

# Reading notes

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April 16, 2013

This is a summary of the readings of the recent functional connectivity papers.

**dynamic connectivity:** It looks like people are beginning to study the dynamic property of the connectivity [Deco et al., 2010]. The conventional brain connectivity analysis assume that the connections between regions are static and do not change with time. Zalesky et al. [2011] test the variation of the fMRI time series by splitting the time series into two part, and use paired t-test to test any difference between two halves with respect to the various statistical measures, including variance, maximum and minimum amplitude, and did not identify significant difference. This suggest there is no long-term variation on the time series. But this is not sufficient to suggest that the functional network is static. The connectivity between any regions can change over time. Modeling the dynamics of the connectivity will help to understand the brain network. If we use graph to model brain network, we can use the rich theory in the dynamics of the graph [Mortveit and Reidys, 2008] to model the dynamics of the brain network. Deco et al. [2010] reviewed three typical methods for modeling the network dynamics.

## 1 Sparsity of Brain Network

There are a few reasons that we should explore the sparse concept of graphical model to fMRI.

- **Consistence with neurophysiology** The coefficients computed the regression with sparsity method corresponds to the partial correlation after removing the influence of all other nodes in the graph. This amounts to the direct connection between two regions. The regular correlation matrix have a marginal interpretation. The inverse covariance matrix of the multi-variate Gaussian gives a *conditional* interpretation. The zeros in the precision matrix means conditional independence given all other nodes, and the coefficients means partial covariance (or partial correlation, after normalization of the the data).

Any two regions of the human may have some degree of correlation marginally, due to the possible connections to other nodes. The partial correlation answer the questions

like what is the direct link between two regions. This can also be explained with diffusion tensor imaging where fiber tracts either directly or indirectly connect two white matter regions.

- **Rich method for optimization**
- **Network analysis as postprocessing**
- **Possibility to parallelize** The graphical Lasso problem can be seen as  $P$  independent linear regression problem, which can be parallelized.

## 2 April 2 - 9

The functional network is said to be organized in a hierarchical way. We can explore this.

Markov Random field can be used in functional connectivity of fMRI data and represent the statistical dependency of spatial adjacent variables. The representation can be either in voxel level or in a higher level where objects or regions of interest are variables. The topology or structure of the graph used by MRFs can be known as regular lattice, or it can be learned from the data. The model as a prior information, helps the statistical inference of the connectivity.

## 3 April 9 - 16

Need to test synthetic data for parameter estimation. Find a scenario where the parameters can be decently estimated. We need a good validation method for this hierarchical MRF method.

Also need to revise the thesis claim. And for the dynamical network, draft a summary of the readings.

[Honey et al. \[2007\]](#) studies the dynamics of functional network on a single subject. It is helpful if we can build a model that can use information from multiple subjects. in [Honey et al. \[2007\]](#), the structure connectivity matrix is first computed, and neural dynamical potential signal is *simulated* by some models. The neural potential has high sampling rate. The functional connectivity is computed from this simulated time course signal at different temporal scale. BOLD signal is also *simulated* from the neural potential signal by the *balloon* model. It seems the simulated BOLD signal has coarse spatial resolution compared the neural potential signal, i.e., BOLD is simulated per region. The conclusion is that functional connectivity estimated from the whole neural potential signals are more consistent with structural network, while the network estimated from a segment of neural signals have more transient network patterns.

My comments: For the study of fMRI, we do not have to assume a model for neural potential signal and simulate it. We can just assume a dynamic for BOLD signal. The model should

take account multiple subjects. We should model the common property among all the subjects. For example, although different subjects may not in the same state at same time point on same ROI, they may share probability of transiting from one state to the next. Subjects must share something.

To model the dynamics of the network, we can either explicitly model the time delay due to the transmission of the neural signal in the fibers, or we can choose not model this time delay. [Honey et al. \[2007\]](#) does not model it. We probably should not model it either, because the low temporal resolution of BOLD signal. The time delay, compared to the TR of BOLD, can be ignored.

[Ghosh et al. \[2008\]](#) is the second paper that [Deco et al. \[2010\]](#) reviewed. In [Ghosh et al.](#), the low level neural signal is also simulated similar to [Honey et al.](#), and BOLD signal is computed from these simulated signals. The difference from [Honey et al.](#) is they add time delay between the regions, and the delay is proportional to the distance between the regions.

