Estimating NOMINATE scores over time using penalized splines

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Abstract: DW-NOMINATE scores are the most widely-used measure of congressional legislators' positions in an abstract "ideology" space. By constraining how individual legislators' positions can change over their careers, DW-NOMINATE produces estimates that are comparable across time, allowing DW-NOMINATE scores to serve as the basis of much of the research on political polarization (for example Binder 2014; McCarty, Poole and Rosenthal 2006). However, recent studies have raised concerns about the plausibility of DW-NOMINATE's strong constraints on member's ideological trajectories and how those constraints

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affect inferences we make about polarization (for example Bateman and Lapinski 2016). In this paper, we develop Penalized Spline DW-NOMINATE (PSDW-NOMINATE), a new, flexible, approach to estimating the trajectories of legislators' ideal points over time within the NOMINATE framework. We use penalized spline functions (Eilers and Marx 1996, 2010) to model each legislator's ideal points over her career. PSDW-NOMINATE allows us to consider a continuum of degrees of constraint and to explore how the constraint that is placed on members' movements affects inferences about political polarization.

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1. Introduction

First introduced in 1997, DW-NOMINATE (Poole and Rosenthal 1997) scores have become the most widely-used measure of the positions of members of congress in an abstract "ideology" space. These scores are foundational to much recent empirical scholarship on the United States congress and are central to recent studies of political polarization in the United States.[1] DW-NOMINATE is appealing largely because it uses each legislator's entire roll call voting record to recover efficient and objective summaries of her choices in each legislative session that are generally highly predictive of voting on the important issues of the day and

[1]DW-NOMINATE scores are regularly used in news reports and commentary to describe to the extremity of individual members of the congress (for example Aguirre 2018), shifts in the ideologies of parties (for example Rakich 2018), or political polarization in historical contest (for example Krugman 2016). The term "DW-NOMINATE" appears in over 850 articles and books housed in the JSTOR digital library (`https://about.jstor.org/`). In the scholarly literature, the scores are used to assess polarization (e.g. Butler 2009; Carson et al. 2007; Farina 2015; Fleisher and Bond 2004; Han and Brady 2007; Heberlig, Hetherington and Larson 2006; Hirano et al. 2010; Krasa and Polborn 2014; McCarty, Poole and Rosenthal 2006; McTague and Pearson-Merkowitz 2013; Roberts and Smith 2003; Taylor 2003; Theriault 2006), to control for, or explain, legislators' ideological positions in studies of legislative behavior (e.g. Binder and Maltzman 2004; Brady, Han and Pope 2007; Broz 2005; Cameron, Kastellec and Park 2013; Carnes 2012; DeVault 2010; Gerber and Lewis 2004; Gailmard and Jenkins 2009; Griffin and Newman 2005; Hayes 2013; Jacobsmeier 2015; Jessee and Mahotra 2010; Kleinberg and Fordham 2013; Lee, Moretti and Butler 2004; Mian, Sufi and Trebbi 2010; Rocca, Sanchez and Uscinski 2008), and to study lawmaking and gridlock (e.g. Binder 2014; Jenkins and Monroe 2012; Miller and Overby 2010; Lebo, McGlynn and Koger 2007; Monroe and Robinson 2008; Roberts 2005; Schickler 2000) among other things.

which are comparable—under the maintained assumptions of the model—across time. As described below, DW-NOMINATE places very strong and unrealistic assumptions on members' over-time ideological trajectories. While these strong restrictions allow members to be placed in an way that is comparable over time, far weaker assumptions are sufficient for that purpose. In this paper, we present a new version of DW-NOMINATE that provides for comparable over-time measurements of members' ideologies that also allows their ideological positions to evolve flexibly over time.

DW-NOMINATE scores are predicated on a simple spatial model of political preference and voting. Each legislator is assumed to have a location in an abstract ideological or "basic" (Poole 1998) space. The space is generally taken to be two dimensional.[2] Each roll call vote is understood as a choice between two alternative positions. Legislators are assumed to probabilistically prefer alternatives that are closer to their locations—their "ideal points"—to alternatives that are farther away. For each roll call, a dividing line can be drawn through the space such that those members on one side of the line are expected to vote "yea" and those on the other are expected to vote "nay." Empirically, legislators' preferences, as revealed by their roll call votes on nearly every issue that congress considers, are powerfully summarized and predicted by their locations in this two-dimensional space.

Because members' locations are latent quantities, the scale, location, and rotation of the space in which they are placed is arbitrary; only the relative distances between members are identified by the data. Over short periods of time, such as a single congress, in which

[2]Adding further dimensions does not greatly enhance the fit of the model (Poole and Rosenthal 2000). Indeed, for much of US history, variation along the second dimension accounts for little of the voting in congress.

membership is largely static and members' location might be taken as fixed, the arbitrary choice of location, scale, and rotation of the two dimensions is of little consequence. However, the question of how to anchor the space over longer periods of time as membership churns and individual legislators' locations may evolve is a central challenge.

Poole and Rosenthal establish the comparability of DW-NOMINATE estimates over time by assuming that members' positions are either fixed over time ("constant" DW-NOMINATE) or allowed to move linearly through the space at a fixed velocity (the original DW-NOMINATE model).[3] These assumptions are restrictive and stronger than those required.

In this paper, we replace the linear trajectories assumed by DW-NOMINATE with penalized smoothing splines. By adjusting the smoothing parameter of the penalized smoother, we can continuously vary the constraint on members' ideal points over time from the case where member's locations are fixed over time to the case where no constraint is imposed. We call this new estimator Penalized Spline DW-NOMINATE, or PSDW-NOMINATE for short. This method of modelling ideal point dynamics is isomorphic to that employed by Martin and Quinn (2002), who model the ideologies of Supreme Court justices as a random walk over time. The smoothing parameter that governs the constraint in our model is analogous to the innovation variance in Martin and Quinn's random walk.

We also address two other long-standing challenges in the implementation of DW-NOMINATE. First, the DW-NOMINATE algorithm is computationally intensive. Our new approach uses parallel computing to speed estimation, allowing us to apply stricter convergence criteria than does Poole and Rosenthal's original implementation. Second, while the original linear-change

[3]In the linear change variant, Poole and Rosenthal also constrain the locations of members serving fewer than 10 years to be fixed.

DW-NOMINATE model defined the scale of the ideological space by (largely) restricting the space to the unit circle, it only constrains members' locations to be inside the unit circle in the middle of their careers. Long-serving members' linear over-time trends can carry them far outside of the unit circle to locations outside of the conceptual boundary of the space that shorter-serving members cannot reach (see Figure 2 and surrounding text below) . This strikes us as undesirable and unrealistic. We use contemporary optimizers to constrain the ideological locations of every member in each congress to fall inside the unit-circle boundary of the ideological space.

We apply this new estimator to all roll call votes taken from the 46th to the 115th United States congress (1879 – 2018). We estimate the model for a range of assumptions about how smoothly members' ideological locations change over time.[4] We then explore how dependent conclusions about legislative polarization are on these assumptions and also explore the distribution of over time ideological movement across members. These questions have been considered in recent work (Caughey and Schickler 2016; Clinton, Katznelson and Lapinski 2016; Bonica 2014), but we take a different approach by embedding the possibility of flexible ideal point dynamics directly inside the DW-NOMINATE model.

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[4]While the optimal degree of over-time constraint can be estimated using fit criteria, as is the case with many smoothing exercises, the choice of how much to smooth members' locations over time is ultimately subjective. Selecting the smoothing parameter involves a trade-off between allowing members' full measure of preference variability to be expressed and improving the efficiency of the estimates and the comparability of the ideological space over time. Too much constraint averages away real changes in members' locations. Too little makes a consistent over-time underlying choice of location, scale and rotation for the ideological space difficult (and, in the limit, impossible) to recover.

We follow Poole in considering what we are measuring to be a "basic" policy space. We will assume that members' locations on this basic space move relatively slowly over time and that way in which individual issues map onto this space can change over time. We take this "basic" space to be like a price index in that it measures on-average variation that should not be expect to reflect all changes at the level of every individual issue (or product in the case of a price index). A more detailed discussion of what DW-NOMINATE measures and how comparability of the scale over time is established see Appendix A. Given this perspective, the question then becomes how best to model the trajectory of each member's positions over time in a way that allows changes in members' locations to be detected while still maintaining the comparability of the underlying ideological dimensions across time. We present PSDW-NOMINATE as one such answer to this question.

We begin by briefly describing the workings of the DW-NOMINATE model and its assumptions that establish inter-temporally comparable ideological estimates. We then present PSDW-NOMINATE, our penalized spline approach to estimating overtime variation in a legislators' ideological locations over time. We then use our new estimator to study how varying the level of constraint that we place on legislators' positions across time affects the conclusions that we draw about ideological change at the individual, party caucus and chamber levels across the history of the US congress. We consider implications for our measurement of political polarization as well as how entry and exit, when compared with within legislator changes, contribute to political polarization. Finally, we demonstrate how our estimator allows for within subject designs—such as difference-in-differences designs—by estimating that presidential primary candidates from 1972–2016 move towards the "left", regardless of party, during the session they are vying for their party nomination.

2. The mechanics and varieties of DW-NOMINATE

The DW-NOMINATE algorithm estimates three sets of parameters: (1) the ideal point of each legislator i in some K-dimensional space at time t, $(x_{it1}, \ldots, x_{itK})$; (2) the bill parameters that govern the hyperplane that divides this K-dimensional space, which are the "outcome" points associated with the yea and nay votes on roll call j at time t, (O_{jkty}, O_{jktn}); and (3) the β and w_k hyperparameters, which govern the inverse variance of the random binary vote choices and the weight given to each of the k dimensions, respectively (Poole 2005). Here we restrict ourselves to the case where $K = 2$.[5]

The utility that the ith legislator associates with alternative $a \in \{y, n\}$ of rollcall j in the tth congress is defined as

$$U_{ijta} = \beta \exp\left(-\sum_{k=1}^{2} \frac{1}{2} w_k (x_{ikt} - O_{jkta})^2\right) + \epsilon_{ijta}$$

where $\epsilon_{ijta} \overset{i.i.d.}{\sim} N(0, \sqrt{2}/2)$. Accordingly, the probability of the ith legislator voting yea on the jth roll call taken in the tth congress is $\Phi\left(U_{ijty} - U_{ijtn}\right)$ where Φ is the standard Normal CDF. In order to establish the scale of the underlying space, $w_1 = 1$ and each legislator's ideal point is constrained to lie in the unit circle in the middle term of their time in congress $(x_{i\bar{t}_i1}, x_{i\bar{t}_i2})$. Additional constraints are placed on O_{jkty} and O_{jktn} such that at least one of the two outcomes falls inside the unit circle and the midpoint between the two alternatives falls inside the unit circle. The likelihood of the data given the parameters, L_{nom}, is simply

[5] In cases where $K = 1$, restrictions on parameters described as requirements to fall in the unit circle become restrictions to lie in the $[-1, 1]$ interval. For $K > 2$, these restrictions become restrictions to lie in the unit (hyper)sphere.

the product of the probabilities assigned to each vote made by each legislator over all of observed voting decisions.

Putting aside the constraints placed on the locations of the alternatives and ideal points, it is clear that because the utilities are functions of Euclidean distances between the ideal points and alternatives, the same utility values obtain under any distance-preserving transformation (such as a shift or rotation) of the ideological space. Thus, the likelihood does not uniquely identify the parameters of the model. The various constraints outlined above help to identify the space by establishing its scale. While full treatment of the sufficient set of restrictions required for exact identification of DW-NOMINATE's parameters is beyond the scope of this paper, it should be clear that this identification problem is particularly vexing with respect to comparing members' locations over time. If members' locations are allowed to vary freely across time and if no restrictions are placed on how the votes on the same topic divide the ideological space over time, the likelihood can be optimized congress-by-congress.[6] However, because the space recovered for each congress would then depend on an independent choice of scale and rotation, there is no reason to suppose that the recovered locations would be comparable from one congress to another. This problem and its consequences are discussed in Appendix A.

In order to establish the comparability of the recovered space across time, the varieties of DW-NOMINATE impose constraints on how members' locations can change over time. These constraints cause the votes taken by a member in one Congress to affect the their estimated locations in other congresses in which they serve. Consequently, with these constraints, the overall likelihood cannot be broken into congress-by-congress optimizations as

[6] Conditional on the hyperparameters, w and β.

long as every session has a sufficient number of returning members from the last (as is the case in the US congress).[7] Thus, these constraints overcome the incomparability problem that arises when the likelihood can be optimized congress-by-congress. If the assumed dynamics are correct, it is then possible to compare the estimates from one congress to the next and, by transitivity, each congress to any other congress.[8]

In the DW-NOMINATE algorithm, these three sets of parameters—the legislators' ideal points, the bills' outcome points (which are a simple reparameterization of the roll call's cutting line), and the β, w_1 and w_2 hyperparameters are estimated sequentially. This means, given the set of roll calls cast by each member, the algorithm holds the bill parameters and hyperparameters fixed while estimating the ideal points that best explain a member's roll calls. Then, given those new ideal points and the same hyperparameters, the bill parameters that best explain the set of votes cast by members on that bill are estimated. Then, the hyperparameters are estimated given the new set of ideal points and bill parameters. This three-step process is then repeated several times until the overall improvement in fit is small.

