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On Using Metropolis-Hastings to Analyze Democratic Support

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1 Introduction

In recent years scholars have found declining support for democracy in long-established democracies. (Denemark et al. 2016; Foa and Mounk 2016, 2017; Norris 2017; Voeten 2016). This finding raises two important questions: First, what are the reasons for this decline, and second, what are its implications, in particular, does a decline in democratic support endanger the survival of democracy?

A series of recent articles (Claassen 2019, 2020a, 2020b) researches these questions and presents novel results. Regarding the first question, Claassen (2020a) finds – in contrary to the widely held belief of self-reinforcing democracies – that democratic support naturally fluctuates over time. The reason is that increases in democracy levels lead to decreases in public support and vice versa. Regarding the second question, so far the results about the relationship between democratic support and its survival have been mixed. Claassen (2020a), however, finds supporting evidence for the natural theory that democratic support plays a positive role in the system’s survival.

A main obstacle for researching democratic support is that current panel data contains a large number of missing values. Claassen (2019) develops an approach to deal with this problem by simulating dense panel data from the actual fractured data. The two most recent studies both rely on this simulated data. His approach consists of three steps: First, assume a probabilistic structural model of democratic support. Second, estimate its parameters via the Metropolis Hastings algorithm from the fractured data. Third, simulate new data using the model and the parameter estimates.

Claassen’s method appears to be very powerful and could potentially be applied to many more topics for which panel data is sparse. However, it is noteworthy that he estimates a large number of parameters from the data that he has. This work’s research questions thus are: How reliable is Claassen’s method? And, can we improve his method? I approach these questions the following way: First, I check the robustness of Claassen’s results towards hyperparameter changes. This is important because arbitrary hyperparameter choices can potentially lead to false or at least arbitrary results. Second, I compare the results obtained from old

data with the results from slightly updated data. If the results differ too much, this would suggest that the structural model overfits the data.

I come to the following results: First, updating the dataset by three additional years (about one tenth) changes the results noticeably. This finding suggests that Claassen’s approach would still require more data for robust results. Second, Claassen uses too many iterations for his estimation procedure. By determining the minimal number of iterations necessary for convergence he could have saved about two third of the computation time. Not wasting too much computational resources is important for two reasons: First, it allows spending more time on further robustness checks, and second, it makes it easier for other researchers to replicate and build upon past research. The third finding is that the default hyperparameters recommended by Stan Development Team (2018) deliver the benchmark results with the smallest variation and don’t have to be changed.

The final paper is structured as follows: Section 2 reviews the literature of public support of democracy with a focus on Claassen’s papers, defines the support concept and looks at the data. Section 3 explains Claassen’s model and its estimation. Section 4 presents the approach for the robustness checks and the results. Section 5 discusses the findings. Section 6 concludes.

2 Literature Review and Data

2.1 The Concept of Democratic Support

There are two major conceptualizations of public support for democracy (PSD)¹. First, the *implicit* approach that requires the support for broader sociopolitical values like post-materialism and egalitarianism. Here, people support democracy implicitly if they support the values that are framed as particularly democratic. Second, the *explicit* approach that requires both an appraisal of democracy and a rejection of autocratic alternatives. Different studies use different concepts although the explicit approach is more direct.

¹Some studies also refer to PSD measured on the national level as “mood.”

2.2 Drivers of Democratic Support

The main theory about why citizen and societies begin to support democracy are called *generational socialization* and *instrumental regime performance*. The first theory assumes that individuals are taught to support the regime under which they are socialized during late adolescence (Mannheim 1970; Niemi 1974). One implication is that after a shift to democracy, the support for it will grow over time (Denemark et al. (2016)). Indeed, several single-country studies have found evidence for this claim, for example for in 1970s Germany (Baker et al. (1981)), in 1980s Spain (Montero, Gunther, and Torcal (1997)), and in 1990s Russia (Mishler and Rose (2007)). On the other hand, other studies come to different results: First, Mishler and Rose (2002) do not find such an effect analyzing other Central and Eastern European countries. Second, more recent studies even find a decline in PSD over the last years (Foa and Mounk 2016, 2017).

Regarding the second theory, instrumental regime performance, PSD rises if the system performs well in terms of instrumental benefits such as economic growth, and it declines if regimes perform poorly (Dalton 1994; Magalhães 2014). Hence, PSD should decline during economic crises. However, the results are mixed. There are case-studies that find (Dalton 1994; Magalhães 2014; Mishler and Rose 1996) and that do not find this relationship in the data (Graham and Sukhtankar (2004)).

Claassen (2020b) offers an alternative theory in transferring the thermostatic model of public opinion and policy (Wlezien (1995)) to democracy and democratic support. In particular, he argues that there is a negative feedback loop between PSD and democracy so that PSD decreases if democracy supply increases and vice versa. In short, the reasoning is that the output of democratic rights and institutions overshoots the initial demand for these rights. This causes another overcompensation in favor of lower levels of democracy, and so on. Moreover, Claassen (2020b) differentiates two causal channels, one for electoral and a second for minoritarian democracies. These two sub-types differ in the degree to which the majority holds juridical power. He tests the following hypotheses: First, increases in democracy have a negative effect on PSD (H1), Second, he specifically looks at electoral (H1-elec) and minoritarian democracies (H1-min).

In his analysis he finds evidence for H1 and H1-min but not for H1-elec.

2.3 Democratic Support and Survival of Democracy

Claassen (2020a) distinguishes between two types of PSD: *principled* and *specific*. Specific PSD is instrumental and focuses on regime outputs (similar to the instrumental regime performance theory), whereas principled support is normative and focuses on the principles of the regime. Therefore, principled PSD is more durable than specific support and helps cushioning regimes in times of political or economic crises. Hence, it is principled PSD that helps to ensure the survival of democracy. Although the theory is widely accepted (e.g., Norris (2017), Booth and Seligson (2009), Mattes and Bratton (2007)), so far the findings are mixed, too. There are supporting contributions (Inglehart 2003; Welzel and Inglehart 2005) and contributions against the theory (Fails and Pierce 2010; Hadenius and Teorell 2005; Qi and Shin 2011; Welzel 2007). Astonishingly, these studies all essentially analyze the same data from the World Value Survey starting at wave 3 where respective PSD items are included and still come to different results.