If we have a dynamical model for BOLD signal, how could we simulated it to see the simulated BOLD signal look like the real data? Dynamical Gaussian Markov Random Field???

In [Yeo et al. \[2011\]](#), 7 and 17 functional network is estimated by clustering approach. This functional atlas is used in a review of ADHD [[Castellanos and Proal, 2011](#)]. From [Castellanos and Proal](#), DMN is has less anti-correlation for ADHD patients, since the strong anti-correlation is believed to related to the better behavioral performance.

Another interesting thing to do is building a spatial-temporal model of fMRI data. The model will depict the spatial dependency, as well as the temporal correlation of the BOLD signal. This model can be used to estimate and remove noise. Such a model is related to the MRF because spatially it would be a MRF, and temporal domain the image at time point  $t$  will depend on the image at  $t - 1$ .

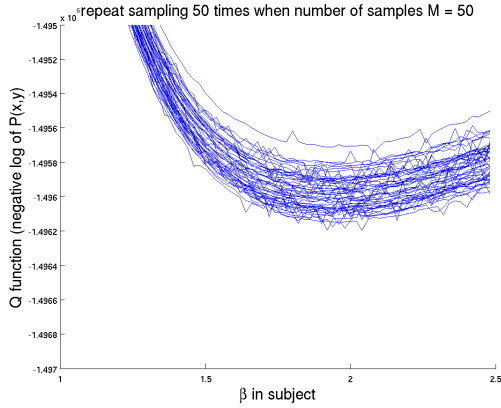
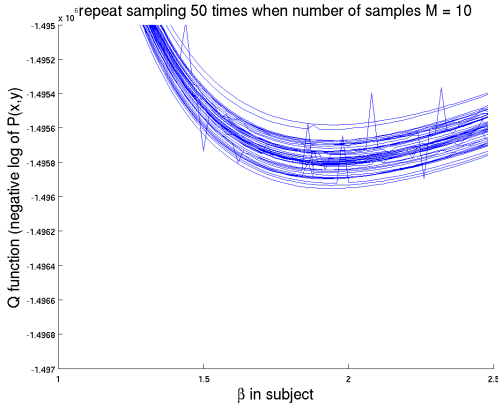
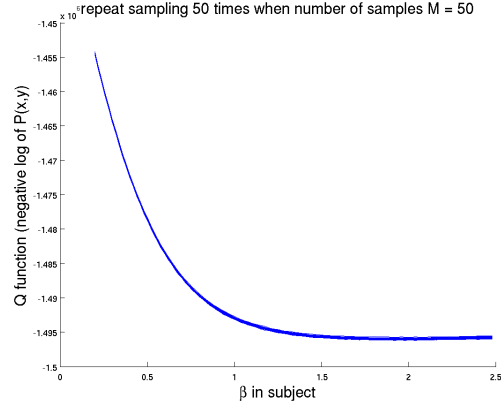
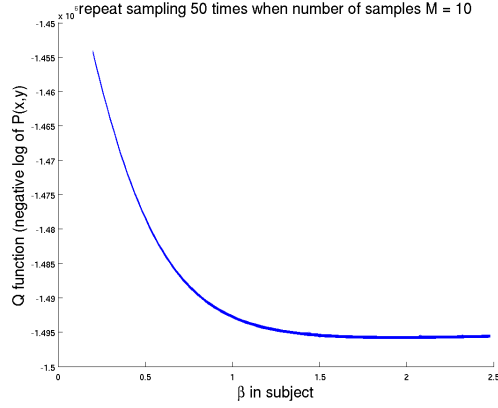
## 4 April 23 - 30

What we have been done so far is far from being a journal paper.

The advantage of variational inference: 1) Able to estimate number of components  $K$ . 2) Use indicator vector notation instead of scalar variable for hidden variables. 3) Introduce Dirichlet distribution for the mixing coefficients  $\pi_i$ . 4) Less memory usage. 5) Less running time. 6) Possible for full Bayesian analysis.

The advantage of using `lemon` graph library for rewriting the code: 1) Graph structure separate from data. 2) Easier to change graph structure without changing other code. 3) Ease to change MRF neighborhood structure, say, from 6 neighbors to 26 neighbors.