There are three variants of DW-NOMINATE that are commonly used today. All three set the dimensionality, K, to two and fix the weight on the first dimension, w_1, to one. The first

[7]Three members is sufficient in two dimensions (for rigorous treatment of this problem in close related setting see Rivers 2003).

[8]If a sufficient number of members serve in both the House and the Senate over their careers and if their locations sufficiently constrained as they move from one chamber to the other, then locations estimated for the House and Senate are also comparable. If, however, no constraint is placed on how members' locations change when they move from one chamber to another then the likelihood could be optimized chamber-by-chamber and scales would not be comparable across the chambers.

and most commonly used set of estimates is the "common-space constant" DW-NOMINATE ideal point scores, for which a legislator's ideal point is held constant over their tenure. The second, "linear change" DW-NOMINATE estimates, allow legislators to move through the two-dimensional space over time along straight lines. The third, "Nokken-Poole" DW-NOMINATE estimates, allow legislators to have new positions in each congress. In order to solve the indeterminacy problem mentioned above, Nokken and Poole (2004) estimate these congress-specific legislator ideal points by fixing the bill parameters and hyperparameters to values estimated by the "common-space constant" algorithm. We discuss these three commonly used varieties of DW-NOMINATE in turn.

2.1. The "common-space constant" model

In the "common-space constant" model, members of the House and Senate are jointly estimated and the positions of legislators are fixed over time.[9] Thus, these DW-NOMINATE estimates only return one ideal point, (x_{i1}, x_{i2}), for each member and these ideal points are constrained to fall within the unit circle that defines the DW-NOMINATE ideological space. Note that the two-dimensional ideological space is often portrayed as an ellipse rather than a unit circle. This is due to the second dimension weight, w_2, being around half the size of the first-dimension weight (fixed to one). When this weight is applied in the visualization to make the importance of distances between pairs of displayed points along each of the two dimensions comparable, the second dimension is squeezed. Furthermore, as mentioned

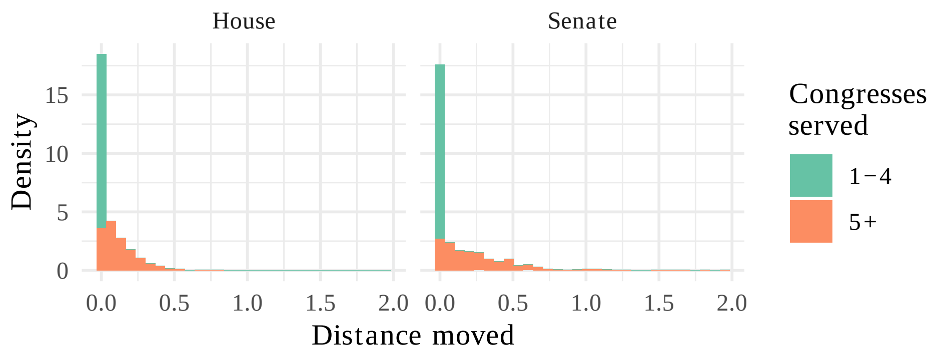
[9]An exception being where members change major parties, such as Senator Strom Thurmond. After a dramatic party change, these members are treated as entirely new legislators entering congress.

above, the bill parameters are also constrained so that one of the outcome locations, either the yea or the nay outcome point, are within the unit circle and the midpoint between the yea and nay outcome points falls in the unit circle. This guarantees that the line that divides those expected to vote yea from those expected to vote nay also cuts through the unit circle. Of course, the main shortcoming of this method is that all legislators are treated as fixed throughout their tenures. While the assumption is sufficient to establish the comparability of the estimated locations over time, it is far stronger than is required.

2.2. The "linear change" model

The "linear change" model relaxes the constraint that members have one ideal point throughout their tenures and allows those that served in at least five congresses (more than 8 years) to move in a linear fashion. Formally, fixing the locations of those serving in fewer than five congress is sufficient to establish the comparability of the space of over time. However, in practice and as shown below, if longer-serving members' locations are then allowed to vary freely, the congress-to-congress variation in the estimated locations for those members is sufficiently large to suggest that the space is not well-established by fixing the locations of short-serving members alone. Figure 1 shows the distribution of movements by members of congress from 1879–2014 as estimated by the linear-change DW-NOMINATE model. The large green bar at zero indicates the large plurality of members who served in fewer than five congresses and are unable to move. Meanwhile, other members of congress in the right tail of the distribution move enough to span nearly the entire DW-NOMINATE ideological space—i.e., their total movements are near to or greater than one.

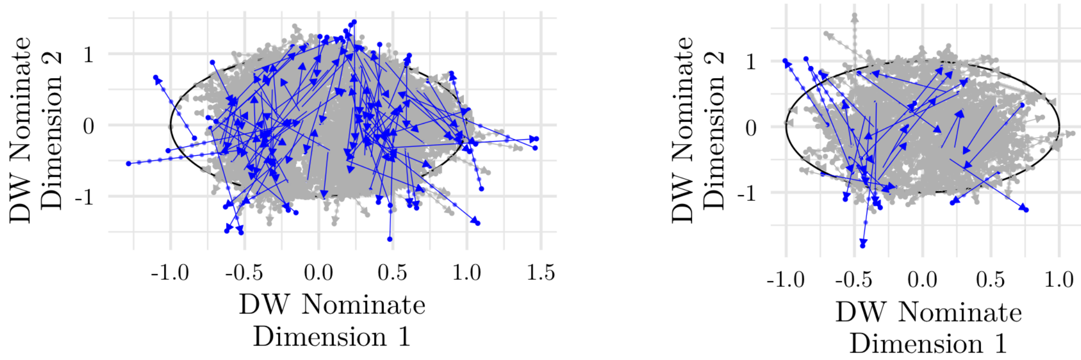
Figure 1: Distribution of legislators by total career distance traveled in NOMINATE scores from "linear change" model



This figure plots the distribution of legislators by how much they moved along the NOMINATE 1st dimension over their entire career. We take the absolute value of each session-to-session change in the "linear change" DW-NOMINATE model and sum it over each legislator's career. Note that we stack those who served fewer than 5 congresses in another color as they are unable to move at all and thus their total career distance is fixed at 0.

The linear change model, while attractive because it relaxes the unrealistic constraint that members do not change ideological positions over their tenures, has two shortcomings. First, as implemented by Poole and Rosenthal, members are only constrained to have the midpoint of their ideal point trajectory within the unit circle. Figure 2 shows the trajectories of all members of congress from 1879 to 2014, estimated with the linear-change model. The members in blue, who are in the top five percent of movement over their tenures, often start outside or leave the circle. Second, linear movements are unlikely to capture the true dynamics of how members' voting behavior changes over their tenures. While the linear change model is far less restrictive than the constant model and does establish comparable measurements over time, it is still unnecessarily restrictive.

Figure 2: “Linear” DW-NOMINATE positions of every member in every congress, 1879–2014



(a) House (b) Senate

Every dot represents the estimate DW-NOMINATE location of a member in given year. The dots representing the same member over time as connected by a line. The arrowhead on each line gives the direction of movement. The blue dots and lines represent the trajectories of the fastest-moving 5 percent of all Senators and House members. Notice that dots frequently appear outside of the ellipse that DW-NOMINATE uses to bound the positions of the members whose locations are fixed and to bound the location of the midpoint of every member’s line of locations.

2.3. Nokken-Poole Scores

“Nokken-Poole” scores further relax constraints placed on the movements of members by allowing them to have a separate ideal point for each congress in which they voted (See Nokken and Poole 2004). In order to establish a comparable scale across time, Nokken and Poole (2004) take a partial likelihood approach. To estimate members’ congress-wise ideal points, they hold fixed the yea and nay bill parameters and hyperparameters at the values estimated by the “common-space constant” DW-NOMINATE algorithm and then find the optimal locations of every member in every congress resulting in distinct ideal point estimates for each member in each congress. While not arising from an internally coherent statistical model because the locations of the alternatives are not estimated under the same assumptions as the members’ locations, Nokken-Poole scores do allow members’ locations to evolve flexibly over time. They are also useful for assessing the assumption that members' locations are fixed across their careers by estimating how much each member's trajectory would deviate from constancy if allowed to do so while holding all other members' locations fixed over time.[10]

2.4. Comparing various DW-NOMINATE estimates

In Table 1, we present the correlations of the three different DW-NOMINATE scores by party for the first NOMINATE dimension; we also include correlations with the PSDW-NOMININATE scores that we discuss below. On the whole, the correlations among the three canonical DW-NOMINATE models are quite high—they range from 0.82 for the correlation between Nokken-Poole and the constant model for Republicans to 0.93 for the linear change model and the constant model for the Democrats. In Table 2, we present the same correlations but for the second NOMINATE dimension. Again, the correlations among the different DW-NOMINATE models are quite high. Furthermore, while the correlations are slightly higher for the Democratic party, all correlations across dimensions and parties tend to be close to 0.9.[11].

In Panel (a) of Figure 3, we present the ideal point trajectories of all legislators in the House and Senate from the 46th congress until the 113th congress (1879–2014) for the three

[10]This is in fact the logic under which Nokken and Poole employ the estimator. They consider whether the small number of legislators across US history who switch parties during their congressional careers appear to deviate more strongly from the constancy assumption when it is relaxed for them than do other members (Nokken and Poole 2004).

[11]When we combine all members regardless of party, the correlations are even stronger, with 0.96 the lowest for the first dimension and 0.86 the lowest for the second dimension

Table 1: Correlation in NOMINATE first dimension across models by party

	Democratic party						
	DW			PS-DW			
	Constant	Linear	Nokken-Poole	Lambda=0	Lambda=500	Lambda=10^4	Lambda=10^7
Constant DW	1						
Linear DW	0.93	1					
Nokken-Poole DW	0.85	0.92	1				
PS-DW (Lambda=0)	0.76	0.78	0.85	1			
PS-DW (Lambda=500)	0.87	0.89	0.88	0.87	1		
PS-DW (Lambda=10^4)	0.89	0.86	0.81	0.8	0.93	1	
PS-DW (Lambda=10^7)	0.91	0.83	0.76	0.76	0.86	0.95	1
	Republican party						
	DW			PS-DW			
	Constant	Linear	Nokken-Poole	Lambda=0	Lambda=500	Lambda=10^4	Lambda=10^7
Constant DW	1						
Linear DW	0.89	1					
Nokken-Poole DW	0.82	0.91	1				
PS-DW (Lambda=0)	0.79	0.73	0.8	1			
PS-DW (Lambda=500)	0.89	0.82	0.81	0.88	1		
PS-DW (Lambda=10^4)	0.92	0.81	0.77	0.82	0.96	1	
PS-DW (Lambda=10^7)	0.95	0.8	0.74	0.81	0.91	0.97	1

In this table we present correlations by party. If we pool the parties together and include independents and members of other parties, every single correlation is greater

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Table 2: Correlation in NOMINATE second dimension across models by party

	Democratic party						
	DW			PS-DW			
	Constant	Linear	Nokken-Poole	Lambda=0	Lambda=500	Lambda=10^4	Lambda=10^7
Constant DW	1						
Linear DW	0.94	1					
Nokken-Poole DW	0.87	0.93	1				
PS-DW (Lambda=0)	0.85	0.84	0.89	1			
PS-DW (Lambda=500)	0.91	0.86	0.82	0.89	1		
PS-DW (Lambda=10^4)	0.93	0.85	0.8	0.86	0.98	1	
PS-DW (Lambda=10^7)	0.97	0.89	0.83	0.86	0.95	0.98	1

	Republican party						
	DW			PS-DW			
	Constant	Linear	Nokken-Poole	Lambda=0	Lambda=500	Lambda=10^4	Lambda=10^7
Constant DW	1						
Linear DW	0.93	1					
Nokken-Poole DW	0.82	0.89	1				
PS-DW (Lambda=0)	0.78	0.79	0.86	1			
PS-DW (Lambda=500)	0.92	0.89	0.83	0.87	1		
PS-DW (Lambda=10^4)	0.93	0.85	0.77	0.79	0.96	1	
PS-DW (Lambda=10^7)	0.95	0.87	0.78	0.78	0.93	0.98	1

In this table we present correlations by party. If we pool the parties together and include independents and members of other parties, the majority of the correlations are greater, and no correlation dips below 0.80

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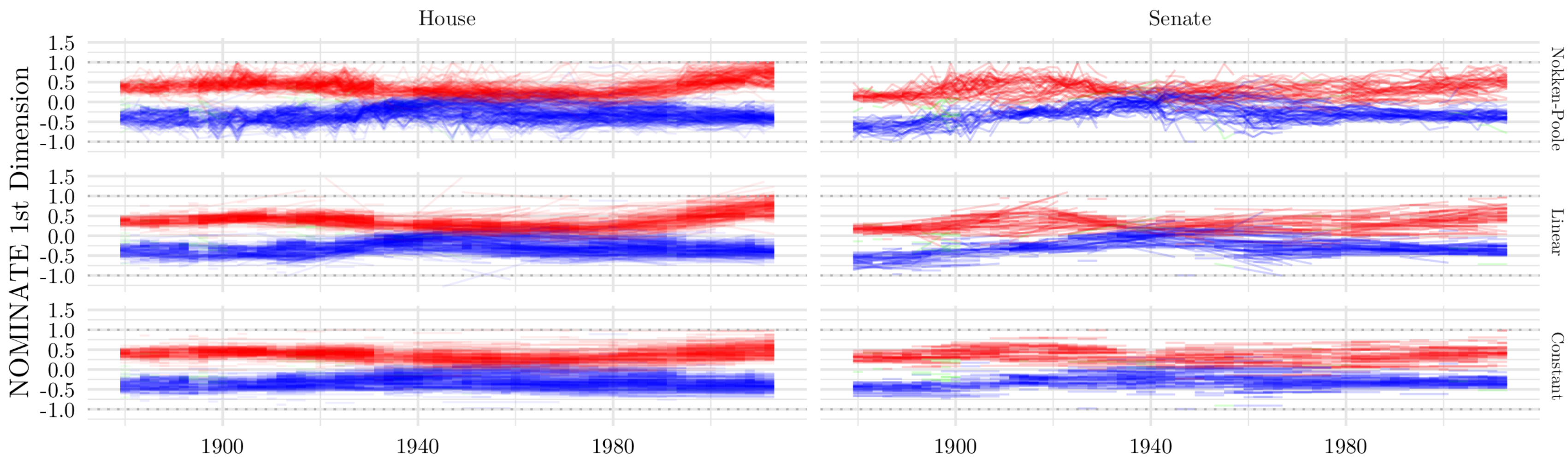
canonical DW-NOMINATE models produced by Keith Poole.[12] In the first row we present the Nokken-Poole estimates, in the second row we present the "linear change" model, and in the third row we present the "common-space constant" model. On the y-axis is the first dimension NOMINATE ideology score. The x-axis shows the congress. Each line in the figure represents a single legislator's trajectory over time. Republicans are colored red, Democrats blue, and all independents and other parties are colored green.