Claassen (2020a) does not only look at the relationship between PSD and democratic survival but also between PSD and democratic emergence in autocracies based on an argument made by Qi and Shin (2011). That is, PSD may also function as democratic demand, and increases the probability of transitioning from autocracy to democracy. Claassen's hypotheses are: First, PSD is positively associated with subsequent change in democracy regardless of the initial level of democracy. Second, he specifically looks at PSD in already-existing democracies (H2-dem) and at PSD in autocracies (H2-aut). He finds evidence in support of H2-dem, mixed evidence for H2 and no evidence for H2-aut.

2.4 Measuring Democratic Support and the Data Challenge

We measure PSD with survey data on the national level. In particular, we focus on principled support. The questions ask for the respondent's opinion on the appropriateness or desirability of democracy and undemocratic alternatives, and

comparisons between both.²

Such items are available in 14 survey projects³, for 150 countries from 1988 to 2017. The combined dataset includes 3,765 nationally aggregated binary responses from 1,390 nationally representative survey samples.

Yet, the data poses the following challenge: It is highly fractured across time and space, with many, oftentimes large, gaps along the time dimension for all countries. Although we look at a 30 years time span, the average number of covered years is slightly below eight. Take for instance China as the country with most participants over all years (20.895). From 1988 to 2017, however, the data available covers only eight years: 2001-2003, 2006-2009, and 2011/2012. Many countries are only surveyed once or are not covered at all. The South American countries tend to have the best coverage. For example, Argentina tops the list with 23 years included. Germany and the US are available for 12 and 13 years, respectively. Figure 1 gives an overview of the sparseness of the data. The first panel shows the availability of at least one survey item across a selection of eight countries from 1990 to 2017. The other three panels focus on the three most common question themes. We see that the single item data is indeed sparse and that even the aggregated data contains lots of gaps.

²The eight included survey items and their different variants can be found on [the author's webpage](#).

³World and European Values Surveys, the Afrobarometer, Arab Barometer, Latinobarometer, Asiabarometer, Asian Barometer, South Asia Barometer, New Europe Barometer, Latin American Public Opinion Project, Eurobarometer, European Social Survey, pew Global Attitudes Project, and the Comparative Study of Electoral Systems

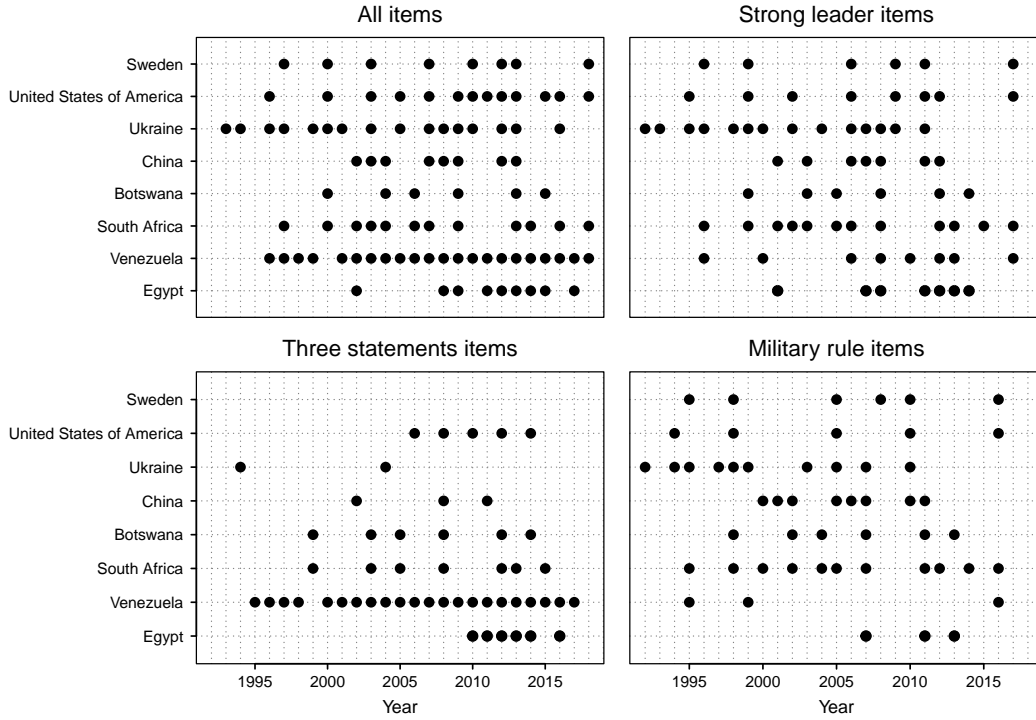


Figure 1: Sparseness of Aggregate Support for Democracy By Country, Year, and Survey Item. The figure is an update by three years of Figure 1 in Claassen (2019).

So far, past research has responded to this issue by discarding most of the available data and by using only small cross-sectional data sets consisting of observations from only one survey project for one year (Inglehart 2003; Qi and Shin 2011; Welzel 2007). Of course, this disregards not only all other countries but also other available items. Claassen (2019) describes how to use most available data for simulating a dataset that is dense across the yearly time dimension. This dataset can then be used for subsequent statistical analyses (Claassen 2020a, 2020b). The next section describes the approach.

3 Model and Estimation

Claassen (2019)’s approach for simulating dense PSD panel data has the following three main steps: Step 1 is to define a sensible model of PSD item responses as a function of latent public opinion. Step 2 is to estimate the model parameters with the Metropolis Hastings algorithm. Step 3 is to simulate the the data from

the estimated model.

3.1 The Latent Variable Model

Claassen (2019) draws three principles from the literature to model cross-national PSD timeseries: First, public opinion is an unobserved, latent trait that differs for each year and country. And each observed item response is a function of the latent trait. The function that maps latent PSD to the data should therefore contain item-specific parameters for a sub-function that disaggregates the latent trait into multiple item responses in order to account for heterogeneous item functioning. Second, estimating the latent variable from item-specific responses can be thought of as *smoothing* the opinion estimate over items since the latent variable does not contain this dimension. One should also smooth over the time dimension by not only estimating the latent traits for each time period but also by estimating the parameters that define a transitional model that holds for all periods. So the other values can additionally be simulated from some start value. Third, we should not model the percentage of positive item responses but rather the number of positive and negative responses directly. With that, we can model the problem of smaller response samples. In the following I describe how Claassen (2019) incorporates these principles in the definition of his main model⁴ which we call f .

