Supplementary Material

Main document: *A compositional model to assess expression changes from single-cell RNA-seq data*

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This supplement is organized to match the sectioning of the main document. In summary,

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1. Introduction.

1.1. *R package.* Reference can be found at github site ...

on scDDboost, web page, etc

2. Modeling.

2.1. *Data Structure, Sampling Model, and Parameters.* Proof of Theorem 2.

PROOF. Recall $\theta = (\phi, \psi, \mu, \sigma)$. Through the sampling procedure of our model (Figure 3), assuming we known number of cells within each conditions (n_1, n_2). We have z^1, z^2 are multinomial draw given ϕ and ψ, thus the generation of y, z only depends on (ϕ, ψ) Also given z, $X_{g,c}$ is sampled through NB(μ_{g,z_c}, σ_g), only depends on (μ, σ). Thus $P(X, y, z|\theta) = P(y, z|\phi, \psi)P(X|z, \mu, \sigma)$, and we independently give priors for (μ, σ) and (ϕ, ψ) By the Baye's rule,

$$\begin{aligned} P(\theta|X, y, z) &\propto P(X, y, z|\theta)P(\theta) \\ P(X, y, z|\theta)P(\theta) &= P(y, z|\phi, \psi)P(X|z, \mu, \sigma)P(\mu, \sigma|z)P(\phi, \psi) \\ P(\phi, \psi|y, z) &\propto P(y, z|\phi, \psi)P(\phi, \psi) \\ P(\mu, \sigma|X, z) &\propto P(X|z, \mu, \sigma)P(\mu, \sigma|z) \\ \text{Thus } P(\theta|X, y, z) &\propto P(\phi, \psi|y, z)P(\mu, \sigma|X, z) \end{aligned}$$

From this we know
1. Given X, y and z, $(\phi, \psi) \perp (\mu, \sigma)$
2. Given condition and subtypes label y, z, (ϕ, ψ) is independent with X
3. Given X and z, (μ, σ) is independent with y
Thus we have $P\left(A_\pi \cap M_{g,\pi}|X, y, z\right) = P\left(A_\pi|y, z\right)\ P\left(M_{g,\pi}|X, z\right)$. □

2.2. *Method Structure and Clustering.*

2.2.1. *EBSeq.* Suppose we have K subtypes, let $X_g^I = X_{g,1}^I, ..., X_{g,S_1}^I$ denote transcripts at gene g from subtype $I, I = 1, ...K$. In the EBSeq model it assumed that counts within subtype I are distributed as Negative Binomial: $X_{g,s}^I|r_{g,s}, q_g^I \sim NB(r_{g,s}, q_g^I)$ Where

$$P(X_{g,s}^I|r_{g,s}, q_g^I) = \binom{X_{g,s} + r_{g,s} - 1}{X_{g,s}} (1 - q_g^I)^{X_{g,s}^I} (q_g^I)^{r_{g,s}}$$

and $\mu_{g,s}^I = r_{g,s}(1 - q_g^I)/q_g^I$; For the ease of later deriving the prior predictive function of EB framework we use q rather than μ to parameterize the NB.

The EBSeq model assumed a prior distribution on $q_g^I : q_g^I|\alpha, \beta^{I_g} \sim Beta(\alpha, \beta^{I_g})$. The hyperparameter α is shared by all the isoforms and β^{I_g} is I_g specific. Now we are using EBSeq for expression inference of genes rather than isoforms, we made a modification to the original prior from EBSeq. We still make α to be shared by all the genes and β^g becomes gene specific parameter.

The modeling of $r_{g,s}$ is the same as what EBSeq does. Specifically, we further assume that $r_{g,s} = r_{g,0} * l_s$ where $r_{g,0}$ is an isoform specific parameter common across subtypes and $r_{g,s}$ depends on it through the sample-specific normalization factor l_s. Here we expected normalized data, so $l_s = 1$ for all samples, that is $r_{g,s}$ degenerate to σ_g, which does not depend on sample. We use σ_g instead of $r_{g,s}$ in the following.

What we are interested at those K groups comparison is the expression pattern,

$$M_{g,\pi} = \{\theta \in \Theta : \ \mu_{g,k} = \mu_{g,k'} \iff k, k' \in b, b \in \pi\}.$$

For example $K = 3$, there are 5 expression pattern, $P_1, P_2, ..., P_5$, Comparison between μ is equivalent as comparison between q.

$$\begin{aligned}
&P1 : q_g^1 = q_g^2 = q_g^3 \\
&P2 : q_g^1 = q_g^2 \neq q_g^3 \\
&P3 : q_g^1 \neq q_g^2 = q_g^3 \\
&P4 : q_g^1 = q_g^3 \neq q_g^2 \\
&P5 : q_g^1 \neq q_g^2 \neq q_g^3 \text{ and } q_g^1 \neq q_g^3
\end{aligned}$$

Under the assumption that two groups I and J share the same q_g we can pool the counts from the two groups by viewing them come from same distribution i.e. $X_g^{I,J}|\sigma_g, q_g \sim NB(\sigma_g, q_g)$, $q_g|\alpha, \beta^g \sim Beta(\alpha, \beta^g)$ and obtained the prior predictive function $f_0^g(X_g^{I,J}) = \int_0^1 P(X_g^{I,J}|r_g, q_g) * P(q_g|\alpha, \beta^g) dq_g = \left[\prod_{s=1}^{S} \binom{X_{g,s}+\sigma_g-1}{X_{g,s}}\right] \frac{Beta(\alpha+\Sigma_{s=1}^S \sigma_g, \beta^g+\Sigma_{s=1}^S X_{g,s})}{Beta(\alpha,\beta^g)}$. Consequently, we have prior predictive function for $P1, ..., P5$ as

$$\begin{aligned}
h_1^g(X_g^{1,2,3}) &= f_0^g(X_g^{1,2,3}) \\
h_2^g(X_g^{1,2,3}) &= f_0^g(X_g^{1,2}) f_0^g(X_g^3) \\
h_3^g(X_g^{1,2,3}) &= f_0^g(X_g^1) f_0^g(X_g^{2,3}) \\
h_4^g(X_g^{1,2,3}) &= f_0^g(X_g^{1,3}) f_0^g(X_g^2) \\
h_5^g(X_g^{1,2,3}) &= f_0^g(X_g^1) f_0^g(X_g^2) f_0^g(X_g^3)
\end{aligned}$$

Then the marginal distribution of counts $X_g^{1,2,3}$ is $\sum_{k=1}^{5} p_k h_k^g(X_g^{1,2,3})$, where the marginal $p_k = P(M_{g,\pi}|z)$ (shared by all genome) satisfying $\sum_{k=1}^{5} p_k = 1$ and are estimated by EM algorithm. Thus, the posterior probability of an expression pattern k is obtained by:

$$\frac{p_k h_k(X_g^{1,2,3})}{\sum_{k=1}^{5} p_k h_k^g(X_g^{1,2,3})}$$

In the optimization steps for determining the hyper parameters (α, β^g, p), the computation and memory increase exponentially with the number of subtypes K. We use one-step EM as an approximation for the solution, that is α and β^g are updated through gradient ascent. p is updated by the explicit form of the maximizer of the log likelihood.

2.2.2. *modalClust.* **Product Partition Model**

Let $X = (X_1, X_2, ..., X_n)$ be n one dimension observed data, given a partition for the data $\pi = \{S_1, ..., S_q\}$, where S_i are disjoint subsets of $\{1, 2, ..., n\}$ and $\bigcup_{i=1}^{q} S_i = \{1, 2, ..., n\}$. The likelihood for X satisfying such partition is

$$p(X|\pi) = \prod_{i=1}^{q} f(X_{S_i})$$

where X_{S_i} is the vector of observations corresponding to the items of component S_i, The component likelihood $f(X_S)$ is defined for any non-empty component S and can take any form. The partition π is the only parameter we are interested at. Any other parameters that may have been involved in the model have been integrated over their prior.

The prior distribution for a partition π is also taken as a product form. We use the MAP partition(maximize the posterior $p(\pi|X) \propto p(X|\pi)p(\pi)$) as the estimated clustering.

Dahl demonstrated by some choice of f and prior of π, we can reduce the time complexity of finding the MAP partition from factorial(n) to $O(n^2)$ (Dahl, 2009), And the crucial condition for f is that if X_{S_1} and X_{S_2} are overlapped in the sense that $\min\{X_{S_2}\} < \max\{X_{S_1}\} < \max\{X_{S_2}\}$ or $\min\{X_{S_1}\} < \max\{X_{S_2}\} < \max\{X_{S_1}\}$, let $X_{S_1^*}$ and $X_{S_2^*}$ be the sets of swapping one pair of those overlapped terms and keep the other unchanged. Then $f(X_{S_1})f(X_{S_2}) \leq f(X_{S_1^*})f(X_{S_2^*})$. Under such condition, we know that possible MAP candidates must be those partition πs that for any two blocks $b_1, b_2 \in \pi$, either $\max_{i \in b_1}(X_i) \leq \min_{j \in b_2}(X_j)$ or $\min_{i \in b_1}(X_i) \geq \max_{j \in b_2}(X_j)$.