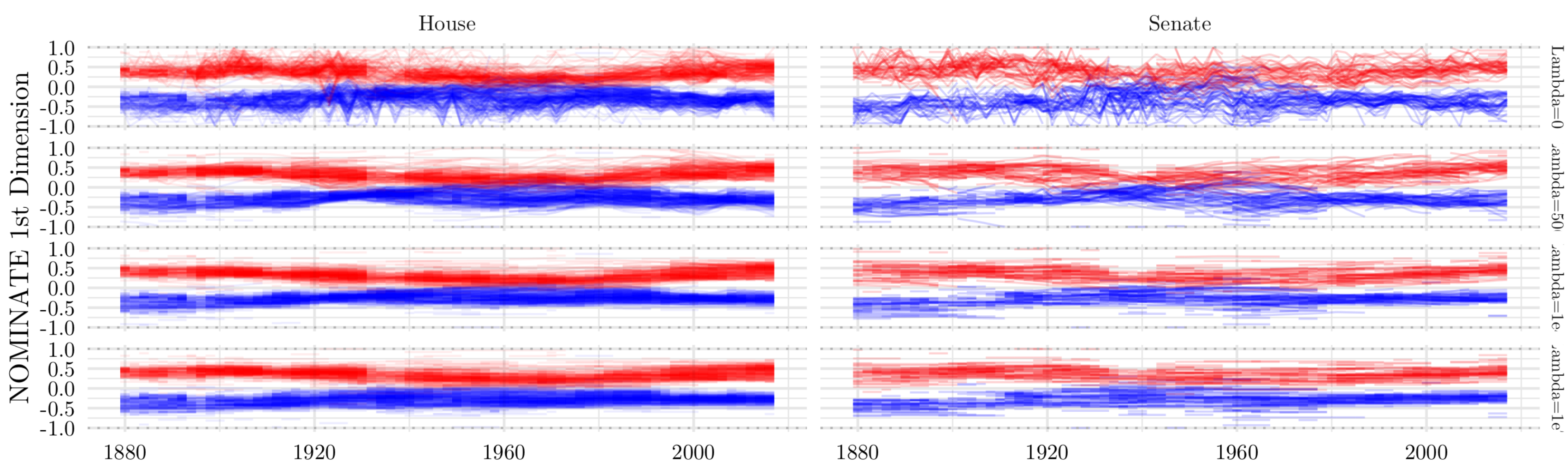
There are three main insights from panel (a). First, all three show general patterns of the Republican and Democratic parties moving away from one another in recent periods after being relatively close in the post-World War II era. We return to this in Section 4 where we further discuss polarization. Second, as shown in the ellipses in Figure 2, some legislators end up outside of the unit circle in the "linear" DW-NOMINATE model (with first dimension NOMINATE estimates greater than 1 or less than -1). Third, the Nokken-Poole estimates are far more volatile than the other estimates. While allowing this underlying movement may improve the fit of the model, it is unlikely that the ideology of legislators is actually moving in this way and instead we may be overfitting the ideal points to congress-specific voting histories. We present our new estimator, PSDW-NOMINATE to address the limitations of these models and produce flexible, yet reasonable, estimates of legislator trajectories over time.

[12]Data is archived at `https://legacy.voteview.com/`.

Figure 3: DW-NOMINATE and PSDW-NOMINATE ideal point trajectories over time



(a) DW-NOMINATE



(b) PSDW-NOMINATE

Each congress is represented as the first year in which that congress met (e.g. the 46th congress is represented as 1879). Each line represents one member of congress.

3. PSDW-NOMINATE: using P-splines to model legislators' positions across time

We propose using P-splines (see Eilers and Marx 1996, 2010) to more reasonably and flexibly model the trajectory of each legislator's ideal point across her career. Rather than assume the members of locations are fixed as in the constant DW-NOMINATE model or that their locations track linearly as in the linear DW-NOMINATE model, we model each member's location using P-splines with a discrete penalty.

3.1. P-spline functions

Our objective is to provide a general, flexible and tunable method for allowing members' locations to evolve smoothly over time that maintains the comparability of the underlying scale. Following Poole and Rosenthal, we treat time as discrete. That is, we assume that each legislator has a location $(x_{i1}(t), x_{i2}(t))$ for each time period $t = 1, 2, \ldots, T_i$ where T_i represents the last congress in which member i served and t is defined such that the first congress in which each member serves is $t = 1$.[13] Again following Poole and Rosenthal, we consider members' locations to be fixed within any given congress.

In order to constrain/smooth each member's over-time trajectories without making strong

[13] Note that we define t in term of the congresses since a member's first election even if that member's period of service is interrupted. For example, a House member who is defeated for reelection after her first term, returned to the House two year's later, and then retires after her second term in office will have $T_i = 3$ even though she did not serve in the congress for which her $t = 2$.

parametric assumptions about those trajectories, we employ a special case of Eilers and Marx's 1996 penalized spline smoother. This special case was originally introduced by Whittaker (1922) and is sometimes referred to as Whittaker smoothing. More recently, Eilers (2003) has referred to it as "a perfect smoother." The special case arises because we need only evaluate each member's location at a discrete set of evenly-spaced points in time ($t = 1, \ldots, T_i$). In particular, we fit a zero-degree basis for the spline with knots located at each of the T_i periods for each member i. The choice of a zero-degree basis for the spline is not restrictive because we need only evaluate the function at the discrete set of points at which we have placed knots; therefore how the spline interpolates the points between knots is irrelevant. Now we can simply write

$$x_{i1}(t) = x_{i1t} \text{ and } x_{i2}(t) = x_{i2t}.$$

Note that the coefficients of the spline function are just the parameters that describe each member's ideal point at each period in time. So far, all we have is a long-winded way of describing a model in which each member's location in each congress is freely estimated as each congress is a knot in the spline and the time between congresses is not of interest. As discussed above, this model is not identified without further restriction. To constrain and smooth members' locations across time requires the imposition of the P-spline's difference penalties. In particular, we add an additional term to the log-likelihood, $\ln L_{nom}$, defined above, that penalizes differences in the coefficients on the spline's basis functions, which in this case is simply a penalty on changes to each of the two coordinates describing each legislator's location in each congress in which they serve:

$$S = \ln L - \lambda \left(\sum_{i=1}^{N} \sum_{t=2}^{T_i} \sum_{k=1}^{2} (x_{ikt} - x_{ik(t-1)})^2 \right). \tag{1}$$

When $\lambda = 0$, no penalty is imposed and each legislator's location is freely estimated in each congress. As λ grows very large, each legislator's ideal point is held constant across time. At intermediate values the of λ, each member's trajectory follows a smoothed path that falls between the unconstrained trajectory associated with $\lambda = 0$ and the fixed location enforced when $\lambda = \infty$. The amount of smoothness that λ dictates is a function of the curvature of the log-likelihood. As the amount of information in the voting data increases, the effect of the penalty diminishes. Note that we assume that the penalty is ansiotropic (moves in any direction are penalized equally).

We hold fixed the positions of all legislators whose last congress is fewer than 10 years since their first congress—i.e., $T_i < 5$. This is similar to the constraint Poole and Rosenthal place on legislators who served fewer than 10 years, although again we allow members whose tenures were interrupted to move so long as their first and last sessions are 10 years apart. This constraint is important to improving the stability of estimates; without this constraint, there is a much larger set of scales, locations, and rotations of the space that would allow for very similar fits over time. Furthermore, when $\lambda = 0$, there is no other constraint on the movement of legislators, and the space would be unidentified as discussed above.[14]

Figure 4 provides an initial illustration of how λ smooths the estimates of members' lo-

[14]Note that there is nothing particularly special about having served 10 years. Other minimum lengths of time are also possible.

cations over time. The figure shows the estimated evolution of Senator Kenneth McKellar's location over his 36-year career for various values of λ. A well-known Democratic Senator of his time, McKellar represented Tennessee. Pope's (1976) careful historical account of McKellar career, relying on interviews and the documentary record, suggests that McKellar's views became increasingly conservative on the sorts of economic issues captured by NOMINATE's first-dimension as he moved away from supporting Roosevelt's New Deal programs that he had backed earlier in his career (Pope 1976, Chapter 6). That same historical treatment notes that McKellar took strong segregationist positions on votes in the 1940s (Pope 1976, Chapter 6) suggesting that his 2nd Dimension NOMINATE score might be expected to shift during the later part of his career as well.[15] We choose McKellar to illustrate how member's over-time trajectories are affected by choice of λ because he is among the members whose estimated position is the most dynamic.

In sub-figure (a), we plot how McKellar moves over time along each dimension; in the top panel we plot movement along the first dimension and in the bottom panel we plot movement along the second dimension. In each panel, we have different lines for four different values of λ, from 0 where movement congress-to-congress is unconstrained by the penalty, to 10,000,000 (10^7) where the penalty prevents almost all movement. For the values of λ where movement is possible, we see that McKellar moves in a way consistent with Pope's historical account and with many Southern Democrats in the post-World War II period: towards the center on the first dimension and and towards 1.0 on the second dimension. Along the first dimension, we see that values of λ below 10^7 allow McKellar to move from around -0.3 to -0.1,

[15]Poole and Rosenthal (1997) observe that the second DW-NOMINATE dimension is associated with issues of race during this time period.

as he moves towards the Republican party. Similarly we see McKellar moving towards 1.0 on the second dimension. In both panels, as λ increases, the estimated trajectory becomes smoother and smoother. When λ is 10^7, there is essentially no movement, and thus McKellar starts his career more conservatively (more positive on the first dimension) and with a higher value on the second dimension than in the models where he is allowed to move that way later in his career.

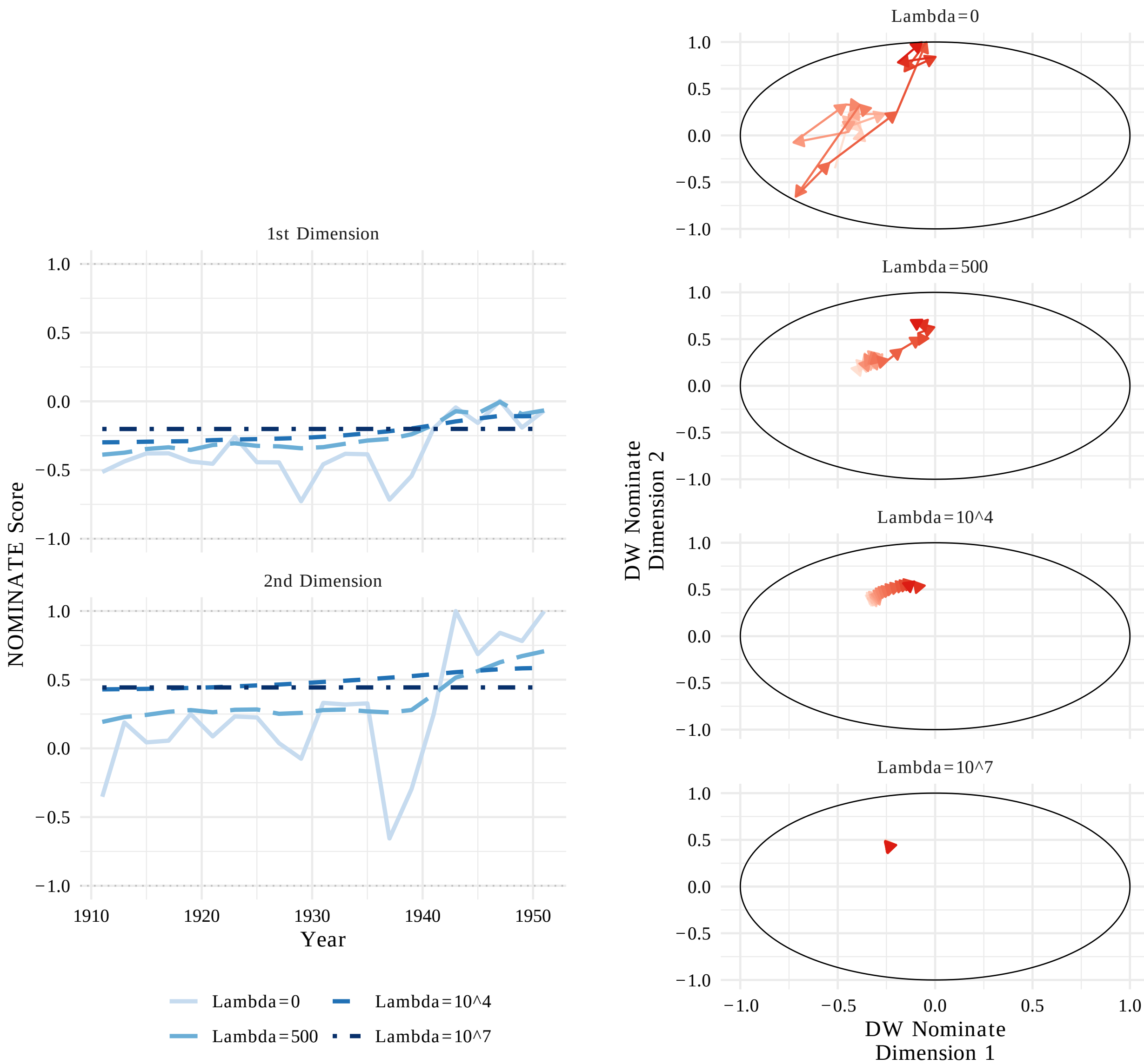
Sub-figure (b) plots McKellar's trajectory along both dimensions within the NOMINATE two-dimensional space. Each panel represents McKellar's trajectory at a different value of λ; the arrows indicate the new location McKellar moved to each session, and the lines become a darker red as time passes. We can see that as λ increases, the movement towards the center on the first dimension and movement towards 1.0 on the second dimension becomes much smoother.