For each country i , year t , and survey item k , the number of positive answers is distributed binomially with s as the number of total respondents and π as the probability of responding with yes.

$$y_{ikt} \sim \text{Binomial}(s_{ikt}, \pi_{ikt}) \quad (1)$$

We could now model π_{ikt} directly as a function of country-year and item-specific effects, θ_{it} and λ_k , respectively. However, we introduce additional dispersion by using another link function. The reason is that survey data on public opinion are

⁴The main model is called model 5 in Claassen (2019). It achieves the lowest discrepancy between simulated and actual data. Additionally, it has the fifth highest complexity of six different model variants.

subject to various kinds of errors, for instance, translation, selection, and interviewer mistakes. We model this error with the additional dispersion introduced by the beta distribution in Equation (2).

$$\pi_{ikt} \sim \text{Beta}(\alpha_{ikt}, \pi_{ikt}) \quad (2)$$

Further, we reparametrize the two shape parameters α and β to an expectation parameter η , and a dispersion parameter ϕ in Equation (3) and (4).

$$\alpha_{ikt} = \phi \eta_{ikt} \quad (3)$$

$$\beta_{ikt} = \phi(1 - \eta_{ikt}) \quad (4)$$

Now, we define the expectation of the number of positive responses per year, item and country as a function of item bias λ , country-specific item bias δ , and latent, dynamic, country-specific PSD θ as in Equation (5).

$$\eta_{ikt} = \text{logit}^{-1}(\lambda_k + \delta_{ik} + \theta_{it}) \quad (5)$$

The item bias effect is distributed normally with expectation μ_λ and variance σ_λ^2 .

$$\lambda_k = \mathcal{N}(\mu_\lambda, \sigma_\lambda^2) \quad (6)$$

To model the heterogeneity of item bias across countries (Stegmueller (2011)), we introduce the set of item by country effects that we call δ in Equation (7).

$$\delta_k = \mathcal{N}(0, \sigma_\delta^2) \quad (7)$$

Our main parameter set, the latent parameters θ , capture the underlying time- and country-specific support for democracy. We fully capture the time dimension of f by modelling the dynamics of θ as an AR(1) process with normally distributed error term with variance σ_θ^2 , zero intercept, and zero covariance as implied by Equation (8).

$$\theta_{it} = \mathcal{N}(\theta_{i,t-1}, \sigma_\theta^2) \quad (8)$$

3.2 Model Estimation with Metropolis-Hastings

One main application for the MH algorithm (Chib and Greenberg (1995)) is Bayesian inference⁵. Specifically, we want to estimate parameters Θ of some probabilistic model f . We have only limited prior knowledge of the distribution of Θ , for example, about its domain. We use this knowledge to define prior distributions $p(\Theta)$. And we have a likelihood sample of f given the unknown parameters Θ , namely $p(y|\Theta)$. This is our PSD data y_{ikt} . We want to use both, our prior knowledge and our data, to obtain the posterior distribution $p(\Theta|y)$ in Equation (9). In this equation, posterior and likelihood are scaled by $\frac{1}{p(y)}$. Without closed-form distributions for prior and likelihood, $p(y)$ is usually unknown. The posterior is proportional to the product of likelihood and prior. However, without the scaling factor it is not a probability distribution.

$$p(\Theta|y) = \frac{\mathcal{L}(y|\Theta)p(\Theta)}{p(y)} \propto \mathcal{L}(y|\Theta)p(\Theta) \quad (9)$$

An important insight is that our parameter vector Θ does not only include parameters defined as distributional means, for instance θ , but also standard deviations like σ_θ . If our problem would not include these variation parameters, a simpler option would be to solve $\mathcal{L}(y|\Theta)p(\Theta)$ directly with the usual optimization algorithms. The algorithm would propose new values of Θ , evaluate its prior probability and the likelihood of the data given Θ until convergence, and return the posterior mode. The mode is also called the maximum a posteriori probability (MAP) estimate. Yet, since we need to estimate standard deviations, we have to generate the whole parameter distributions to compute mean and variation. To this end, we use a Markov chain Monte Carlo (MCMC) method, namely the Metropolis Hastings (MH) algorithm.

Markov chains are stochastic processes that define distributions dependent on the values from the previous period only. The MH algorithm uses Markov chains to sample candidate parameters Θ_i^* depending on Θ_{i-1} . For each candidate Θ_i^* , the algorithm uses the unscaled posterior $\mathcal{L}(y|\Theta_i)p(\Theta_i)$ and compares it with the posterior of Θ_{i-1} to accept or reject new candidates (not requiring constant $p(y)$). Comparing relative posterior probabilities and using this comparison

⁵See Lambert (2018), Chapters 4 - 7.

for the selection of new candidates proportional to their relative probability allows us to sample from the posterior probability distribution without knowing $p(y)$ and to compute its mean and variation. The algorithm thus explores the domain proportionally to the posterior probability after a number of initial iterations. Besides the model specification, using the MH algorithm requires among others the following choices⁶: the prior distribution(s) $p(\Theta)$, the proposal distribution $g(y_i, y_{i-1})$, and the number initial parameter draws to drop from the whole MCMC sample, i.e. the length of the warmup period. Usually one initializes multiple Markov chains at once and combines the samples less the warmup afterwards. This practice decreases the dependency on the starting value. Hence, the number of chains is an additional hyperparameter. I include a more technical explanation of the MH algorithm with a more general notation in the Appendix.

3.3 Simulation

We can now use the parameter estimates and the probabilistic model with its distributional assumptions to simulate the dense PSD panel data. It is important to note that Claassen does not use the actual PSD item data but replaces it by the average of multiple simulation runs. Therefore, his method is not an imputation but a smoothing and completion method.

4 Analysis and Results

The research questions are, first, how reliable is Claassen’s method?, and second, can we improve his approach? In the following sections, I explain the changes that we will introduce to the model and the specific quantity of interest (QoI) that we will test for its robustness towards this changes.

