. However, the relative performance of the GMS Plan, the House Plan, the Governor's Plan, and the 2018 Plan, as discussed below, does not change when projected to epsg:5070.

to districts tends to prefer plans with smooth-looking boundaries, the Reock measure tends to prefer those that are more circular in overall shape, and the Convex Hull Ratio prefers districts that do not contain significant indentations or tendrils. It is not possible to create a plan of all circular districts, since circles do not pack together efficiently to cover a territory like a state. Additionally, due to factors such as the external boundary of the state, coastlines or other complex and constraining features, and irregular boundaries of the underlying units used to create the map, among others, the average compactness value across the districts in a reasonable plan is not expected to be near to 1, even for plans designed to maximize performance on these compactness metrics.

¶ 57 While no single compactness measure can perfectly capture all facets of the regularity of a shape or the intuitive notion suggested by the reference to compactness in the Commonwealth's Constitution, each measure represents a different, potentially relevant portion of the full geometric information. So, taking these measures together provides a more comprehensive view of the district's shape than considering any one measure alone.

¶ 58 An example of this analysis is demonstrated below in Figure 5, showing the city boundary of Pittsburgh, together with its minimum bounding circle (shown in the center panel) and convex hull (shown in the right panel). In the left panel, we get a clear view of the many knobs and bumps on the city boundary. These knobs and bumps increase the city's perimeter without enclosing significant additional area. As a result, the city has a poor Polsby-Popper score. The tendrils in the city boundaries also cause the bounding circle shown in the central panel to extend significantly away from the main portion of the city, lowering its Reock score. The convex hull shown in the final panel is also impacted by the tendrils but to a lesser degree than the circle, since the convex hull can "hug" the outline of the figure. This means the city of Pittsburgh performs significantly better on the Convex Hull measure as compared to the Polsby-Popper and Reock measures.



(a) City Boundary (b) Bounding Circle (c) Convex Hull

Figure 5: Examples of compactness measures on Pittsburgh

¶ 59 In evaluating how the GMS Plan (and the other plans discussed in this report) perform on compactness, I consider the extent to which the ability to improve compactness is constrained by compliance with other redistricting criteria. For example, measures that depend on the district's perimeter, like Polsby-Popper, are determined by the properties of the discrete units. This means that a map built out of larger structures, like voting districts or municipal units instead of Census blocks, has less flexibility to tune the districts to be compact under these measures. Combining Figures 1 and 5, for example, we can see that there are some potential consequences for compactness in preserving the boundary of Pittsburgh. That is, following Pittsburgh's boundary to keep that city intact is likely to reduce the compactness measures for the districts that follow all or part of Pittsburgh's boundary. This type of tradeoff is common in a redistricting analysis, and the tension between competing metrics—in this case compactness and the preservation of meaningful political boundaries—is one of the difficult tasks faced by map makers. The need for such tradeoffs must be taken into account to properly analyze a map's performance across a set of metrics.

¶ 60 The Polsby-Popper, Reock, and Convex Hull compactness measures are defined for individual districts. So, the district-by-district scores have to be combined or averaged in some fashion to obtain a score for the entire redistricting plan. Below, I report the mean value on each compactness measure across the 17 districts of the GMS Plan, the House Plan, and the Governor's Plan, and the 18 districts of the 2018 Plan. Using the mean treats each district equally and allows one to assess the plan's overall level of compactness.

¶ 61 All compactness measures that rely on geographic length and area measurements suffer from some potential distortions due to map projections and other data issues [Bar-Natan–Najt–Schutzmann 2020, Solomon and Barnes 2021].

Accordingly, some mathematicians recently have proposed using discrete measures that are less sensitive to some of these geometric perturbations to support compactness claims in redistricting [Duchin and Tenner 2018]. A common choice for a discrete measure is the number of cut edges, which represents the count of the number of adjacent units like wards or blocks that are not placed in the same district. This can be viewed as measuring a discrete version of the perimeter of the plan, assessed not in miles but rather in the number of pairs of adjacent but separated units. To compute this value, a dual graph is constructed for the state, by selecting appropriate units and connecting each pair of units that share a common boundary. Then, the number of these connections or "edges" that must be "cut" or separated to disconnect the districts from each other is computed. In other words, the Cut Edges score reflects the plan's "scissors complexity." In this report, I evaluate the number of cut edges in the census-block-level dual graph. This is the only one of my four measures of compactness for which a lower number denotes a more compact plan.

V.C.2 Analysis

¶ 62 The GMS Plan scores better than the 2018 Plan on the mean Polsby-Popper measure, the mean Convex Hull measures, and the block-level Cut Edges measure, while it performs slightly lower than the 2018 Plan on the mean Reock measure.

¶ 63 The GMS plan outperforms the House Plan on all four compactness measures.

¶ 64 The GMS Plan achieves slightly lower compactness values than found in the Governor's Plan. Both the Governor's Plan and the GMS Plan use a number of municipal boundaries as district boundaries, so compactness scores for these two plans are partially determined by the geographic properties of those units. The competitive scores on these measures between the GMS Plan and the Governor's Plan highlight the balancing and tradeoffs among criteria that must take place during redistricting. As noted above, the GMS Plan does not split Pittsburgh, instead choosing to use a portion of Pittsburgh's irregular border as part of the border separating Districts 14 and 17. The Governor's Plan, by contrast, splits the city of Pittsburgh into two districts, and as shown in Figure 6, the district boundaries in this area for the most part do not follow Pittsburgh's irregular boundary. This difference affects the plans' compactness scores.

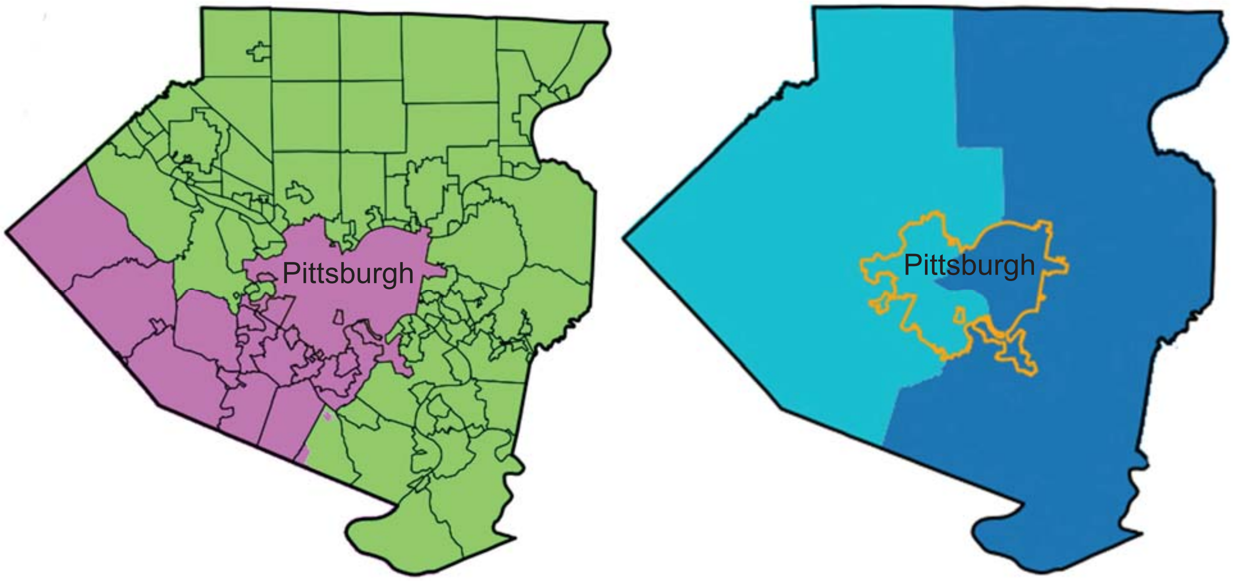


Figure 6: Allegheny County in the GMS Plan (on the left), keeping Pittsburgh intact and following its boundary for a portion of Districts 14 and 17, compared to Allegheny County in the Governor's Plan (on the right), splitting Pittsburgh into Districts 16 and 17

¶ 65 Table 4 summarizes the results of my assessment of the four compactness measures among the three proposed plans (the GMS Plan, the House Plan, and the Governor's Plan), with the additional comparator of the 2018 Plan.[9] In Appendix C, I include a table listing the compactness scores for each of the 17 districts in the GMS Plan individually.

Compactness Measure	GMS	House	Governor	2018
Mean Polsby-Popper *(higher is more compact)*	.333	.310	.366	.323
Mean Reock *(higher is more compact)*	.395	.383	.401	.428
Mean Convex Hull *(higher is more compact)*	.799	.779	.809	.791
Cut Edges *(lower is more compact)*	5,546	5,882	5,154	5,789

Table 4: Compactness Metrics for the Proposed Plans and the 2018 Plan

[9] The plans have different numbers of districts, so for the mean Polsby-Popper, Reock, and Convex Hull Ratio scores, I am taking the mean of 17 values for the GMS Plan, House Plan, and Governor's Plan, and 18 values for the 2018 Plan.

V.D Contiguity

¶ 66 Contiguity is the principle that districts should be connected, usually in the sense that they could be traversed from point to point without needing to leave the district. To evaluate the GMS Plan, the House Plan, the Governor's Plan, and the 2018 Plan, I apply the definition of contiguity that requires a path that both connects each pair of census blocks in a district and consists of only adjacent blocks belonging to that same district. All plans I considered satisfy this binary requirement.

V.E Partisan Fairness

V.E.1 Criterion

¶ 67 The Free and Equal Elections Clause of the Pennsylvania Constitution prohibits partisan gerrymandering in congressional redistricting plans. *League of Women Voters*, 178 A.3d at 816, 818. The Supreme Court has recognized that statistical measures can be used to help identify plans that have been drawn to achieve unfairly partisan aims. *Id.* at 820. Among the measures presented to the Court in *League of Women Voters* were the mean-median score and the efficiency gap. In this report, I evaluate the partisan performance of the GMS Plan using those and other standard metrics.

V.E.2 Elections Data

¶ 68 For each of my partisan-fairness metrics, I have used election results from 18 statewide general elections that took place in the Commonwealth between 2012 to 2020. This represents the general elections races for U.S. President, U.S. Senate, Governor, Attorney General, Auditor General, and State Treasurer. This dataset includes examples of elections where each of the major political parties' candidates won the overall statewide vote. Many of these races were decided by small margins, particularly those in which a Republican candidate won the overall election. Thus, I also included the 2017 Supreme Court Justice election in my analysis, as that election had a larger margin of victory for the Republican candidate than the other elections had. Looking at this breadth of election results helps us better understand and model the political geography of a state and related realistic vote outcomes.

¶ 69 The election data I used is summarized in Table 5 below. As the elections under discussion are general elections, the percentages reported reflect the two-party vote share from the two most successful candidates, which in these elections were always the Democratic and Republican candidates.

¶ 70 Each of the partisan-fairness metrics that I analyze below requires one first to determine, for each of the 18 general elections, which candidate, the Democrat or Republican, carried each of the districts in each redistricting plan at issue. To do that, I simply add up the votes cast for each candidate in each VTD, or precinct, that is located within each district. For the relatively few VTDs that are split by district lines, I prorate the VTD's vote totals onto the corresponding census blocks and then aggregate back up to the full district. Once I have the vote totals for each candidate, in each district, in each plan, it is easy to see which candidate carried each district—the Democrat or the Republican. The percentage of major-party votes cast statewide that were cast for the Democratic candidate is known as the Democratic "vote share." And the number of districts in any given plan that were carried by the Democratic candidate is known as the Democratic "seat share." These values, for each of the 18 general elections, are then used to plot a seats-votes curve, and they also become inputs for the partisan-symmetry computations described below.

¶ 71 The election summary data in Table 5 shows that Pennsylvania has been a competitive state in statewide general elections in the past decade, particularly in the more recent years, with many of the elections since 2016 having vote margins of less than 5%. The "purpleness" of Pennsylvania elections is also reflected in the current 9-9 partisan makeup of its Congressional delegation and the fact that it is currently represented in the U.S. Senate by one member of each party.

Office	Year	Winner	Winning Margin
U.S. President	2012	D	5.5
U.S. Senate	2012	D	9.2
Attorney General	2012	D	14.9
Auditor General	2012	D	3.4
State Treasurer	2012	D	8.8
Governor	2014	D	9.9
U.S. President	2016	R	0.8
U.S. Senate	2016	R	1.5
Attorney General	2016	D	2.8
Auditor General	2016	D	5.2
State Treasurer	2016	D	6.8
Supreme Court Justice	2017	R	4.6
Governor	2018	D	17.3
U.S. Senate	2018	D	13.3
U.S. President	2020	D	1.1
Attorney General	2020	D	4.6
Auditor General	2020	R	3.2
State Treasurer	2020	R	0.8

Table 5: Statewide elections considered for partisan-fairness analysis

V.E.3 Metrics

¶ 72 Similar to the way in which using several compactness measures collectively provides more information about a map's level of compactness than singling out any one metric, I believe it is helpful to consider several metrics of partisan fairness. Together, the metrics provide a more comprehensive picture than any single measure alone, of how the proposed redistricting plan treats voters of both political parties. This is also why it is important to use a broad collection of underlying election results to evaluate each plan.

Majority Responsiveness

¶ 73 The first partisan-fairness metric that I analyze is a simple measure of direct majority responsiveness, computing for a given election whether the party that won statewide also would have won carried a majority of districts in the proposed redistricting plan. While there is a large literature describing metrics related to partisan behavior and fairness, the principle that winning a majority of the vote should allow a party to win a majority of the districts—without making any stronger claims about the relationship between the percentages of votes and seats—is a common feature of this type of analysis.

¶ 74 Under the majority responsiveness measure, a map that symmetrically allows either party a solid chance to convert a majority vote share into a majority seat share appears fairer than a map that makes it much harder for one party than the other to do so. The existence of close general elections won by both parties in the 18-election dataset makes it possible to more reliably evaluate this type of behavior within a proposed redistricting plan.

¶ 75 Pennsylvania will now have an odd number of congressional districts, so one party must win a majority of the seats, as a tie between the two major political parties is not possible with an odd number of districts. Hence, the majority responsiveness metric is binary for each election evaluated: The party whose candidate won a majority of the votes either did or did not carry the majority of districts (seats) in the proposed plan. Thus, I also consider extensions and refinements of this measure next.

¶ 76 Across the 18 elections, and for each proposed plan, I also track the number of times each party had the larger statewide vote share but failed to carry most of the seats. This metric provides one way to compare how similarly a given redistricting plan treats voters aligned with each political party. For example, a proposed redistricting plan could yield lopsided results, in which only one party repeatedly fails to translate a majority vote share into a majority seat share. That lopsidedness would suggest that the proposed redistricting plan is not treating voters from both political parties evenhandedly. Conversely, the instances in which the party that wins the votes does not also carry most districts could be split evenly or relatively evenly between the two parties—a much more evenhanded outcome.

"Safe" Districts

¶ 77 For my second metric of partisan fairness, I report the number of districts that preferred at least one candidate from each party over the full set of 18 general elections, compared to the number of districts that voted for candidates from only one party. The former could be considered "responsive" districts, while the latter could be considered "safe," or unresponsive, districts. As with the previous majority-responsiveness measure, we might expect a plan that has similar numbers of "safe" districts for each of the two major parties to be more balanced than one that has significantly more safe districts favoring one party over the other. However, this metric is also heavily influenced by the political geography of and distribution of voters throughout the state, so it is especially important not to consider this metric, standing alone, to evaluate partisan fairness.

Mean-Median Score

¶ 78 My third metric is the mean-median score. The mean-median score is a metric related to partisan symmetry.[10] In simple terms, a plan that exhibits partisan symmetry is one that is likely to treat the parties similarly in terms of seat outcomes given equal votes received by all candidates statewide. That is, if Party *A* is expected to turn a 55%-to-45% statewide vote advantage into a 10-to-7 seats advantage, then a symmetric result would require Party *B* to turn a similar 55%-to-45% statewide vote advantage into a 10-to-7 seats advantage.

¶ 79 To calculate the mean-median score, I start by computing the percentage of major-party votes cast in each district that were garnered by the Democratic statewide candidate and compute the median of this collection. Then, I subtract the statewide voteshare, representing the average or mean vote percentage for the election, from the median. This differs slightly from the definition of mean-median score described by the experts in *League of Women Voters*, which used the mean of the individual district vote percentages. The version applied here has the advantage of comparing each plan to the same baseline, without being impacted by different turnout rates across the districts. In this formulation, negative values correspond to Republican-favoring plans and positive values correspond to Democratic-favoring plans (but this designation of course has no impact on the substantive conclusions).[11] Intuitively, the mean-median score is the amount by which the Democratic share of the major-party vote would diverge from 50% when Democrats are expected to win, on average, half the districts in the proposed redistricting plan. Thus, values closer to zero on this metric (whether positive or negative) are considered more symmetrical and evenhanded because in an "ideal" plan, neither party could consistently win a majority of the seats with less than 50% of the major-party vote.

Efficiency Gap

¶ 80 My final partisan-fairness metric is the efficiency gap, which is designed to measure the relative quantities of "wasted votes" cast for each party. A vote is

[10] The mean-median score is only one of many ways to measure partisan symmetry, the concept of which is treated in detail in [Katz, King, and Rosenblatt 2020].

[11] The choice of sign simply follows from computing Democratic rather than Republican vote shares. More algebraic descriptions of the metrics described in this section can be found in Section 3.1.3 of [DeFord and Duchin 2019 and DeFord et al. 2020]

considered "wasted" by this measure if it was a vote for the losing candidate in a district, or a vote for the district's winning candidate beyond the number of votes needed to win that district (that is, beyond a bare majority of the two-party vote). The thinking is that the most efficient distribution of votes is to carry as many districts as possible by as narrow a margin as possible, while having the opposing party win its districts by large majorities.

V.E.4 Analysis

¶ 81 In this section, I report on the performance of the GMS Plan, the House Plan, and the Governor's Plan under my five partisan fairness metrics, using vote totals from 18 statewide general elections occurring between 2012 and 2020.

Majority Responsiveness

¶ 82 Using the vote totals from these 18 elections, my analysis shows that the party whose candidate won in 15 of the 18 elections would have carried most of the GMS Plan's districts.

¶ 83 The three elections that did not have this property in the GMS Plan split as evenly as possible, as two elections (for State Auditor in 2012 and in 2016) saw the Democratic candidate win statewide but carry fewer than half the districts, and one election (for U.S. Senator in 2016) saw the Republican candidate win statewide but carry fewer than half the districts.