Inspection of (1) also reveals that this formulation of the P-spline is equivalent to the placing a Gaussian random walk prior on each member's locations over time (see Eilers, Marx and Durbán 2015, p. 150). It is easily shown that λ is equivalent to $\frac{1}{2\Delta^2}$ where Δ^2 is the innovation variance of the equivalent Gaussian random-walk prior.[16] Gaussian random walk priors are used by Martin and Quinn (2002) to identify (establish the comparability of) the ideological locations of US Supreme Court Justices space over time.

Given the intuitive nature of the random walk prior formulation of this approach to smoothing and fact that the random walk priors have been used in the context of establishing comparable over-time ideal point in the literature, one might wonder why we go to the trouble constructing this estimator using the logic of P-splines. We do this for two reasons.

[16]The Gaussian random walk prior defines $x_{ikt} \sim N(x_{ik(t-1)}, \Delta^2)$.

Figure 4: Increasing lambda smooths a member's movement over time



(a) Each dimension over time

(b) Movement in both dimensions

This figure shows the trajectory of Kenneth McKellar, a long-serving Democrat from Tennessee. In figure (a), the top panel shows his movement in the first dimension over time and the bottom panel shows his movement along the second dimension over time. In figure (a), we present trajectories for four different values of λ, with the color and type of the line representing the different values of λ. Each congress is represented as the first year in which that congress met (e.g. the 62nd congress is represented as 1911). In figure (b), we plot how McKellar's ideal point moves over time in both dimensions at the same time. Each panel represents a different value of lambda, and the lines and arrows get darker for later years in McKellar's career.

First, we did not want to reinterpret DW-NOMINATE as a fully Bayesian model. Given the many complex constraints placed on the various parameters in the model (described above), this seemed like an unnecessary challenge. Second, the P-spline logic can be extended to the case in which members' locations are allowed to evolve continuously through each congress in a way that is less computationally intensive than would be the case for the random walk prior. Bonica (2014) considers this sort of within-congress movement to members' locations using a very different approach and is able to address interesting questions that cannot be answered using models that assume members' locations are fixed within a given congress. With the P-spline framework, a higher-order set of basis splines with a specified number of evenly spaced knots that is much fewer than the number of legislative days could be combined with difference penalties to compactly, yet flexibly, model legislator's day-by-day ideological movements. We leave this extension for future work.

In addition to the "roughness" penalty on the ideal point trajectories, we also constrain the ideal point paths such that they can never escape the unit circle. Further, we follow Poole and Rosenthal in constraining the parameters associated with each roll call as described above, ensuring that cutting lines intersect the unit circle. These constraints are imposed using inequality constraints within the SLSQP numerical optimization algorithm (Kraft 1988) as implemented in Python's (Python Core Team 2018) SciPy (Jones et al. 2001–) package.[17]

[17]All software and data used in this paper is available at `http://github/voteview/pynominatedyn`.

3.2. Smoothing legislator's ideal-point estimates across time

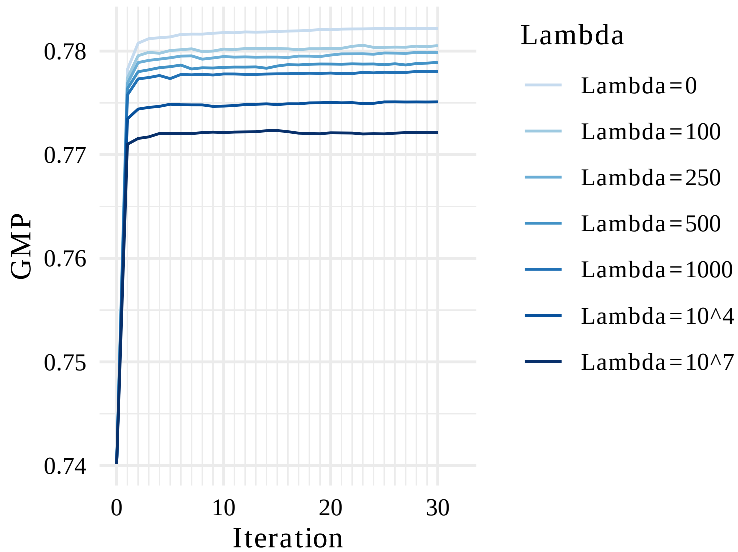
We estimate PSDW-NOMINATE using the history of roll call votes from the 46th to the 115th congress (1879 – 2018).[18] We take the latest run of the common-space constant DW-NOMINATE model on Voteview.com as our starting values[19], and we treat β and w_1 as fixed, to ensure historical comparability with other NOMINATE estimates.

We also vary the size of the penalty parameter, λ, in order to study how varying constraints on legislator movement produce different fits, legislator dynamics, and different understandings of polarization. In Figure 5, we demonstrate the overall fit of the data across iterations and the penalty parameter. The y-axis is the geometric mean probability, a convenient monotonic transformation of the log-likehood that provides a measure of the (geometric) average probability of the observed votes, $\exp \frac{\ln L(\boldsymbol{V};\boldsymbol{\alpha},\boldsymbol{\phi},\lambda)}{N}$, where N is the total number of observed of roll call vote choices. As with other regularized methods, increasing the penalty parameter necessarily decreases the fit, as the estimator prefers simpler estimates to those that fit the data best. Therefore, when λ is 0, the fit is highest, and when λ is 10^7, the fit is lowest. Of course, better in-sample fit does not mean that the unpenalized model is the best, nor that it accurately captures legislator dynamics. In what follows, we present results for the unconstrained case ($\lambda = 0$), a highly constrained case ($\lambda = 10^7$), and two intermediate cases, when $\lambda = 500$ and $\lambda = 10^4$. As mentioned above, these penalties correspond to the "innovation" variance of a random walk, $\Delta^2 = \frac{1}{2\lambda}$. The unconstrained case corresponds to

[18]As with the original NOMINATE models, we only admit votes where the minority of the yeas and nays comprise at least 2.5 percent of the total vote, therefore removing unanimous and nearly unanimous votes.

[19]Retrieved on March 12, 2019.

Figure 5: Convergence of estimates after 30 iterations



Note that with greater smoothing we necessarily get poorer fits, as larger values of lambda place greater priority on stability of estimates rather than within-congress fit.

a random-walk where the prior variance placed on changes over time is unbounded; when $\lambda = 500$ the standard deviation of the prior on the period-to-period moves is 0.032 and when $\lambda = 10^4$, the standard deviation of the prior on period-to-period moves is 0.007.

The differences in legislator movement by penalty is made clear by panel (b) of Figure 3. The y-axis is the NOMINATE first dimension ideal point; movements upwards and downwards correspond to changes across the most important dimension of the NOMINATE model. The first row contains the trajectories of all legislators by chamber for the unconstrained model. In this model, legislators vary widely congress-to-congress in ways that are unlikely to be attributable to underlying changes in the voting decision making process, but that fit the data quite well. Note that this model estimates trajectories with even greater variance than the Nokken-Poole estimates in row 1 of panel (A); this is likely due to the fact that the Nokken-Poole model takes the roll call parameters as fixed, while PSDW-

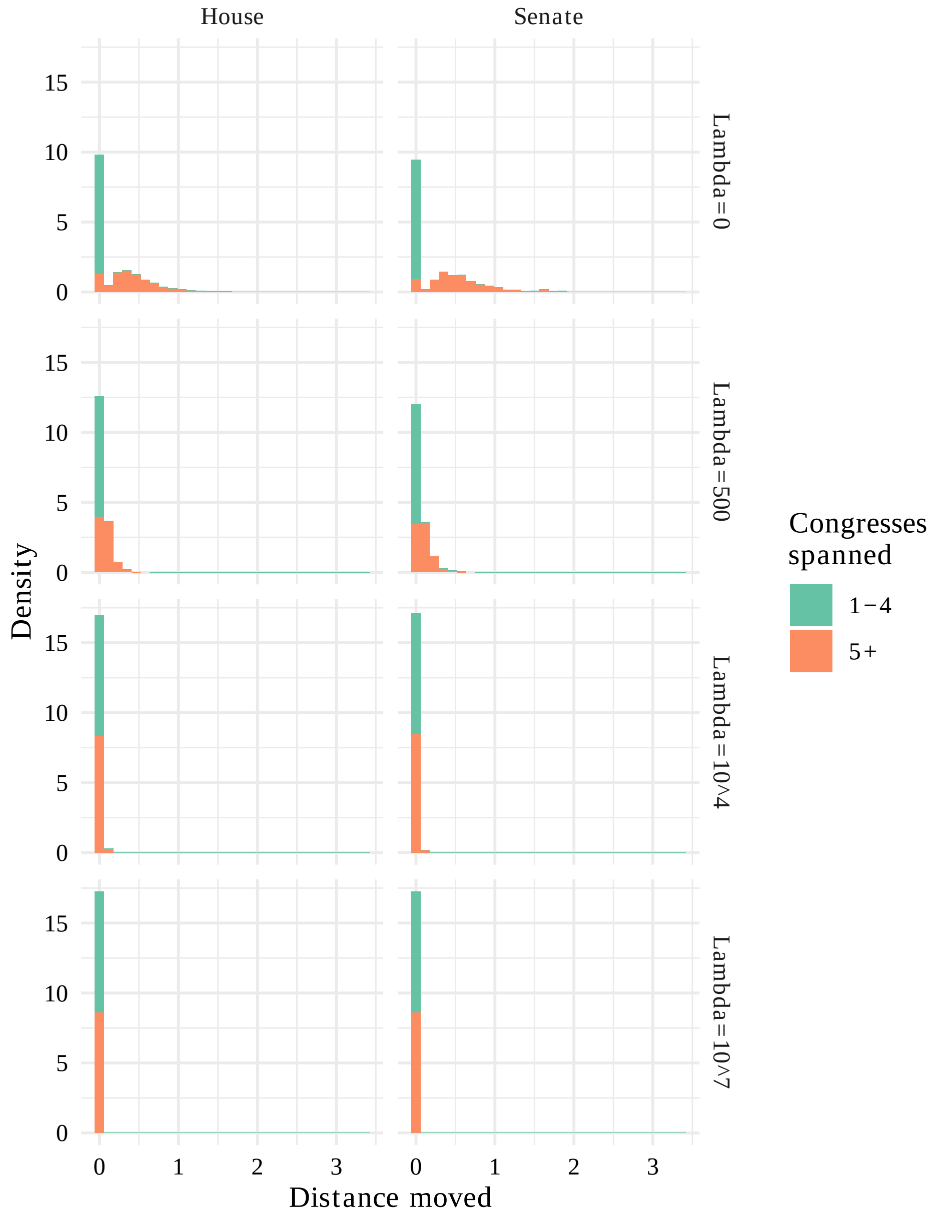
NOMINATE($\lambda = 0$) re-estimates the roll calls and relies solely on the fixed legislators—those whose tenures span fewer than five congresses—to fix the space. The second and third rows of panel (b) correspond to the other two sets of PSDW-NOMINATE results we present here. In this model legislators are able to move smoothly over time, either in a nearly linear fashion, or sometimes with sharp breaks in their trajectory mid-career. The most constrained model is nearly a constant model, although some members have such stark changes in their voting behavior that they still move over a considerable amount of the space. The amount of variance in the trajectories is also reflected in the total distance members move, presented in Figure 6.