In Poisson-Gamma Model we assuming:

$$\begin{aligned} X_i|\pi, \lambda &\sim Poisson(X_i|\lambda_1 \mathbf{I}\{i \in S_1\} + ... + \lambda_q \mathbf{I}\{i \in S_q\}) \\ \pi &\sim p(\pi) \\ \lambda_j &\sim Gamma(\alpha_0, \beta_0) \end{aligned}$$

where $p(\pi) \propto \prod_{i=1}^{q} \eta_0 \Gamma(|S_i|)$. Integrate out λ, $f(X_S)$ is obtained as:

$$f(X_S) = \frac{\beta^\alpha}{(|S| + \beta)^{\sum_{i \in S} X_i + \alpha}} \frac{\Gamma(\sum_{i \in S} X_i + \alpha)}{\Gamma(\alpha)} \frac{1}{\prod_{i \in S} X_i}$$

To apply modal-cluster on Poisson-Gamma model, we need to show $f(X_S)$ still satisfying the condition mentioned before.

PROOF. if X_{S_1} and X_{S_2} are overlapped, without loss of generality, we assume $\min\{X_{S_2}\} < \max\{X_{S_1}\} < \max\{X_{S_2}\}$, and we swap $\max\{X_{S_1}\}$ with $\min\{X_{S_2}\}$ and keep the rest unchanged or we could also swap $\max\{X_{S_1}\}$ with $\max\{X_{S_2}\}$. We denote the new set forming by swap of $\max\{X_{S_1}\}$ with $\min\{X_{S_2}\}$ as S_1^* and S_2^* and swap of $\max\{X_{S_1}\}$ with $\max\{X_{S_2}\}$ as S_1^{**}, S_2^{**} accordingly.

Then we need to show at least one of the following happens

(1) $$f(X_{S_1^*})f(X_{S_2^*}) \geq f(X_{S_1})f(X_{S_2})$$

(2) $$f(X_{S_1^{**}})f(X_{S_2^{**}}) \geq f(X_{S_1})f(X_{S_2})$$

Let $a = \max\{X_{S_1}\}$, $b = \min\{X_{S_2}\}$ and $c = \max\{X_{S_2}\}$. $h_1 = \sum_{i \in S_1} X_i - a$ and $h_2 = \sum_{i \in S_2} X_i - b$, n_1 and n_2 are the number of elements in S_1 and S_2. Then

$$f(X_{S_1^*})f(X_{S_2^*}) \geq f(X_{S_1})f(X_{S_2})$$
$$\Longleftrightarrow$$
$$\frac{\Gamma(h_1+a+\alpha)}{(n_1+\beta)^{h_1+a+\alpha}}\frac{\Gamma(h_2+b+\alpha)}{(n_2+\beta)^{h_2+b+\alpha}} \leq \frac{\Gamma(h_2+a+\alpha)}{(n_2+\beta)^{h_2+a+\alpha}}\frac{\Gamma(h_1+b+\alpha)}{(n_2+\beta)^{h_1+b+\alpha}}$$
$$\Longleftrightarrow$$
$$\frac{\Gamma(h_1+a+\alpha)}{\Gamma(h_1+b+\alpha)}\frac{\Gamma(h_2+b+\alpha)}{\Gamma(h_2+a+\alpha)} \leq (\frac{n_1+\beta}{n_2+\beta})^{a-b}$$

Left hand side of above formula is $\text{LHS}_1 = \frac{(h_1+b+\alpha)...(h_1+a-1+\alpha)}{(h_2+b+\alpha)...(h_2+a-1+\alpha)}$ by the property of Gamma function and X_i are integer.

Similarly,

$$f(X_{S_1^{**}})f(X_{S_2^{**}}) \geq f(X_{S_1})f(X_{S_2})$$
$$\Longleftrightarrow$$
$$\frac{\Gamma(h_2+c+\alpha)}{\Gamma(h_2+a+\alpha)}\frac{\Gamma(h_1+a+\alpha)}{\Gamma(h_1+c+\alpha)} \leq (\frac{n_2+\beta}{n_1+\beta})^{c-a}$$

Left hand side of above formula is $\text{LHS}_2 = \frac{(h_2+a+\alpha)...(h_2+c-1+\alpha)}{(h_1+a+\alpha)...(h_1+c-1+\alpha)}$

If $h_1 \leq h_2$, then $\text{LHS}_1 \leq (\frac{h_1+a-1+\alpha}{h_2+a-1+\alpha})^{a-b}$ and $\text{LHS}_2 \leq (\frac{h_2+c-1+\alpha}{h_1+c-1+\alpha})^{a-b}$

So if $\frac{h_1+a-1+\alpha}{h_2+a-1+\alpha} \leq \frac{n_1+\beta}{n_2+\beta}$ then (12) holds, if $\frac{h_2+c-1+\alpha}{h_1+c-1+\alpha} \leq \frac{n_1+\beta}{n_2+\beta}$ then (13) holds

We multiply those two inequalities, we found that $\frac{h_1+a-1+\alpha}{h_2+a-1+\alpha} * \frac{h_2+c-1+\alpha}{h_1+c-1+\alpha} = \frac{h_1+a-1+\alpha}{h_1+c-1+\alpha} * \frac{h_2+c-1+\alpha}{h_2+a-1+\alpha} \leq 1$ as $c > a$ and $h_1 \leq h_2$ But $\frac{n_1+\beta}{n_2+\beta} * \frac{n_1+\beta}{n_2+\beta} = 1$. At least one equality holds, consequently at least one of (12) and (13) holds.

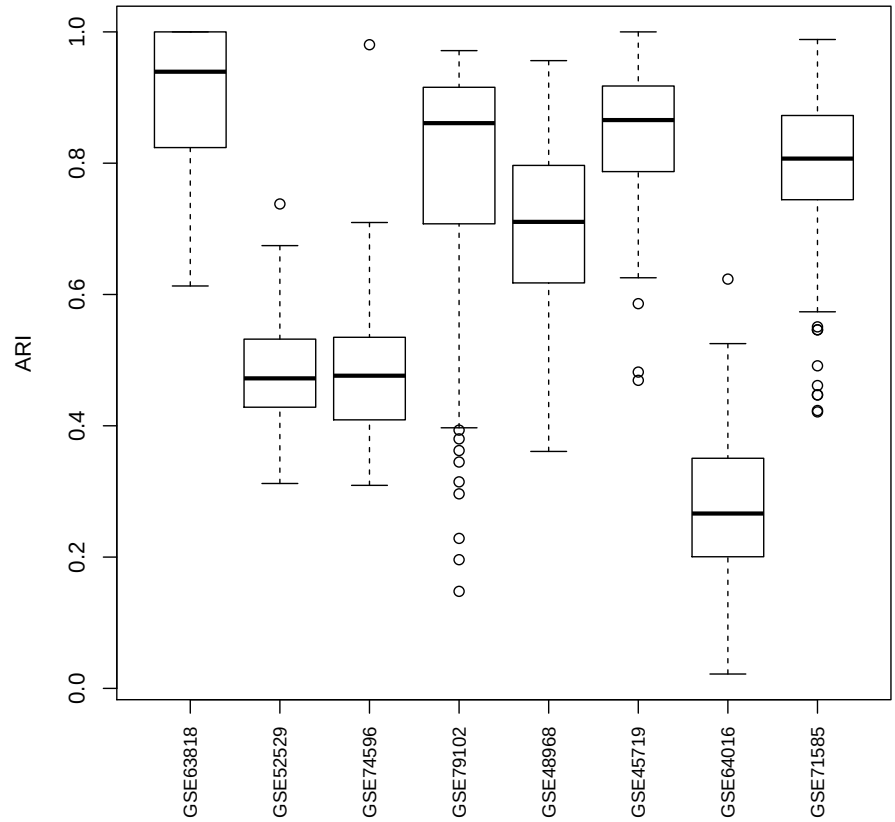
Similar proof for the case $h_1 > h_2$.

□

2.2.3. *Randomized K−means.* To find the value of a_0, a_1 and d_0, we have the marginal likelihood of $d_{i,j}$.

$$P(d_{i,j}|a_0, a_1, d_0) = \frac{\Gamma(a_0+a_1)}{\Gamma(a_0)\Gamma(a_1)}\frac{d_0^{a_0} d_{i,j}^{a_1-1} a_1^{a_1}}{(d_0 + a_1 * d_{i,j})^{a_0+a_1}}$$

We estimate d_0 by treating $d_{i,j} \approx \Delta_{i,j}$ and based on the mean-variance ratio ($\frac{\text{E}(1/\Delta_{i,j})}{\text{Var}(1/\Delta_{i,j})} = d_0$), d_0 can be approximately estimated by moments of $1/d_{i,j}$, then we obtain a_0, a_1 from MLE of marginal density of $d_{i,j}$. The MLE estimators are obtained through "nlminb" function in r, one issue is that the default value for tolerance rate of stopping is 1e-10, which yields large value of $a_1 + a_0$ and resulting in non-randomness of our weighting matrix. We set tolerance rate as 1e-3. And obtained moderate deviation from D (supplementary Figure 1)