¶ 84 The majority responsiveness metric thus shows that, in the GMS Plan, both parties can convert small vote-share majorities into seat majorities. The fact that in over 80% of these elections (15 of 18), the party that had the larger vote share also received the larger seat share, combined with the fact that the deviations from this majority responsiveness principle were split between the two parties, suggests that the GMS Plan both allows for effective majority representation and treats voters from both parties roughly equally.

¶ 85 By contrast, the House Plan, put forward by Republicans, faithfully converted popular majorities in only 13 of the 18 elections, and all five of the failures to convert were elections in which the Democratic candidate prevailed statewide but failed to carry most of the districts. In other words, Republican voters were the beneficiary in all the instances in the House Plan in which the winning party failed to convert its success into seats.

¶ 86 The Governor's plan converted majorities in 14 of the 18 elections, and the four that are not converted are split evenly between the parties.

¶ 87 My analysis of the majority-responsiveness metric for the GMS Plan, the House Plan, and the Governor's Plan, along with the 2018 Plan as additional information, is summarized in Tables 6 and 7. In Table 6, the elections with antimajoritarian outcomes in the three proposed plans are shaded in either red (denoting outcomes favoring Republicans) or blue (favoring Democrats).

Election		Winner	Democratic Vote Share	Share of Democratic Seats			
Office	**Year**			**GMS (seats/17)**	**House (seats/17)**	**Governor (seats/17)**	**2018 (seats/18)**
U.S. President	2012	D	52.7%	58.8% (10)	52.9% (9)	58.8% (10)	50% (9)
U.S. Senator	2012	D	54.6%	58.8% (10)	52.9% (9)	58.8% (10)	55.6% (10)
Attorney General	2012	D	57.5%	70.5% (12)	76.5% (13)	70.5% (12)	66.7% (12)
Auditor General	2012	D	51.7%	**41.2% (7)**	**35.3% (6)**	**47.1% (8)**	38.9% (7)
State Treasurer	2012	D	54.4%	58.8% (10)	47.1% **(8)**	58.8% (10)	55.6% (10)
Governor	2014	D	54.9%	58.8% (10)	52.9% (9)	58.8% (10)	55.6% (10)
U.S. President	2016	R	49.6%	47.1% (8)	41.2% (7)	**52.9% (9)**	44.4% (8)
U.S. Senator	2016	R	49.3%	**52.9% (9)**	29.4% (5)	35.3% (6)	27.8% (5)
Attorney General	2016	D	51.4%	58.8% (10)	**41.2% (7)**	58.8% (10)	55.6% (10)
Auditor General	2016	D	52.6%	**47.1% (8)**	**41.2% (7)**	**47.1% (8)**	50% (9)
State Treasurer	2016	D	53.4%	58.8% (10)	58.8% (10)	58.8% (10)	55.6% (10)
Supreme Court Justice	2017	R	47.7%	41.2% (7)	35.3% (6)	35.3% (6)	33.3% (6)
Governor	2018	D	58.7%	64.7% (11)	58.8% (10)	64.7% (11)	66.7% (12)
U.S. Senator	2018	D	56.7%	58.8% (10)	58.8% (10)	64.7% (11)	61.1% (11)
U.S. President	2020	D	50.6%	52.9% (9)	**47.1% (8)**	52.9% (9)	50% (9)
Attorney General	2020	D	52.3%	58.8% (10)	58.8% (10)	58.8% (10)	55.6% (10)
Auditor General	2020	R	48.4%	47.1% (8)	29.4% (5)	47.1% (8)	38.9% (7)
State Treasurer	2020	R	49.6%	47.1% (8)	41.2% (7)	**52.9% (9)**	50% (9)

Table 6: Majority-responsiveness metric across the proposed plans.
For the 2018 Plan, 9-9 ties are counted as majoritarian outcomes.

	GMS	House	Governor	2018
Democrat-Favoring Outcome	1	0	2	0
Republican-Favoring Outcome	2	5	2	1
Total	**3**	**5**	**4**	**1**

Table 7: Number of elections, by political party, where the redistricting plan did not convert a majority of the votes into a majority of the seats (districts)

¶ 88 Figure 7 shows that the symmetric performance of the GMS Plan is also clear from the seats-votes points corresponding to the 18 statewide general elections analyzed in this report. The horizontal axis is the percentage of major-party votes won by the Democratic candidate statewide, and the vertical axis is the percentage of districts carried by that same candidate. Each dot corresponds to one of the 18 elections. The yellow line marks the values where y = x, which would correspond to strict proportionality, while the black line is a linear regression on the (seats, votes) pairs for the GMS plan, which has a slope of 2.05, or approximately the slope that would correspond to ideal performance on the efficiency gap metric. The points colored blue (Democrat) and red (Republican) correspond to the elections where the party that won the majority of the votes also won the majority of the seats, while the three points marked in gray reflect the three elections where this did not occur (the 2012 and 2016 Auditor races and the 2016 U.S. Senator race) as discussed above.

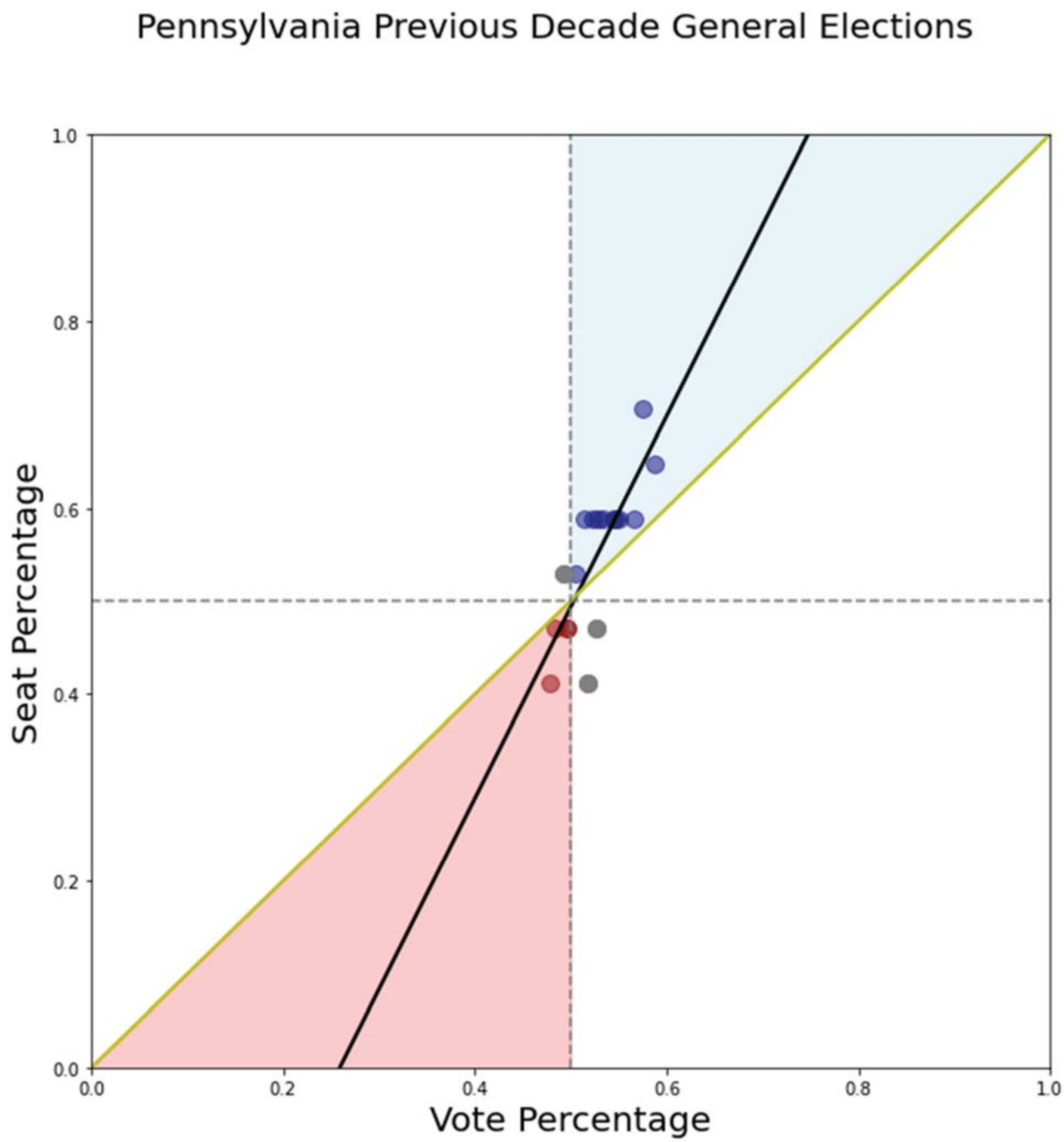


Figure 7: Seats-Votes Curve for the GMS Plan for the 18 statewide elections

¶ 89 The portions of Figure 7's plot that have colored backgrounds highlight the regions of the plot where each party converted a majority of votes to a majority of seats with at least proportional representation. That is, points that fall within these regions represent elections in which the winning candidate received a seat share that was at least as large as its vote share (and hence by definition converted a majority of votes into a majority of seats). Beyond achieving a majority, it is common to expect a "winner's bonus" leading to more seats than strict proportionality, although the specific coefficient or functional form of the bonus varies between models. All the elections that convert majorities also outperform the corresponding vote share in the GMS Plan. Additionally, applying the linear model shows that the regression line nearly intersects the (.50,.50) point, which provides additional support for the claim that the GMS Plan allows both parties to convert even small voting majorities into representative majorities.

"Safe" Districts

¶ 90 The GMS Plan's symmetrical treatment of voters of both parties as revealed by the majority responsiveness metric is bolstered by the results on my second metric, involving district responsiveness.

¶ 91 Across the 18 statewide elections I analyzed, there were ten districts total in the GMS Plan that voted for candidates from the same party in each election, five that favored Republicans and five that favored Democrats. These would be considered "safe" districts.

¶ 92 For each of the other seven districts in the GMS Plan, each party won at least one election. That suggests that those districts have the potential to be responsive to preferences in actual elections—that is, they are "responsive." This provides additional evidence that the GMS Plan treats voters of both political parties equally.

¶ 93 The results of my assessment of district responsiveness in the three proposed plans are summarized in Table 8, along with the results in the 2018 Plan as additional information:

	GMS	**House**	**Governor**	**2018**
Safe R	5	4	4	5
Safe D	5	4	6	5
At least one each	7	9	7	8

Table 8: Potentially Responsive Districts in the Proposed Plans and the 2018 Plan

Partisan Symmetry; Mean-Median and Efficiency-Gap Measures

¶ 94 I conclude this section by reporting on the performance of the GMS Plan under the mean-median and efficiency-gap measures.

¶ 95 Figures 8 and 9 below show the values for the mean-median score and efficiency gap measure for each election on each plan. The points are colored red for values that favor Republican voters and blue for values the favor Democratic voters and the vertical purple line marks the "ideal" zero value. As discussed above, plans that perform well on these metrics will have the majority of their values near zero and will have some elections that favor each party (so, some red dots and some blue dots, with few, if any, located far from the purple line).

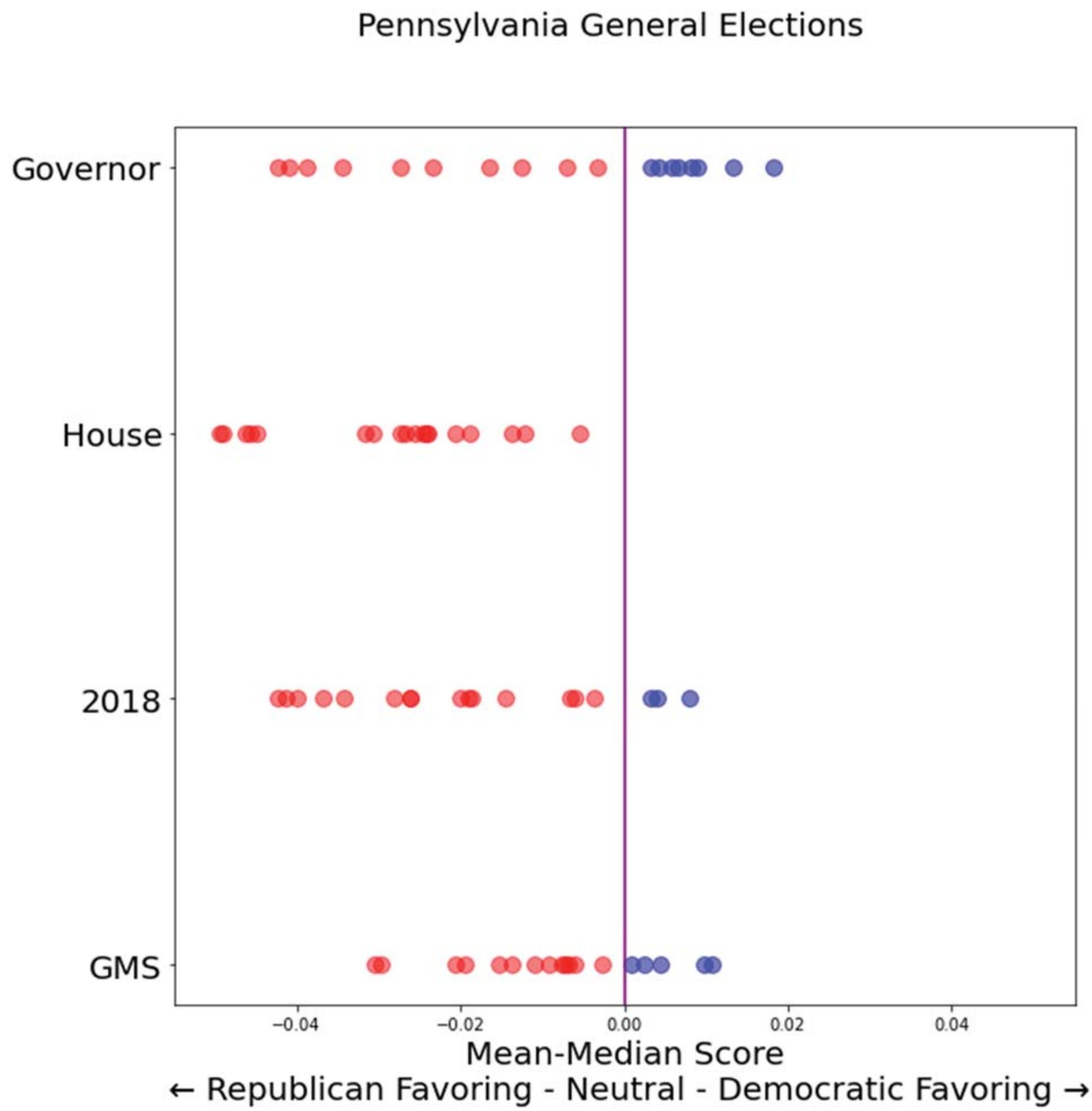


Figure 8: Mean-Median Score in the Proposed Plans and in the 2018 Plan

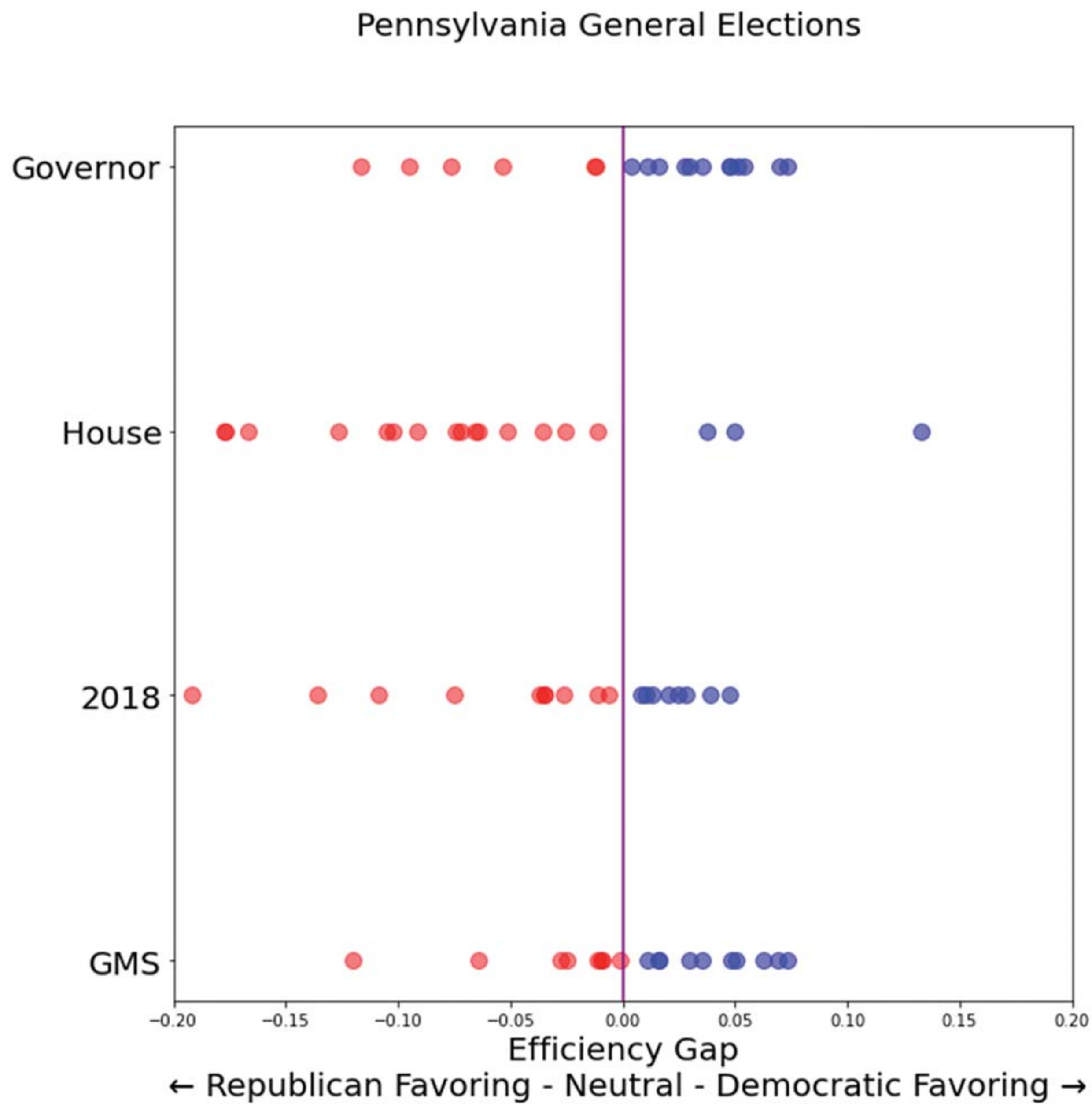


Figure 9: Efficiency Gap in the Proposed Plans and in the 2018 Plan

¶ 96 These figures show that the GMS Plan performs very well compared to all comparator plans on the mean-median measure, and both the GMS Plan and the Governor's Plan perform well on the efficiency gap measure.