In Tables 1 and 2, we demonstrate the within-party correlation of PSDW-NOMINATE scores for both the first and second NOMINATE dimension, respectively. As with the DW-NOMINATE scores, the estimates are quite consistent within the PS-DWNOMINATE models, with no correlation among them dipping below 0.76. In general, we see that the $\lambda = 0$ model has lower consistency with the other PSDW-NOMINATE estimates, largely owing to how much congress-to-congress variance is possible in that model.[20] Furthermore, the correlations between the PSDW-NOMINATE estimates and the canonical DW-NOMINATE estimates are also quite high, showing that the desirable properties of the flexible estimator we present here do not come at the cost of comparability with canonical models and results that utilize DW-NOMINATE scores.[21]

[20]When we combine all members regardless of party, the correlations with PSDW-NOMINATE models are even stronger with are even stronger, with 0.95 the lowest correlation for the first dimension and 0.84 the lowest for the second dimension.

[21]Again, when we pool members across parties, the correlations between the DW-NOMINATE and PSDW-NOMINATE estimates are even greater.

Figure 6: Distribution of legislators by total career distance traveled in NOMINATE scores from penalized spline models



This figure plots the distribution of legislators by how much they moved along the NOMINATE 1st dimension over their entire career. Each represents a different λ used in PSDW-NOMINTE. We take the absolute value of each session-to-session change and sum it over each legislator's career. Note that we stack those whose tenure spans fewer than 5 congresses in another color as they are unable to move at all and thus their total career distance is fixed at 0.

In Figure 7 we present the trajectories of two interesting cases; Ron Paul, Republican of Texas (serving in the House from 1975 to 1977, 1979 to 1985, and 1997-2013), and Kirsten Gillibrand, Democrat of New York (serving in the House from 2007 to 2009 and in the Senate from 2009 to the present). First, with $\lambda = 0$ or $\lambda = 500$, PSDW-NOMINATE finds that Ron Paul begins his career as a major outlier within the Republican Party, before his move towards the rest of his party coinciding with his Republican presidential bids. However, with larger values of λ, we see the model accommodates Paul's later move towards the center of the Republican party by having him start from a position closer to the other members of the Republican party. Rather than being nearly a 1 on the right edge of the NOMINATE first dimension, Paul starts at around a 0.75 in this constrained model. Here we see the constrained model limiting Paul from appearing as radical in his early career, in exchange for estimates that more easily explain his later behavior. This is emphasized in how the unconstrained model places Paul closest to the center of the Republican party during the two congresses in which he sought the Republican nomination for the presidency, highlighted in the two dashed red lines.

Second, Gillibrand's trajectory reveals similar differences between the different PSDW-NOMINATE model estimates. In all three, Gillibrand is moving sharply to the left, especially after her transition to the Senate in 2009. First elected to the House from a conservative district from upstate New York, Gillibrand was seen as a fairly conservative member of the Democratic party who became more liberal as she moved to the Senate (for example, see Walsh, Pak and Szabo 2019). For example, she starts her congressional career with an 'A' rating from the National Rifle Association which has turned to an 'F' in recent years (Walsh, Pak and Szabo 2019). Indeed, both of the flexible PSDW-NOMINATE models capture this change. Gillibrand starts among the most conservative Democrats and has moved strongly left since becoming a senator. Indeed, using PSDW-NOMINATE($\lambda = 500$), Gillibrand is estimated to be the most liberal member of the Senate in 2017. Again, the more constrained PSDW-NOMINATE($\lambda = 10^4$) model trades-off the difference between her conservative days in the house with her liberal days in the Senate, and places her in the middle of the Democratic party, slowly moving towards the left. While we cannot definitely say which better value of λ best captures members' true ideological trajectories, these examples highlight how the model trades off stability against fit.

It turns out, the movement of Ron Paul and Kirsten Gillibrand is part of a systematic movement to the "left" that legislators make when competing for their party's nomination for president. We explore these dynamics more fully in an applied example in Section 5.

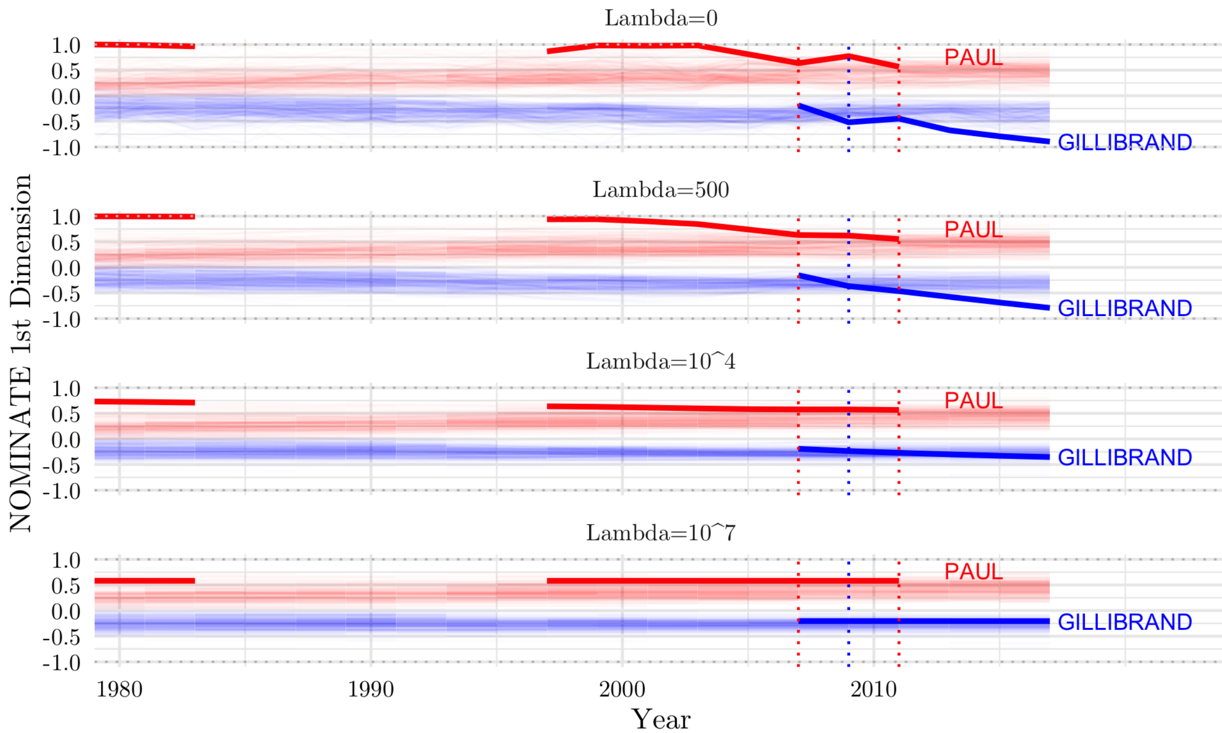
3.3. Largest movers

In Table 3 we list the legislator's with the greatest average session-to-session movement under the linear DW-NOMINATE model and the PSDW-NOMINATE($\lambda = 500$) model. For each model, we estimate the total, weighted Euclidean distance from their final ideal point to their initial ideal point as

$$\Delta\text{Euc} = \sqrt{(x_{k=1,t=T} - x_{k=1,t=1})^2 + (w_2(x_{k=2,t=T} - x_{k=2,t=1}))^2},$$

where T is the last session they served in, relative to the first congress they served in ($t = 1$). The differences in the first and second dimensions (ΔD1 and ΔD2) are measured similarly. To compute $\overline{\Delta\text{Euc}}$ we divide the total, weighted Euclidean distance by the num-

Figure 7: Trajectories of Ron Paul and Kirsten Gillibrand under different PSDW-NOMINATE models



Each congress is represented as the first year in which that congress met (e.g. the 111th congress is represented as 2009).

ber of sessions served. We then ranked all legislators by their average congress-to-congress weighted Euclidean movement and present the top 10 from two models in Table 3. In general, the two models agree that these members moved a great deal over their careers, with Dubois and Schafer appearing as top ten movers under both models.

Table 3: Biggest movers across different DW-NOMINATE models

		PS-DW (Lambda = 500)					Linear DW				
Name	Sessions	Rank	ΔD1	ΔD2	ΔEuc	$\overline{\Delta\text{Euc}}$	Rank	ΔD1	ΔD2	ΔEuc	$\overline{\Delta\text{Euc}}$
CAMPBELL, Thomas J. (CA-R)	5	1	0.33	-0.36	0.37	0.07	88	0.25	-0.29	0.28	0.06
DUBOIS, Fred Thomas (ID-R)	6	2	-0.42	0.01	0.42	0.07	8	-0.69	-0.68	0.76	0.13
SCHAFER, John Charles (WI-R)	6	3	0.31	-0.44	0.38	0.06	7	0.01	-1.66	0.80	0.13
MARCANTONIO, Vito Anthony (NY-R)	7	4	-0.43	0.04	0.43	0.06	50	-0.45	-0.24	0.46	0.07
POINDEXTER, Miles (WA-R)	6	5	0.34	-0.26	0.36	0.06	20	0.51	-0.20	0.52	0.09
PETTIGREW, Richard Franklin (SD-R)	6	6	-0.36	0.04	0.36	0.06	13	-0.54	0.30	0.56	0.09
KUCINICH, Dennis (OH-D)	8	7	0.13	-0.95	0.47	0.06	251	-0.33	-0.06	0.33	0.04
REES, Thomas Mankell (CA-D)	6	8	0.34	0.12	0.34	0.06	159	0.29	0.04	0.29	0.05
BULOW, William John (SD-D)	6	9	0.33	-0.07	0.33	0.06	30	0.41	0.48	0.47	0.08
BUSBY, Thomas Jefferson (MS-D)	6	10	0.33	0.01	0.33	0.05	11	0.59	0.46	0.63	0.10
SMITH, Frederick Cleveland (OH-R)	6	304	0.14	0.06	0.14	0.02	1	1.01	0.13	1.01	0.17
UNDERHILL, Charles Lee (MA-R)	6	2022	0.02	0.05	0.03	0.01	2	-0.92	0.78	1.00	0.17
JOHNSON, Timothy V. (IL-R)	6	264	0.06	-0.28	0.15	0.02	3	0.77	-1.30	1.00	0.17
HOOK, Frank Eugene (MI-D)	5	156	-0.12	-0.15	0.14	0.03	4	-0.37	-1.37	0.75	0.15
GILBERT, Ralph Waldo Emerson (KY-D)	5	135	0.13	0.13	0.15	0.03	5	0.54	1.05	0.74	0.15
BAILEY, Joseph Weldon (TX-D)	6	68	-0.21	-0.14	0.22	0.04	6	-0.11	-1.79	0.86	0.14
INGLIS, Robert Durden (SC-R)	6	17	0.17	-0.51	0.30	0.05	9	0.44	-1.07	0.68	0.11
KNOX, Philander Chase (PA-R)	5	363	0.11	-0.03	0.11	0.02	10	0.52	0.30	0.54	0.11

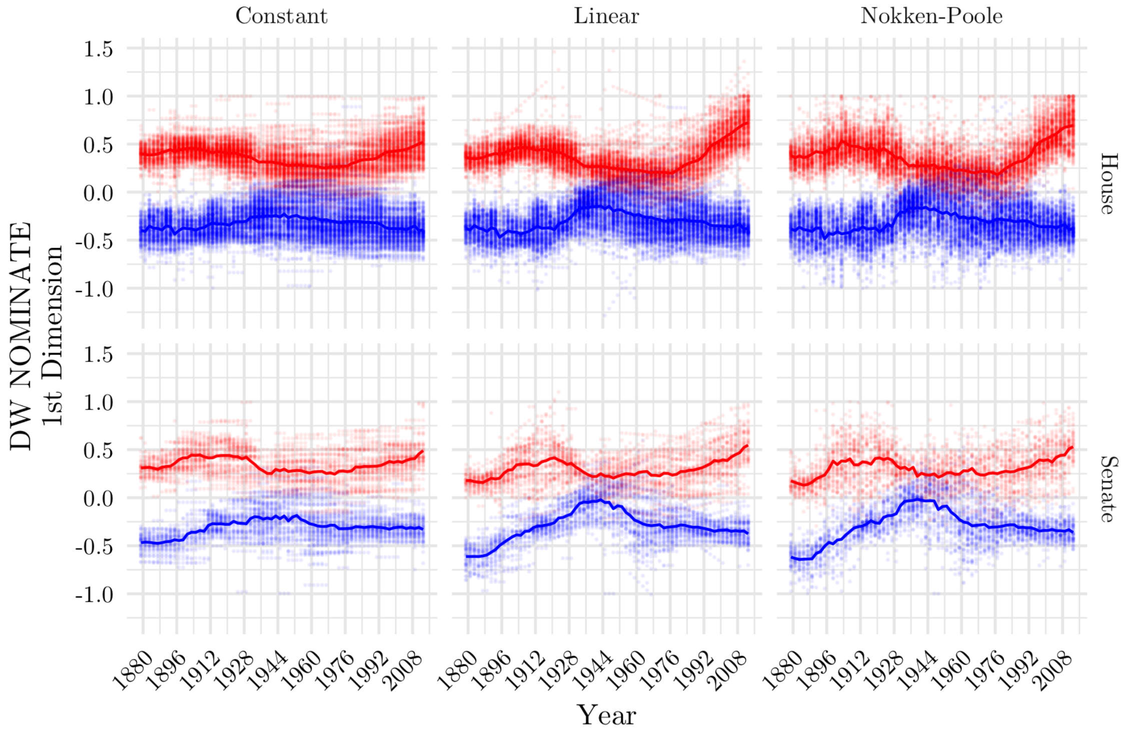
This table contains the 10 largest movers under the PSDW-NOMINATE($\lambda = 500$) and linear DW-NOMINATE models by average congress-to-congress weighted Euclidean movement $\overline{\Delta\text{Euc}}$. We compute $\Delta\text{Dk} = x_{k,t=T} - x_{k,t=1}$ for both dimensions, and then the total, endpoint-to-endpoint weighted Euclidean distance as $\Delta\text{Euc} = \sqrt{(\Delta\text{D1})^2 + (w_2\Delta\text{D2})^2}$. We then average this over sessions served to get $\overline{\Delta\text{Euc}}$.