4.1 Hyperparameter Selection

Our first goal is to analyze the sensitivity of the MH algorithm towards changes in its hyperparameters. The main options are the models, the priors, the pro-

⁶Note that there are much more potential choices depending on the MH variant and the specific setup and context.

positional distribution, the number of iterations, the warmup length, and the number of chains. Claassen (2019) already tests different models and priors. Therefore, we concern with the other options. Testing different proposal distribution poses the following challenge: MCMC estimation of complex models with sparse data is computationally costly. For instance, one run with the default settings in Claassen (2019) takes 50 minutes on my machine⁷. Therefore, it is important to use highly optimized libraries such as STAN or JAGS. However, these libraries each implement only one preferred proposal method. STAN uses a proposal distribution based on Hamiltonian dynamics (Stan Development Team (2018)), whereas JAGS uses Gibbs sampling (Plummer (2003)). The main idea of Gibbs sampling is to iteratively sample from the conditional distribution $p(\Theta|X, \Theta_{-d})$ where Θ_{-d} is Θ without the d th parameter and to use an acceptance probability equal one. Learning and especially extending these frameworks for additional proposal distributions requires a substantial amount of time and is beyond the scope of this work. Therefore, we will not vary the proposal distributions but follow Claassen’s choice STAN. Taken together, we restrict ourselves to analyzing the effect of changes in the remaining hyperparameters: the number of iterations, the warmup length, and the number of chains. Our second goal is to analyze the effect of adding three additional years, namely 2015-2017, to the dataset. Claassen uses this data in his two most recent publications on PSD but not in his first. In the following analysis the default chain number is four and the default warmup is half the chain length (as used by Claassen and as recommended by STAN) unless stated differently.

4.2 Quantity of Interest Selection

The most illustrative choice would be statistical coefficients that represent the main results in Claassen (2020b) and Claassen (2020a) and the associated substantial effects. This choice, however, has the two following disadvantages. First, because these statistical parameters are estimated from simulated data, they are influenced by randomness from the data simulation that we cannot distinguish from the estimation-inherent randomness. Second, the additional steps of sim-

⁷I use an Intel Core i7-8550U CPU with 8 1.80GHz cores

ulating data and estimating statistical models would potentially double the computation time. For these reasons, I choose the latent, dynamic, country-specific PSD θ as the quantity of interest. This has the disadvantage that we cannot evaluate how Claassen’s substantial results would change. For instance, we cannot say whether his main coefficients stay equal, become insignificant or change in direction. We can only determine whether the intermediate results, the PSD coefficients, show changes in magnitude that suggest a too strong dependence on the hyperparameter choices, or not.

4.3 The Effect of Number of Iterations

Figure 2 shows latent PSD for year 2008 in two sets of countries. The dots represent the data points.⁸ The set shown by the warm-colored lines are the countries with the smallest number of years with available data: Austria, Azerbaijan and Bahrain. These three countries have only two years with at least two available PSD items. The cold-colored lines represent the countries with the highest data availability: Uruguay (22), Venezuela (22), and Argentina (23). The vertical gray line shows the number of iterations that Claassen (2019) uses. We can make two observations: First, the parameter estimates have converged to a reasonable degree around 150. This is only a fraction of what Claassen (2019) chooses. Second, the parameter estimates for countries with less available data show a larger initial error and slower convergence. The main takeaway is that we can save a lot of computational time in our estimation by using much shorter Markov chains. For the next simulations, I use the reduced iteration number.

⁸Although it would be interesting to see confidence intervals in this graph, I do not report them as this would require me to re-run three days of computations. It can be expected that the uncertainty is proportional to the first derivative of each line. This means, it vanishes quickly but even more for the countries with more data.

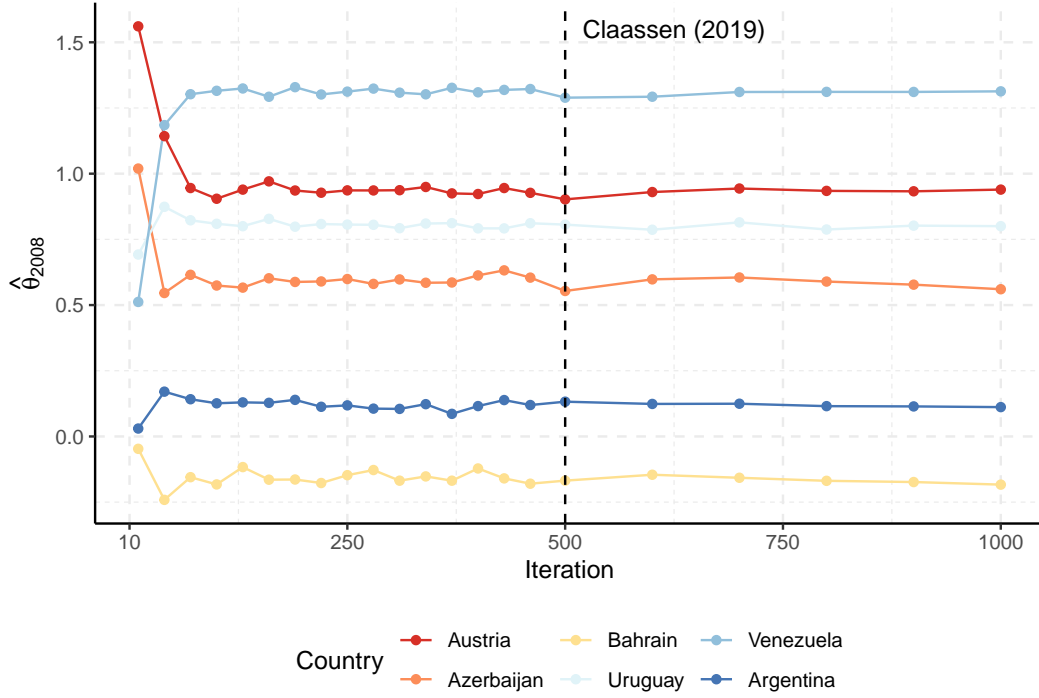


Figure 2: The effect of changes in the number of MH iterations on latent PSD in 2008.

4.4 The Effect of Warmup Length

Figure 3 shows the distributions of 10 latent PSD estimates obtained from MCMC samples with warmup lengths between 0 and 135 (or 0 to 90 percent chain length). Note that the warmup period is part of the actual MCMC sample and not a separate prior sample. The red horizontal line shows the parameter estimate obtained from a run with 1000 iterations. We make two observations: First, the default warmup of half the chain indeed achieves the results closest to the benchmark. This makes sense because, on the one hand, a too small warmup implies that the chains has less iterations to converge. On the other hand, a too high warmup leaves a smaller sample with a less stable mean. Second, as can be expected it is worse choosing a too small as choosing a too high warmup in terms of precision.