¶ 97 Also important is the fact that in both measures, the GMS Plan has multiple elections that favor each party. The collection of values observed in the GMS Plan are clustered near the ideal value of zero and, depending on the election, slightly favor one party or the other but not the same party consistently. On the mean-median score, we see that there are 13 elections favoring Republican voters, with the remaining 5 favoring Democratic voters. The most Republican favoring value is 3%, and the most Democratic favoring value is 1.1%, for an overall range of 4.1%.

¶ 98 For comparison, in the House Plan ***all*** elections have a mean-median score favoring Republicans, with a maximum value of 4.9%.

¶ 99 The Governor's Plan has 10 Republican favoring and 8 Democratic favoring values but a much wider range of values than in the GMS Plan. The Governor's Plan has more extreme scores of 4.2% and 1.8% for the parties—both of which are larger than the corresponding values for the GMS Plan—and a corresponding range of 6.1%, which is significantly larger than the range of the GMS Plan.

¶ 100 My conclusions on the mean-median and efficiency-gap scores are summarized in Tables 9 and 10. In these tables, I report the number of elections for each plan that return values favoring each party, as well as the range, or the gap from the most Republican voter-favoring value to the most Democratic voter-favoring value. As discussed above, I expect plans that treat voters from each party equally to have most of their values close to zero and also to have similar numbers of elections favoring each party. The second criterion is less critical than the first given the slight Republican-favoring tilt to the political geography. Thus, in addition to having values closer to zero having a smaller overall range is a sign of a good plan.

	GMS	**House**	**Governor**	**2018**
Favoring Republicans	13	18	10	15
Favoring Democrats	5	0	8	3
Min. Score	-0.030	-0.049	-0.042	-0.042
Max. Score	0.011	-0.005	0.018	0.008
Range	0.041	0.044	0.061	0.050

Table 9: Mean-Median Scores in the Proposed Plans and in the 2018 Plan

	GMS	House	Governor	2018
Favoring Republicans	8	15	6	10
Favoring Democrats	10	3	12	8
Min. Score	-0.120	-0.177	-0.116	-0.192
Max. Score	0.074	0.133	0.073	0.047
Range	0.194	0.310	0.189	0.239

Table 10: Efficiency-Gap Scores in the Proposed Plans and in the 2018 Plan

¶ 101 The GMS Plan also performs well when I focus on the most recent statewide elections. Figures 10 and 11 show the mean-median and efficiency-gap scores, averaged across three sets of six elections (2012-2014, 2016-2017, and 2018-2020), with the bars colored according to the corresponding plan (red for the House Plan, brown for the Governor's Plan, yellow for the 2018 Plan, and green for the GMS Plan). In the mean-median scores in particular, we can see that as the elections become more recent, the values for the GMS Plan get closer to zero—reflecting a higher degree of partisan fairness. As these more recent elections are more likely to be reflective of the current political geography, this is another piece of good evidence for the strong performance of the GMS Plan under these metrics.

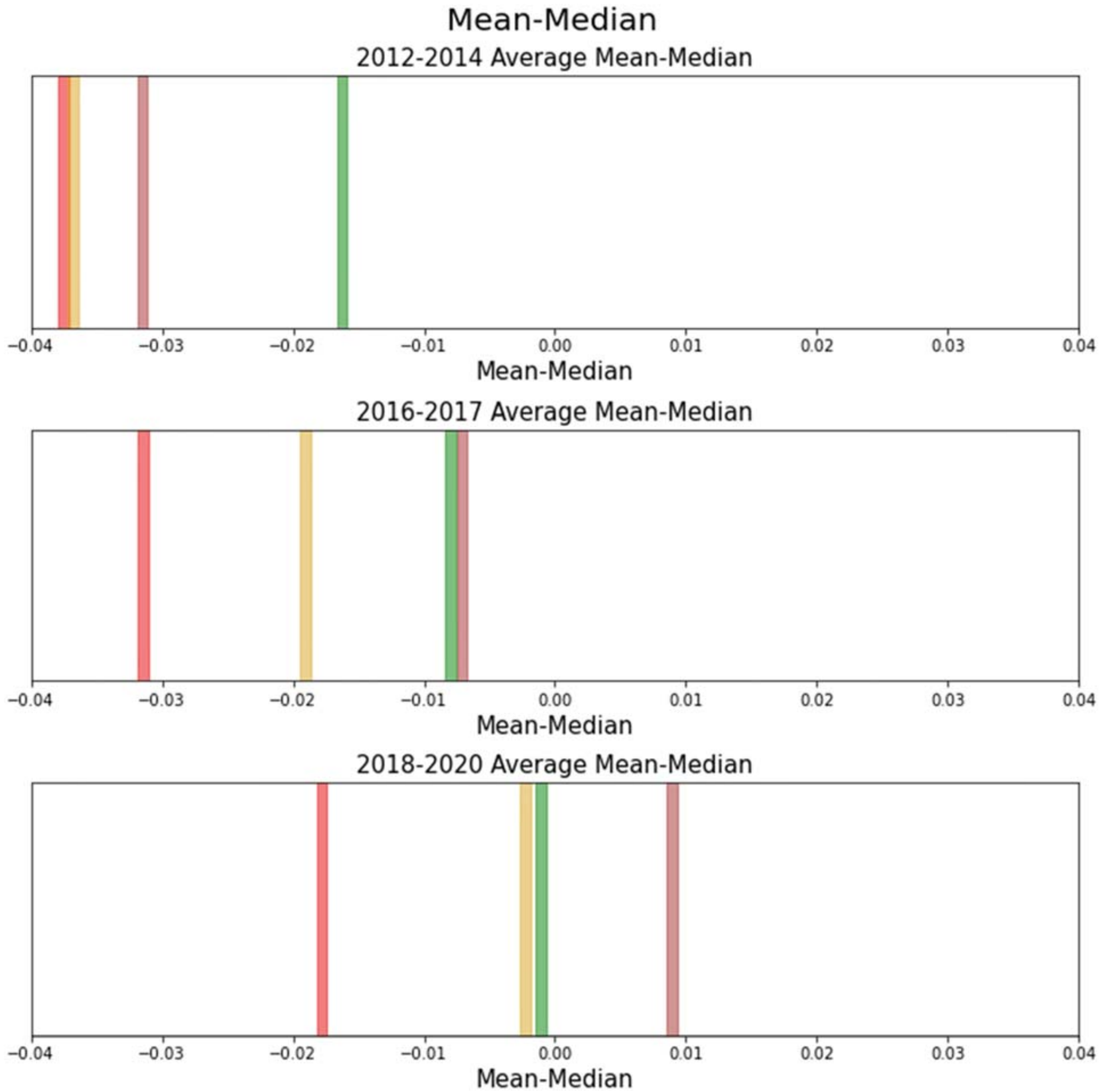


Figure 10: Mean-Median Scores for the House Plan (red),
the Governor's Plan (brown), the 2018 Plan (yellow), and the GMS Plan (green),
averaged for each two-year period between 2012 and 2020

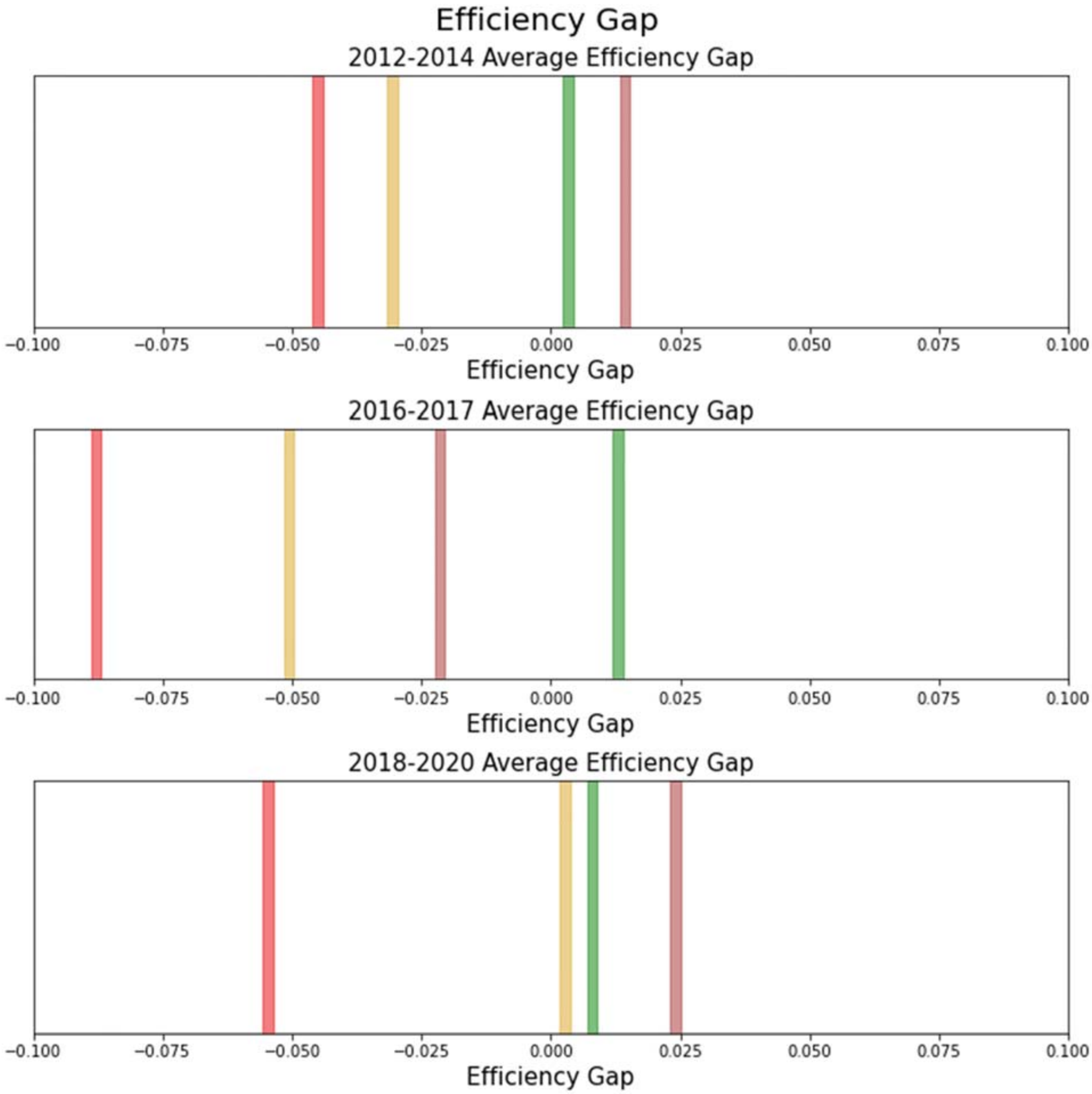


Figure 11: Efficiency-Gap Scores for the House Plan (red),
the Governor's Plan (brown), the 2018 Plan (yellow), and the GMS Plan (green),
averaged for each two-year period between 2012 and 2020

¶ 102 Finally, in Figures 12 and 13, I report on the analyzed plans' mean-median and efficiency-gap scores, averaged across all 18 elections.

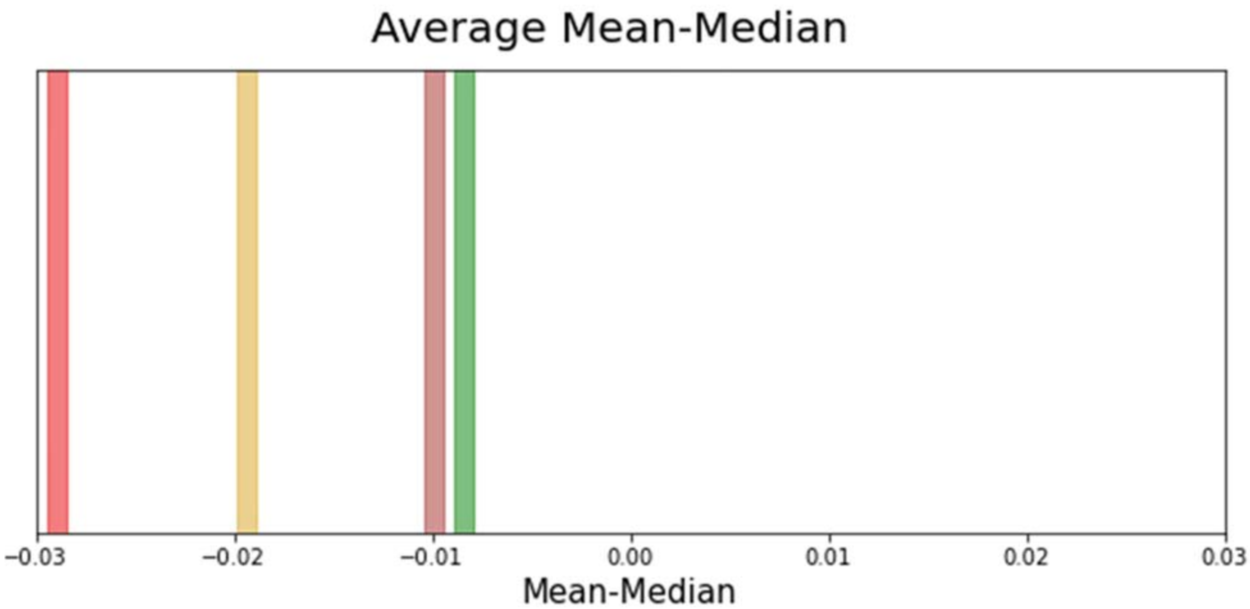


Figure 12: Average Mean-Median Scores for the House Plan (red),
the Governor's Plan (brown), the 2018 Plan (yellow), and the GMS Plan (green)

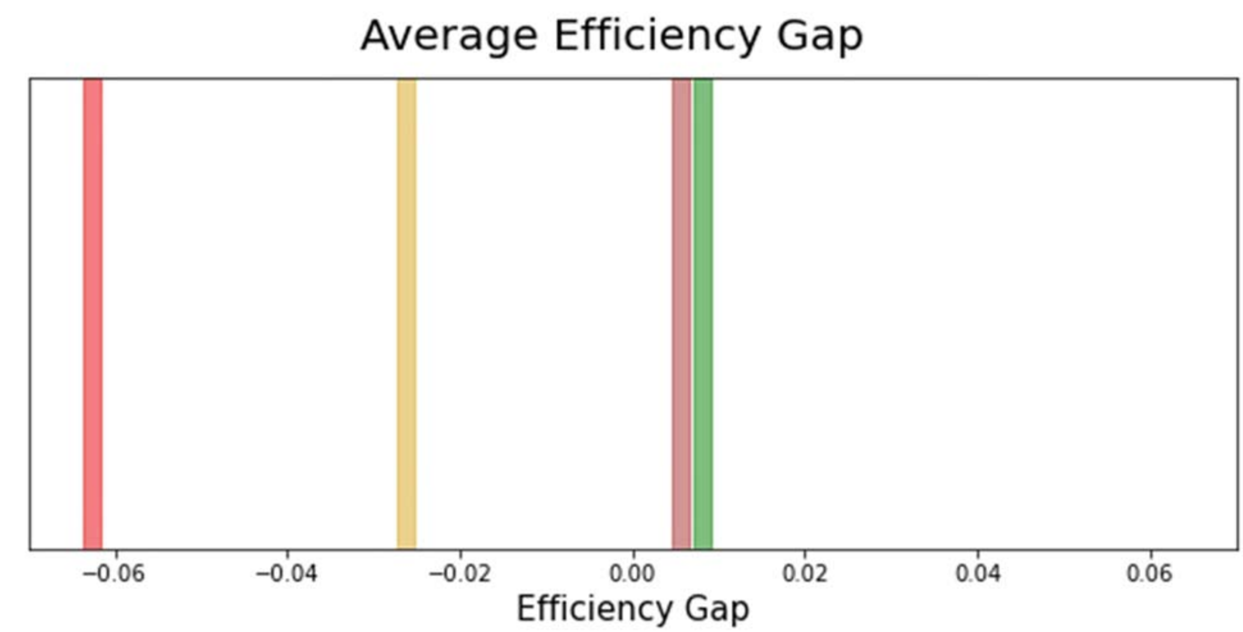


Figure 13: Average Efficiency-Gap Scores for the House Plan (red),
the Governor's Plan (brown), the 2018 Plan (yellow), and the GMS Plan (green)

¶ 103 Overall, the mean-median and efficiency-gap scores for the GMS Plan show a slight lean toward Republican-favoring values, but the absolute sizes of the metrics are small, and for each measure there are some elections that obtain Democratic-favoring scores. Both these observations are good signs, as a plan with many large values on these two metrics, or one where all the scores leaned to a particular political party, would be potential evidence of partisan unfairness. That is what we see in the House Plan; the maximum value is large (4.9%), and the scores all favor Republican voters. Although the Governor's Plan has scores that favor Republican voters and scores that favor Democratic voters, its overall range is larger than the GMS Plan, suggesting that its performance on some individual elections is more asymmetric in the treatment of voters from both parties. The GMS Plan thus outperforms both the House Plan and the Governor's Plan on these metrics.

¶ 104 Further, at least one expert in the *League of Women Voters* case identified a partisan advantage to Republicans based on the political geography of the state. So, it is not necessarily a surprise to see a slight tilt favoring Republicans on these two metrics, when evaluated across a variety of elections. Indeed, the observation by the expert in *League of Women Voters* is consistent with my own assessment of the way in which the state's political geography relates to partisan fairness. The state's political geography requires districts satisfying the legal criteria—that is, compact, contiguous, population-balanced districts that follow political-subdivision boundaries—to necessarily include a large number of Democratic voters who are grouped together in the Philadelphia and Pittsburgh areas. For example, there were over 1,000 voting districts that supported the Democratic candidate in the 2020 presidential election by 90% or more, mostly in the Philadelphia and Pittsburgh areas. By contrast, there were fewer than 50 voting districts in the Commonwealth that had a similar level of support for the Republican candidate, meaning that there is not a part of the state where Republican voters are as heavily concentrated as Democratic voters are in the Philadelphia and Pittsburgh areas. Nonetheless, the GMS Plan still manages to treat both parties evenhandedly across a wide range of election outcomes. That makes the overall partisan-fairness performance of the GMS Plan particularly impressive.