4. Application: congressional polarization

Regardless of whether and how individual member's ideal points are allowed to move over time, all of the variants of DW-NOMINATE allow for the study of the polarization of the political parties by studying how much overlap there is between the parties and the distance between averages of party members' ideal points. A common approach is to use the mean first dimension ideal point location of a party's members. Figure 8 shows each member's location on the first dimension as well as the location of the party mean from 1879 to 2014 for the three different NOMINATE models discussed above (for example, see Poole and Rosenthal 2017).

The three traditional NOMINATE models—(1) the fixed "common-space constant" model, (2) the "linear change" DW-NOMINATE model, and (3) the freely moving "Nokken-Poole" model—present a similar story about polarization in the United States congress. The party mean locations in Figure 8 shows the parties largely converging in the early 1930s and then diverging, with an acceleration in polarization starting in the 1970s. Furthermore, across all three of the canonical DW-NOMINATE varieties, Republicans shifting further rightward appear to be the main drivers of polarization. In the "common-space constant" model, the increase in polarization can only be explained by new entrants being placed at greater extremes than their predecessors. However, when legislators are allowed to move either linearly or by congress the resulting estimates indicate that Republican House members are becoming more extreme through both replacement by more extreme members and through movement away from Democrats. This can be seen by how much steeper the Republican mean in the House is increasing in the two varieties that allow over-time movement in ideological posi-

Figure 8: DW-NOMINATE estimates of party first dimension locations over time by chamber and method of estimation



Each congress is represented as the first year in which that congress met (e.g. the 46th congress is represented as 1879).

tions. We can also represent the growth in polarization by taking the difference between the party means, as we do in Figure 10.

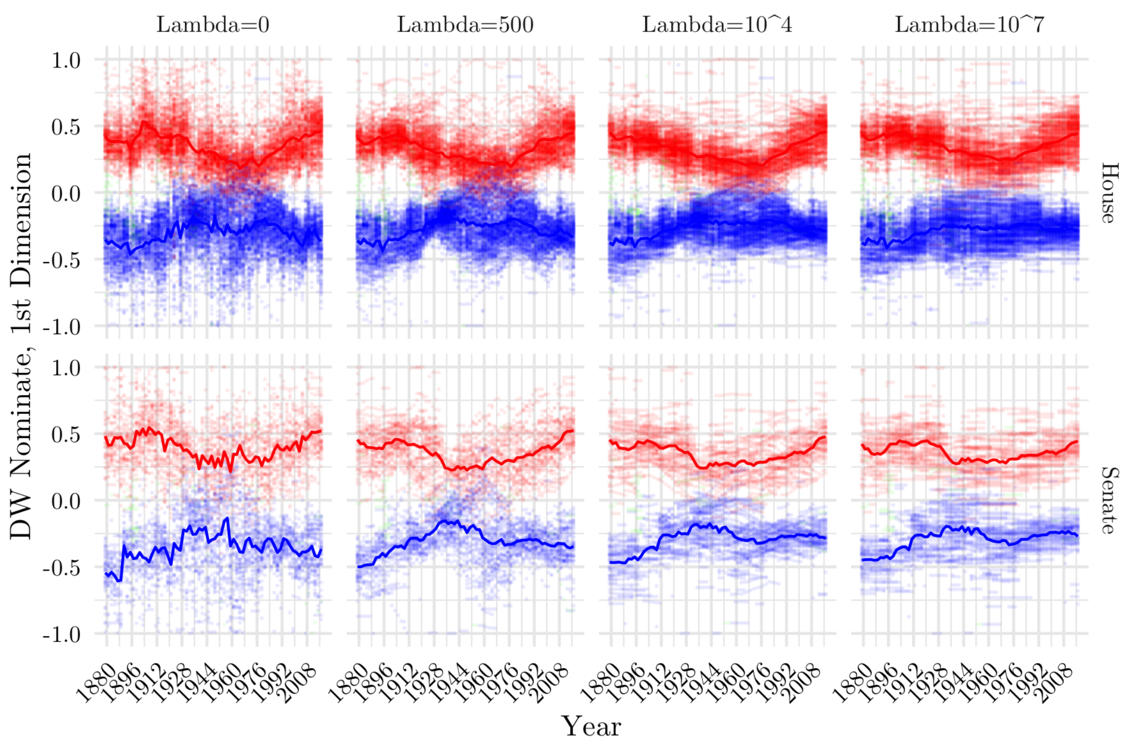
Despite weakening the assumptions made by the constant space or linear DW-NOMINATE models, our new estimates of party means using PSDW-NOMINATE paint a similar picture of polarization. In Figures 9 and 10, we replicate the original DW-NOMINATE figures using our PSDW-NOMINATE estimates. In general, the implications for polarization are similar across estimators: the distance between the two major parties has been increasing since the end of World War II, with the gap accelerating in the 1970s and later. Furthermore, the recent shift in polarization seems to be driven slightly more by movements in the Republican party rather than movements in the Democratic party.

There are two noticeable, although small, differences between the old NOMINATE estimates and the new PSDW-NOMINATE estimates presented here. The polarization in the late 1800s appears to be greater in the PSDW-NOMINATE models, and the House has not become quite as polarized as the Nokken-Poole and linear change DW-NOMINATE models suggest. In general, across both the older models and the new PSDW-NOMINATE models, constraining legislator movement over time leads to less apparent polarization in recent years than the more mobile models uncover. Note that this is not obvious *a priori*. Under a model with no change over time whatsoever, such as the common-space constant DW-NOMINATE model, party means may still move with the entry and exit of members. Furthermore, there is no reason to assume that incumbents are the driving forces behind polarization, rather than newcomers. Indeed, among the canonical DW-NOMINATE models, the constant model suggests the least polarization in the post-World War II era.

4.1. Sources of polarization

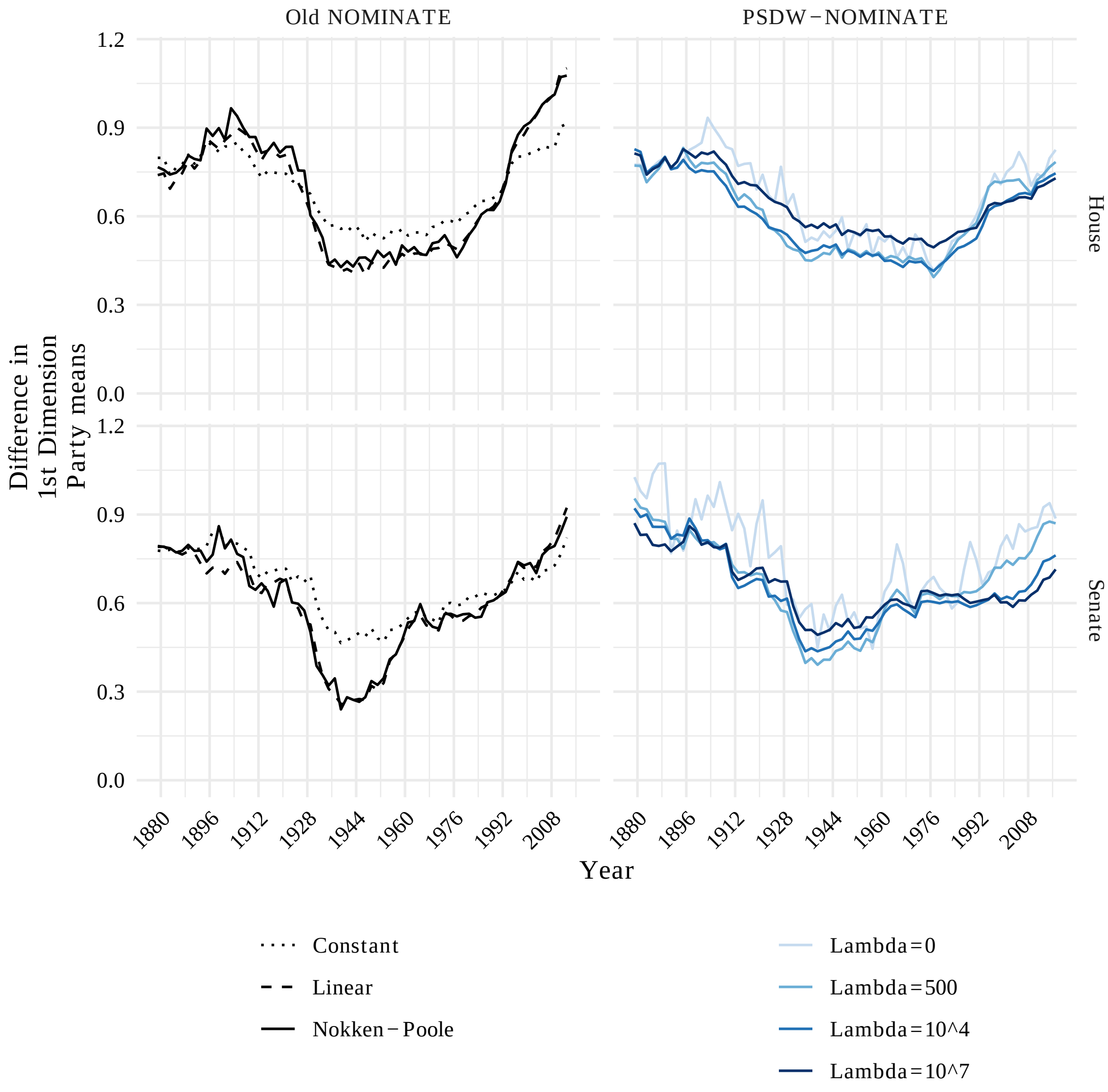
Who is driving this observed polarization in congress? In a model where legislators are taken as fixed over time, polarization can only occur through replacement. If no members of congress entered or exited, party means would stay fixed. Therefore, in the common space constant DW-NOMINATE model, only the replacement of incumbents with more extremely positioned newcomers can drive polarization. With the PSDW-NOMINATE model, polarization can come from incumbents shifting their positions as well as from replacement of incumbents with new members with different ideologies. While this analysis is also possible

Figure 9: PSDW-NOMINATE estimates of party first dimension locations over time by chamber and amount of smoothing



Each congress is represented as the first year in which that congress met (e.g. the 46th congress is represented as 1879).

Figure 10: Combined NOMINATE estimates of inter-party polarization



Each congress is represented as the first year in which that congress met (e.g. the 46th congress is represented as 1879).

with the Nokken-Poole and linear-change DW-NOMINATE models, we focus on the PSDW-NOMINATE estimates because PSDW-NOMINATE allows members' ideologies to evolve over time in a way that is much less restrictive than linear-change DW-NOMINATE and which is founded on a complete and coherent voting model unlike Nokken-Poole.

In Table 4 we present changes in party means by decade, with each panel representing a different decade. Each row represents a set of PSDW-NOMINATE estimates at the corresponding value of λ. For each party, the "Total" column contains the difference in the first dimension party from the end to the start of the decade. The "Incumbent" column contains the difference in first dimension party mean among legislators that were present in the the first and last congresses of the decade, and represents how much legislators who stayed throughout the decade changed. The "Replacement" column contains the change in first dimension party mean from the legislators who started but did not end the decade in congress to legislators who ended but did not start the decade in congress. Therefore, this represents the change in means among party members who were replaced—although not necessarily in their own constituencies—over the course of a decade.