The Dirichlet prior on mixing coefficient  $\pi_i$  is different from the MRF on hidden variable  $z$ .



## 5 April 30 - May 6

### 5.1 Consistency test

This test aims to see the consistency of the joint log likelihood function  $p(x, y)$  over the number of MC samples.

### 5.2 Swendsen-Wang

First I will explain how Swendsen-Wang sampling works on a simple Ising or Potts model. Define the Potts mode as

$$f(x) = \frac{1}{Z} \exp\{H(x)\}, \quad H(x) = \sum_{i < j} \beta \mathbf{1}_{(x_i = x_j)}.$$

This is a slightly different definition with our previous definition of Potts model, but they both prefer smoothed labels between spatial neighbors when  $\beta > 0$ . Now to generate a sample from  $f(x)$ , we introduce a auxiliary random variable  $y_{ij}, i \leq j$ . Conditioned on  $x$ , the  $y_{ij}$  are independent. Each  $y_{ij}$  is uniformly distribution on the interval  $[0, a_{ij}]$ , with

$a_{ij} = \exp(\beta \mathbf{1}_{(x_i=x_j)}) \leq 1$ . So the conditional pdf of  $y = \{y_{ij}\}$  given  $x$  is

$$f(y|x) = \prod_{i \leq j} \frac{\mathbf{1}_{(y_{ij} \leq a_{ij})}}{a_{ij}} = \left( \prod_{i \leq j} \mathbf{1}_{y_{ij} \leq a_{ij}} \right) \exp\{-H(x)\}$$

Due to this definition of  $f(y|x)$ , the joint pdf  $p(x, y)$  is also uniformly distributed because of the cancellation of  $H(x)$  and  $-H(x)$ .

$$\begin{aligned} f(x, y) &= f(x)f(y|x) = \frac{1}{Z} \exp\{H(x)\} \cdot \left( \prod_{i \leq j} \mathbf{1}_{y_{ij} \leq a_{ij}} \right) \exp\{-H(x)\} \\ &= \frac{1}{Z} \prod_{i \leq j} \mathbf{1}_{y_{ij} \leq a_{ij}} = \begin{cases} \frac{1}{Z} & \text{if } y_{ij} \leq a_{ij}, \forall i < j, \\ 0 & \text{otherwise} \end{cases} \end{aligned}$$

More importantly,  $p(x|Y) \propto f(x, y)$  is also uniformly distributed over the set  $\mathcal{A} = \{x : y_{ij} \leq a_{ij}\}$ . Now either  $y_{ij} \in [0, 1]$  or  $y_{ij} \in (1, e^\beta]$ . if  $y_{ij} \leq 1$ , it is impossible to tell if  $x_i = x_j$ . But if  $y_{ij} > 1$ ,  $a_{ij}$  must be greater than 1 to allow draw a uniform sample  $y_{ij} > 1$  from  $f(y_{ij}|x)$ , and hence  $x_i = x_j$ . Therefore, The sites  $i$  and  $j$  for which  $y_{ij} > 1$  can be gathered into clusters, and within each such cluster the  $x$  must be same. And the value of  $x$  is uniformly distributed. The  $x_i$  and  $x_j$  value for those  $y_{ij} \leq 1$  are not constrained to be same and can be different.

Hence we can sample from  $f(y|x)$  and  $f(x|y)$ . At last we discard  $y$  and the  $x$  will be samples from marginal distribution  $f(x)$ . To simplify matters further, note that instead of the exactly  $y_{ij}$  it suffices to know only the variables  $u_{ij} = \mathbf{1}_{y_{ij} \leq 1}$ . Given  $x$ ,  $u_{ij} \sim \text{Ber}(1 - e^{-\beta})$  if  $x_i = x_j$ , and  $u_{ij} = 0$  otherwise. Hence we have the Swendsen-Wang algorithm as: 1) Given  $x_i$ , generate  $u_{ij} \sim \text{Ber}(1 - e^{-\beta})$  if  $x_i = x_j$ , and  $u_{ij} = 0$  otherwise. 2) Given  $\{u_{ij}\}$ , generate  $x$  by clustering all the sites and choosing a label value for each cluster independently and uniformly from  $\{1, \dots, K\}$ .