V.F Compliance with the Voting Rights Act

V.F.1 Criterion

¶ 105 The Voting Rights Act of 1965 (VRA) imposes an additional federal requirement on redistricting plans, requiring in Section 2 that lines cannot be drawn to deny racial, ethnic, or language minority voters an equal opportunity to "to participate in the political process and to elect representatives of their choice." Discussion around this constraint frequently focuses on the construction and existence of "opportunity districts" that allow groups the ability to nominate and elect candidates of their choice. Compliance with the Supreme Court precedent also requires that lines not be drawn with race as the predominant factor, but I understand that analysis of opportunity districts focuses not on intent, but rather on results for minority voters. This means that districts that were previously well-tuned to satisfy VRA concerns could fail to perform effectively for minority voters in the next redistricting cycle due to shifts in population or voting preferences between groups.

¶ 106 I have been instructed that litigation over VRA violations centers on three *Gingles* factors, originally derived from the Supreme Court's 1986 ruling in *Thornburg v. Gingles* and further extended through a significant body of case law. These factors require a demonstration that:

1. it is possible to create an additional, reasonably compact majority-minority district,

2. members of the minority group vote cohesively for the same candidates, and

3. nonminority voters typically oppose those minority-preferred candidates and thus can usually defeat them in districts with insufficient minority populations.

¶ 107 The combined existence of the conditions described in the final two criteria is known as racially polarized voting and requires the application of statistical inference to determine likely voting behaviors by group. The techniques commonly used for this analysis are known as ecological regression and ecological inference, or EI. These techniques attempt to estimate the voting propensities for different demographic groups by analyzing precinct- or ward-level returns, together with demographic information about the precincts or wards. The methodology used to estimate these quantities for this report is described in Section V.F.2 below.

¶ 108 While the *Gingles* factors are used in court to analyze whether an enacted map violates Section 2 of the VRA, I understand that VRA analysis at the district-drawing stage does not necessarily require the construction of districts that meet certain thresholds of minority population as in *Gingles*. Instead, there is a focus on whether specific districts are likely to offer an effective opportunity for minority groups to nominate and elect their preferred candidates, using historical election data and the same types of statistical methods used for evaluating vote polarization between groups.

¶ 109 In the 2018 map in Pennsylvania, much of the VRA focus has been on the Third District, centered in Philadelphia. The current Third District has a Black Citizen Voting Age Population (BCVAP) of over 50%. In this report, I analyze the voting results for this district, as well as the proposed Districts 2, 3, and 5 in the GMS Plan, all of which have sizable minority populations, to determine whether each is an effective district for minority voters. I also make comparisons between districts in the 2018 Plan and in the House and Governor's Plans that contain some portion of Philadelphia.

¶ 110 Based on this analysis, in this report I consider a district as "effective" for Black voters if it satisfies the following conditions:

- A significant proportion of the citizen voting age population (CVAP) is Black,
- with respect to historical voting data, the district would have favored the Black-preferred candidate in general elections, and
- in the primary elections for the party that usually wins the general elections, the district would have favored the Black-preferred candidate.

In considering District 2 in the GMS Plan, where the Latino percentage is larger than the Black percentage for both VAP (voting-age population) and CVAP, I also analyze the performance of candidates preferred by Latino voters.

¶ 111 Note that with respect to the first criterion, a district may be considered effective for a particular group even if it that group does not constitute a majority of the district's voting-age population. The GMS Plan does, however, include three districts in the Philadelphia area in which minority group members constitute a majority of the voting-age population—that is, these districts are "majority-minority districts." Given that minority group members constitute almost 20% of Pennsylvania's citizen voting-age population and that Pennsylvania will now have 17 districts, a total of three minority-effective districts would be roughly proportional. Having only two minority-effective districts would be significantly sub-proportional and thus could be dilutive of minority voting strength.

V.F.2 Methodology

¶ 112 Two analytical tasks were performed for my VRA analysis in this report. The first was to determine the preferred candidate of Black and Latino voters in each election contest. This analysis relied on information on the racial and ethnic demographics of the election districts (here, they were defined as Census Voter Tabulation Districts or VTDs), as well as information on the votes cast for each candidate in each VTD. The demographics used here are the Citizen Voting-Age Population (CVAP) for Blacks, Latinos, Whites who are not Latino, and all others, as reported by the Census Bureau in the redistricting summary file of the American Community Survey (ACS). The ACS CVAP data is reported in five-year summary files released each year, and the five-year file with the center year closest to the relevant election year was utilized here.

¶ 113 For example, the most recent ACS CVAP redistricting file available from Census is the five-year 2015-2019 file that is centered on 2017. That demographic data was used for the most recent election years, including 2017 and forward. For the 2016 elections, the previous five-year ACS CVAP 2014-2018 file, centered on 2016, was employed, and similar adjustments were made going back to earlier years.

¶ 114 This demographic data at the VTD level, along with votes cast for each candidate at the VTD level, were the inputs into an Ecological Inference (EI) statistical analysis (specifically the RxC EI technique labeled as MD-Bayes in the current version of the 'R' programing EI module labeled EiPack).

¶ 115 This analysis was performed for the statewide primary and general elections utilizing the more than 2,500 VTDs in the five-county area (Philadelphia, Bucks, Chester, Delaware, and Montgomery Counties) that encompasses all the geography of all the proposed Philadelphia-area Congressional districts in all the redistricting plans, existing and proposed, that are analyzed here. This analysis provides the proportion reported in each of the tables below under the heading "EI Estimates" for the estimated proportion of Black and Latino (or Hispanic) voters supporting each of the candidates in each election contest across the five-county Philadelphia area. A small number of VTDs, typically fewer than three (or 1/10th of one percent), were dropped from the analysis because the precinct either had no votes, no CVAP, or had more recorded votes than CVAP in the district. For the Philadelphia primaries used in Table 12 for District 3, this same sort of RxC EI analysis was repeated for only the Philadelphia VTDs (more than 1,600 VTDs).

¶ 116 The second analytical task for the results reported in Tables 11-14 was to compile reconstituted election results (using election results provided by counsel) for each contest within the geography of each of the three most heavily minority districts in each of the plans. This reconstitution was conducted by summing the votes cast for each candidate in each contest in each whole VTD contained within each district in each plan. In addition, there were a small number of VTDs that were split in each plan, and the votes in those split VTDs were allocated to the two districts involved in the split according to the proportion of the Voting Age Population (VAP) assigned to each district in each split VTD. The VTD-level votes cast for each candidate in each contest were then simply summed up to the district level to provide the vote proportion that each candidate would have received if the election were totaled up within that single district, rather than statewide.

V.F.3 Analysis

¶ 117 Evaluating the performance of the GMS Plan according to the effectiveness criteria shows that the three majority-minority districts (Districts 2, 3, and 5) each perform very well. In Districts 2, 3, and 5 in the GMS Plan, minority-group members constitute 52%, 57%, and 51% of the voting-age population, or VAP, respectively. I consider each of the districts in turn, together with the comparable district in the current plan, and conclude that all three majority-minority districts in the GMS Plan consistently vote, in both Democratic primaries and general elections, for the same minority-preferred candidates who prevail in the most heavily minority district in the 2018 Map (current District 3)

Congressional District 3

¶ 118 Current District 3 is a Black opportunity district (in much the same territory as District 2 prior to the court ordered redrawing of the congressional plan in 2018) that has been represented by a Black Representative who is also the candidate of choice of Black voters. The district has a 2020 Census Voting Age Population (VAP) that is 49% Black, and a 2015-2019 estimated CVAP that is 56% Black. In its current configuration, the district is overwhelmingly Democratic in the general election. In 2020, Dwight Evans won the district with 91% of the vote over Michael Harvey, his Black Republican opponent. In the same election, based on reconstituted election analysis of actual votes cast within the geography of the district, Joe Biden won the district over Donald Trump with 92% of the vote compared to only 50% of the vote statewide. The same sort of lopsided Democratic victories are evident in the district in other general elections over the last decade, including 95% for Casey in the 2018 U.S. Senate contest, 93% for Clinton in the 2016 Presidential contest, 94% for Wolf in the 2014 election for Governor, and 92% for Obama in the 2012 Presidential contest.

¶ 119 In the GMS Plan, District 3 has a lower Black population proportion at 39% VAP and 44% CVAP, but remains an overwhelmingly Democratic district and a clear Black opportunity district. Based again on reconstituted-election analysis of actual votes cast within the geography of the GMS Plan's District 3, Joe Biden would have won the district over Donald Trump with 88% of the vote. The same sort of lopsided victories are also demonstrated in the proposed district in other reconstituted general elections over the last decade, including 92% for Casey in the 2018 U.S. Senate contest, 90% for Clinton in the 2016 Presidential Contest, 92% for Wolf in the 2014 election for Governor, and 90% for Obama in the 2012 Presidential contest.

¶ 120 This same pattern of secure victory for the Democratic candidate is repeated in the version of District 3 that exists in the House Plan. Based on reconstituted-election analysis of votes cast within the geography of the proposed District 3 in the House Plan, Joe Biden would have won the district over Donald Trump with 91% of the vote. The same sort of lopsided victories are also demonstrated in the proposed district in other reconstituted general elections over the last decade including 94% for Casey in the 2018 U.S. Senate contest, 92% for Clinton in the 2016 Presidential contest, 94% for Wolf in the 2014 election for Governor, and 93% for Obama in the 2012 Presidential Contest.

¶ 121 The Governor's Plan also shows the same pattern of secure victory for the Democratic candidate in that plan's version of District 3. Based on reconstituted-election analysis of votes cast within the geography of the proposed District 3 in the Governor's Plan, Joe Biden would have won the district over Donald Trump with 92% of the vote. The same sort of lopsided victories are also demonstrated in the proposed district in other reconstituted general elections over the last decade including 94% for Casey in the 2018 U.S. Senate contest, 93% for Clinton in the 2016 Presidential contest, 94% for Wolf in the 2014 election for Governor, and 92% for Obama in the 2012 Presidential Contest.

¶ 122 With all the proposed District 3 configurations clearly secure for the candidate of choice of Black voters in the partisan general election, the key consideration here is the performance of the district for Black-preferred candidates in the Democratic primary, as the Democratic nomination is tantamount to election.

Table 11 below summarizes the results of an EI analysis to estimate the preferred candidate of Black voters across the five-county Philadelphia area in the Democratic primary for contested statewide offices over the last decade. In addition, Table 11 includes the reconstituted election results for the existing configuration of District 3, as well as the configurations of this district in the GMS Plan, the House Plan, and the Governor's Plan.

¶ 123 Scanning down the table shows that the preferred candidate of Black voters is also the top vote getter in the Democratic primary for every election in the existing district and in each plan's proposed district, with the narrow exception of the 2018 primary for Lt. Governor in the proposed GMS district. In that five-way contest, Black voters were divided, but a plurality of 46% preferred Stack. In the reconstituted election, Stack would have narrowly prevailed with 33% of the vote and with Ahmad a close second at 32% of the vote. This is narrowly reversed in the proposed GMS district with Ahmad a narrow plurality winner with 33% over Stack with 31%. Overall, it is clear that the performance of the Black-preferred candidate is very similar in all the plans, with an average vote of 63.3% in the existing plan, 62.3% in the GMS Plan, 63.4% in the House Plan, and 63.2% in the Governor's Plan.

Contest	Statewide Result	Last Name	Party	Race/ Ethnicity	EI Estimates Black	Hispanic	Reconstituted Elections Existing	GMS	House	Gov
12P_AG	52.8%	Kane	D	White	0.37	0.49	0.37	0.38	0.37	0.37
12P_AG	47.2%	Murphy	D	White	**0.63**	**0.51**	**0.63**	**0.62**	**0.63**	**0.63**
12P_US_Senate	80.9%	Casey	D	White	**0.79**	0.47	**0.82**	**0.81**	**0.81**	**0.82**
12P_US_Senate	19.1%	Vodvarka	D	White	0.21	**0.53**	0.18	0.19	0.19	0.18
14P_Governor	16.8%	McCord	D	White	0.15	0.19	0.17	0.17	0.16	0.17
14P_Governor	7.7%	McGinty	D	White	0.03	0.16	0.03	0.04	0.03	0.03
14P_Governor	17.6%	Schwartz	D	White	0.31	0.18	0.32	0.33	0.32	0.32
14P_Governor	57.9%	Wolf	D	White	**0.51**	**0.47**	**0.48**	**0.47**	**0.48**	**0.48**
14P_Lt_Governor	15.9%	Critz	D	White	0.04	0.22	0.03	0.03	0.03	0.03
14P_Lt_Governor	11.9%	Koplinski	D	White	0.02	0.12	0.04	0.04	0.03	0.04
14P_Lt_Governor	10.8%	Neuman	D	White	0.05	0.12	0.04	0.04	0.04	0.04
14P_Lt_Governor	14.6%	Smith	D	White	0.06	0.13	0.06	0.06	0.06	0.06
14P_Lt_Governor	46.8%	Stack	D	White	**0.83**	**0.41**	**0.83**	**0.82**	**0.83**	**0.83**
16P_AG	16.2%	Morganelli	D	White	0.09	0.26	0.09	0.09	0.09	0.09
16P_AG	47.0%	Shapiro	D	White	**0.58**	0.18	**0.62**	**0.63**	**0.59**	**0.61**
16P_AG	36.7%	Zappala	D	White	0.32	**0.57**	0.29	0.28	0.31	0.29
16P_President	55.6%	Clinton	D	White	**0.70**	**0.76**	**0.64**	**0.61**	**0.64**	**0.64**
16P_President	0.9%	DeLaFuente	D	Latino	0.00	0.02	0.00	0.00	0.00	0.00
16P_President	43.5%	Sanders	D	White	0.30	0.22	0.36	0.39	0.35	0.36
16P_US_Senate	19.5%	Fetterman	D	White	0.16	**0.35**	0.17	0.19	0.17	0.17
16P_US_Senate	42.5%	McGinty	D	White	**0.48**	0.18	**0.46**	**0.45**	**0.46**	**0.46**
16P_US_Senate	32.6%	Sestak	D	White	0.23	0.15	0.27	0.27	0.26	0.27
16P_US_Senate	5.5%	Vodvarka	D	White	0.12	0.31	0.10	0.09	0.11	0.10
18P_Lt_Governor	23.8%	Ahmad	D	Other	0.24	0.16	0.32	**0.33**	0.31	0.32
18P_Lt_Governor	18.6%	Cozzone	D	White	0.21	0.23	0.15	0.14	0.16	0.15
18P_Lt_Governor	37.5%	Fetterman	D	White	0.07	0.18	0.19	0.21	0.17	0.19
18P_Lt_Governor	3.6%	Sosa	D	Latino	0.02	0.12	0.01	0.01	0.01	0.01
18P_Lt_Governor	16.6%	Stack	D	White	**0.46**	**0.31**	**0.33**	0.31	**0.36**	**0.33**
20P_Auditor	36.4%	Ahmad	D	Other	**0.74**	**0.37**	**0.73**	**0.73**	**0.73**	**0.73**
20P_Auditor	7.5%	Conklin	D	White	0.03	0.12	0.02	0.02	0.02	0.02
20P_Auditor	6.0%	Davis	D	Black	0.06	0.18	0.04	0.04	0.05	0.04
20P_Auditor	9.0%	Fountain	D	Black	0.06	0.10	0.07	0.06	0.07	0.07
20P_Auditor	14.0%	Hartman	D	White	0.02	0.09	0.04	0.04	0.03	0.04
20P_Auditor	27.1%	Lamb	D	White	0.09	0.14	0.09	0.09	0.10	0.09
20P_President	79.3%	Biden	D	White	**0.87**	**0.61**	**0.80**	**0.77**	**0.80**	**0.80**
20P_President	2.7%	Gabbard	D	Other	0.01	0.11	0.01	0.01	0.01	0.01
20P_President	18.0%	Sanders	D	White	0.12	0.28	0.19	0.22	0.19	0.19

Table 11: Statewide Democratic Primaries in District 3
in the 2018, GMS, House, and Governor's Plans

¶ 124 One limitation of these statewide primary contests is the fact that they are typically not racially contested, meaning that all the candidates are from the same demographic group. In fact, only the 2020 State Auditor contest involved any Black candidates for office in the analyzed elections. That election included two

Black candidates who were not competitive, as together they are estimated to have drawn the support of only 12% of Black voters in the Philadelphia area. To address this limitation, Table 12 below includes racially or ethnically contested Democratic primaries for Philadelphia city- or county-level offices since 2015. It is possible to perform this analysis for the current District 3, for the GMS Plan's District 3, and for District 3 in each of the comparator maps because they are wholly contained within Philadelphia, so all the geography in these versions of District 3 will be fully represented in the reconstructed-election analysis.