Examining the "Total" columns for both parties, we see the two parties steadily drifting away from each other. In most decades, and across most values of λ, the Democrats move towards -1 and the Republicans move towards +1. Only between 1979-1988 and 1999-2008 do we see the Democrats moving right, and these moves are small and only present for certain values of λ. For the Democrats, the decades where they moved the most are 1989-1998 and 2009-2018. In both of these instances, across values of λ, Democrats move between -0.030 and -0.073 along the first dimension. When $\lambda = 10^7$—i.e. movement of legislators across time is very difficult—this shift left is, by design, due to the replacement of old legislators

Table 4: Change in PSDW-NOMINATE first dimension party means by decade, broken down by replacement and incumbent change

Panel A: 1979-1988

	Democrat			Republican		
Lambda	Total	Incumbent	Replacement	Total	Incumbent	Replacement
0	-0.008	-0.023	0.014	0.086	0.060	0.110
500	-0.027	-0.037	-0.012	0.076	0.050	0.100
10^4	-0.004	-0.011	0.008	0.050	0.019	0.080
10^7	0.006	0.000	0.017	0.038	0.000	0.075

Panel B: 1989-1998

	Democrat			Republican		
Lambda	Total	Incumbent	Replacement	Total	Incumbent	Replacement
0	-0.073	-0.041	-0.093	0.055	0.010	0.090
500	-0.066	-0.035	-0.085	0.079	0.036	0.112
10^4	-0.039	-0.013	-0.055	0.070	0.025	0.105
10^7	-0.030	0.000	-0.049	0.047	0.000	0.084

Panel C: 1999-2008

	Democrat			Republican		
Lambda	Total	Incumbent	Replacement	Total	Incumbent	Replacement
0	-0.035	-0.049	-0.023	0.031	0.006	0.065
500	0.023	0.016	0.022	0.018	-0.003	0.046
10^4	-0.002	-0.009	0.001	0.036	0.009	0.072
10^7	0.008	0.000	0.012	0.028	0.000	0.065

Panel D: 2009-2018

	Democrat			Republican		
Lambda	Total	Incumbent	Replacement	Total	Incumbent	Replacement
0	-0.067	-0.052	-0.072	0.036	-0.002	0.065
500	-0.054	-0.027	-0.073	0.049	0.016	0.075
10^4	-0.032	-0.005	-0.057	0.045	0.009	0.072
10^7	-0.035	0.000	-0.070	0.038	0.000	0.064

Each row represents a set of PSDW-NOMINATE estimates at the corresponding value of λ. For each party, the "Total" column contains the difference in the first dimension party mean between the end and the start of the decade. The "Incumbent" column contains the difference in first dimension party mean among legislators that were present in the the first and last congresses of the decade, and represents how much legislators who stayed throughout the decade have changed. The "Replacement" column contains the change in first dimension party mean from the legislators who started but did not end the decade in congress to legislators who ended but did not start the decade in congress.

with new legislators. However, if we examine the cases where legislator movement is not restricted—i.e. $\lambda = 0$—we see that the shift for Democrats is due to both incumbents moving and the replacement of legislators with new Democrats. For example, if we examine the $\lambda = 0$ estimates for the 1989 to 1998 time period, Democrats who were present at the beginning and end of the decade moved 0.041 points to the left, and legislators who left were replaced with new legislators who were on average 0.093 points to the left. In almost all specifications and decades where Democrats move a considerable amount, it is due to both incumbents changing and replacement, although the replacement effect appears to introduce slightly more left-leaning legislators.

For the Republican party, the estimates depict a very similar pattern, although the picture is more consistent across decades and models. In all decades and for all specifications, the Republican party moved towards the right. Furthermore, for all decades and all specifications, the mean among replaced legislators moves more than the mean among legislators who served the full decade. Furthermore, the change among incumbent Republicans goes to zero in the later decades, indicating that the vast majority of the Republican contribution to polarization comes from the replacement of less conservative legislators with more conservative legislators.

Table 4 also demonstrates how increasing the smoothing parameter λ changes our understanding of the determinants of polarization. For both parties across all decades, when $\lambda = 10^7$, there is no movement in incumbent legislator's positions by design as the estimates are all 0.000. Thus in these models, all polarization is due to replacement. However, even when we relax the smoothing parameter and allow incumbents to move, replacement remains a large driver of polarization.

5. Application: legislative behavior of presidential primary candidates

Allowing legislators to move over time also permits within-legislator designs, such as difference-in-differences designs that study, for example, the effects of reelection campaigns or geographically-clustered exogenous shocks. Of course, smoothing the splines suppress over-time variation resulting in conservative estimated effects. However, in the example presented below, there is little evidence that the smoothing spline substantially attenuates the estimated effects except at the largest values of λ.

In this section, we use a difference-in-differences design to examine how the legislative behavior of candidates competing for their party's presidential nomination changes during the session they are running for president. We use data from the America Votes series published by CQ Press to code all presidential primary candidates that appeared on any state primary ballot from the 1972 through 2012 elections for the Republican and Democratic parties (Scammon, McGillivray and Cook N.d.). We manually coded those who appeared on 2016 election state ballots. We then manually checked which of those candidates were serving in the U.S. Congress at any point in the session during which the primary and general elections were held. We then subset the PSDW-NOMINATE data to the sessions that span from the 1972 election to the 2016 election and we only admit legislators who served at least five sessions of congress and thus are permitted to move by our estimator. Using this sample, we estimate the difference-in-differences model

$$Y_{ij} = \tau P_{ij} + \text{Legislator}_i + \text{Session}_j,$$

where Y_{ij} is the first dimension PSDW-NOMINATE score for the ith legislator[22] in session j, P_{ij} is that legislator-session's indicator for whether the corresponding legislator appeared on a major party's primary ballot during that session, and Legislator_i and session_j are the unit (legislator) and time (session) fixed effects.

We fit this model using OLS, estimate heteroskedastic consistent (HC1) standard errors, and present the results for four different values of λ in Table 5.[23] We first split the sample into Democrats and Republicans, and report the results for each sample in Panels A and B, respnectively.[24] Each column represents a separate difference-in-differences model estimated using a different set of PS-DWNOMINATE(λ) estimates. For all four values of λ and across both parties, presidential primary candidates move towards the "left"—i.e. their first-dimension NOMINATE score becomes more negative—during the session they are on presidential primary ballots, relative to the rest of their career and the movements of other legislators in the same sessions. For Democrats, in Panel A, this estimate is only statistically significant at the 0.05 level for PSDW-NOMINATE($\lambda = 500$), while for the Republicans the estimates are all statistically significant at the 0.05 level and are substantially larger than the estimates for Democrats. The magnitude of the effect is also relatively large; the standard deviation of PSDW-NOMINATE($\lambda = 500$) 1st dimension scores is about 0.12 for both parties in the 2015-2016 session. The estimates in column 2 indicate that legislators move to the "left" about one-third to one-half of the standard deviation of their party's DW-NOMINATE

[22]Technically we use ICPSR number, as discussed above, where legislator's who change party are considered separate legislator's for the sake of DW-NOMINATE estimation.

[23]We also present analogous clustered standard errors at the legislator level in braces.

[24]Bernie Sanders is not officially a Democrat, however as he was seeking the Democratic nomination for president, he is included in the Democrats sample.

scores during a presidential campaign.

Table 5: Difference-in-differences estimates of legislator first dimension estimates during presidential primary campaigns

Outcome: DW Nominate, 1st Dimension

Panel A: Democrats

	Lambda=0	Lambda=500	Lambda=10^4	Lambda=10^7
Pres. Primary Candidate	-0.014	-0.035*	-0.011†	-0.000
	(0.021)	(0.014)	(0.006)	(0.000)
	[0.021]	[0.014]	[0.007]	[0.000]
R^2	0.695	0.857	0.948	1.000
Num. obs.	5454	5454	5454	5454

Panel B: Republicans

	Lambda=0	Lambda=500	Lambda=10^4	Lambda=10^7
Pres. Primary Candidate	-0.061*	-0.056*	-0.022*	-0.000*
	(0.031)	(0.025)	(0.010)	(0.000)
	[0.044]	[0.037]	[0.013]	[0.000]
R^2	0.796	0.911	0.976	1.000
Num. obs.	4293	4293	4293	4293

$^{***}p < 0.001$; $^{**}p < 0.01$; $^{*}p < 0.05$; $^{\dagger}p < 0.1$. All models fit using OLS with legislator and session fixed effects. Heteroskedastic consistent (HC1) standard errors in parentheses and are used for the significance tests reported using the stars. Analogous clustered standard errors (CR1), with clustering by legislator, are reported in brackets. Data used are PSDW-Nominate estimates subset to the 92nd-114th congresses. Only legislators who served more than four sessions are admitted in to this analysis. See Appendix B for the same model with those legislators added back in, as well as for estimates when pooling across party.

Of course, the magnitude of this estimate for the larger values of λ is much smaller than for the smaller values of λ as the within-legislator variation decreases. This is also represented in the R^2—it approaches 1.00 as λ increases and the individual fixed effects explain nearly all of the variation in NOMINATE scores. Nonetheless, the value of λ primarily will affect the scale of any movements—the rollcalls and what they imply for legislator ideal points are unchanged. Therefore, even with a large λ we should expect similarly signed, although smaller scale, movements.

Because there are few presidential candidates in this time frame who are also legislators, we plot each of their individual PSDW-NOMINATE 1st Dimension trajectories in Figure 11. Each panel represents one legislator in our difference-in-differences sample who appeared on a major party's primary ballot at least once. The x-axis is the second year of a session of congress, centered at each legislator's first primary run. Therefore, someone running for the first time in 2012 would have the session ending in 2012 as 0, and then the subsequent session would be coded as 2 instead of 2014. The y-axis is the PSDW-NOMINATE 1st dimension ideal estimate centered to the 1st dimension estimate from the session of their first primary bid. Therefore, each panel shows the legislator's 1st dimension position relative to their first presidential campaign. We also highlight all presidential campaigns with black dots, and we plot the trajectories for the two more volatile values of λ. The panels are ordered by average rescaled PSDW-NOMINATE 1st Dimension scores, showing that Bernie Sanders and Ron Paul have the highest average 1st dimension scores over their careers, relative to the year they first ran for president.

6. Conclusion

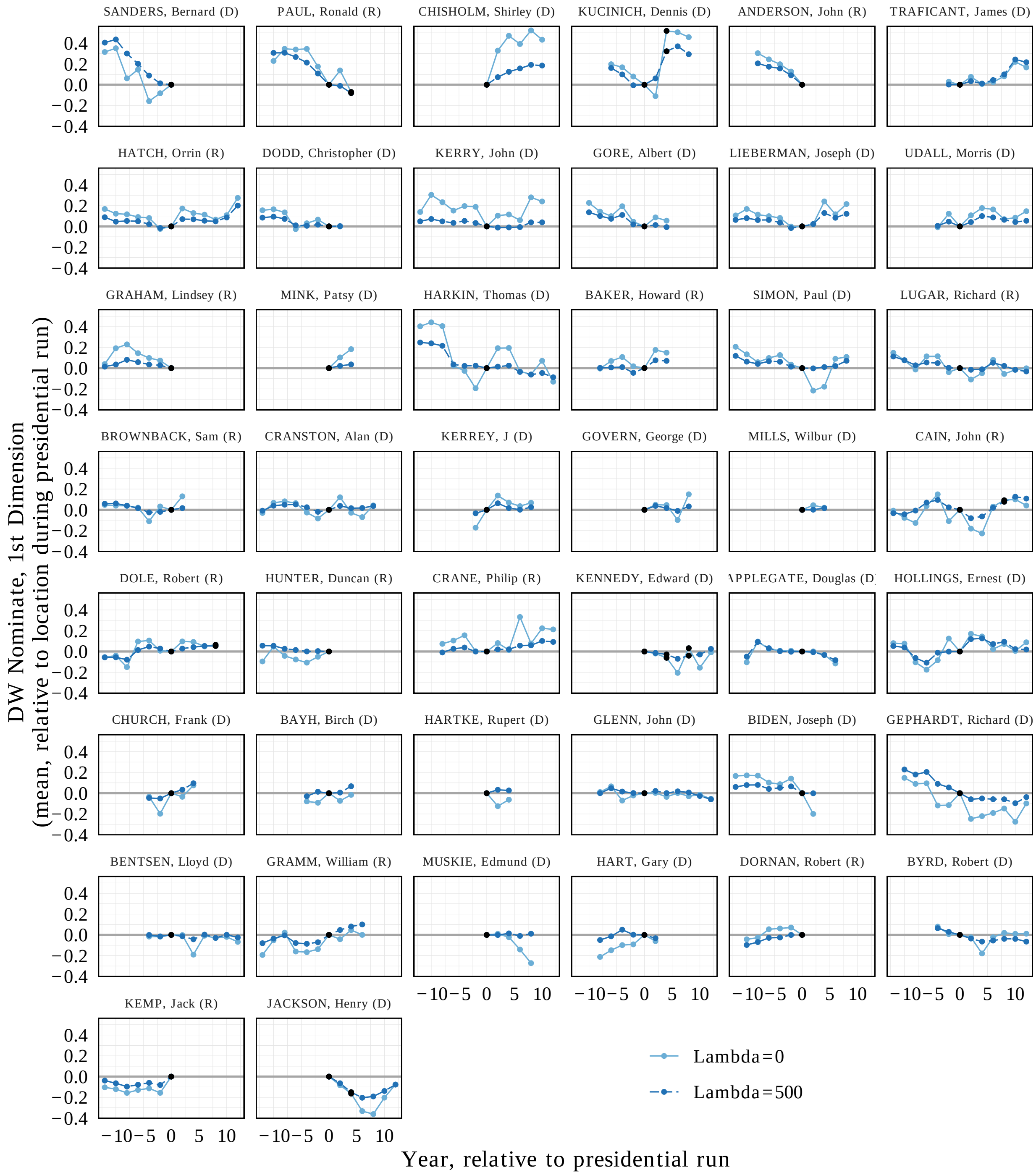
By taking a modern and flexible approach to modelling members' ideal-point dynamics, the PSDW-NOMINATE model relaxes the strong assumptions of the original linear-change and constant-space DW-NOMINATE models. While estimates produced by PSDW-NOMINATE are highly correlated with those of the original estimators, the new estimators allow researchers to study and account for over-time changes in members' locations in ways that had heretofore not been possible.