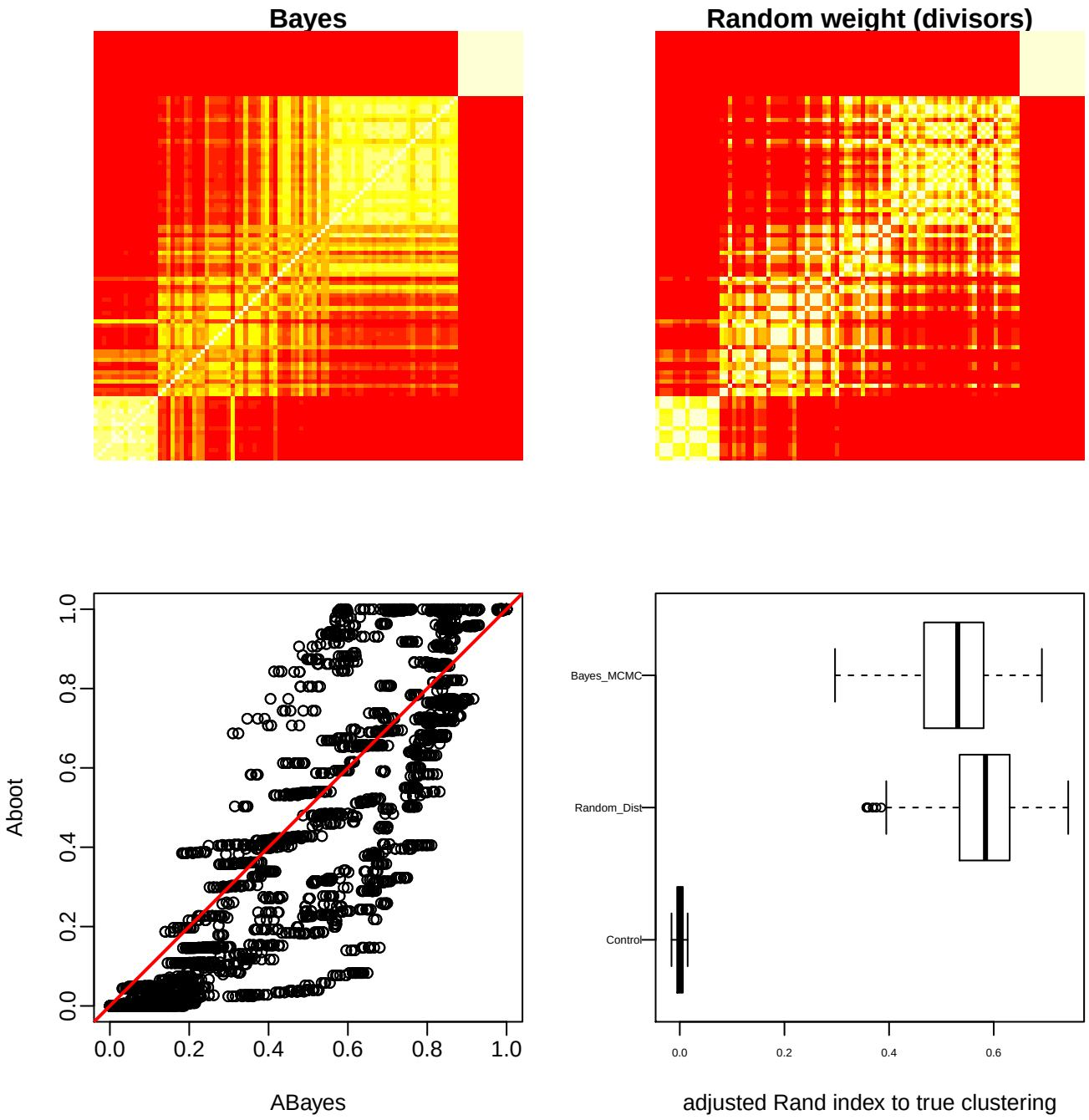


Supplementary Figure 1: Adjusted rand indexes to the clustering based on the original distance matrix without dividing weights. We investigate the randomness of clustering given by our weights through 8 datasets. All have stopping threshold for nlminb optimizing function in r with relative tolerance as 0.001

We plot the ARI(adjusted random index) between the randomly generated clustering to clustering under the original distance across eight datasets. Though the mean varies, the interquartile range is wide enough presenting a reasonable variation of our random weighting scheme.

We also check validity of random weighting on simulated dataset. We random generate one-dimensional data X from a mixture of 5 normal distributions with different means and same variance. We compare clustering results between random weighting and bayesian clustering with Dirichlet process prior in terms of posterior probabilities that two elements belong to the same class given the whole data. We also compare accuracy of the two procedures by looking at the ARI comparing to true class label (supplementary Figure 2). We found that random weighting scheme tends to give better results than classical bayesian clustering.

2.2.4. *Selecting K.* In order to determine the number of clusters and inspired by `validity`defined in Ray and Turi (2000), We consider a modified `validity`= $\frac{\textbf{intra}}{\textbf{inter}}$. where $\textbf{intra} = \frac{1}{N}\sum_{i=1}^{K}\sum_{x\in C_i}||x - z_i||^2$, $\textbf{inter} = mean(||z_i - z_j||^2), i, j = 1, 2, ...K$ and z_i is the center(medoids) of cluster i. **intra** is the average of distance of a point to its corresponding cluster center, which measures the compactness of clusters. We made a small change here, in original paper **inter** was defined as minimum distance between medoids, we use average instead for the purpose of getting a smoother quantity. **inter** is the average distance of two cluster centers, which measures the separation between clusters. We want to have a small intra-cluster distance and a big inter-cluster distance, consequently we want to minimize



Supplementary Figure 2: comparison between random weighting scheme and bayesian clustering procedure in terms of posterior probabilities that two elements belong to the same class given the whole data and adjusted rand index comparing to the underlying true class label

the `validity`.From empirical study, we constantly observe a monotone decreasing relation between number of clusters and `validity`.However this quantity stabilize when K is sufficiently large. The stopping rule for searching K is when $\texttt{validity}_K < \epsilon$ is satisfied. We set the default value of ϵ to be 1. As we found DD analysis results to be most consistent with other scRNA method.

2.3. *Double Dirichlet Mixture.* On the double Dirichlet masses, using notation as in Section 2.3 we have density functions:

$$p_\pi(\phi, \psi) = q_\pi(\Phi_\pi, \Psi_\pi) \prod_{b \in \pi} [p(\tilde{\phi}_b) p(\tilde{\psi}_b)]$$

with

$$q_\pi(\Phi_\pi, \Psi_\pi) = \frac{\Gamma(\sum_{b\in\pi}\beta_b)}{\prod_{b\in\pi}\Gamma(\beta_b)}\left[\prod_{b\in\pi}\Phi_b^{\beta_b-1}\right] 1\left[\Phi_\pi = \Psi_\pi\right]$$

and

$$p(\tilde{\phi}_b) = \frac{\Gamma(\sum_{k\in b}\alpha_k)}{\prod_{k\in b}\Gamma(\alpha_k)}\prod_{k\in b}\tilde{\phi}_k^{\alpha_k-1}, \qquad p(\tilde{\psi}_b) = \frac{\Gamma(\sum_{k\in b}\alpha_k)}{\prod_{k\in b}\Gamma(\alpha_k)}\prod_{k\in b}\tilde{\psi}_k^{\alpha_k-1}.$$

Those computing units will serve as key components for proofing property $1 \sim 6$ in section 2.3

Proof of property 1

PROOF. When ϕ and ψ only satisfy the coarsest constrants: $\sum_{i=1}^K \phi_i = \sum_{i=1}^K \psi_i = 1$. ϕ and ψ are independently Dirichlet distributed. When ϕ and ψ satisfy finer constraints, $P(\phi|\psi) \neq P(\phi)$ as there is some subsets b such that $\sum_{i\in b}\phi = \sum_{i\in b}\psi$. So ϕ and ψ are dependent □

Proof of property 2

PROOF. $E_\pi(\phi_k) = E_{\tilde{\phi}_b}(\tilde{\phi}_k)E_\Phi(\Phi_b)$ where b is the block containing subtype index k. As $\tilde{\phi}_b \sim \text{Dirichlet}_{N(b)}[\alpha_b^1]$ and $\Phi_\pi \sim \text{Dirichlet}_{N(\pi)}[\beta_\pi]$ We have $E_{\tilde{\phi}_b}(\tilde{\phi}_k) = \frac{\alpha_k^1}{\sum_{k'\in b}\alpha_{k'}^1}$ and $E_\Phi(\Phi_b) = \frac{\beta_b}{\sum_{b'\in\pi}\beta_{b'}}$. Similarly we could proof the case for $E_\pi(\psi_k)$ □

Proof of property 3

PROOF. t^1/t_π^1 is independent with t^2/t_π^2 conditioning on t_π^1 and t_π^2 by the Neutrality property of dirichlet distribution □

Proof of property 4

PROOF. For $j = 1, 2$, let T_b^j be the vector of t_k^j such that $k \in b$. Recall $t_b^j = \sum_{k\in b} t_k^j$. Without loss of generality, we consider the case condition $j = 1$. We can decompose the density to each blocks by the property of multinomial distribution

$$p_\pi(t^1|t_\pi^1, y) = \prod_{b\in\pi}(p(T_b^1|t_b^1, y))$$

and prior predictive function can be obtained via integral out $\tilde{\phi}_b$ given the prior Dirichlet$[\alpha_b^1]$ and $p(T_b^1|\tilde{\phi}_b)$ is multinomial$(\tilde{\phi}_b)$ distributed.

$$\begin{aligned} p(T_b^1|t_b^1, y) &= \int_{\tilde{\phi}_b} p(T_b^1|\tilde{\phi}_b)p(\tilde{\phi}_b)d\tilde{\phi}_b \\ &= \left\{\left[\frac{\Gamma(t_b^j+1)}{\prod_{k\in b}\Gamma(t_k^j+1)}\right]\left[\frac{\Gamma(\sum_{k\in b}\alpha_k^j)}{\prod_{k\in b}\Gamma(\alpha_k^j)}\right]\left[\frac{\prod_{k\in b}\Gamma(\alpha_k^j+t_k^j)}{\Gamma(t_b^j+\sum_{k\in b}\alpha_k^j))}\right]\right\} \end{aligned}$$