	Countywide			Race/	EI Estimates		Reconstituted Elections			
Contest	Result	Last Name	Party	Ethnicity	Black	Hispanic	Existing	GMS	House	Gov
15P_Mayor		Abraham	D	White	0.04	0.09	0.07	0.08	0.06	0.07
15P_Mayor		Diaz	D	**Latino**	0.02	**0.51**	0.02	0.03	0.02	0.02
15P_Mayor		Kenney	D	White	**0.44**	0.19	**0.52**	**0.59**	**0.52**	**0.52**
15P_Mayor		Oliver	D	**Black**	0.06	0.05	0.05	0.05	0.05	0.05
15P_Mayor		Street	D	**Black**	0.02	0.05	0.02	0.02	0.02	0.02
15P_Mayor		Williams	D	**Black**	0.42	0.10	0.31	0.24	0.32	0.31
		Summed Black		**Blacks**	0.50		0.38	0.31	0.39	0.38
17P_DA		Deni	D	White	0.01	0.08	0.01	0.01	0.01	0.01
17P_DA		Khan	D	Asian	0.17	0.12	0.21	0.22	0.20	0.21
17P_DA		Krasner	D	White	**0.38**	0.13	**0.43**	**0.44**	**0.42**	**0.43**
17P_DA		Negrin	D	White	0.11	**0.36**	0.12	0.13	0.12	0.12
17P_DA		ONeill	D	White	0.02	0.10	0.03	0.04	0.04	0.03
17P_DA		Shabazz	D	**Black**	0.22	0.08	0.13	0.11	0.14	0.13
17P_DA		Untermeyer	D	White	0.09	0.13	0.07	0.06	0.07	0.07
19P_Mayor		Butkovitz	D	White	0.03	0.22	0.05	0.06	0.05	0.05
19P_Mayor		Kenney	D	White	**0.63**	**0.54**	**0.70**	**0.73**	**0.69**	**0.70**
19P_Mayor		Williams	D	**Black**	0.34	0.24	0.24	0.20	0.26	0.24
19P_Municipal_Judge		Brunson	D	**Black**	**0.52**	0.49	0.46	0.43	0.46	0.45
19P_Municipal_Judge		Conroy	D	White	0.48	**0.51**	**0.54**	**0.57**	**0.54**	**0.55**
19P_Register_Wills		Donatucci	D	White	0.37	**0.39**	0.36	0.38	0.37	0.36
19P_Register_Wills		Gordon	D	**Black**	**0.45**	0.35	**0.47**	**0.46**	**0.46**	**0.47**
19P_Register_Wills		Whaumbush	D	**Black**	0.17	0.27	0.17	0.16	0.17	0.17
21P_DA		Krasner	D	White	**0.84**	0.35	**0.79**	**0.75**	0.78	0.78
21P_DA		Vega	D	**Latino**	0.16	**0.65**	0.21	0.25	0.22	0.22
21P_Superior_Judge		Beck	D	White	0.08	0.34	0.10	0.11	0.10	0.10
21P_Superior_Judge		Lane	D	**Black**	**0.91**	**0.43**	**0.88**	**0.86**	**0.88**	**0.88**
21P_Superior_Judge		Neft	D	White	0.02	0.23	0.02	0.03	0.02	0.02

Table 12: Philadelphia Democratic Primaries in District 3
in the 2018, GMS, House, and Governor's Plans

¶ 125 Again, as was the case in the statewide primaries in Table 11, the Black-preferred candidate in these primaries is typically also the top vote-getter in the reconstituted elections. The Black-preferred candidate received an average of 60.6% of the reconstituted vote in the existing district compared to an almost identical 60.8% in the GMS Plan's proposed District 3, 60.0% in the House Plan's proposed District 3, and 60.6% in the Governor's Plan's proposed District 3. Two of the contests merit a closer look. In the 2019 primary for Municipal Judge, Black voters were split narrowly, 52% to 48%, between the Black and the White candidate, and the Black candidate narrowly lost in the reconstituted elections in all four plans. In the 2015 six-way Mayoral primary, Black voters also did not vote in a cohesive bloc, but the narrow plurality-preferred candidate of Black voters was Kenney, one of the White candidates, and Kenney carried the district in all three proposed plans. The fact that there were three Black candidates fractured the Black vote slightly, leaving Williams, the Black candidate most preferred by Black votes, at 42%, which fell slightly short of the level of Black voter support for Kenney. However, even combined, the three Black candidates were supported by only 50% of Black voters, and the combined reconstituted votes for the three Black candidates fell well short of Kenny's majority vote in all the plans.

¶ 126 In summary, the modest reduction in the Black population of District 3 in the GMS Plan from its current levels in the existing 2018 Plan district is not consequential. District 3 in the GMS Plan, like the current District 3 in the 2018 Plan, consistently and securely nominates and elects Black-preferred candidates.

Congressional District 5

¶ 127 Current District 5 is a Democratic district (in territory similar to District 7 prior to the court-ordered redrawing of the congressional plan in 2018) that is currently represented by a White Representative in Congress. The district has a 2020 census Voting Age Population (VAP) that is 23% Black, and a 2015-2019 estimated CVAP that is 22%. In its current configuration, the district is solidly Democratic in general elections. In 2020, Democrat Mary Gay Scanlon won the district with 65% of the vote over Dasha Pruett, her Republican opponent. In the same election, based on reconstituted election analysis of actual votes cast within the geography of the district, Joe Biden won the district over Donald Trump with 64% of the vote compared to only 50% of the vote statewide. The same sort of clear Democratic victories are evident in the district in other general elections over the last decade, including 69% for Casey in the 2018 U,S, Senate contest, 65% for Clinton in the 2016 Presidential contest, 64% for Wolf in the

2014 election for Governor, and 64% for Obama in the 2012 Presidential contest.

¶ 128 In the GMS Plan, District 5 has a higher Black population proportion at 39% VAP and 39% CVAP compared to the current District 5. The proposed GMS District 5 remains a solidly Democratic district and, with the boost in Black population, it is a clear Black opportunity district. Based again on reconstituted-election analysis of actual votes cast within the geography of the proposed District 5, Joe Biden won the district over Donald Trump with 71% of the vote, compared to only 50% of the vote statewide. The same sort of clear Democratic victories are evident in the district in other general elections over the last decade, including 74% for Casey in the 2018 U.S, Senate contest, 71% for Clinton in the 2016 Presidential contest, 71% for Wolf in the 2014 election for Governor, and 72% for Obama in the 2012 Presidential contest.

¶ 129 This same pattern of secure victories for Democratic candidates in general elections in District 5 is repeated in the House Plan. Based on reconstituted-election analysis of votes cast within the geography of the proposed District 5 in the House Plan, Joe Biden would have won the district over Donald Trump with 63% of the vote. The same sort of clear Democratic victories are also evident in the proposed district in other reconstituted general elections over the last decade, including 66% for Casey in the 2018 U.S. Senate contest, 61% for Clinton in the 2016 Presidential contest, 60% for Wolf in the 2014 election for Governor, and 60% for Obama in the 2012 Presidential contest.

¶ 130 The Governor's Plan also shows the same pattern of secure victory for the Democratic candidate in District 5. Based on reconstituted-election analysis of votes cast within the geography of the proposed District 5 in the Governor's Plan, Joe Biden would have won the district over Donald Trump with 66% of the vote. The same sort of clear Democratic victories are also evident in the proposed district in other reconstituted general elections over the last decade, including 69% for Casey in the 2018 U.S. Senate contest, 65% for Clinton in the 2016 Presidential contest, 64% for Wolf in the 2014 election for Governor, and 63% for Obama in the 2012 Presidential contest.

¶ 131 With both the existing and proposed District 5 configurations clearly secure for the Democratic candidate in the partisan general election, the key consideration here is the performance of the district for Black candidates of choice in the Democratic primary, as the Democratic nomination is tantamount to election. Table 13 below summarizes the results of an EI analysis to estimate the preferred candidate of Black voters across the five-county Philadelphia area in the Democratic primary for contested statewide offices over the last decade. In addition, Table 13 includes the reconstituted election results for the existing configuration of District 5, as well as the configurations for District 5 as proposed in the GMS Plan, the House Plan, and the Governor's Plan.

¶ 132 Overall, Table 13 shows that the preferred candidate of Black voters is also the top vote-getter in the Democratic primary for most of the elections in the existing district, as well as all three proposed districts, with the exception of the 2016 primary for the U.S. Senate and the 2018 primary for Lt. Governor. In both of those multi-candidate contests, Black voters provided slightly less than majority support for their preferred candidate, and their plurality-preferred candidate did not prevail in either the existing or the other configurations of the district. In the 2018 five-way primary contest for Lt. Governor, Black voters were divided, but a plurality of 46% preferred Stack. In the reconstituted election, Ahmad prevailed in the current District 5 with 36% of the vote, compared to Stack with only 22%% of the vote. Ahmad prevailed by a similarly large margin in the proposed District 5 in the House Plan and in the Governor's Plan. The result is the same in the GMS Plan's configuration of District 5, but Ahmad's margin of victory is narrowed to 32% versus 29% for Stack. Similarly, in the 2016 primary for U.S. Senate, Sestak's margin of victory over McGinty, the Black preferred candidate, is reduced from 24 percentage points in the existing district (25% in the House Plan, 23% in the Governor's Plan) to 12 percentage points in the GMS configuration. This narrowing of the loss for this particular Black-preferred candidate may suggest that District 5 is somewhat more effective for Black voters in the GMS Plan than in the other plans.

¶ 133 Overall, it is clear that the performance of the Black-preferred candidate is similar in all the plans, with an average vote of 59.4% in the existing plan and 61.2% in the GMS Plan, 58.8% in the House Plan, and 59.5% in the Governor's Plan. Again, these figures may suggest that District 5 is somewhat more effective for Black voters in the GMS Plan than in the other plans.

Countywide				Race/	EI Estimates		Reconstituted Elections			
Contest	Result	Last Name	Party	Ethnicity	Black	Hispanic	Existing	GMS	House	Gov
12P_AG	52.8%	Kane	D	White	0.37	0.49	0.37	0.36	0.38	0.37
12P_AG	47.2%	Murphy	D	White	**0.63**	**0.51**	**0.63**	**0.64**	**0.62**	**0.63**
12P_US_Senate	80.9%	Casey	D	White	**0.79**	0.47	**0.85**	**0.82**	**0.86**	**0.85**
12P_US_Senate	19.1%	Vodvarka	D	White	0.21	**0.53**	0.15	0.18	0.14	0.15
14P_Governor	16.8%	McCord	D	White	0.15	0.19	0.17	0.16	0.17	0.17
14P_Governor	7.7%	McGinty	D	White	0.03	0.16	0.05	0.05	0.06	0.05
14P_Governor	17.6%	Schwartz	D	White	0.31	0.18	0.29	0.28	0.25	0.30
14P_Governor	57.9%	Wolf	D	White	**0.51**	**0.47**	**0.49**	**0.52**	**0.51**	**0.48**
14P_Lt_Governor	15.9%	Critz	D	White	0.04	0.22	0.04	0.04	0.04	0.04
14P_Lt_Governor	11.9%	Koplinski	D	White	0.02	0.12	0.08	0.06	0.10	0.08
14P_Lt_Governor	10.8%	Neuman	D	White	0.05	0.12	0.05	0.05	0.05	0.05
14P_Lt_Governor	14.6%	Smith	D	White	0.06	0.13	0.12	0.10	0.13	0.13
14P_Lt_Governor	46.8%	Stack	D	White	**0.83**	**0.41**	**0.71**	**0.75**	**0.68**	**0.71**
16P_AG	16.2%	Morganelli	D	White	0.09	0.26	0.10	0.11	0.11	0.10
16P_AG	47.0%	Shapiro	D	White	**0.58**	0.18	**0.61**	**0.57**	**0.64**	**0.64**
16P_AG	36.7%	Zappala	D	White	0.32	**0.57**	0.29	0.32	0.25	0.27
16P_President	55.6%	Clinton	D	White	**0.70**	**0.76**	**0.60**	**0.64**	**0.60**	**0.61**
16P_President	0.9%	DeLaFuente	D	Latino	0.00	0.02	0.00	0.00	0.00	0.00
16P_President	43.5%	Sanders	D	White	0.30	0.22	0.39	0.36	0.40	0.39
16P_US_Senate	19.5%	Fetterman	D	White	0.16	**0.35**	0.09	0.11	0.08	0.09
16P_US_Senate	42.5%	McGinty	D	White	**0.48**	0.18	0.31	0.35	0.32	0.32
16P_US_Senate	32.6%	Sestak	D	White	0.23	0.15	**0.55**	**0.47**	**0.57**	**0.55**
16P_US_Senate	5.5%	Vodvarka	D	White	0.12	0.31	0.05	0.08	0.03	0.04
18P_Lt_Governor	23.8%	Ahmad	D	Other	0.24	0.16	**0.36**	**0.32**	**0.35**	**0.36**
18P_Lt_Governor	18.6%	Cozzone	D	White	0.21	0.23	0.22	0.23	0.29	0.21
18P_Lt_Governor	37.5%	Fetterman	D	White	0.07	0.18	0.19	0.14	0.16	0.20
18P_Lt_Governor	3.6%	Sosa	D	Latino	0.02	0.12	0.02	0.02	0.02	0.03
18P_Lt_Governor	16.6%	Stack	D	White	**0.46**	**0.31**	0.22	0.29	0.18	0.20
20P_Auditor	36.4%	Ahmad	D	Other	**0.74**	**0.37**	**0.69**	**0.71**	**0.64**	**0.68**
20P_Auditor	7.5%	Conklin	D	White	0.03	0.12	0.04	0.03	0.04	0.04
20P_Auditor	6.0%	Davis	D	Black	0.06	0.18	0.04	0.05	0.04	0.04
20P_Auditor	9.0%	Fountain	D	Black	0.06	0.10	0.07	0.07	0.07	0.07
20P_Auditor	14.0%	Hartman	D	White	0.02	0.09	0.09	0.07	0.15	0.10
20P_Auditor	27.1%	Lamb	D	White	0.09	0.14	0.07	0.07	0.06	0.07
20P_President	79.3%	Biden	D	White	**0.87**	**0.61**	**0.82**	**0.84**	**0.83**	**0.83**
20P_President	2.7%	Gabbard	D	Other	0.01	0.11	0.01	0.01	0.01	0.01
20P_President	18.0%	Sanders	D	White	0.12	0.28	0.17	0.15	0.16	0.16

Table 13: Statewide Democratic Primaries in District 5 in the 2018, GMS, House, and Governor's Plans

Congressional District 2

¶ 134 Current District 2 is a Democratic district that is currently represented by a White Representative in Congress. The district has a 2020 census Voting-Age

Population (VAP) that is 22% Latino and 24% Black. In its current configuration, the district is solidly Democratic in the general election. In 2020, Democrat Brendan Boyle won the district with 72% of the vote over David Torres, his Republican opponent. In the same election, based on reconstituted-election analysis of actual votes cast within the geography of the district, Joe Biden won the district over Donald Trump with 71% of the vote compared to only 50% of the vote statewide. The same sort of clear Democratic victories are evident in the district in other general elections over the last decade, including 79% for Casey in the 2018 U.S. Senate contest, 75% for Clinton in the 2016 Presidential contest, 80% for Wolf in the 2014 election for Governor, and 78% for Obama in the 2012 Presidential contest.

¶ 135 In the GMS Plan, District 2 has a 22% Latino Voting-Age Population and a 19% Black Voting-Age Population and remains a solidly Democratic district. Based again on reconstituted-election analysis of actual votes cast within the geography of the proposed District 2, Joe Biden won the district over Donald Trump with 63% of the vote, compared to only 50% of the vote statewide. The same sort of clear Democratic victories are evident in the district in other general elections over the last decade, including 72% for Casey in the 2018 U.S. Senate contest, 67% for Clinton in the 2016 Presidential contest, 73% for Wolf in the 2014 election for Governor, and 72% for Obama in the 2012 Presidential contest.

¶ 136 This same pattern of secure victory for the Democratic candidate in District 2 is repeated in the House Plan's configuration of existing District 2. Based on reconstituted-election analysis of votes cast within the geography of the district in the House Plan, Joe Biden would have won the district over Donald Trump with 73% of the vote. The same sort of lopsided Democratic victories are also demonstrated in the proposed district in other reconstituted general elections over the last decade, including 81% for Casey in the 2018 U.S. Senate contest, 76% for Clinton in the 2016 Presidential contest, 80% for Wolf in the 2014 election for Governor, and 78% for Obama in the 2012 Presidential contest.

¶ 137 The Governor's Plan also shows the same pattern of secure victory for the Democratic candidate in that plan's configuration of District 2. Based on reconstituted election analysis of votes cast within the geography of the district in the Governor's Plan, Joe Biden would have won the district over Donald Trump with 70% of the vote. The same sort of lopsided Democratic victories are also demonstrated in the proposed district in other reconstituted general elections over the last decade, including 78% for Casey in the 2018 US Senate contest, 74% for Clinton in the 2016 Presidential contest, 79% for Wolf in the

2014 election for Governor, and 77% for Obama in the 2012 Presidential contest.

¶ 138 With both the existing and proposed District 2 configurations clearly secure for the Democratic candidate in the partisan general election, the key consideration here is the performance of the district for minority candidates of choice in the Democratic primary, as the Democratic nomination is tantamount to election. Table 14 below summaries the results of an EI analysis to estimate the preferred candidates of Black and Latino voters across the five-county Philadelphia area in the Democratic primary for contested statewide offices over the last decade. In addition, Table 14 includes the reconstituted election results for the existing configuration of District 2, as well as that district's configurations in the three proposed plans.

Contest	Statewide Result	Last Name	Party	Race/ Ethnicity	EI Estimates Black	Hispanic	Anglo	Reconstituted Elections Existing	GMS	House	Gov
12P_AG	52.8%	Kane	D	White	0.37	0.49	0.35	0.36	0.34	0.36	0.36
12P_AG	47.2%	Murphy	D	White	**0.63**	**0.51**	**0.65**	**0.64**	**0.66**	**0.64**	**0.64**
12P_US_Senate	80.9%	Casey	D	White	**0.79**	0.47	**0.90**	**0.78**	**0.79**	**0.79**	**0.78**
12P_US_Senate	19.1%	Vodvarka	D	White	0.21	**0.53**	0.10	0.22	0.21	0.21	0.22
14P_Governor	16.8%	McCord	D	White	0.15	0.19	0.16	0.13	0.13	0.14	0.13
14P_Governor	7.7%	McGinty	D	White	0.03	0.16	0.05	0.05	0.06	0.05	0.05
14P_Governor	17.6%	Schwartz	D	White	0.31	0.18	0.32	0.33	0.31	0.33	0.33
14P_Governor	57.9%	Wolf	D	White	**0.51**	**0.47**	**0.47**	**0.49**	**0.51**	**0.48**	**0.49**
14P_Lt_Governor	15.9%	Critz	D	White	0.04	0.22	0.02	0.04	0.04	0.04	0.04
14P_Lt_Governor	11.9%	Koplinski	D	White	0.02	0.12	0.10	0.03	0.04	0.03	0.03
14P_Lt_Governor	10.8%	Neuman	D	White	0.05	0.12	0.04	0.03	0.04	0.03	0.03
14P_Lt_Governor	14.6%	Smith	D	White	0.06	0.13	0.11	0.05	0.06	0.05	0.06
14P_Lt_Governor	46.8%	Stack	D	White	**0.83**	**0.41**	**0.73**	**0.84**	**0.82**	**0.84**	**0.84**
16P_AG	16.2%	Morganelli	D	White	0.09	0.26	0.09	0.13	0.14	0.12	0.13
16P_AG	47.0%	Shapiro	D	White	**0.58**	0.18	**0.72**	**0.50**	**0.49**	**0.52**	**0.50**
16P_AG	36.7%	Zappala	D	White	0.32	**0.57**	0.19	0.37	0.36	0.35	0.37
16P_President	55.6%	Clinton	D	White	**0.70**	**0.76**	**0.54**	**0.61**	**0.61**	**0.60**	**0.61**
16P_President	0.9%	DeLaFuente	D	Latino	0.00	0.02	0.01	0.01	0.01	0.01	0.01
16P_President	43.5%	Sanders	D	White	0.30	0.22	0.46	0.39	0.38	0.40	0.39
16P_US_Senate	19.5%	Fetterman	D	White	0.16	**0.35**	0.10	0.20	0.17	0.20	0.20
16P_US_Senate	42.5%	McGinty	D	White	**0.48**	0.18	**0.45**	**0.39**	**0.39**	**0.39**	**0.39**
16P_US_Senate	32.6%	Sestak	D	White	0.23	0.15	0.43	0.27	0.31	0.28	0.28
16P_US_Senate	5.5%	Vodvarka	D	White	0.12	0.31	0.02	0.14	0.12	0.12	0.13
18P_Lt_Governor	23.8%	Ahmad	D	Other	0.24	0.16	**0.29**	0.18	0.17	0.22	0.19
18P_Lt_Governor	18.6%	Cozzone	D	White	0.21	0.23	0.22	0.16	0.18	0.15	0.17
18P_Lt_Governor	37.5%	Fetterman	D	White	0.07	0.18	0.25	0.16	0.15	0.19	0.16
18P_Lt_Governor	3.6%	Sosa	D	Latino	0.02	0.12	0.06	0.01	0.03	0.01	0.02
18P_Lt_Governor	16.6%	Stack	D	White	**0.46**	**0.31**	0.17	**0.48**	**0.47**	**0.41**	**0.47**
20P_Auditor	36.4%	Ahmad	D	Other	**0.74**	**0.37**	**0.59**	**0.70**	**0.68**	**0.70**	**0.70**
20P_Auditor	7.5%	Conklin	D	White	0.03	0.12	0.03	0.04	0.04	0.03	0.04
20P_Auditor	6.0%	Davis	D	Black	0.06	0.18	0.03	0.06	0.06	0.05	0.06
20P_Auditor	9.0%	Fountain	D	Black	0.06	0.10	0.07	0.05	0.05	0.06	0.05
20P_Auditor	14.0%	Hartman	D	White	0.02	0.09	0.20	0.05	0.07	0.06	0.05
20P_Auditor	27.1%	Lamb	D	White	0.09	0.14	0.08	0.10	0.09	0.10	0.10
20P_President	79.3%	Biden	D	White	**0.87**	**0.61**	**0.81**	**0.79**	**0.81**	**0.77**	**0.79**
20P_President	2.7%	Gabbard	D	Other	0.01	0.11	0.01	0.02	0.03	0.02	0.02
20P_President	18.0%	Sanders	D	White	0.12	0.28	0.18	0.19	0.17	0.21	0.19

Table 14: Statewide Democratic Primaries in District 2 in the 2018, GMS, House, and Governor's Plans

¶ 139 Table 14 shows that the preferred candidate of Black and Latino voters is also the top vote-getter in the Democratic primary for most of the elections in the existing district, the proposed District 2 in the GMS Plan, and the proposed districts in the House Plan and in the Governor's Plan. In all ten primaries, the Black-preferred candidate is the top vote-getter in every plan, and in seven of the ten primaries, the preferred candidate of Latino voters is also the top vote-getter in all the plans. Of the three contests where the choice of Latino voters did not, the top vote-getter in the reconstituted elections was the first choice of both Black and White voters. But there was also one election, the 2020 Democratic primary for State Auditor, where the first choice of Black and Latino voters was the top vote-getter in all the plans, despite not being the first choice of White voters.