Interestingly, allowing for more flexible dynamics in members' locations does not by-and-large alter Poole's (2007) conclusion that most members' locations vary little over time. While we highlighted a few members whose locations did evolve substantially over their careers and we could (*ex post*) square those changes with the historical and qualitative accounts of those members' ideological evolution, we leave to future work the careful study of which members move, by how much, and why.

Given that so much of our understanding of polarization in the contemporary US congress and the nation more generally relies on DW-NOMINATE estimates, it is reassuring that those results are generally reproduced by PSDW-NOMINATE. Consistent with the previous DW-NOMINATE estimates, we find that it is replacement rather than the ideological drift of continuing members that accounts for the bulk of the increase in partisan polarization observed in recent decades. Neither the strong assumptions about member's over-time trajectories or the estimation compromises arising from the computing-limitations faced by Poole and Rosenthal in the 1990s drive the conclusion that the congress is more polarized now than it has been at any point since the 19th Century.

Moving forward, we expect and intend that PSDW-NOMINATE estimates will supplant the ageing DW-NOMINATE scores as the core summary of members' general ideological dispositions and roll call voting records.

Figure 11: Mean PSDW-NOMINATE 1st dimension trajectories for presidential primary candidates



This figure plots all legislators who served in more than four sessions of congress and who were on a major party's primary ballot at least once from 1972 to 2016. Each panel represents one legislator. The x-axis is the second year of a session of congress, centered at each legislator's primary run. The y-axis is the PSDW-NOMINATE 1st dimension score for the corresponding session, centered the 1st dimension score in the year of the legislator's primary run. If a legislator competed for their party's nomination more than once, we use their first primary run. Therefore, each panel shows the legislator's 1st dimension position relative to their first presidential campaign; note that all presidential campaigns are also highlighted in black dots, and the two lines represent two separate values of λ for which we estimate PSDW-NOMIANTE scores. The panels are ordered by average rescaled DW NOMINATE 1st Dimension scores, showing that Bernie Sanders and Ron Paul have the highest average 1st dimension scores over their careers, relative to the year they first ran for president.

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Appendices

A. Why comparing ideal-point estimates over time is difficult

The fundamental problem of across-time comparisons of legislators' ideological positions recovered from roll call votes, such as DW-NOMINATE, is that legislators' voting records only reveal information about the *relative* positions of the members. No matter how many votes are taken, the most that can be inferred is a mapping of legislators' locations up to a choice of scale (and a choice of rotation if more than one dimension is to be recovered) (see McCarty 2011). This problem is particularly vexing when trying compare members' locations across time because the relative positions of members not voting on common roll calls cannot be established without additional and strong assumptions. We begin by providing an intuitive account of this problem and also a discussion of the previous research on this and other closely-related questions.

A.1. Two approaches to establishing inter-temporal comparability of ideal point estimates and their limitations

Test taking serves as a common and useful analogy. Suppose that two groups of students each take a different test on the same subject (analogous to voting in separate legislative sessions). Note that we could not infer that the first group of students had greater mastery of the subject because they correctly answered a larger fraction of the questions on their test than the second group of students answered correctly on their test. It could be that the questions posed to the first group of students were easier. However, if there were some students who took both tests and if we assume that the subject mastery of those students was constant across the two tests, then we could curve the second test to the first by adjusting the scores on the second test such that the curved second-test scores were maximally similar to the first-test scores for those students who took both tests. For example, if every student who took both tests scored five points higher on the second test than they did on the first, curving every second test score down by five points would allow us to compare the test scores of the students who only took the second to test to those who only took the first. By making an assumption about how the level of subject mastery differed (or did not differ) for at least some of the students who took both tests, a comparable scale can be established. This sort of adjustment can be made across any number of tests as long as one can construct at least one chain of pairwise adjustments based on common test takers that bridges from each test to every other test.[25]

Returning to estimating legislators' locations, restricting the movement in positions is an attractive way to create a comparable scale because: (1) this approach allows us to be generally agnostic about the nature of the set of proposals on which votes are being cast and (2) there is good reason to suppose that legislator's basic voting decision calculus is not likely to be subject to dramatic change over a short period of time. However, as the recent literature

[25]In one dimension, as we might expect with a test score, this requires at least two common test takers. In two dimensions, as with a legislator's estimated first and second dimension DW-NOMINATE score, this requires at least three common legislators in each pair of congresses (see Rivers 2003).

has noted, identifying the ideological space over a long period of time in this way suggests seemingly implausible conclusions. For example, Bateman, Clinton and Lapinski (2017) show how estimates provided by DW-NOMINATE imply that current Georgia congressman and civil rights leader, John L. Lewis would have voted, with high probability, against an anti-lynching bill considered by the congress in 1922! Similar conundrums can be found across a range of policy domains in which it is clear that strong "leftward" or "rightward" shifts (in terms of contemporary political understandings) have taken place that are not evidenced in the DW-NOMINATE scores. Similarly, there are other issue positions that DW-NOMINATE associates with being on the "left" in one period and on the "right" in another. This brings into question exactly what the meaning of the dimensions recovered by DW-NOMINATE are and how we should think about the sort of counterfactuals posed by Bateman, Clinton and Lapinski.

An alternative approach to establishing comparability over time is exemplified by Bailey (2007). Rather than constraining the movement of legislators over time, this approach seeks to identify the ideological space over time by constraining the way that questions (roll calls) divide the space. In particular, this approach seeks to find common decisions faced by legislators over time. In terms of our standardized test analogy, this is equivalent to identifying individual test questions that are common across the tests administered. Students' performance on those common questions can then be used to estimate differences in the distribution of subject mastery among the groups of students taking each test and ultimately used to curve all of the tests to a single comparable performance scale. Curving the tests in this way requires us to believe that each of the common questions is equally effective at revealing mastery across each group of test takers. This may not be the case. For example, one group of test takers may have seen a question presented in class while other students did not, or a question might have a cultural bias that makes it easier for one group of test takers than for others. Similarly, identifying pairs of roll calls that we expect legislators serving at different times to respond to in the same way is quite difficult. Even if the proposed policy, such as the level of the minimum wage, is evidently the same across the different votes, the *status quo* policy, amendment agenda, the economic context in which the vote is taken, as well as the understanding of the effect that the policy will have, may not be.

While it is unquestionably the case that the meaning of the ideological locations recovered by methods such as NOMINATE would be considerably more clear if they could be stated in terms of something tangible such as a preferred top marginal tax rate or set of conditions under which abortion should be legal, it is not clear to how such measurements can be made or even what information they would convey. For example, does the downward shift in the ideal top marginal tax rate of the median member of congress (as evidenced by the precipitous drop in that rate since the 1950s) reflect a rightward shift in American's taste for redistribution or is it better explained by changes in beliefs about the adverse broader economic affects that the rates in place in the 1950s would have if they were imposed today?

Given this, we follow Poole and Rosenthal's basic approach to constructing comparability across time. We will assume sufficient constraint in members' locations from one congress to the next to allow us to construct chains of members who served in overlapping congresses such that the same underlying measurement scale is preserved over the entire set of congresses studied. Of course, this strategy is only as good as the assumption that members' positions change little at least over short periods of time. It is these overlapping short periods of (near) constancy that establishes comparability over longer periods of time. While the effect of slowly changing attributes may seem negligible from one year or congress to the next, the cumulative effect of imposing overlapping short-term constraints on ideological change may, over the long run, obscure important secular shifts.

A useful, if imperfect, analogy is to the measurement of the cost of living where related inferential problems arise (for detailed discus sion of the challenge associate with measuring the consumer price index see Boskin et al. 1998). The traditional Laspreyes index calculates the cost of a basket of goods that is fixed over time and calculates the year-over-year changes in the cost of that basket. Over a short periods of time in which the basket of goods that a representative consumer buys is relatively stable (both in composition and quality), this works well, but over a longer time, it becomes problematic—particularly as new transformative goods and services such as air travel, antibiotics, computers, and cell phones are introduced. In order to address changes in the composition of the basket, chained indices can be constructed in which the price increase in each year is determined by the basket of goods the consumers bought in the previous year. In this case, the basket of goods is updated each year. Even here, allowances must be made for rapid technological change (Boskin et al. 1998). The consumer price index (CPI) maintained by the US Bureau of Labor Statistics highlights the issue. The overall cost of living, as measured by the CPI, has increased more than 2700 percent since 1900, suggesting that it would take 1/27th the number of dollars to achieve the same standard of living in 1900 that it does in today. While the idea that a dollar went much farther in 1900 than it does today is sensible when it comes to the cost of housing or bread, in other cases it is clearly absurd. Many things that we consume today simply could not be purchased for any price in 1900 let alone for 4 percent of their 2018 price. While this includes many things that perhaps are not critical to basic well being like radios and televisions, it also includes other things like penicillin that clearly are.[26]

Perhaps not surprisingly, we can find the same sort of anomalies when we try to construct a comparable measure of legislators' "ideological" positions over time. As in the case of inflation where the basket of goods can be dramatically affected by the introduction of a new good or rapid improvements in technology, there are moments in which the ways in which particular policies map onto the "ideologies" identified by DW-NOMINATE change abruptly or move in steadily in one direction over a longer period of time. In such cases, the overall index of ideological positions (DW-NOMINATE scores) that we create by assuming that the preferences of individual members are fixed or slow moving over short periods of time can lead us to absurd conclusions when it comes to the counterfactual constructions such as whether congressman Lewis would have voted against anti-lynching legislation in 1917 just as a price index would wildly mis-estimate the cost of an iPhone™ in 1900. Just as the idea of a consumer price index is to provide an objective way to broadly measure the changes in the price level and the effects that those changes have on consumer welfare, the locations estimated by DW-NOMINATE provide a broad and objective measure of how legislative preferences move across time.

Moreover, because DW-NOMINATE scores are not constrained to map onto any one policy question in any particular way, what exactly the scores capture and whether, and in what way, it makes sense to compare the scores assigned to members serving in the 2010s to those serving in say the 1920s, 1880s or 1790s are very important questions. These questions have received considerable recent attention (Lee 2016; Clinton, Katznelson and Lapinski 2016; Bateman, Clinton and Lapinski 2017; Bateman and Lapinski 2016; Muskowitz, Rogowski

[26] Penicillin was first used for medical treatment in the US in 1942 (Grossman 2008).

and Snyder 2017; McCarty 2016). While these question are important, they are not the subject of our inquiry here.

B. Alternative specification for presidential primary candidate applied example

Table B1 reports the same estimates as in Tabe 5, although with all legislators pooled across party. Table B2 adds back in candidates who served fewer than five sessions of congress—i.e., those who are fixed in place by design by our estimator.

Table B1: Difference-in-differences estimates of legislator first dimension estimates during presidential primary campaigns - pooled estimates

Outcome: DW Nominate, 1st Dimension

Panel A: All parties

	Lambda=0	Lambda=500	Lambda=10^4	Lambda=10^7
Pres. Primary Candidate	-0.026	-0.034**	-0.010*	-0.000†
	(0.018)	(0.013)	(0.005)	(0.000)
	[0.021]	[0.015]	[0.005]	[0.000]
R^2	0.942	0.976	0.994	1.000
Num. obs.	9755	9755	9755	9755

$^{***}p < 0.001$; $^{**}p < 0.01$; $^{*}p < 0.05$; $^{\dagger}p < 0.1$. All models fit using OLS with legislator and session fixed effects. Heteroskedastic consistent (HC1) standard errors in parentheses and are used for the significance tests reported using the stars. Analogous clustered standard errors (CR1), with clustering by legislator, are reported in brackets. Data used are PSDW-Nominate estimates subset to the 92nd-114th congresses. Only legislators who served more than four sessions are admitted in to this analysis.

Table B2: Difference-in-differences estimates of legislator first dimension estimates during presidential primary campaigns - pooled estimates

Outcome: DW Nominate, 1st Dimension

Panel A: All parties

	Lambda=0	Lambda=500	Lambda=10^4	Lambda=10^7
Pres. Primary Candidate	-0.023	-0.031**	-0.009†	-0.000†
	(0.016)	(0.012)	(0.004)	(0.000)
	[0.019]	[0.014]	[0.005]	[0.000]
R^2	0.954	0.981	0.995	1.000
Num. obs.	12523	12523	12523	12523

Panel A: Democrats

	Lambda=0	Lambda=500	Lambda=10^4	Lambda=10^7
Pres. Primary Candidate	-0.015	-0.033*	-0.010†	-0.000
	(0.021)	(0.014)	(0.005)	(0.000)
	[0.021]	[0.014]	[0.006]	[0.000]
R^2	0.768	0.899	0.965	1.000
Num. obs.	6788	6788	6788	6788

Panel B: Republicans

	Lambda=0	Lambda=500	Lambda=10^4	Lambda=10^7
Pres. Primary Candidate	-0.050†	-0.046*	-0.018*	-0.000*
	(0.027)	(0.022)	(0.009)	(0.000)
	[0.038]	[0.032]	[0.011]	[0.000]
R^2	0.845	0.934	0.983	1.000
Num. obs.	5717	5717	5717	5717

$^{***}p < 0.001$; $^{**}p < 0.01$; $^{*}p < 0.05$; $^{\dagger}p < 0.1$. All models fit using OLS with legislator and session fixed effects. Heteroskedastic consistent (HC1) standard errors in parentheses and are used for the significance tests reported using the stars. Analogous clustered standard errors (CR1), with clustering by legislator, are reported in brackets. Data used are PSDW-Nominate estimates subset to the 92nd-114th congresses.