### 5.3 Generalized Swendsen-Wang

The generalized Swendsen-Wang by [Barbu and Zhu \[2005\]](#) has a few things to note:

- It choose only one cluster to change label  $x$  in each iteration, instead of sample all clusters.
- It seems the posterior distribution used in their sampling only includes likelihood term (i.e. the data term), and not includes the smoothness prior. This need special attention.

## 6 May 14 – May 21

Since the SW algorithm takes longer time than regular Gibbs sampler, I used a profiler to look into the call trace of valgrind tool, and found that: When sampling on a single larger

image (128x128x128, which amounts to 10 subjects data of real fMRI), about half of the running time is spent on finding connect component. Around 25% time is used for generating random samples. About 11% is spent on the other operations on the graph such as access nodes and edges.

If we want to re-write the code in parallel, at most 50% of the routine can be optimized, and the connect component routine can not be parallelized easily, since it is provided by the `lemon` library. We do need this library in order to define a data structure for both graph nodes and edges. Even if we do not use this library, and write our own connected component routine, it is not straightforward how to optimize it in parallel, since the algorithm is implemented with a breath-first-search algorithm.

Other issues: Critical temperature, variance map.

## 7 Aug 24 – Aug 27

I'm currently working on two things: 1) I think we may need a change on the hierarchical model. We don't really need the MRF in group level, since the subjects MRF can enforce the smoothness of group. There are advantages of this simplification: a) we can define 1-of-K binary vector on subjects level, and define a continuous variable on group. So the group naturally acts as a prior probability, just as we tried to do some time ago. b) It would be possible to define a Dirichlet prior on group, and we can probably even estimate the number of clusters K. 2) If the sampling algorithm's issue is too difficult to solve, there is no reason we can not try other optimization methods like Variational Inference. The benefits are: a) Full Bayesian. b) faster. The solution would still be a local optima, though. There are rich theory along this path, so we don't worry about the lack of good methodology/theory.

OK this is not the right thing to do for now.

Wednesday: Spent some time on MTGL graph library. Though the computation time is not a issue if the algorithm works fine, it is an issue when in debugging stage. The MTGL library is claim to have parallel algorithm than can use multiple threads. After looking into it, I found this is not what I want. I just need use the Lemon graph library and update each node with my own pthread routine. I don't really need a parallel a parallel graph library. MTGL's parallel implementation is on some specific algorithm, which I don't need except in a Swendsen-Wang algorithm for connected component analysis.

So if I do need a graph library, Lemon is the choice so far. But to migrate the current code to the Lemon graph is low priority compared to testing on new datasets.

Thursday and Friday: Downloaded NYU's test-retest dataset and working on the preprocessing scripts. The plan is to use fcon 1000's scripts which uses FSL and AFNI tool. This scripts is similar to ADHD200's scripts but is more geenral.

## 8 Apr 14: Selecting $\alpha$

This section is for choosing the optimal  $\alpha$  parameter of the hierarchical MRF model. I will define  $\alpha$  as part of the model, and choosing  $\alpha$  turns into a model selection problem. The Bayesian method of model selection is to compute the marginal data likelihood, given as

$$P(D|\mathcal{M}) = \int P(D|\theta)P(\theta|\mathcal{M}) d\theta,$$

with  $D$  the data, and  $\mathcal{M}$  the model, and  $\theta$  the set of parameters. In our model, the hidden network labels also need to be integrated out in order to compute the above marginal distribution. Besides, the data used to train the model should be different with the data for testing. Define  $x$  is the training subjects' fMRI data, and  $y$  the training subjects label (include both group map  $y_g$  and subject maps  $y_{sub}$ ), and  $x_t$ ,  $y_t$  are the test subject's fMRI and label map. We can use the posterior predictive distribution defined as

$$P(x_t|\mathcal{M}, x) = \int P(x_t|y_t; \theta_t)P(y_t|\mathcal{M}, x; \theta) dy_t. \quad (1)$$