¶ 140 Overall, District 2 performs, in all the plans, for both Black and Latino voters in all the general elections and in at least 70% of the Democratic primaries. Looking across the plans, there is little difference in the performance of any of the individual plans in the statewide elections from the last decade. The same candidates were winners across all the plans in every election and the vote differences were seldom more than one or two percentage points. However, because District 2 in the GMS Plan contains some fast-growing Latino neighborhoods, the district's Latino CVAP percentage has recently been increasing by about a half percentage point per year. In the May 2021 Democratic primary for Philadelphia District Attorney, the Latino-preferred Latino candidate, Carlos Vega, who captured only 33% of the vote citywide, easily won the Philadelphia portion of the GMS Plan's District 2, with nearly 64% of the vote. Because about 80% of the population of GMS Plan's District 2 resides in Philadelphia, this more recent outcome suggests that the district may be becoming increasingly effective for Latino voters as the district becomes more heavily Latino. As noted earlier, the district already, according to the 2020 Census and the 2015-2019 American Community Survey, has more Latino adults than Black adults and more Latino adult citizens than Black adult citizens, and the gap between the two groups appears to be increasing over time in this majority-minority district.

Summary

¶ 141 The GMS Plan contains three majority-minority districts—unlike the 2018 Plan, the House Plan, and the Governor's Plan, each of which has only two such districts. And the GMS Plan's three majority-minority districts routinely and consistently nominate and elect minority-preferred candidates, according to not only a full set of recent statewide elections but also, where applicable, a full set of county- or city-wide primary elections involving candidates of color. Furthermore, one of the GMS Plan's three majority-minority districts would, for the first time, contain more Latino adult citizens than Black adult citizens, making Latinos the district's largest minority group and thus providing Pennsylvania's fast-growing Latino communities with greater electoral opportunity.

V.G Incumbent Pairings

¶ 142 I was also asked to evaluate the maps with respect to the location of the current residences of Pennsylvania's Representatives in Congress.

¶ 143 I obtained the point data from the Redistricting Data Hub[12] and merged it with the LRC blocks to identify the district into which each incumbent's residence is placed under each of the proposed plans. This was supplemented with additional updated data provided by Counsel. According to this data, the number of districts that contain two current Representatives in each proposal are shown in Table (below).

¶ 144 Because the proposed plans all have 17 districts and the current 2018 Plan has 18 incumbents, there must be at least one pairing in any plan. Congressman Doyle from the current 18th District is retiring. Congressman Lamb has announced that he is not running for reelection.[13] Pairings containing these current representatives will not impact the upcoming elections under the proposals analyzed here.

¶ 145 The results of my analysis of incumbent pairings are summarized in Table 15 below.

[12] Initially gathered and processed by Dr. Carl E. Klarner

[13] "Conor Lamb Gets In, and a Crucial Senate Fight Takes Shape in Pennsylvania," N.Y. Times, Aug. 6, 2021, https://www.nytimes.com/2021/08/06/us/politics/conor-lamb-senate-race-pa.html.

Plan	Number of Districts with Paired Incumbents	Names of Paired Incumbents
GMS	1	**District 14:** Reschenthaler (R) and Lamb* (D)
House	2	**District 8:** Meuser (R) and Cartwright (D) **District 15:** Lamb* (D) and Doyle* (D)
Governor	2	**District 5:** Dean (D) and Scanlon (D) **District 12:** Keller (R) and Joyce (R)

Table 15: Paired Incumbents, with * denoting those ***not*** seeking re-election

VI Conclusion

Congressional districting plans in Pennsylvania must balance and satisfy a large collection of constraints, while attempting to simultaneously optimize for performance on criteria including population equality, preservation of political boundaries, and compactness that are often in tension with each other. In this report I have evaluated the GMS Plan and comparator maps on metrics relevant to these legal requirements and found that the GMS Plan demonstrates excellent performance across these criteria, while also successfully managing potential tradeoffs as exhibited by the performance of other plans. For example, the GMS Plan splits fewer political-subdivision boundaries than the other proposals while also achieving excellent scores on measures of partisan fairness that outperform those of other maps.

Overall, the GMS plan exhibits very strong performance on measures relating to all of the criteria that I considered in this report. The improvements of these values on many metrics compared to those of the 2018 Plan provides significant evidence of the effectiveness of the GMS Plan at managing the requisite tradeoffs and succeeding as an effective districting plan.

VII References

[Bar-Natan–Najt–Schutzmann 2020] Assaf Bar-Natan, Elle Najt, and Zachary Schutzmann, The gerrymandering jumble: Map projections permute districts' compactness scores. Cartography and Geographic Information Science, Volume 47, Issue 4, 2020, 321–335.

[Solomon and Barnes 2021] Richard Barnes and Justin Solomon, Gerrymandering and Compactness: Implementation Flexibility and Abuse. Political Analysis, Volume 29, Issue 4, 2021, 448–466.

[Duchin and Tenner 2018] Moon Duchin and Bridget Tenner, Discrete geometry for electoral geography. ArXiv: 1808.05860, 2018, 1-18.

[King, Katz, and Rosenblatt 2020] Jonathan N. Katz, Gary King, and Elizabeth Rosenblatt, Theoretical Foundations and Empirical Evaluations of Partisan Fairness in District-Based Democracies, American Political Science Review, 114(1), 2020, 164–178.

[Deford and Duchin 2019] Daryl DeFord and Moon Duchin, Redistricting Reform in Virginia: Districting Criteria in Context, with M. Duchin, Virginia Policy Review, 12(2), 2019, 120-146

[DeFord et al. 2020] Daryl DeFord, Natasha Dhamankar, Moon Duchin,Varun Gupta, Mackenzie McPike, Gabe Schoenbach, and Ki Wan Sim, Implementing partisan symmetry: Problems and paradoxes, https://arxiv.org/pdf/2008.06930.pdf, 2020, 1-20.

"Conor Lamb Gets In, and a Crucial Senate Fight Takes Shape in Pennsylvania," N.Y. Times, Aug. 6, 2021, https://www.nytimes.com/2021/08/06/us/politics/conor-lamb-senate-race-pa.html.

Appendix A: CV

DARYL R. DEFORD

Curriculum Vitae
328 Neill Hall WSU Pullman, WA ⋄ (509) 205–7347
daryl.deford@wsu.edu ⋄ daryldeford.com

ACADEMIC APPOINTMENTS

Washington State University, Pullman, WA — *August 2020 – Present*
Assistant Professor of Data Analytics – Department of Mathematics and Statistics

Massachusetts Institute of Technology, Cambridge, MA — *June 2018 – July 2020*
Postdoctoral Associate – CSAIL Geometric Data Processing Group
Advisor: Justin Solomon

Tufts University, Medford, MA — *June 2018 – July 2020*
Visiting Scholar – Jonathan M. Tisch College of Civic Life
Advisor: Moon Duchin

EDUCATION

Dartmouth College, Hanover, NH — *September 2013 – June 2018*
Ph.D. Mathematics — *Awarded June 2018*
Advisor: Dan Rockmore
Dissertation: Matched Products and Dynamical Models for Multiplex Networks
A.M. Mathematics — *Awarded November 2014*

Washington State University, Pullman, WA — *August 2010 – May 2013*
B.S. in Theoretical Mathematics — *Awarded May 2013*
Summa Cum Laude

RESEARCH PUBLICATIONS

Accepted Papers

A24: *Random Walks and the Universe of Districting Plans* (with M. Duchin), Book Chapter in *Political Geography*, Birkhäuser, to appear 2022.

A23: *Implementing Partisan Symmetry: Problems and Paradoxes* (with N. Dhamankar, M. Duchin, V. Gupta, M. McPike, G. Schoenbach, K. W. Sim), Political Analysis, arxiv: 2008.06930, to appear 2022.

A22: *Empirical Sampling of Connected Graph Partitions for Redistricting* (with L. Najt and J. Solomon), Physical Review E, 104(6), 064130, 2021.

A21: *Partisan Dislocation: A Precinct-Level Measure of Representation and Gerrymandering* (with N. Eubank and J. Rodden), Political Analysis, 1-23, doi:10.1017/pan.2021.13, 2021.

A20: *Colorado in Context: Congressional Redistricting and Competing Fairness Criteria in Colorado* (with J. Clelland, H. Colgate, B. Malmskog, and F. Sancier-Barbosa), Journal of Computational Social Science, doi:10.1007/s42001-021-00119-7, 2021.

A19: *ReCombination: A family of Markov chains for redistricting* (with M. Duchin and J. Solomon), Harvard Data Science Review, 3(1), 2021.

A18: *Medial Axis Isoperimetric Profiles* (with J. Solomon and P. Zhang), Computer Graphics Forum, 39(5), 1-13, 2020.

A17: *On the Spectrum of Finite, Rooted Homogeneous Trees* (with D. Rockmore), Linear Algebra and its Applications, 598, 165-185, 2020.

A16: *Competitiveness Measures for Evaluating Districting Plans* (with M. Duchin and J. Solomon), Statistics and Public Policy, 7(1), 69-86, 2020.

A15: *Mathematics of Nested Districts: The Case of Alaska* (with S. Caldera, M. Duchin, S. Gutenkust, and C. Nix), Statistics and Public Policy, 7(1), 39-51, 2020.

A14: *Aftermath: The ensemble approach to political redistricting* (with J. Clelland and M. Duchin), MAA Math Horizons, 28(1), 34-35, 2020.

A13: *Total Variation Isoperimetric Profiles* (with H. Lavenant, Z. Schutzman, and J. Solomon), SIAM J. Appl. Algebra Geometry, 3(4), 585-613, 2019.

A12: *Spectral Clustering Methods for Multiplex Networks* (with S. Pauls) Physica A: Statistical Mechanics and its Applications, 533, 121949, 2019.

A11: *Redistricting Reform in Virginia: Districting Criteria in Context* (with M. Duchin), Virginia Policy Review, 12(2), 120-146, 2019.

A10: *A New Framework for Dynamical Models on Multiplex Networks* (with S. Pauls), Journal of Complex Networks, 6(3), 353-381, 2018.

A9: *Cyclic Groups with the same Hodge Series*, (with P. Doyle), Revista de la Uniòn Matemática Argentina, 59(2), 241–254, 2018.

A8: *Multiplex Dynamics on the World Trade Web*, Proc. 6th International Conference on Complex Networks and Applications, Studies in Computational Intelligence, Springer, 1111–1123, 2018.

A7: *Random Walk Null Models for Time Series Data*, (with K. Moore), Entropy, 19(11), 615, 2017.

A6: *Enumerating Tilings of Rectangles By Squares*, Journal of Combinatorics, 6(3), 339-351, 2015.

A5: *Enumerating Distinct Chessboard Tilings*, Fibonacci Quarterly, 52(5), 102-116, 2014.

A4: *Pulsated Fibonacci Sequences* (with K. Atanassov and A. Shannon), Fibonacci Quarterly, 52(5), 22-27, 2014.

A3: *Seating Rearrangements on Arbitrary Graphs*, Involve: A Journal of Mathematics, 7(6), 787-805, 2014.

A2: *Empirical Analysis of Space-Filling Curves for Scientific Computing Applications* (With A. Kalyanaraman), Proc. 42nd International Conference on Parallel Processing, 170-179, 2013.

A1: *Counting Rearrangements on Generalized Wheel Graphs*, Fibonacci Quarterly, 51(3), 259-273, 2013.

Preprints

P4: *Bayesian Inference of Random Dot Product Graphs via Conic Programming* (with D. Wu and D. Palmer), arXiv:2101.02180.

P3: *Complexity and Geometry of Sampling Connected Graph Partitions* (with L. Najt and J. Solomon), arXiv: 1908.08881.

P2: *Fourier Transforms on* $SL_2(\mathbb{Z}/p^n\mathbb{Z})$ *and Related Numerical Experiments* (with B. Breen, J. Linehan, and D. Rockmore), arXiv:1710.02687.

P1: *A Random Dot Product Model for Weighted Networks* (with D. Rockmore) arXiv: 1611.02530.

Technical Reports

T7: *Expert Reports in Wisconsin State Supreme Court Litigation*, for Citizen Mathematicians and Scientists, 2021 and 2022.

T6: *Ensemble Analysis for 2021 Legislative Redistricting in Colorado, First and Second Staff Plans* (with J. Clelland, B. Malmskog, and F. Sancier-Barbosa), Colorado in Context Report, 2021.

T5: *Ensemble Analysis for 2021 Congressional Redistricting in Colorado* (with J. Clelland, B. Malmskog, and F. Sancier-Barbosa), Colorado in Context Report, 2021.

T4: *Comparison of Districting Plans for the Virginia House of Delegates* (with M. Duchin and J. Solomon), MGGG Technical Report, 2019.

T3: *Amicus Brief of Mathematicians, Law Professors, and Students* (with M. Duchin and G. Charles et al.), Rucho v. Common Cause, Supreme Court, 2019.

T2: *Study of Reform Proposals for Chicago City Council* (with M. Duchin et al.), MGGG Technical Report, 2019.

T1: *An Application of the Permanent–Determinant Method: Computing the Z-Index of Arbitrary Trees*, WSU Department of Mathematics Technical Report Series 2013 #2, 2013.

TEACHING EXPERIENCE

Washington State University Pullman, WA
Instructor *Fall 2020 - Present*

- Designed syllabi and daily lectures. Wrote and graded homework, quizzes, and exams. Fully responsible for course content and material.

Math 448/548 - Numerical Analysis *Spring 2022*

Fundamental course on numerical computation, including: finding zeroes of functions, approximation and interpolation, numerical integration, numerical solution of ordinary differential equations, and numerical linear algebra.

STAT 419 - Introduction to Multivariate Statistics *Fall 2021*

Introductory course covering multidimensional data, multivariate normal distribution, principal components, factor analysis, clustering, and discriminant analysis.

Data 115 - Introduction to Data Analytics *Fall 2020, 2021 Spring 2021*

Basic techniques and methodology of data science, with an emphasis on data processing and software tools. This course provides a foundation for beginning data analytics majors as well as students from across the university who are looking to develop data and quantitative literacy.

Math 581 - Topics in Math (Computational Methods in Complex Networks) *Fall 2020*

Introduction to computational methods and software for analyzing complex systems as well as applications of partition sampling to political redistricting.

Metric Geometry and Gerrymandering Group Cambridge, MA
VRDI Instructor *Summer 2018, 2019*

- Organized and led student research groups during an eight week summer program on political redistricting for 80+ graduate and undergraduate students. Met with students daily and both generated and supervised a wide variety of research projects in computational, mathematical, and political topics.

Tufts University Medford, MA
Co-Instructor *Spring 2019*

- Co–taught STS 10: Reading Lab on Mathematical Models in Social Context. This is a reading and discussion based course focused on providing an STS perspective to students who are taking technically-focused modeling classes.

Massachusetts Institute of Technology Cambridge, MA
IAP Instructor *January 2019*

- Developed a four-week course on computational methods for political redistricting. The course incorporated cutting edge mathematical and computational techniques for analyzing gerrymandering.

Dartmouth College Hanover, NH
Instructor *September 2015 - May 2018*

- Designed syllabi and daily lectures. Wrote and graded homework, quizzes, and exams. Fully responsible for course content and material.