□

Proof of property 5

PROOF. t_π^1 and t_π^2 given the condition label y are independent identical distributed. $t_\pi^1|\Phi \sim$ multinomial(Φ)

$$\begin{aligned} p_\pi(t_\pi^1, t_\pi^2|y) &= \int_\Phi p(t_\pi^1|\Phi)p(t_\pi^2|\Phi)p(\Phi)d\Phi \\ &= \left[\frac{\Gamma(n_1+1)\Gamma(n_2+1)}{\prod_{b\in\pi}\Gamma(t_b^1+1)\Gamma(t_b^2+1)}\right]\left[\frac{\Gamma(\sum_{b\in\pi}\beta_b)}{\prod_{b\in\pi}\Gamma(\beta_b)}\right]\left[\frac{\prod_{b\in\pi}\Gamma(\beta_b+t_b^1+t_b^2)}{\Gamma(n_1+n_2+\sum_{b\in\pi}\beta_b)}\right]. \end{aligned}$$

As prior of Φ is Dirchlet$[\beta]$ and $n_j = \sum_{b\in\pi} t_b^j$ for $j = 1, 2$ □

LEMMA 1. *If π_2 is not refinement of π_1 then $A_{\pi_1} \cap A_{\pi_2}$ is a lower dimensional subset of A_{π_2}*

in order to proof property 6 we gave a lemma of dimensionality of the intersection of two A_πs Proof of lemma 1

PROOF. Let V denote the orthogonal space of $\phi - \psi$, when $(\phi, \psi) \in A_{\pi_1} \cap A_{\pi_2}$, and $\dim(A_{\pi_1} \cap A_{\pi_2}) = \dim(\phi - \psi) + \dim(\psi) = 2K - \dim(V) - 1$. Also let $\pi_1 = \{b_1^1, ..., b_s^1\}, \pi_2 = \{b_1^2, ..., b_t^2\}$. The corresponding vectors are $v_1^1, ..., v_s^1$ and $v_1^2, ..., v_t^2$. We claim there must be a $b_i^1 \in \pi$ whose corresponding v_i^1 is linear independent with $v_1^2, ..., v_t^2$. If not, for every v_i^1 there exists $\alpha_1^i, ..., \alpha_t^i$ such that

$$v_i^1 = \sum_{j=1}^{t} \alpha_j^i v_j^2 \qquad (*)$$

If $b_j^2 \cap b_i^1 \neq \emptyset$, then multiply v_j^2 on both sides of (*), we obtain $v_i^1 * v_j^2 = \alpha_j^i (v_j^2)^2$, as v_j^2 are orthogonal vectors, and $v_i^1 * v_j^2 > 0$ implies $\alpha_j^i > 0$. Consider $x = f(b_j^2 \setminus b_i^1)$, we have $x * v_i^1 = 0$ and we multiply x on both sides of (*) to obtain $\alpha_j^i v_j^2 * x = 0$, thus x must be zero vector and $b_j^2 \setminus b_i^1 = \emptyset$, which implies $b_j^2 \subset b_i^1$. That is to say when $b_j^2 \cap b_i^1 \neq \emptyset$, b_j^2 must be subset of b_i^1. So b_i^1 is union of some blocks in π_2. Which implies π_2 is refinement of π_1, contradiction.
Consequently there exists $b \in \pi_1$ with $v(b)$ linear independent with $v(b'), b' \in \pi_2$. $\dim(V)$ is at least $N(\pi_2) + 1, \dim(A_{\pi_1} \cap A_{\pi_2}) < \dim(A_{\pi_2})$ □

Proof of property 6

PROOF. by lemma 1, it is easy to verify. □

Proof of theorem 3

PROOF. $p_\pi(t^1|t_\pi^1, y)p_\pi(t^2|t_\pi^2, y)p_\pi(t_\pi^1, t_\pi^2|y)$ The DDM: $p(\phi, \psi) = \sum_{\pi\in\Pi} p_\pi(\phi, \psi)$. we know $p(\phi, \psi|y, z) \propto p(\phi, \psi, y, z) = \sum_{\pi\in\Pi} p(y, z|\phi, \psi)p_\pi(\phi, \psi)\omega_\pi$ And $p(y, z|\phi, \psi)p_\pi(\phi, \psi) = p(y, z|\tilde{\phi}, \tilde{\psi}, \Phi_\pi)p(\tilde{\phi})p(\tilde{\psi})p(\Phi_\pi)$ consider the support of $p_\pi(\phi, \psi)$.
Right hand side of the above equation is

$$U_\pi = A_1 * A_2 * A_3 * \prod_{k=1}^{K} (\tilde{\phi}_k)^{t_k^1+\alpha_k^1} (\tilde{\psi}_k)^{t_k^2+\alpha_k^2} \prod_{b\in\pi} (\Phi_b)^{t_b^1+t_b^2+\beta_b}$$

Where A_1 is the product of normalizing terms from multinomial distribution of z^1 and z^2, $A_1 = \frac{\Gamma(n_1+1)\Gamma(n_2+1)}{\prod_{j=1}^{2}\prod_{k=1}^{K}\Gamma(t_k^j+1)}$

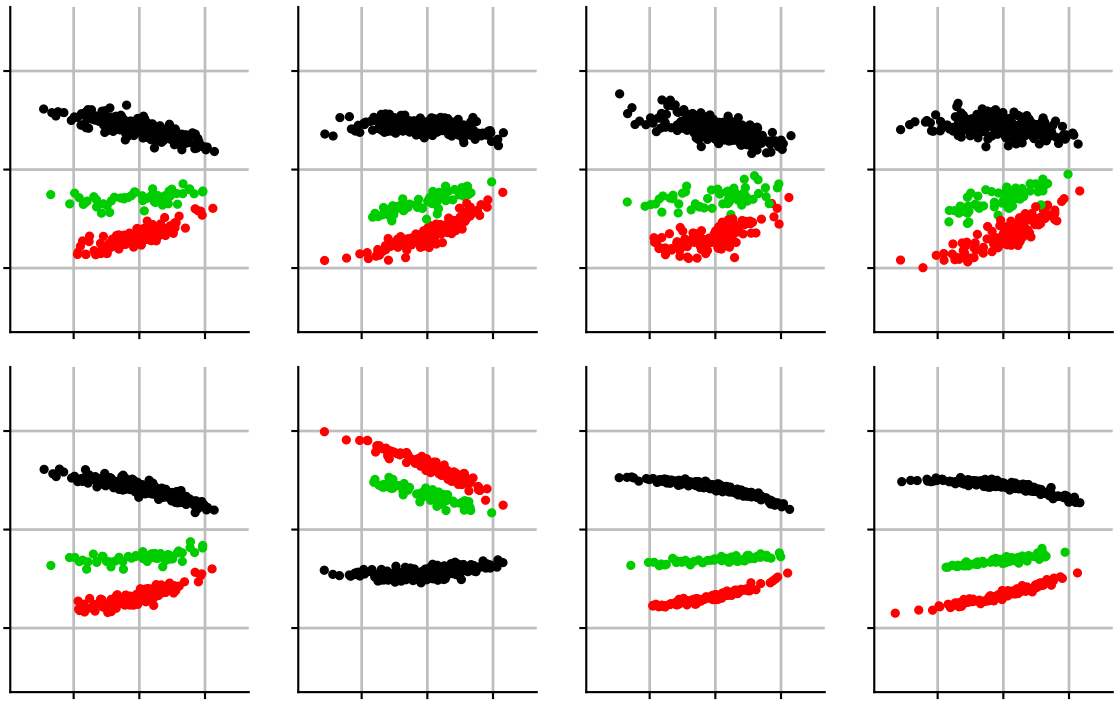
A_2 is the product of normalizing terms from Dirichlet distribution of $\tilde{\phi}$ and $\tilde{\psi}$, $A_2 = \frac{\Gamma(\sum_{k=1}^{K}\alpha_k^1+1)\Gamma(\sum_{k=1}^{K}\alpha_k^2+1)}{\prod_{j=1}^{2}\prod_{k=1}^{2}\Gamma(\alpha_k^j+1)}$

A_3 is the normalizing term from Dirichle distribution of Φ_π, $A_3 = \frac{\Gamma(\sum_{b\in\pi}\beta_b+1)}{\prod_{b\in\pi}\Gamma(\beta_b+1)}$
To convert U_π to have form similar of p_π, We need $U_\pi \propto f_1 f_2 f_3$ proportional to product of three Dirichlet densities. We know $f_1 \sim \text{Dirichlet}[\alpha^1 + t^1]$, $f_2 \sim \text{Dirichlet}[\alpha^2 + t^2]$ and $f_3 \sim \text{Dirichlet}[\beta + t^1 + t^2]$. Considering the normalizing factors for f_1, f_2 and f_3, and multiplying them with A_1, A_2 and A_3. We have the $U_\pi = C_\pi * f_1 f_2 f_3$. The final normalizing term is $p_\pi(t^1|t^1_\pi, y)\, p_\pi(t^2|t^2_\pi, y)\, p_\pi(t^1_\pi, t^2_\pi|y)$ Then we have $(\phi, \psi)|y, z \sim \text{DDM}\left[\omega^{\text{post}} = (\omega^{\text{post}}_\pi), \alpha^1 + t^1, \alpha^2 + t^2\right]$ and $\omega^{\text{post}}_\pi \propto p_\pi(t^1|t^1_\pi, y)\, p_\pi(t^2|t^2_\pi, y)\, p_\pi(t^1_\pi, t^2_\pi|y)\, \omega_\pi$. Notice in DDM, we constrained $\beta = \alpha^1 + \alpha^2$.