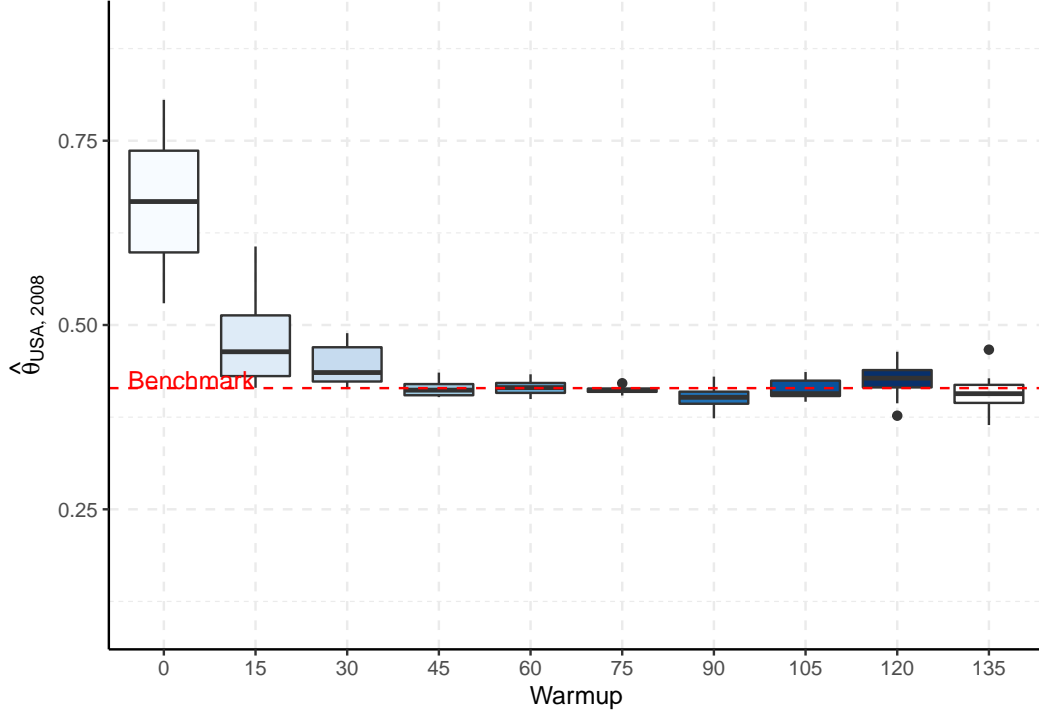


Figure 3: The effect of changes in the warmup lengths on latent PSD in 2008 in the US. Three outliers for zero warmup are not shown.

4.5 The Effect of Number of Chains

Figure 4 shows the distribution of three latent PSD estimates for MCMC samples with one to eight chains. In this experiment the number of chains has no significant effect on the latent PSD estimates. The higher the number of chains, the smaller is each single chain. Hence, there should be a configuration where the smaller subsamples have just not converged to the posterior distribution. There, we could potentially find some differences resulting from variation in the number of chains. This point, however, is also dependent on the warmup and the number of iterations. Unfortunately, ablating these three hyperparameters at once to find this point would take too many computations for this paper.

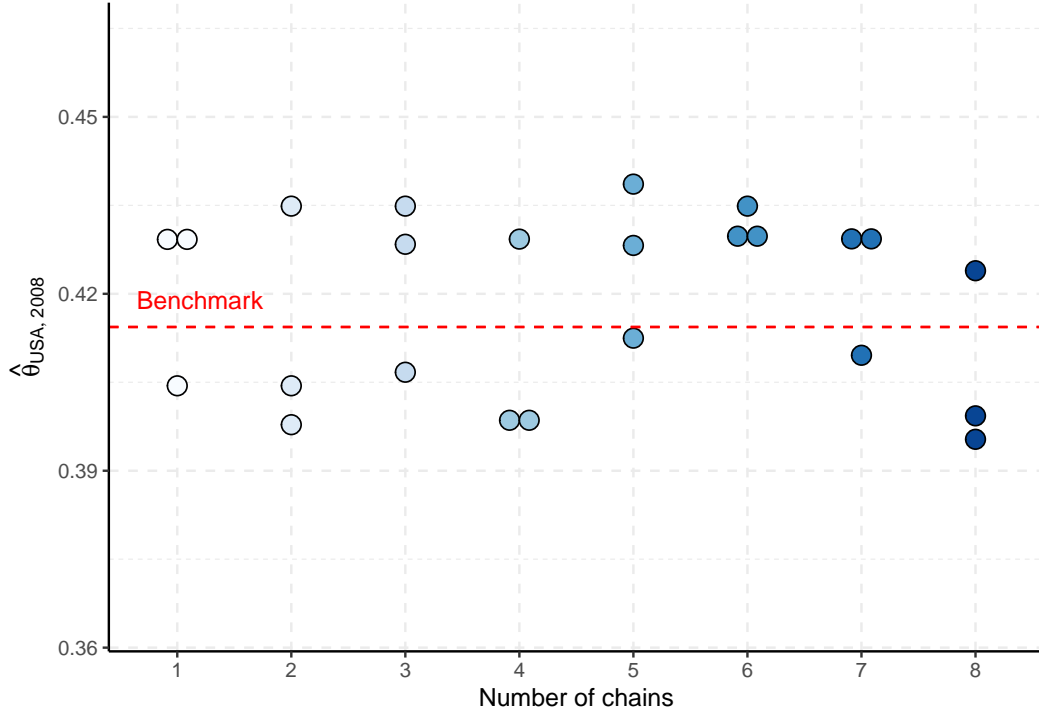


Figure 4: The effect of changes in the number of chains on latent PSD in 2008 in the US.

4.6 The Effect of Three Additional Years of Data

Figure 5 shows the effect that adding years 2016-2018 to the dataset from 1998 - 2015 has for the USA, China and South Africa. The pale lines show the QoI obtained from the smaller dataset and the strong lines the ones obtained from the updated data. We observe two points. First, all updated QoIs are more extreme in the sense that they have a larger difference from zero. However, the ranking between countries over time remains the same. Therefore, the more data is added, the better we can differentiate between latent PSD in different countries. Second, there is a pronounced shift in directions between the old estimates and the updated estimates for China in the period from 2006 to 2007. It is remarkable that we can see such a difference although the added data is roughly 10 years later. Moreover, it is realistic to expect that we could find such anomalies for a number of other countries, too. Such shifts like that can potentially have a strong impact on the data simulations and question the reliability of Claassen's results and his

method.