Math 36/QSS 36 - Mathematical Modeling in the Social Sciences *Fall 2017*

Data driven course exploring mathematical models and analysis techniques

UNSG 100 - Graduate Ethics Seminar *Fall 2017, 2016, 2015*

Seminar on ethical and professional issues in science and mathematics

Math 8 - Calculus of Functions of one and Several Variables *Winter 2017*

Second term calculus course covering infinite series, vector functions, and partial derivatives

Math 1 - Calculus with Algebra *Fall 2015*
Introductory calculus course with an emphasis on limits and differentiation

Teaching Assistant *September 2013 - June 2015*

· Held tutorial sessions three times per week. Graded quizzes and exams. Designed computing assignments and tutorials for linear algebra.
Math 23 - Differential Equations *Spring 2015*
Math 22 - Linear Algebra with Applications *Fall 2014*
Math 3 - Calculus *Winter 2014*
Math 12 - Calculus Plus *Fall 2013*

Washington State University Pullman, WA
Undergraduate Teaching Assistant *August 2012 - May 2013*

· Held tutorial sessions and graded homework and exams. Supervised a mathematical computing lab.
Math 320 - Modern Algebra *Spring 2013*
Math 330 - Secondary Teaching *Spring 2013*
Math 315 - Differential Equations *Fall 2012*

EDUCATIONAL OUTREACH

UW Data Science for Social Good Seattle, WA
Project Lead *Summer 2021*

· Designed and supervised a research project for four data science fellows on applications of ensemble methods to initial districting plan evaluation. The fellows gave a public presentation of their work and developed a user guide "Applying GerryChain: A Users Guide for Redistricting Problems" with accompanying website, case studies, and code examples to demonstrate good modeling practives and support other researchers working on these problems.

New Hampshire State Math Team Manchester, NH
Math Team Coach *Fall 2018–2020*

· Designed practice problems and preparatory exercises for the AMC exams, ARML, MMATH, and HMMT. Led monthly problem solving sessions and group activities.

LaTeX Workshops Hanover, NH
Organizer *Fall 2016–May 2018*

· Designed and presented a series of eleven one hour–long and two three hour–long workshops on mathematical typesetting in LaTeX with D. Freund and K. Harding. Resources and lesson plans

Crossroads Academy Math Team Lyme, NH
Math Team Coach *September 2015 – May 2018*

· Designed practice problems and preparatory exercises for the AMC exams, MathCounts, and MathLeague. Led weekly problem solving sessions and group activities. During 2015–17, the Crossroads team twice won the Chapter and State MathCounts and MathLeague competitions and placed first in Northern New England on the AMC-8.

New Hampshire State MathCounts Team Lyme, NH
Math Team Coach *March 2017 – May 2017*

· Designed practice problems and preparatory exercises for the national MathCounts exam. Led biweekly problem solving sessions and group activities. Students competed in the national competition in Orlando, Florida.

Johns Hopkins Center for Talented Youth Science and Technology Series Hanover, NH
Workshop Leader

· Developed and presented hour–long workshops for high school students.

Modern Cryptography (with D. Freund) *October 2014*
Forensic Accounting *April 2016*
Binary and Barcodes (with D. Freund) *April 2017*

Dartmouth College Exploring Mathematics Camp Hanover, NH
Co-Instructor

· Organized and presented week long math camps for high school students.
Mathematics of Games *August 2015*
Cryptography *July 2015*

RESEARCH PRESENTATIONS

Talks

1. Analysis Seminar, Pullman, WA *December 2021*
   Introduction to Graphons I and II
2. PPPA Research Colloquium, Pullman, WA *November 2021*
   Computational Methods for Evaluating Districting Plans
3. INFORMS Annual Meeting, Zoom *October 2021*
   Algorithms And Analysis For Centered Redistricting Plans
4. WSU Math Club, Pullman, WA *October 2021*
   Graphs, Geometry, and Gerrymandering
5. Civic Hackathon, Madison, WI *September 2021*
   Introduction to Computational Redistricting
6. Harvard Redistricting Algorithms, Law, and Policy Cambridge, MA *September 2021*
   Technical State of the Art for Computational Redistricting
7. ASA Joint Statistical Meeting, Zoom *August 2021*
   Computational Methods for Assessing Political Redistricting Reforms
8. New Mexico Redistricting Commission, Santa Fe, NM *July 2021*
   Markov chain ensemble metrics for evaluation of redistricting plans
9. Colorado College Summer Program, Colorado Springs, CO *June 2021*
   Computational Redistricting Analysis
10. WSU Seminar in Statistics, Pullman, WA *April 2021*
    Ensemble Analysis for the 2020 Redistricting Cycle
11. Princeton Gerrymandering Project, Princeton, NJ *March 2021*
    Computational Redistricting in 2021
12. Combinatorics, Linear Algebra, and Number Theory, WSU, Pullman, WA *March 2021*
    Gerry-Matchings and Pair-y-Mandering
13. JMM 2021, Washington DC *January 2021*
    Short Course: Mathematical and Computational Methods for Complex Social Systems
14. INFORMS Special Session on Fairness in Operations Research, Baltimore, MD *November 2020*
    Computational Methods For Assessing Districting Plans
15. WSU Seminar in Statistics, Pullman, WA *November 2020*
    Statistical and Computational Methods for Assessing Political Redistricting
16. Pi MU Epsilon Lecture, St. Michael's College, Colchester, VT *October 2020*
    Graphs, Geometry, and Gerrymandering
17. ADSA Annual Meeting, Zoom *October 2020*
    Geospatial Data for Political Redistricting Analysis

18. Common Experience Lecture, Texas State University, San Marcos, TX *October 2020*
Graphs, Geometry, and Gerrymandering
19. Combinatorics, Linear Algebra, and Number Theory, WSU, Pullman, WA *September 2020*
Representations of $SL_2(\mathbb{Z}/p^n\mathbb{Z})$ and spectral properties of Bethe trees
20. CGAD-GTOpt Seminar, Washington State University, Pullman, WA, *July 2020*
Geometric and Optimization Problems Motivated by Political Redistricting
21. Redistricting Conference 2020, Duke University, Durham, NC, *March 2020*
Multiresolution Redistricting Algorithms
22. Math Department Colloquium, College of Charleston, Charleston, SC. *February 2020*
Geospatial Data, Markov Chains, and Political Redistricting
23. Math Department Colloquium, Washington State University, Pullman, WA. *January 2020*
Geospatial Data, Markov Chains, and Political Redistricting
24. JMM 2020, Denver, CO. *January 2020*
Markov chains for sampling connected graph partitions
25. Math Department Colloquium, Pacific University, Forest Grove, OR. *January 2020*
The Mathematics of Nested Legislative Districts
26. MIT Graphics Annual Retreat, North Falmouth, MA. *October 2019*
Connected Graph Partitions and Political Districting
27. Topology, Geometry and Data Seminar, Ohio State University, Columbus, OH. *September 2019*
Hardness results for sampling connected graph partitions with applications to redistricting
28. Math Department Colloquium, Denison University, Granville, OH. *September 2019*
Graphs, Geometry, and Gerrymandering
29. Math Department Colloquium, Oberlin College, Oberlin, OH. *September 2019*
Graphs, Geometry, and Gerrymandering
30. Math Department Colloquium, College of Wooster, Wooster, OH. *September 2019*
Graphs, Geometry, and Gerrymandering
31. Math Monday Colloquium, Kenyon College, Gambier, OH. *September 2019*
Graphs, Geometry, and Gerrymandering
32. Applied Math Seminar, University of Massachusetts Lowell, Lowell, MA. *September 2019*
Hardness results for sampling connected graph partitions with applications to redistricting
33. Math Department Colloquium, Yale University, New Haven, CT. *August 2019*
Mathematical Challenges in Neutral Redistricting
34. Voting Rights Data Institute Seminar, Cambridge, MA. *June 2019*
A Friendly Introduction to Discrete MCMC
35. Voting Rights Data Institute Seminar, Cambridge, MA. *June 2019*
Graphs and Networks: Discrete Approaches to Redistricting
36. Math Department Colloquium, Dartmouth College, Hanover, NH. *April 2019*
Total Variation Isoperimetric Profiles and Political Redistricting
37. ACM Seminar, Dartmouth College, Hanover, NH. *April 2019*
Hardness results for sampling connected graph partitions with applications to redistricting
38. Unrig Summit Masterclass, Nashville, TN. *March 2019*
Legal and Math Deep Dive: Gerrymandering and Redistricting
39. MIT Graphics Seminar, Cambridge, MA. *March 2019*
Computational Challenges in Neutral Redistricting
40. JMM 2019, Baltimore, MD. *January 2019*
Matched Products and Stirling Numbers of Graphs
41. Societal Concerns in Algorithsm and Data Analysis, Weizmann Institute of Science, Rehovot, Israel. *December 2018*
Computational Problems in Neutral Redistricting
42. Math and Law of Redistricting, Radcliffe Institute, Cambridge, MA. *December 2018*
GerryChain and MCMC tutorials
43. Math Colloquium, Tufts University, Medford, MA. *November 2018*
Matched Products and Stirling Numbers of Graphs

44. MIT Graphics Annual Retreat, Dedham, MA. *October 2018*
Mathematical Challenges in Neutral Redistricting
45. SAMSI Workshop on Quantitative Redistricting, Duke University, Durham, NC. *October 2018*
Compactness Profiles and Reversible Sampling Methods for Plane and Graph Partitions
46. Election Teach–in, SMFA, Boston, MA. *October 2018*
Computational Challenges in Political Redistricting
47. STS Seminar, Tufts University, Cambridge, MA. *September 2018*
Mathematical Modeling of Social Connections
48. Voting Rights Data Institute Seminar, Cambridge, MA. *June 2018*
Introduction to Monte Carlo Methods
49. Mathematics Colloquium, University of Central Florida, Orlando, FL. *February 2018*
Dynamical Models for Multiplex Data
50. Mathematics Colloquium GVSU, Grand Valley, MI. *February 2018*
Random Walk Null Models for Time Series
51. Omidyar Fellowship Presentation, Santa Fe, NM. *January 2018*
Mathematical Embeddings of Complex Systems
52. Mathematics Colloquium at University of San Fransisco, San Fransisco, CA. *January 2018*
Dynamical Models for Multiplex Data
53. Mathematics Colloquium at Providence College, Providence, RI. *January 2018*
Dynamical Models for Multiplex Data
54. JMM, San Diego, CA. *January 2018*
Dynamical Modeling for Multiplex Networks
55. International Complex Networks Conference Lyon, France. *December 2017*
Multiplex Dynamics on the World Trade Web
56. Physics Colloquium at Washington University, St. Louis, MO. *October 2017*
Spectral Clustering on Multiplex Data
57. SIAM Annual Meeting, Pittsburgh, PA. *July 2017*
Permutation Complexity Measures for Time Series
58. Applied and Computational Mathematics Seminar, Hanover NH. *November 2016*
Random Dot Product Models for Weighted Networks
59. Inference on Networks: Algorithms, Phase Transitions, New Models and New Data, Santa Fe, NM. *December 2015*
Dynamically Motivated Models for Multiplex Networks
60. Applied Math Days, Troy, NY. *April 2015*
Multiplex Structure on the World Trade Web
61. Graduate Student Combinatorics Conference, Lexington, KY. *March 2015*
Total Dynamics on Multiplex Networks
62. Sixteenth International Fibonacci Conference, Rochester, NY. *July 2014*
Enumerating Distinct Chessboard Tilings
63. Dartmouth Graduate Student Seminar, Hanover, NH. *(Quarterly) 2013 - 2018*
Various Topics
64. Joint Mathematics Meeting, San Diego, CA. *January 2013*
Counting Combinatorial Rearrangements, Tilings with Squares and Symmetric Tilings
65. West Coast Number Theory Conference, Asilomar, CA. *December 2012*
Generalized Lucas Bases
66. Young Mathematician's Conference, Columbus, OH. *July 2012*
Combinatorial Rearrangements on Arbitrary Graphs
67. Northwest Undergraduate Mathematics Symposium, Portland, OR. *March 2012*
Combinatorial Rearrangements on Arbitrary Graphs
68. WSU Graduate Seminar on Combinatorial Geometry, Pullman, WA. *(Quarterly) 2012-2013*
Various Topics

Posters

1. SIAM Workshop on Network Science, Boston, MA. *July 2016*
   Generalized Random Dot Product Models For Multigraphs
2. Dartmouth Graduate Student Poster Session, Hanover, NH. *April 2016*
   Generalized Dot Product Models for Weighted Networks
3. Dartmouth Graduate Student Poster Session, Hanover, NH. *April 2015*
   Multiplex Structures in the World Trade Web
4. WSU SURCA, Pullman, WA. *March 2013*
   Empirical Analysis of Space Filling Curves for Scientific Computing Applications
5. WSU SURCA, Pullman, WA. *April 2012*
   Combinatorial Rearrangements, Restricted Permutations, and Matrix Permanents

HONORS AND AWARDS

- Dartmouth Hannah Croasdale Award *2018*
  College-wide award for the graduating Ph.D. student that best exemplifies the qualities of a scholar.
- Dartmouth Graduate Student Teaching Award *2017*
  College-wide award for the graduate student who best exemplifies the qualities of a college educator.
- Dartmouth Graduate Fellowship *2014–18*
- NSF Graduate Research Fellowship: Honorable Mention *2014, 2015*
- Dartmouth GAANN Fellowship *2013*
- WSU Morris Knebelman Outstanding Senior Award *2013*
- WSU Department of Mathematics Outstanding Senior *2013*
- WSU Emeritus Society Award in the Physical Sciences *2013*
- WSU J. Russell and Mildred H. Vatnsdal Memorial Scholarship *2013*
- WSU SURCA Crimson Award: Computer Science and Mathematics *2012, 2013*
- WSU Auvil Undergraduate Scholars Fellowship *2012*
- WSU Leonard B. Kirschner Scholarship *2012*
- WSU College of Sciences Undergraduate Research Grant *2012*
- Norma C. Fuentes and Gary M Kirk Award for Excellence in Undergraduate Research *2012*

PROFESSIONAL SERVICE

Peer Reviewer

- Election Law Journal
- Transactions on Signal and Information Processing over Networks
- Multiscale Modeling and Simulation: A SIAM Interdisciplinary Journal
- International Conference on Learning Representations (ICLR)
- International Conference on Artificial Intelligence and Statistics (AISTATS)
- AAAI Conference on Artificial Intelligence (AAAI)
- International Conference on Machine Learning (ICML)
- ACM-SIAM Symposium on Discrete Algorithms (SODA)
- Neural Information Processing Systems (NeurIPS)
- Transactions on Pattern Analysis and Machine Intelligence (TPAMI)
- Chaos: An Interdisciplinary Journal of Nonlinear Science
- Involve: A Journal of Mathematics
- Entropy
- MATCH Communications in Mathematical and in Computer Chemistry

Appendix B: Data and Materials

This appendix describes the data and materials that I relied on while performing this analysis and crafting this report.

B.i Data

The primary data sources and document repositories for the analysis in this report are publicly available, including the underlying geospatial data. I made use of data and documents from the following sources:

- Pennsylvania-specific geospatial data and annotations (https://www.redistricting.state.pa.us/maps/)

- Reports from the Pennsylvania Legislature (http://www.paredistricting.com/pcplan)

- Geospatial and population data from the U.S. Census Bureau (https://www.census.gov/geographies/mapping-files/time-series/geo/tiger-line-file.html)

- Filings in the 2018 *League of Women Voters* case [178 A.3d 737 and 181 A.3d 1083]

  – Court order and rulings

  – Data about the 2018 remedial map (https://www.pacourts.us/news-and-statistics/cases-of-public-interest/league-of-women-voters-et-al-v-the-commonwealth-of-pennsylvania-et-al-159-mm-2017, and http://www.redistricting.state.pa.us/Resources/GISData/Districts/Congressional/2018-Remedial/PDF/Feb-22-2018-Textual-Description-of-the-PA-Supreme-Courts-Remedial-Plan-Torres-006879.pdf).

- A block assignment file provided by Counsel for the GMS Plan.

- Shapefiles and reports describing the House passed map from the Pennsylvania Legislature (http://www.paredistricting.com/pcplan)

- Shapefiles, Dave's Redistricting App data, and analysis for the Governor's proposal (https://www.governor.pa.gov/congressional-districts-map-proposals/)

- For analyzing partisan fairness and minority effectiveness I relied on election and CVAP data prepared by counsel that I merged with the Pennsylvania Voting District and Block-level data. Additionally, for the VRA analysis, I also relied on mappings of voting districts to the proposed plans and population proration data for split voting districts and candidate lists containing races for the general and primary elections that were provided by counsel.

- Data from the Redistricting Data Hub, supplemented with data provided by counsel, to identify the locations of Congressional incumbents, in order to analyze pairings.

B.ii Computational Libraries

The bulk of the computational work for this report was carried out using standard libraries of the Python programming language. I also used the following more specialized packages for specific computational tasks.