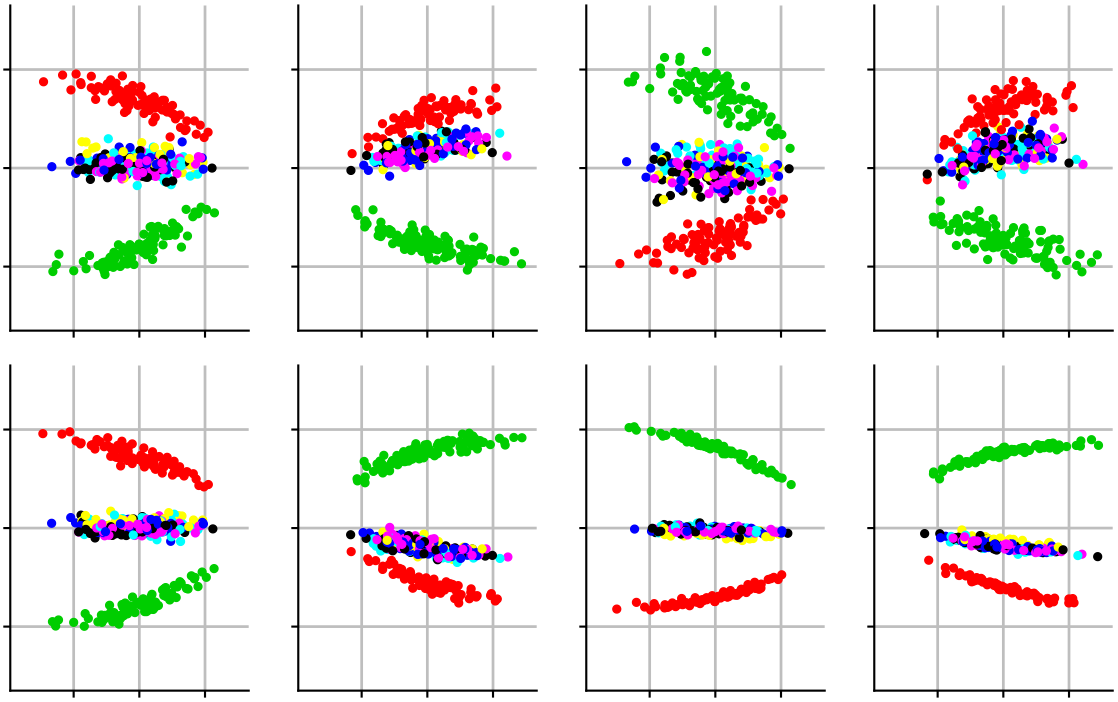
□

3. Numerical Experiments.

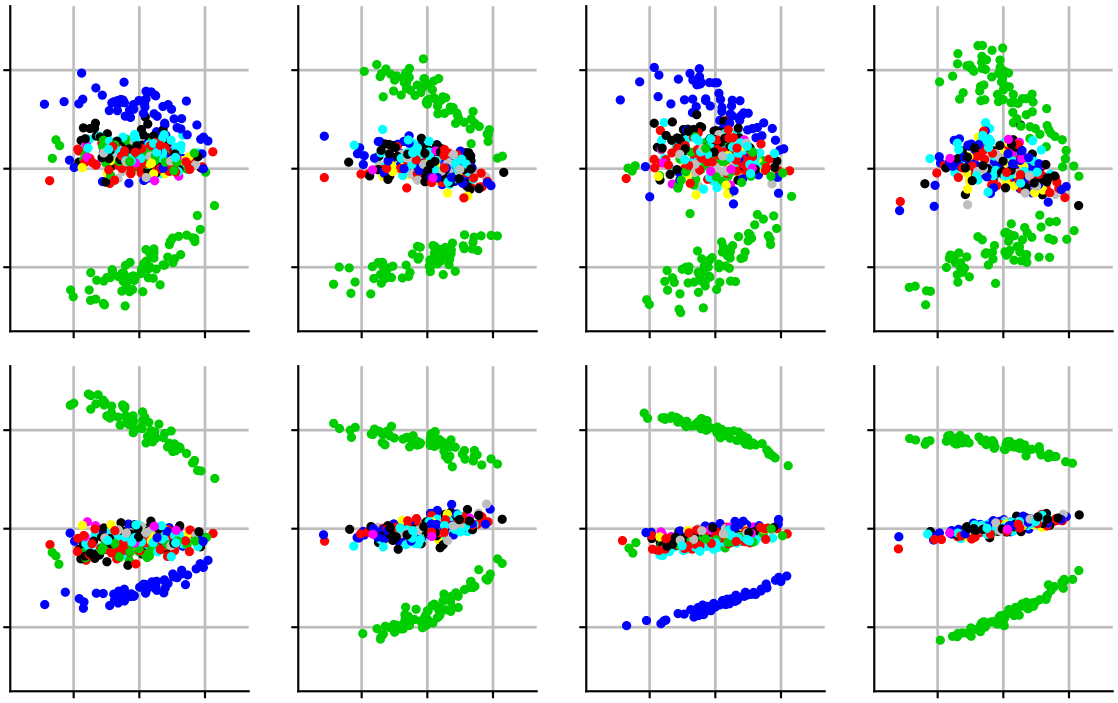
3.1. *Synthetic Data.* We first look at the pca plots of the simulated data (supplementary figure 2,3,4)



Supplementary Figure 3: first two principal components of transcripts under different parameters for simulated data. Different parameters resulted in different degree of separation of subtypes. We have 4 different settings for hyper-parameters of simulation, each setting has 2 replicates K = 3

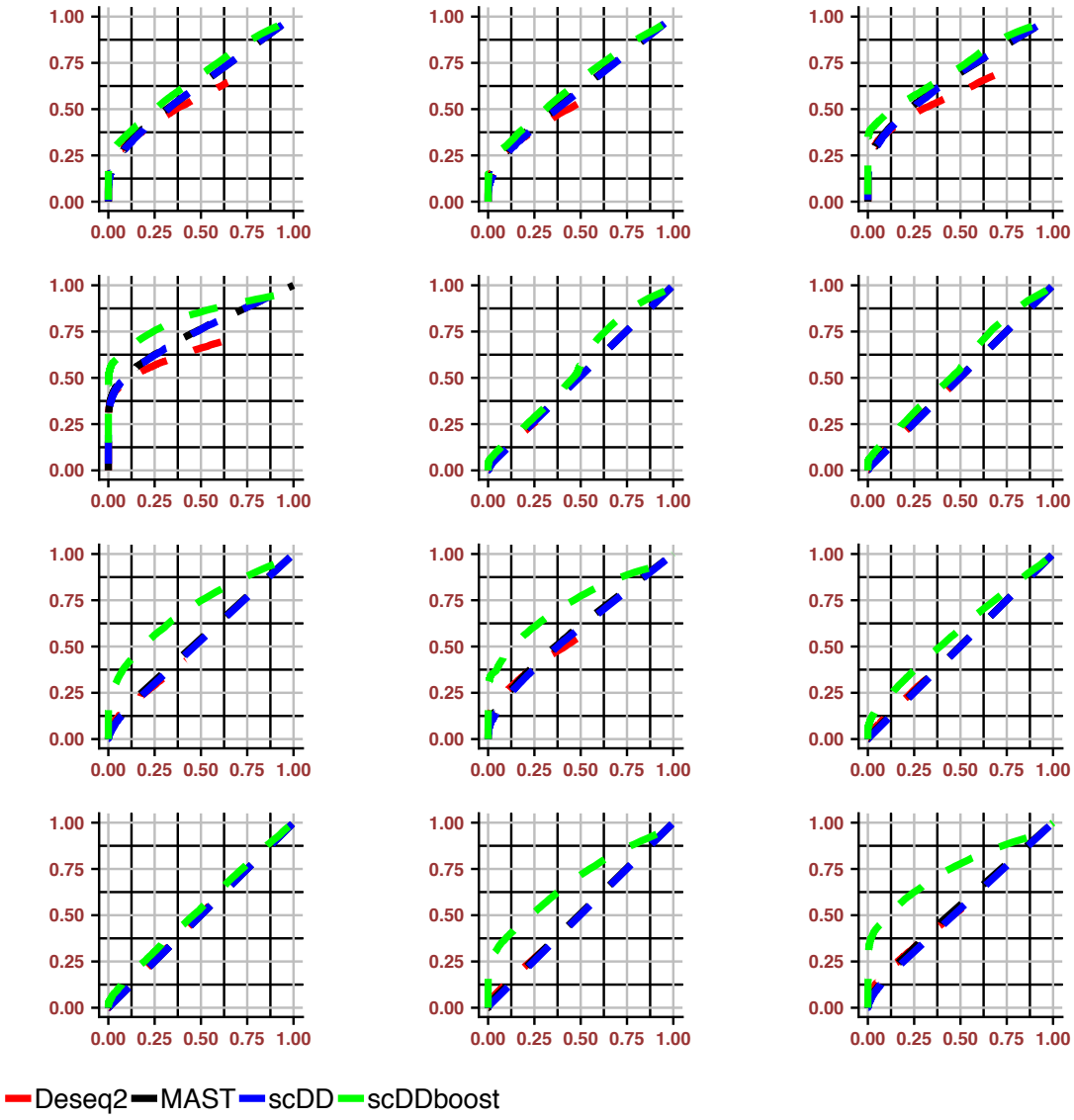


Supplementary Figure 4: K = 7



Supplementary Figure 5: K = 12

We also have roc curve for the simulated data, each sub-figure is averaged over two replicates under the same parameters setting. scDDboost tends to outperform other methods (supplementary figure 5)