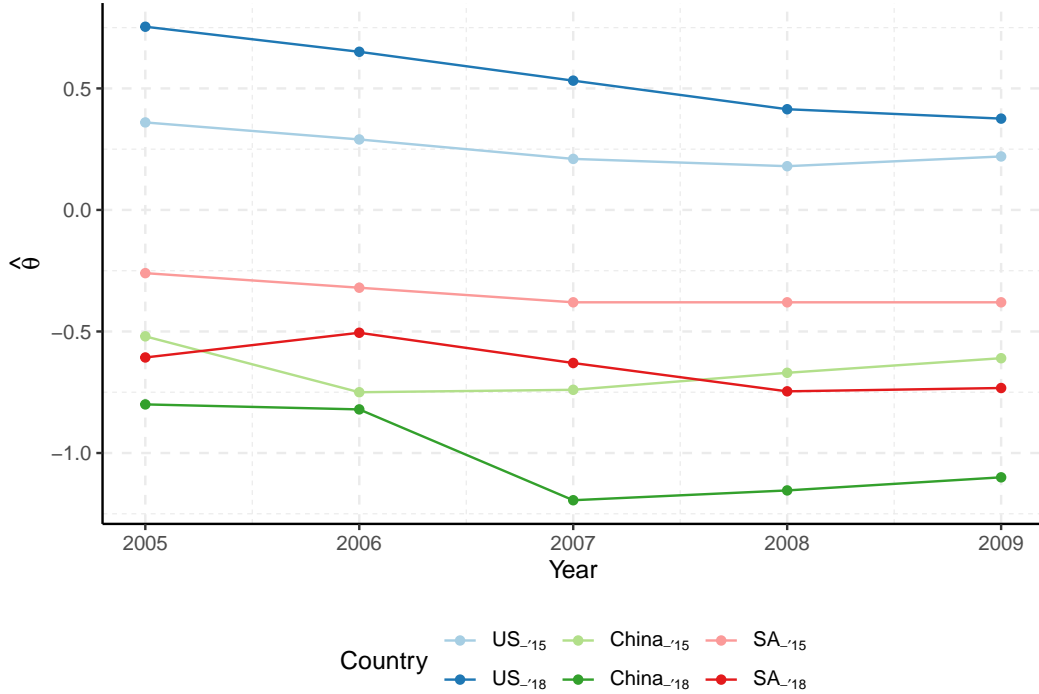


Figure 5: The effect of adding data from 2016 to 2018 on latent PSD in the US, China and South Africa.

5 Discussion

Second, Claassen’s estimation is very inefficient. The reason is not the method as such but simply that he chooses to run much more iterations than necessary. Instead of 500 iterations it is sufficient to use only less than 150. On my machine, this reduces the estimation time from 50 to 20 minutes (by 60 %). Therefore, it would be a rewarding investment to try models with less iterations. This has two advantages: First, more robustness or sensitivity tests can be done with the same resources. Second, it is easier for others to replicate the results and to build on previous work.⁹ However, instead of looking at convergence plots for a small subset of important QoIs in order to find the most efficient number of iterations as done here, I suggest a different procedure for future research: if a satisfying

⁹As Claassen notes in the readme file of his replication directory the runtime for his computations in the estimation section is 12 hours in his setup.

estimation setup is found, re-run the procedure with a set of smaller iteration numbers. After each step compute either the convergence diagnostic by Geweke (1992) or by Brooks and Gelman (1998). The first measure requires only one MCMC chain. It divides the chain less the warmup into multiple partitions and tests whether they are similar enough to reject the hypothesis that the chain has not converged. The second measure requires multiple chains and tests for differences between whole chains and within parts of single chains. This approach is more systematic and scales better to multiple QoIs compared to the approach used here.

Third, the number of chains does not have an effect and the warmup length is ideal at the value recommended by STAN. The takeaway here is that it does not add much value to look at changes to these hyperparameters from the defaults that are recommended by experts as long as the posterior sample converges.

6 Conclusion

This work explores the application of the Metropolis-Hastings (MH) algorithm for the analysis of public support for democracy using panel data. The peculiarity about the data is its sparsity. Therefore, the literature until (Claassen 2019, 2020a, 2020b) has only studied a small subset of the data that is either restricted to a small number of countries or time periods. Claassen (2019), on the other hand, shows how to use the MH algorithm together with the sparse dataset to create an extensive dense dataset. Claassen (2020a) and Claassen (2020b) then analyze the dense data and draw important conclusions about the drivers and the implications of public support for democracy. This work deals with two questions: First, how reliable is Claassen’s method? And second, can we improve his method.

I come to three results: First, updating the dataset from 1997 to 2015 by three additional years leads to noticeable changes in latent PSD. This finding questions the reliability of Claassen (2019)’s approach and the substantial findings in Claassen (2020b) and Claassen (2020a). However, it would be important to not only look at the changes in the estimated model parameters but also to analyze how the addition of new data propagates to the main coefficients of the statistical

models in Claassen (2020a) and Claassen (2020b). Second, Claassen’s estimation is inefficient because he uses an excessive amount of MCMC draws. This makes it hard to replicate and to build on his research. Therefore, it would be good research practice to find the minimal number of iterations by means of convergence tests for Markov chains. Third, the number of chains does not have an effect and the warmup length is ideal at the value recommended by STAN. Therefore, it suffices to rely on STAN’s default values as long as the Markov chains converge. In view of these findings, future research should extend the robustness checks in this work to the main results in Claassen (2020a) and Claassen (2020b). Furthermore, it appears questionable whether Claassen (2019)’s approach should also be applied to other topics with a similar data availability.

7 Appendix: Mathematical Background

7.1 Introduction

The Metropolis-Hastings (MH) algorithm is a method for sampling data points from a probability distribution from which direct sampling is difficult. It places among the top 10 algorithms with the greatest influence on science and engineering in the 20th century (Beichl and Sullivan (2000)). The MH algorithm belongs to the class of Markov chain Monte Carlo (MCMC) methods. In my explanation I assume prior knowledge on Monte Carlo sampling. However, I will describe the basics of Markov Chains. As motivation serves section 3.2. in the main part of this paper about estimating Claassen (2019)’s latent PSD model. There, I also provide a more intuitive, high-level explanation. This section has two parts that both rely on Andrieu et al. (2003) as main reference. First, I explain the basics of Markov chains. Second, I derive the algorithm and show why it works.