- [MAUP github.com/mggg/maup

- [Gerrychain github.com/mggg/gerrychain

- [Geocompactness github.com/leehach/geocompactness

The Ecological Inference analysis was performed using the EiPack package in the R programming language. https://cran.r-project.org/web/packages/eiPack/index.html

Appendix C: Detailed Tables

District	Polsby-Popper	Convex Hull	Reock
1	0.364	0.802	0.360
2	0.320	0.787	0.265
3	0.322	0.731	0.467
4	0.275	0.823	0.291
5	0.381	0.844	0.351
6	0.268	0.723	0.400
7	0.393	0.778	0.463
8	0.314	0.776	0.454
9	0.298	0.772	0.398
10	0.471	0.917	0.379
11	0.479	0.901	0.557
12	0.317	0.827	0.347
13	0.233	0.700	0.264
14	0.274	0.815	0.544
15	0.424	0.863	0.438
16	0.350	0.795	0.320
17	0.178	0.727	0.417

Table 16: Compactness Scores by District in the GMS Plan

District	County
1	Bucks, Montgomery
2	Bucks, Philadelphia
3	Philadelphia
4	Berks, Montgomery
5	Delaware, Philadelphia
6	Berks, Chester, Delaware
7	Carbon, Lehigh, Monroe, Northampton
8	Lackawanna, Luzerne, Monroe, Pike, Wayne,
9	Berks, Bradford, Columbia, Luzerne, Lycoming, Montour, Northumberland, Potter, Schuylkill, Snyder, Sullivan, Susquehanna, Tioga, Union, Wyoming,
10	Adams, Cumberland, York
11	Lancaster, Lebanon, Dauphin
12	Bedford, Blair, Cumberland, Dauphin, Franklin, Fulton, Huntingdon, Juniata, Mifflin, Perry, Snyder
13	Blair, Cambria, Fayette, Greene, Westmoreland, Somerset,
14	Allegheny, Washington
15	Armstrong, Butler, Cameron, Clarion, Centre, Clearfield, Clinton, Elk, Forest, Indiana, Jefferson, McKean, Potter, Warren, Venango
16	Beaver, Butler, Crawford, Erie, Lawrence, Mercer,
17	Allegheny, Beaver

Table 17: Counties Wholly or Partially Contained in Each District in the GMS Plan

County	District
Allegheny	14, 17
Beaver	16, 17
Berks	4, 6, 9
Blair	12, 13
Bucks	1, 2
Butler	15, 16
Cumberland	10, 12
Dauphin	11, 12
Delaware	5, 6
Luzerne	8, 9
Monroe	7, 8
Montgomery	1, 4
Philadelphia	2, 3, 5
Potter	9, 15
Snyder	8, 12

Table 18: Counties that are Split in the GMS Plan

County	District
Philadelphia	2, 3, 5

Table 19: Sole Split City in the GMS Plan

Borough	County Boundary	Districts
Adamstown	Lancaster and Berks	9 and 11
Telford	Bucks and Montgomery	1 and 4
Trafford	Allegheny and Westmoreland	13 and 17

Table 20: Boroughs Splits in the GMS Plan to Preserve Counties

Township	County	Districts
Cheltenham	Montgomery	1, 4
Eulalia	Potter	9, 15
Greenfield	Blair	12, 13
Independence	Beaver	16, 17
Middletown	Bucks	1, 2
Newtown	Delaware	5, 6
Penn	Snyder	9, 12
Ross	Monroe	7, 8
South Newton	Cumberland	10, 12
South Park	Allegheny	14, 17
Spring	Berks	6, 9
Sugarloaf	Luzerne	8, 9
Swatara	Dauphin	11, 12
Tilden	Berks	4, 9
Worth	Butler	15, 16

Table 21: Townships Split in the GMS Plan

County	Ward	District
Allegheny	South Park District 02	14, 17
Berks	Spring District 11	6, 9
Blair	Greenfield District 02	12, 13
Bucks	Middleton District Lower	1, 2
Dauphin	Swatara District 10	11, 12
Delaware	Newtown Precinct 04	5, 6
Luzerne	Sugarloaf District 03	9, 8
Montgomery	Cheltenham District 02	1, 6
Philadelphia	Philadelphia Ward 25	2, 3
Philadelphia	Philadelphia Ward 26	3, 5
Philadelphia	Philadelphia Ward 39	3, 5
Philadelphia	Philadelphia Ward 46	3, 5
Philadelphia	Philadelphia Ward 52	3, 5
Potter	Eulalia District Eulalia	9, 15
Snyder	Penn District 01	9, 12

Table 22: Ward Splits in the GMS Plan

Unit	Actual Splits	Required by Population	Along County Boundary	Non-Intact
County	15	3	0	12
City	1	1	0	0
Town	0	0	0	0
Borough	3	0	3	0
Township	15	0	0	15
Wards	15	0	0	15

Table 23: Summary of Political Subdivision Splits in the GMS Plan

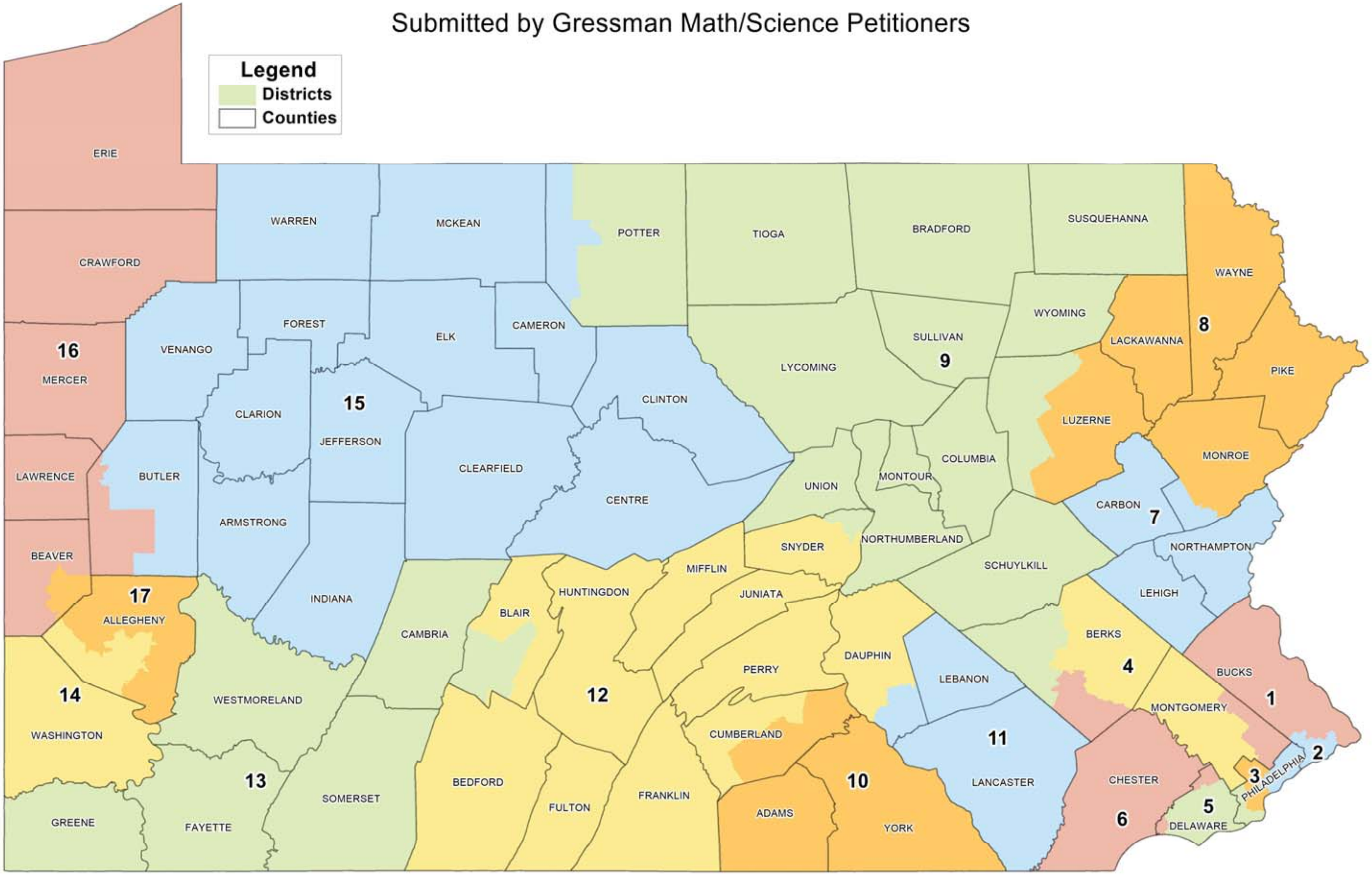
Unit	Minimum Number of Pieces	Total Number of Pieces
County	67	84
City	57	59
Town	1	1
Borough	955	958
Township	1,547	1,562
Wards	4,310	4,325

Table 24: Summary of Pieces in the GMS Plan

EXHIBIT 2

Proposed Congressional Map

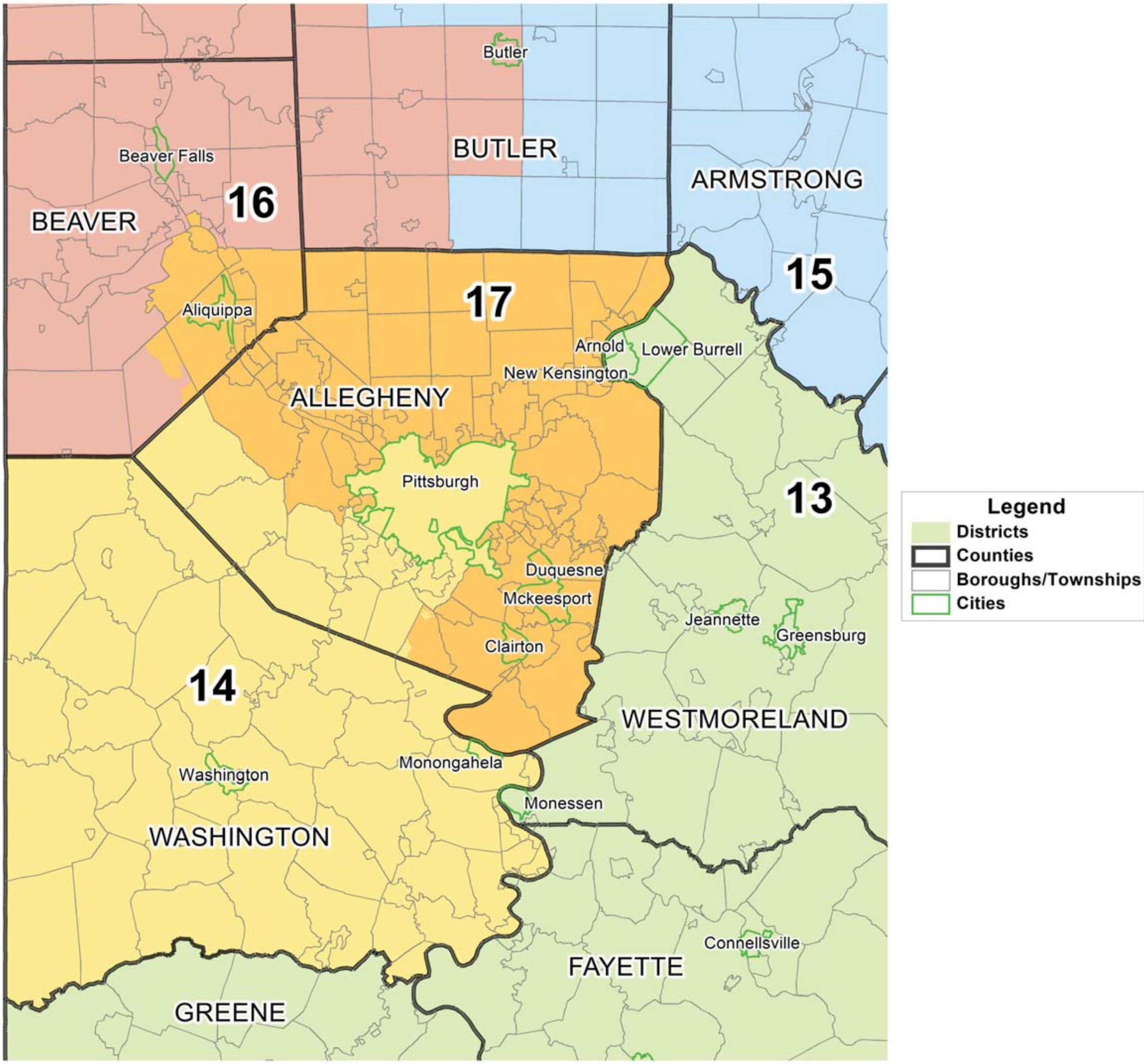
Submitted by Gressman Math/Science Petitioners



Carter v. Chapman, No. 464 M.D. 2021, and Gressman v. Chapman, No. 465 M.D. 2021.

Proposed Congressional Map: Southwest Region

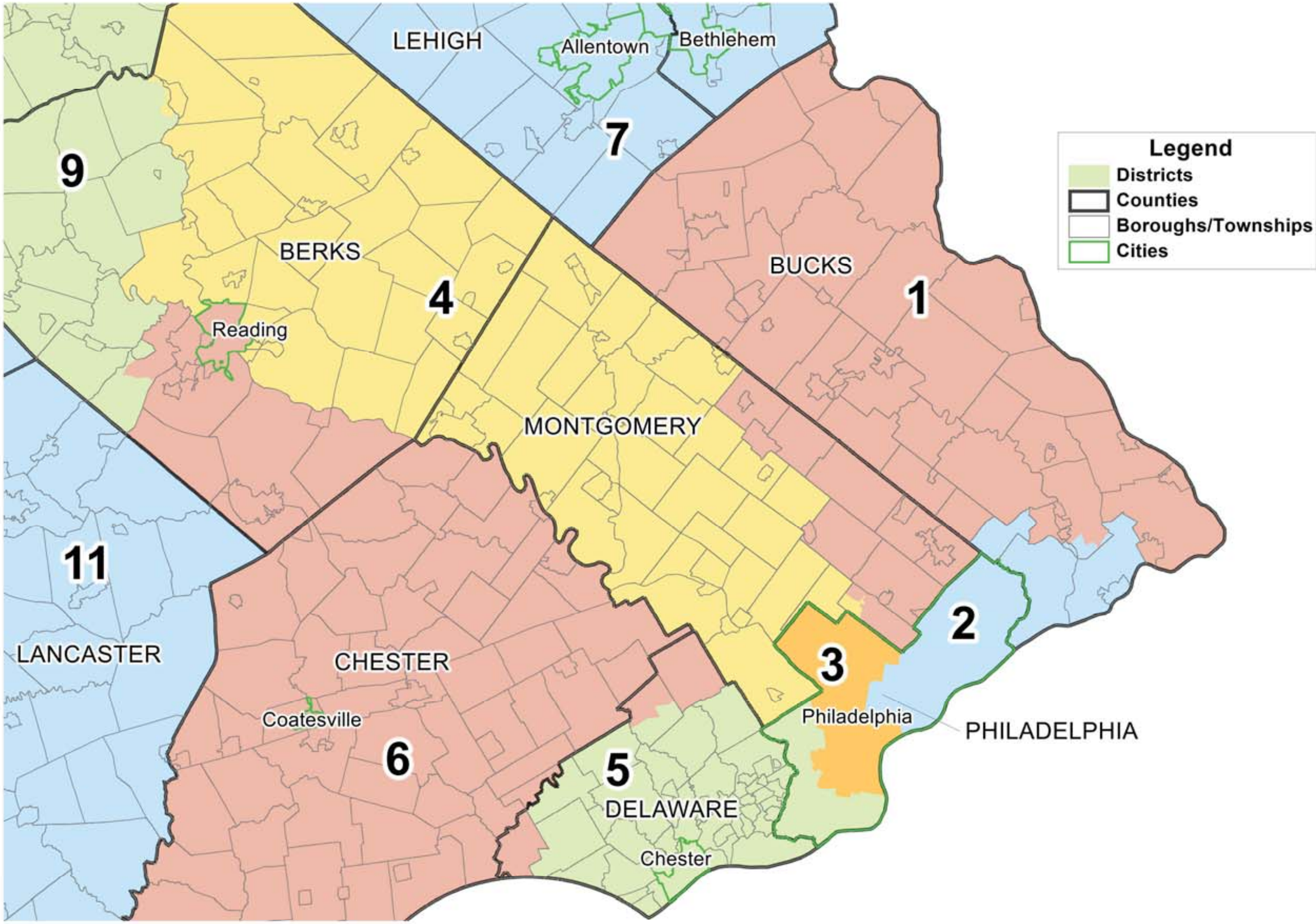
Submitted by Gressman Math/Science Petitioners



Carter v. Chapman, No. 464 M.D. 2021, and Gressman v. Chapman, No. 465 M.D. 2021.

Proposed Congressional Map: Southeast Region

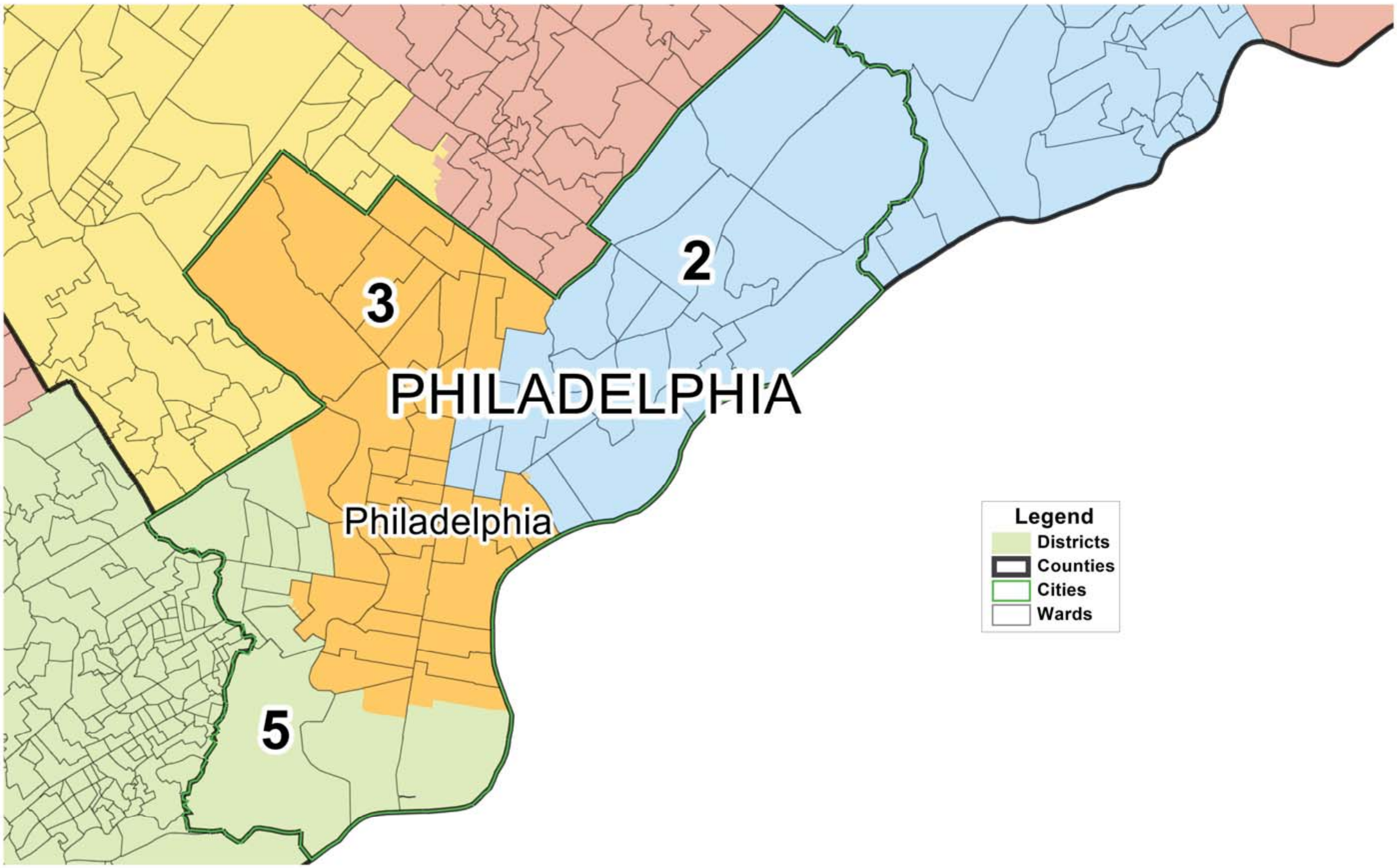
Submitted by Gressman Math/Science Petitioners



Carter v. Chapman, No. 464 M.D. 2021, and Gressman v. Chapman, No. 465 M.D. 2021.

Proposed Congressional Map: Philadelphia

Submitted by Gressman Math/Science Petitioners



Carter v. Chapman, No. 464 M.D. 2021, and Gressman v. Chapman, No. 465 M.D. 2021.