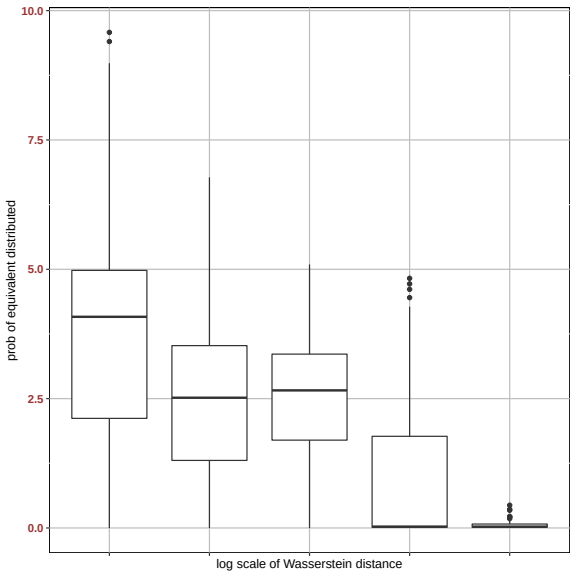


Supplementary Figure 6: Roc curve of the 12 simulation settings, under each setting, TPR and FPR are averaged over two replicates, generally we found scDDboost perform better than other methods

3.2. *Empirical Study.* **Data sets** details for the datasets used in the empirical studies of the main paper and the estimated number of subtypes K (supplementary table 1)

Data set	Conditions	Number of cells/condition	Organism	Ref	K
GSE94383	0 min unstim vs 75min stim	186,145	human	(Lane et al., 2017)	9
GSE48968-GPL13112	BMDC (2h LPS stimulation) vs 6h LPS	96,96	mouse	(Shalek et al., 2014)	4
GSE52529	T0 vs T72	69,74	human	(Trapnell et al., 2014)	7
GSE74596	NKT1 vs NTK2	46,68	mouse	(Engel et al., 2016)	7
EMTAB2805	G1 vs G2M	95,96	mouse	(Buettner et al., 2015)	6
GSE71585-GPL13112	Gad2tdTpositive vs Cux2tdTnegative	80,140	mouse	(Tasic et al., 2016)	4
GSE64016	G1 vs G2	91,76	human	(Leng et al., 2015)	6
GSE79102	patient1 vs patient2	51, 89	human	Kiselev et al. (2017)	4
GSE45719	16-cell stage blastomere vs mid blastocyst cell	50, 60	mouse	(Deng et al., 2014)	4
GSE63818	Primordial Germ Cells, develop- mental stage: 7 week gestation vs Somatic Cells, developmental stage: 7 week gestation	40,26	mouse	(Guo et al., 2015)	6
GSE75748	DEC vs EC	64, 64	human	(Chu et al., 2016)	5
GSE84465	neoplastic cells vs non-neoplastic cells	546, 664	human	(Darmanis et al., 2017)	7

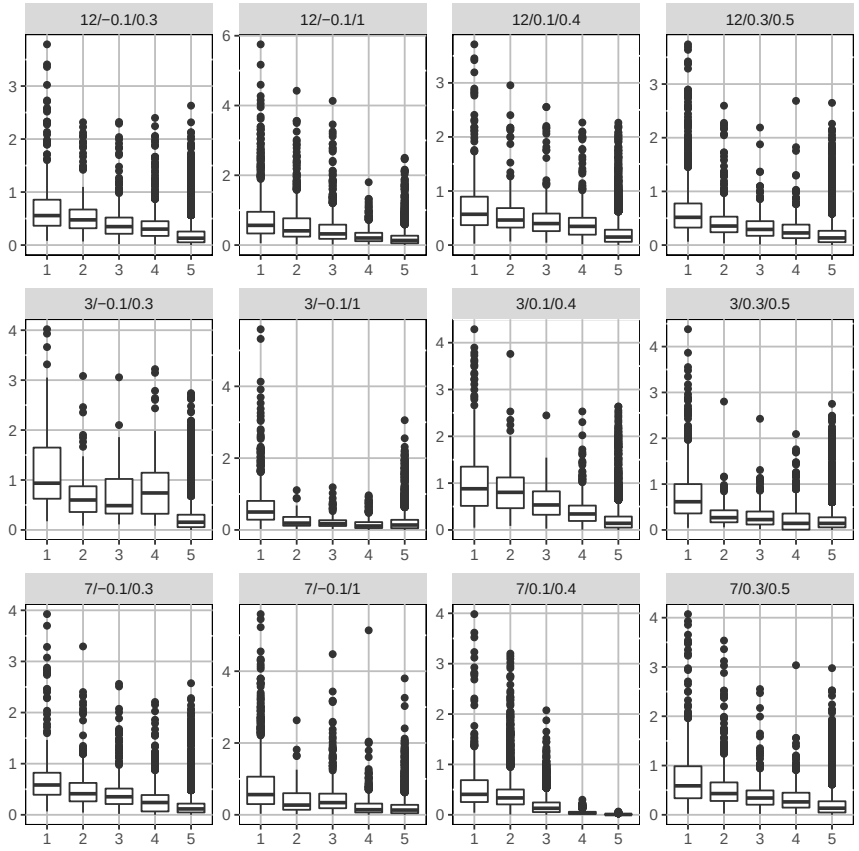
SUPPLEMENTARY TABLE 1
datasets used for comparisons of DD analysis under different methods



Supplementary Figure 7: $P(ED_g|X,y)$ given by scDDboost versus empirical Wasserstein distance. Genes associated with boxes from left to right having $P(ED_g|X,y)$ range from 0 - 0.2, 0.2 - 0.4, 0.4 - 0.6, 0.6 - 0.8, 0.8 - 1, data used: FUCCI

We observed consistent results with scDDboost estimation and wasserstein distance between the

transcripts . Lower probabilities of equivalent distributed are associated with bigger distances. (supplementary Figure 7)



Supplementary Figure 8: $P(ED_g|X,y)$ given by scDDboost versus empirical Wasserstein distance. Genes associated with boxes from left to right having $P(ED_g|X,y)$ range from 0 - 0.2, 0.2 - 0.4, 0.4 - 0.6, 0.6 - 0.8, 0.8 - 1, similar plots as supplementary Fig 7, now is for the simulation cases

3.3. *Null cases.* datasets used for generating the Null cases (supplementary table 2)

Data set	Conditions	Number of cells/condition	Organism
GSE63818null	7 week gestation	20,20	mouse
GSE75748null	DEC	32, 32	human
GSE94383null	T0	93, 93	human
GSE48968-GPL13112null	BMDC (2h LPS stimulation)	48,48	mouse
GSE74596null	NKT1	23,23	mouse
EMTAB2805null	G1	48,48	mouse
GSE71585-GPL13112null	Gad2tdTpositive	40,40	mouse
GSE64016null	G1	46,45	human
GSE79102null	patient1	26, 25	human

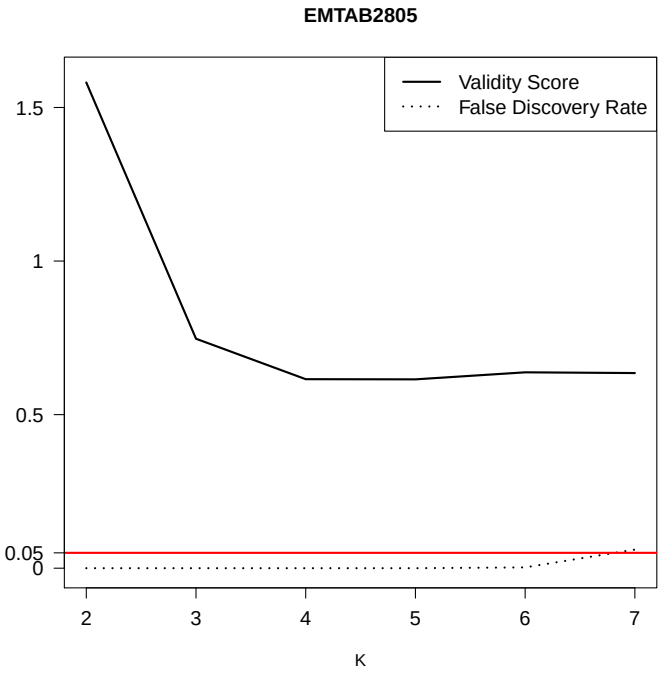
SUPPLEMENTARY TABLE 2

datasets used for null cases, as cells are coming from same biological condition, there should not be any differential distributed genes, any positive call is false positive

4. Random weighting.

4.1. *Stability of posterior under random weighting.* Number of subtypes K is a crucial factor controlling the accuracy of our modeling. Too small K may end up in an underfit such that cells within same subtype can still be very different, mean expression change among subtypes is incapable to capture the distribution change for some genes and consequently reducing the power of scDDboost. Too big K may end up in an overfit such that two subtypes can be very similar, given we have fixed number of samples (cells), allowing more clusters will introduce may patterns (both for mean expression change and proportion change) to infer. Also notice the limitation of DDM model (see section 4), overestimating K in scDDboost may losing FDR control (supplementary Figure 9).