$\theta_t = \{\mu_t, \kappa_t, \beta_t\}$  is the parameter set for the test subject, and  $\theta = \{\mu, \kappa, \beta\}$  is the set of parameters for the training subjects. The  $\alpha$  parameter goes into the model  $\mathcal{M}$ , and we choose  $\alpha$  with the largest distribution given above. To evaluate the above distribution, we can use the MC integration by drawing samples of  $y_t$  from  $P(y_t, \theta|\mathcal{M}, x; \theta)$

$$P(y_t|\mathcal{M}, x) \approx \frac{1}{M} \sum_m P(x_t|y_t^m; \theta_t), \quad y_t^m \sim P(y_t|\mathcal{M}, x; \hat{\theta})$$

The  $\theta = \{\mu, \kappa, \beta\}$  is treated as fixed parameters. We can estimate  $\theta$  from the EM algorithm as we have already done, and use the estimates of  $\hat{\theta}$  instead. In order to generate  $y_t^m$ , we need to write  $P(y_t|\mathcal{M}, x; \hat{\theta})$  as

$$\begin{aligned} P(y_t|\mathcal{M}, x; \hat{\theta}) &= \int P(y_t|y_g) \cdot P(y_g|\mathcal{M}, x; \hat{\theta}) dy_g \\ &\approx \frac{1}{M} \sum_m P(y_t|y_g^m), \quad y_g^m \sim P(y_g|\mathcal{M}, x; \hat{\theta}), \end{aligned} \quad (2)$$

which need a second MC sampling and integration. The formulation is same with what Suyash suggested except that only the group label  $y_g$  is integrated out. In Suyash's formulation, both  $y_g$  and  $y_{sub}$  are integrated out. But after a discussion with Tom, we find  $y_t$  is independent of  $y_{sub}$  given  $y_g$ . Hence there is no need to marginalize  $y_{sub}$ .

Once we have the sample  $y_t^m$ , we can compute the distribution in (1). However, we need  $\theta_t$  to evaluate it, and  $\theta_t$  is not available from the model or the training data. One solution is to estimate  $\theta_t$  given the test subject label map  $y_t^m$  and the data  $x_t$ , and use the estimates  $\hat{\theta}_t$  together with  $y_t^m$  to compute (1).

Suppose we use  $\tilde{y}_g$ , the mode of  $P(y_g|\mathcal{M}, x; \hat{\theta})$  to further approximate the integral (this may or may not be necessary), and have

$$P(y_t|\mathcal{M}, x; \hat{\theta}) \approx P(y_t|\mathcal{M}, \tilde{y}_g),$$

and then draw samples  $y_t^m$  from the above distribution. In this probably over-simplified model, we can ask the question: how does the  $\alpha$  have impact on the samples  $y_t^m$  we draw, and hence have impact on the value of (1)?

If we assume a  $y_t^w$  the estimated label map of the test subject without any group prior (i.e. the regular maximum-likelihood estimates), then  $y_t^w$  will have the largest data likelihood  $P(x_t|y_t^w)$ . We will use  $y_t^w$  as a reference map and compare with  $y_t^m$  generated under different  $\alpha$ . For large value of  $\alpha$ , most of the  $y_t^m$  would be close to  $\tilde{y}_g$ , and the likelihood  $P(x_t|y_t^m)$  will be reasonably large, but less than  $P(x_t|y_t^w)$ . So large  $\alpha$  could not give optimal value of (1). If, on the other hand,  $\alpha$  is close to zero, the samples  $y_t^m$  drawn from  $P(y_t|\mathcal{M}, x; \hat{\theta})$  will be random smooth map. A small number of these samples may happen to be close to  $y_t^w$  and give large data likelihood  $P(x_t|y_t^m)$ , but most will give low likelihood. The average of the likelihood from all these samples (a few good ones + many bad ones) would give low value of (1). So, small  $\alpha$  would not have optimal value on (1) either. Hopefully there is a optimal value of  $\alpha$  that achieves a trade-off between the above two scenario.

There is another issue for sampling (2). That is, how to draw samples of  $y_t$  from (2)? After the second MC approximation,  $P(y_t|\mathcal{M}, x; \hat{\theta})$  can be approximated by the averaging of  $P(y_t|y_g^m)$ , which is a Gibbs distribution, and hence MRF. However, the sum of Gibbs distribution is not necessarily Gibbs distribution. In our case,  $P(y_t|\mathcal{M}, x; \hat{\theta})$  would not be a Gibbs distribution after the first MC approximation, and we can not use Gibbs or Metropolis sampling to draw samples of  $y_t$  from (2).

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