7.2 Markov Chains

A Markov chain $(X_t)_{t \in \mathbb{N}}$ is a stochastic process (over time) with the property that the probability of the realization in the next period depends solely on the realization in the current state and not the complete history. This is called the Markov

property. Because Markov chains with a countable, or discrete, state space are much more accessible than their continuous variant, in this chapter we will look at the discrete case. Formally, the Markov property writes

$$P(X_{t+1}|X_t, X_{t-1}, \dots, X_0) = P(X_{t+1}|X_t). \quad (10)$$

Under some conditions, the stochastic process described by a Markov chain converges to a time-invariant probability distribution, i.e. $P(X_{t+k}|X_{t+k-1}) = P(X_t|X_{t-1}), \forall k > 0$. The crucial step for understanding the MH algorithm is to see how it samples a Markov chain that is certain to converge to a stable posterior distribution. Before exploring how the algorithm achieves this result, however, it is necessary to understand the required conditions conceptually. To this end, we will use the example depicted by the following graph in Figure 6 that shows the intertemporal transition probabilities between three states representing random events.

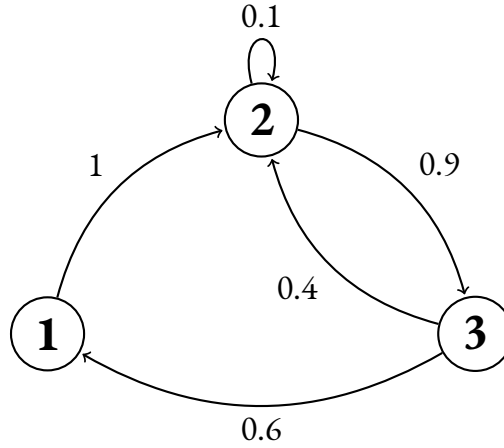


Figure 6: Transition Graph for Markov Chain with 3 states.

This transition graph can be summarized by the $n \times n$ transition matrix T where each element (i, j) represents the probability of moving from state i in period t to state j in period $t + 1$, and where n represents the number of states, i.e. $T_{i,j} = P(X_{t+1} = j|X_t = i)$. For our example, we have

$$T = \begin{pmatrix} 0 & 1 & 0 \\ 0 & 0.1 & 0.9 \\ 0.6 & 0.4 & 0 \end{pmatrix}. \quad (11)$$

7.2.1 Limit Distribution

As touched upon in the previous subsection, an interesting question can be what the probabilities of each state $j \in \{1, \dots, s\}$ are after a finite number or infinitely many steps. For this purpose let $\pi_t(j) = P(X_t = j)$ denote the probability of being in state j in period t . Of course, the probabilities in $t > 0$ depend on the probabilities for the initial state π_0 . We can use the law of total probability to calculate the probability of each state for the next period $t = 1$ by

$$P(X_1 = j) = \sum_{i=1}^3 P(X_1 = j | X_0 = i) \pi_0(i). \quad (12)$$

I.e., to compute the probability of being in state j in $t = 1$, for each initial state i , we multiply its probability $\pi_0(i)$ by the probability of moving from i to state j . This is equivalent to $\pi_1 = \pi_0 T$ in vector notation. Further, we can compute the distributions in an arbitrary future period by repeating the matrix multiplication, e.g, $\pi_2 = \pi_0 T T$, or in general, $\pi_t = \pi_0 T^t$.

Now we are ready to define the limit distribution that describes the probability distribution after infinitely many periods by

$$\pi_\infty = \lim_{t \rightarrow \infty} \pi_t = \lim_{t \rightarrow \infty} \pi_0 T^t. \quad (13)$$

We can further ask two additional important questions. First, does a limit distribution exist? And second, is it unique, or in other words, do we have the same limit distribution independent from the realization of the initial state X_0 ? In our example, there does not only exist a limit distribution with $\pi_\infty = (0.2, 0.4, 0.4)$, it is even unique regardless of start distribution π_0 . This means that independent of the start state, the probability of each state converges to the same number. For the context of the MH algorithm, this is an important property because we always want to compute the same estimates for our parameters θ , regardless of the

starting values of our simulation. In the next section, we introduce and simplify conditions that guarantee a unique limit distribution.

7.2.2 Irreducibility, Periodicity and Stationarity

Definition 7.1. A Markov chain is called *irreducible* if each state is reachable from any other state in a finite number of steps.

Figure 7 shows a Markov chain represented by a bipartite graph. This graph is composed by two times the graph in Figure 6. Obviously, this chain is not irreducible because the initial state impacts all future distributions. More precisely, starting in one subgraph sets the probability of reaching states in the other subgraph to zero. We see that a Markov Chain is only irreducible if there is at least an indirect link between every pair of states. We also observe that if the Markov Chain is not irreducible there can be no limit distribution.

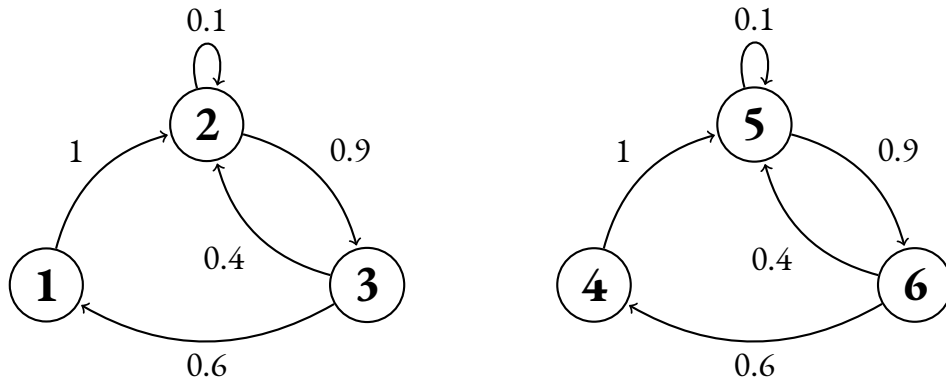


Figure 7: Transition Graph for Irreducible Markov Chain.

Definition 7.2. A state i has a period k if the greatest common denominator of possible revisits is k . A Markov chain is *aperiodic* if the period of all its states is 1.