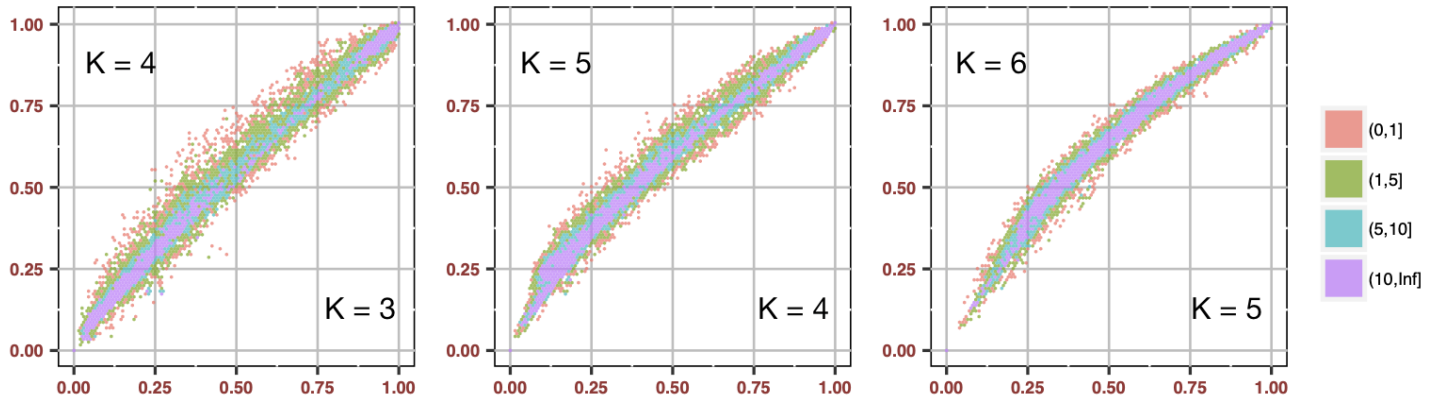
scDDboost may lose FDR control if we keep pushing number of subtypes K bigger.



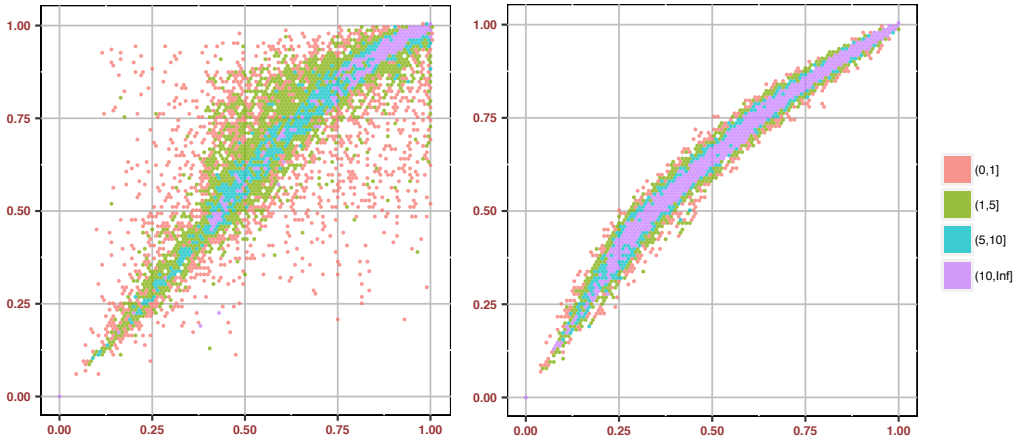
Supplementary Figure 9: under NULL case, using dataset EMTAB2805, when using too big K we may lose FDR control (black dashed line shows proportion of false positive identified by scDDboost under 0.05 threshold, while validity score did not vary too much after K is greater than 2

From our empirical experience, it would be sufficient to capture the heterogeneity underlying cells with number of clusters not greater than 9. And we generally obtain stable in validity score and PDD simultaneously (supplementary Table 1, supplementary Figure 10)

We demonstrate the change of posterior probabilities of differential distribution given different K at data GSE75748. If allowing one more subtype would result in a lot increases in posterior probabilities of DD, which suggests that the number of subtypes is underestimated since we found more distribution differences between conditions given one more mixture component. If posterior inference is stable after increasing the number of subtypes, then we consider previous number of subtypes to be optimal.



Supplementary Figure 10: PDD change under different number of subtypes K, dataset used DEC-EC, our rule for selecting K tends also to make PDD stabilize



Supplementary Figure 11: DEC-EC, PDD under K = 5 vs. K = 6, left panel is without the randomized distance and right panel is with randomized distance. We increase robustness of our methods through random weighting

5. Posterior consistency. As the density of DDM is computed by product or ratio over bunches of gamma function and gamma function is not easy to direct work on it and derive limiting theorem. To proof theorem 4, we need a crucial lemma which gave us an approximation to the gamma function, namely

LEMMA 2. *For $x \geq 1$, $\frac{x^{x-c}}{e^{x-1}} \leq \Gamma(x) \leq \frac{x^{x-1/2}}{e^{x-1}}$, where $c = 0.577215...$ is the Euler-Mascheroni constant.*

PROOF. By (Li and ping Chen, 2007), we have $\frac{x^{x-c}}{e^{x-1}} \leq \Gamma(x) \leq \frac{x^{x-1/2}}{e^{x-1}}$ for $x > 1$ and now we added the case when $x = 1, \Gamma(x) = 1$ so that both sides will include the equality case. □

LEMMA 3. *For positive integer n, $\sqrt{2\pi}n^{n+1/2}e^{-n} \leq \Gamma(n+1) \leq en^{n+1/2}e^{-n}$*

We have another two lemmas and theorem 1 and 2 are just proporsition of the lemma

LEMMA 4. *If $(\phi, \psi) \in A_{\pi_1} \cap A_{\pi_2}$, follow the conditions in theorem 1 then*

$$\frac{\omega^{post}_{\pi_1}}{\omega^{post}_{\pi_2}} \xrightarrow[n\to\infty]{a.s.} 0 \quad \text{if } N(\pi_1) < N(\pi_2)$$

PROOF. Recall $\omega^{\text{post}}_{\pi} \propto p_\pi(t^1|t^1_\pi, y)\, p_\pi(t^2|t^2_\pi, y)\, p_\pi(t^1_\pi, t^2_\pi|y)\, \omega_\pi$. and RHS $= g(\pi, \alpha, \beta, n_1, n_2) f(\pi, t^1, t^2, \alpha, \beta)$ and $\frac{\omega^{\text{post}}_{\pi_1}}{\omega^{\text{post}}_{\pi_2}} = \frac{g(\pi_1,\alpha,\beta,n_1,n_2)}{g(\pi_2,\alpha,\beta,n_1,n_2)} \frac{f(\pi_1,t^1,t^2,\alpha,\beta)}{f(\pi_2,t^1,t^2,\alpha,\beta)}$ where

$$g(\pi, t^1, t^2, \alpha, \beta) = [\prod_{j=1}^{2}\prod_{b\in\pi} \frac{\Gamma(\Sigma_{k\in b}\alpha^j_k)}{\prod_{k\in b}\Gamma(\alpha^j_k)}] \frac{\Gamma(n_1+1)\Gamma(n_2+1)}{\prod_{b\in\pi}\Gamma(\beta_b)} \frac{\Gamma(\Sigma_{b\in\pi}\beta_b)}{\Gamma(n_1+n_2+\Sigma_{b\in\pi}\beta_b)}$$

$$f(\pi, t^1, t^2, \alpha, \beta) = [\prod_{j=1}^{2}\prod_{b\in\pi} \frac{1}{\prod_{k\in b}\Gamma(t^j_k+1)} \frac{\prod_{k\in b}\Gamma(\alpha^j_k+t^j_k)}{\Gamma(t^j_b+\Sigma_{k\in b}\alpha^j_k)}] \prod_{b\in\pi}\Gamma(\beta_b+t^1_b+t^2_b)$$

For notation simplicity, we use the abbreviation $g(\pi), f(\pi)$ to substitute $g(\pi, \alpha, \beta, n_1, n_2), f(\pi, t^1, t^2, \alpha, \beta)$. We take log on $\frac{\omega^{post}_{\pi_1}}{\omega^{post}_{\pi_2}}$, denote it as LR. $LR = \ln g(\pi_1) - \ln g(\pi_2) + \ln f(\pi_1) - \ln f(\pi_2)$. Denote $C(\pi_1, \pi_2, \alpha, \beta) = \ln g(\pi_1) - \ln g(\pi_2)$, $C(\pi_1, \pi_2, \alpha, \beta)$ does not change with sample size n_1, n_2 and is a constant determined by partition π_1, π_2 and hyper parameters α, β. For further convenience of notation let $h(x) = \ln\Gamma(x)$ and $\gamma^j_b = \Sigma_{k\in b}\alpha^j_k$. Denote $R(\pi_1, \pi_2, t^1, t^2, \alpha, \beta) = \ln f(\pi_1) - \ln f(\pi_2)$. And removing the common part of $f(\pi_1)$ and $f(\pi_2)$, we have

$$R(\pi_1, \pi_2, t^1, t^2, \alpha, \beta) = d(\pi_1, t^1, t^2, \alpha, \beta) - d(\pi_2, t^1, t^2, \alpha, \beta)$$

where

$$d(\pi, t^1, t^2, \alpha, \beta) = \sum_{b\in\pi} h(\beta_b + t^1_b + t^2_b) - \sum_{j=1}^{2}\sum_{b\in\pi} h(t_b + \gamma^j_b)$$