Consider the five-state Markov chain in Figure 8 as an illustration for the above definition and suppose we start in state 1. Observe that, independent of the random draw for next period, we will arrive again in state 1 after two or four steps. Therefore, state 1 has a period of 2. If a state is revisited in random rather than a fixed time period then the state has period 1. This is automatically the case if a state has a strictly positive edge with itself.

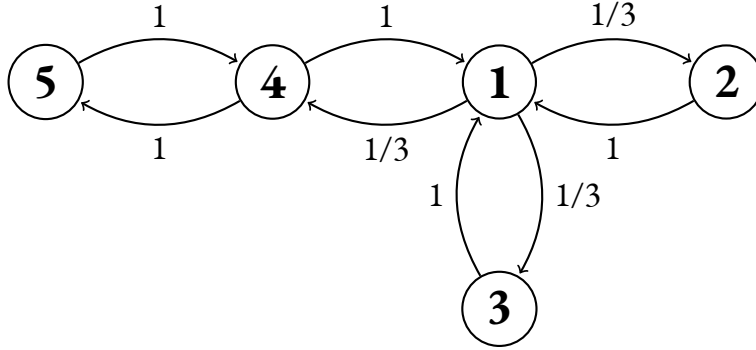


Figure 8: Markov Chain with 2-periodic State 1

Definition 7.3. π^* is the *stationary distribution* of a Markov Chain with Transition matrix in Equation (11) T if $\pi^* = \pi^*T$ and π^* is a probability vector.

Verbally, this means that the probability distribution π^* does not change anymore over time. If π^* is also unique, then π^* , the limit distribution that we are looking for in section 7.3.1, i.e., $\pi^* = \pi_\infty$.

These three definitions are enough to understand the next fundamental theorem.

7.2.3 The Fundamental Theorem of Markov Chains

This theorem formally defines the condition when a Markov Chain converges to a unique distribution, i.e. the limit distribution.

Theorem 7.1. (*Fundamental Theorem of Markov Chains*) *If a Markov chain is irreducible and aperiodic (called ergodic) then it has a stationary distribution π^* that is unique ($\lim_{t \rightarrow \infty} P(X_t = i) = \pi_i^*, \forall i$).*

Therefore, if we want to construct a stable distribution $P(X)$ via Markov chains, we need to ensure that it is irreducible and aperiodic with stationary distribution $\pi^* = P(X)$. In the next subsection, we substitute the stationarity condition by a stronger one before we finally derive the MH algorithm.

7.2.4 Reversibility

Definition 7.4. A Markov chain is *reversible* if there is a probability distribution π over its states such that $\pi(i)T_{ij} = \pi(j)T_{ji}, \forall i, j$ (reversibility condition).

Theorem 7.2. *A sufficient condition for distribution π^* to be a stationary distribution of a Markov chain with transition matrix T is that it fulfills the reversibility condition.*

Proof. $\sum_i \pi(i)T_{i,j} = \sum_i \pi(j)T_{j,i} = \pi(j) \sum_i T_{j,i} = \pi(j) \implies \pi T = \pi$ \square

Reversibility is a stronger condition than stationarity because it requires that the probability flux from i to j is equal to the one from j to i for each possible pair of states. Recall, that stationarity only requires that the probability flux to one state is equal on aggregate and not that it is symmetric between each pair of states over time. Therefore, if we want to achieve a stationary distribution it is enough to ensure that it is reversible.

7.3 The Algorithm

Recall that we want to generate a sample of a desired distribution $P(X)$. For this purpose, we use a Markov process that is uniquely defined by its transition probabilities $P(X_{t+1}|X)$ with limit distribution π so that $\pi = P(X)$. As explained in the previous section, a Markov process has a limit distribution if each transition $X_t \rightarrow X_{t+1}$ is reversible and if the stationary distribution π is ergodic. With the MH algorithm, we construct such a Markov process with stationary distribution $\pi = P(X)$. The derivation starts with another way of writing reversibility¹⁰:

$$P(x'|x)P(x) = P(x|x')P(x') \iff \frac{P(x'|x)}{P(x|x')} = \frac{P(x')}{P(x)} \quad (14)$$

The main idea is to separate transition $P(x'|x)$ in two steps: the proposal step and the acceptance-or-rejection step. Let $g(x')$ be the proposal distribution, i.e., the conditional probability of proposing state x' given x . And let $A(x'|x)$ be the probability of accepting proposed state X' . Formally, we have $P(x'|x) = g(x'|x)A(x'|x)$. Inserting this in Equation (14) gives

$$\frac{P(x')}{P(x)} = \frac{g(x'|x)A(x',x)}{g(x|x')A(x',x)} \iff \frac{A(x',x)}{A(x,x')} = \frac{P(x')}{P(x)} \frac{g(x|x')}{g(x'|x)}. \quad (15)$$

¹⁰We simplify our notation by using x' and x instead of X_{t+1} and X_t .

The following choice, termed the Metropolis choice, is commonly used as an acceptance ratio for sampling x' from $P(x')$ that fulfills the above reversibility condition:

$$A(x', x) = \min \left(1, \frac{P(x')}{P(x)} \frac{g(x|x')}{g(x'|x)} \right) \quad (16)$$

Note that the minimizer in $A(x', x)$ enforces that the probability is smaller/equal 1. The MH algorithm writes as follows:

Algorithm 1 Metropolis-Hastings algorithm

```

Initialize  $X_0$ 
for  $t \leftarrow 0$  to  $T - 1$  do
    Draw  $u \sim \mathcal{U}_{[0,1]}$ 
    Draw candidate  $X^* \sim P(X^*|X_{t-1})$ 
    if  $u < \min\{1, \frac{p(X^*)g(X_t|X^*)}{p(X_t)g(X^*|X_t)}\}$  then
         $X_{t+1} \leftarrow X^*$ 
    else
         $X_{t+1} \leftarrow X_t$ 
    end if
end for

```

Obviously, the construction of the acceptance ratio ensures reversibility. Ergodicity is ensured by the random nature with which we accept proposed states: First, the chain is irreducible because each state is reachable from any other state with positive probability at every single step. Second, for each state x , $P(x' = x)$ is always positive and therefore the Markov chain is aperiodic.

In a general setting, the choice for transition distribution $g(x'|x)$ and the number of iterations until the limit distribution is reached are unclear. These two choices are the hyperparameters of the MH algorithm. In the Bayesian inference application in the article series starting from Claassen (2019), additional important choices are the prior distribution $p(\theta)$ and the model choice f .

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