Recall $\beta_b = \gamma^1_b + \gamma^2_b$ and from lemma 2, $(x-c)\ln(x) - x + 1 \leq h(x) \leq (x-1/2)\ln(x) - x + 1$ we have

$$d(\pi, t^1, t^2, \alpha, \beta) \geq \sum_{b\in\pi} (\beta_b + t^1_b + t^2_b - c)\ln(\beta_b + t^1_b + t^2_b) - \sum_{j=1}^{2}\sum_{b\in\pi} (t^j_b + \gamma^j_b - 1/2)\ln(t^j_b + \gamma^j_b) + N(\pi) \tag{3}$$

$$d(\pi, t^1, t^2, \alpha, \beta) \leq \sum_{b\in\pi} (\beta_b + t^1_b + t^2_b - 1/2)\ln(\beta_b + t^1_b + t^2_b) - \sum_{j=1}^{2}\sum_{b\in\pi} (t^j_b + \gamma^j_b - c)\ln(t^j_b + \gamma^j_b) + N(\pi) \tag{4}$$

$$\text{RHS of (4)} = \Sigma_b\big[(t_b^1+\gamma_b^1)\ln(1+\frac{t_b^2+\gamma_b^2}{t_b^1+\gamma_b^1}) + (t_b^2+\gamma_b^2)\ln(1+\frac{t_b^1+\gamma_b^1}{t_b^2+\gamma_b^2})$$
$$+(1-c)\ln(\beta_b+t_b^1+t_b^2) - 1/2(\ln(1+\frac{t_b^2+\gamma_b^2}{t_b^1+\gamma_b^1}) + \ln(1+\frac{t_b^1+\gamma_b^1}{t_b^2+\gamma_b^2}))\big] + N(\pi)$$

By Taylor expansion at $x=1$, $\ln(x+1) = \ln 2 + 1/2(x-1) - 1/8(x-1)^2 + g(\xi)(x-1)^3$, where $g(\xi)$ is the reminder term of form $\frac{1}{3(1+\xi)^3}$ for $0<\xi<x$ For a fixed n_1, n_2, we have

$$\text{RHS of (4)} = (n_1+n_2)\ln 2 - \Sigma_{b\in\pi}(1/8(X_b^1+X_b^2)$$
$$+g(\xi_b)(Y_b^1+Y_b^2)) + T(\pi) + N(\pi)$$

where $X_b^1 = \frac{(t_b^1-t_b^2+\gamma_b^1-\gamma_b^2)^2}{t_b^1+\gamma_b^1}$, $X_b^2 = \frac{(t_b^1-t_b^2+\gamma_b^1-\gamma_b^2)^2}{t_b^2+\gamma_b^2}$, $Y_b^1 = \frac{(t_b^1-t_b^2+\gamma_b^1-\gamma_b^2)^3}{(t_b^1+\gamma_b^1)^2}$, $Y_b^2 = \frac{(t_b^1-t_b^2+\gamma_b^1-\gamma_b^2)^3}{(t_b^2+\gamma_b^2)^2}$ and $T(\pi) = \Sigma_{b\in\pi}\big[(1-c)\ln(\beta_b+t_b^1+t_b^2) - 1/2(\ln(1+\frac{t_b^2+\gamma_b^2}{t_b^1+\gamma_b^1}) + \ln(1+\frac{t_b^1+\gamma_b^1}{t_b^2+\gamma_b^2}))\big]$
Similarly

$$\text{RHS of (5)} = (n_1+n_2)\ln 2 - \Sigma_{b\in\pi}(1/8(X_b^1+X_b^2)$$
$$+g(\xi_b)(Y_b^1+Y_b^2)) + U(\pi) + N(\pi)$$

$U(\pi) = \Sigma_{b\in\pi}\big[(2c-1/2)\ln(\beta_b+t_b^1+t_b^2) - c(\ln(1+\frac{t_b^2+\gamma_b^2}{t_b^1+\gamma_b^1}) + \ln(1+\frac{t_b^1+\gamma_b^1}{t_b^2+\gamma_b^2}))\big]$

Using above inequalities, we have

$$R(\pi_1,\pi_2,t^1,t^2,\alpha,\beta) \le U(\pi_1) - T(\pi_2) - 1/8(\Sigma_{b\in\pi_1}(X_b^1+X_b^2) - \Sigma_{b\in\pi_2}(X_b^1+X_b^2))$$
$$+\Sigma_{b\in\pi_1}g(\xi_b)(Y_b^1+Y_b^2) - \Sigma_{b\in\pi_2}g(\xi_b)(Y_b^1+Y_b^2)$$

$Y_b^j = \frac{((t_b^1-t_b^2+\gamma_b^1-\gamma_b^2)/\sqrt{n}))^3/\sqrt{n}}{((t_b^j+\gamma_b^j)/n)^2}$, by LLN the denominator goes to a constant and by CLT in the numerator $(t_b^1-t_b^2+\gamma_b^1-\gamma_b^2)/\sqrt{n} \to (t_b^1-t_b^2)/\sqrt{n} \to \sqrt{n}[(t_b^1/n-\Phi_b)-(t_b^2/n-\Psi_b)]$, which goes to a normal distributed random variables when $\Phi_b=\Psi_b$. So Y_b^j is $o_p(1)$. Similarly, $X_b^j = \frac{((t_b^1-t_b^2+\gamma_b^1-\gamma_b^2)/\sqrt{n})^2}{t_b^j+\gamma_b^j/n}$ is asymptotic gamma(χ-square) distributed. $g(\xi_b)$ has bounded variance, $U(\pi_1)-T(\pi_2) = -\ln(n)$ if $N(\pi_2) < N(\pi_1)$ as $\ln(\beta_b+t_b^1+t_b^2) - \ln(\beta_{b'}+t_{b'}^1+t_{b'}^2) = \ln(\frac{\beta_b+t_b^1+t_b^2}{n}) - \ln(\frac{\beta_{b'}+t_{b'}^1+t_{b'}^2}{n}) \to O(1)$ *a.s.* so we complete the proof

□

Lemma 5. *If $(\phi,\psi) \in A_{\pi_1}\cap A_{\pi_2}$, follow the conditions in theorem 1 and further we have $\alpha^j, j=1,2$ be vectors of integers then*

$$\frac{\omega_{\pi_1}^{post}}{\omega_{\pi_2}^{post}} \xrightarrow[n\to\infty]{d} v \quad \text{if } N(\pi_1) = N(\pi_2)$$

v is a random variable

PROOF. follow almost same procedure in lemma 4, but instead of using inequalities in lemma 2, we use lemma 3. And we still have

$$d(\pi, t^1, t^2, \alpha, \beta) = \sum_{b\in\pi} h(\beta_b + t_b^1 + t_b^2) - \sum_{j=1}^{2}\sum_{b\in\pi} h(t_b + \gamma_b^j)$$

and by lemma 3

(5)

$$d(\pi, t^1, t^2, \alpha, \beta) \geq \sum_{b\in\pi} (\beta_b + t_b^1 + t_b^2 - 1/2)\ln(\beta_b + t_b^1 + t_b^2) - \sum_{j=1}^{2}\sum_{b\in\pi} (t_b^j + \gamma_b^j - 1/2)\ln(t_b^j + \gamma_b^j) + \ln(\sqrt{2\pi}) - 1$$

(6)

$$d(\pi, t^1, t^2, \alpha, \beta) \leq \sum_{b\in\pi} (\beta_b + t_b^1 + t_b^2 - 1/2)\ln(\beta_b + t_b^1 + t_b^2) - \sum_{j=1}^{2}\sum_{b\in\pi} (t_b^j + \gamma_b^j - 1/2)\ln(t_b^j + \gamma_b^j) + 1 - \ln(\sqrt{2\pi})$$

$$\begin{aligned} R(\pi_1, \pi_2, t^1, t^2, \alpha, \beta) \approx D(\pi_1) - D(\pi_2) - 1/8(\Sigma_{b\in\pi_1}(X_b^1 + X_b^2) - \Sigma_{b\in\pi_2}(X_b^1 + X_b^2)) \\ -\Sigma_{b\in\pi_1} g(\xi_b)(Y_b^1 + Y_b^2) - \Sigma_{b\in\pi_2} g(\xi_b)(Y_b^1 + Y_b^2) \end{aligned}$$

where $D(\pi) = \Sigma_{b\in\pi}\big[1/2\ln(\beta_b + t_b^1 + t_b^2) - c(\ln(1 + \frac{t_b^2+\gamma_b^2}{t_b^1+\gamma_b^1}) + \ln(1 + \frac{t_b^1+\gamma_b^1}{t_b^2+\gamma_b^2}))\big]$ And $D(\pi_1) - D(\pi_2)$ is O(1) if $N(\pi_1) = N(\pi_2)$ as $\ln(\beta_b + t_b^1 + t_b^2) - \ln(\beta_{b'} + t_{b'}^1 + t_{b'}^2) = \ln(\frac{\beta_b + t_b^1 + t_b^2}{n_1}) - \ln(\frac{\beta_{b'} + t_{b'}^1 + t_{b'}^2}{n_1}) \to 0 \quad a.s.$

□

Proof of theorem 4

PROOF. Recall $\sum_{\pi\in\Pi} \omega_\pi^{\text{post}} = 1$ and $P(A_\pi|y, z) = \sum_{\tilde{\pi}\in\Pi} \omega_{\tilde{\pi}}^{\text{post}} 1[\tilde{\pi} \text{ refines } \pi]$. If $(\phi, \psi) \notin \text{Q}$, for all the A_π covers (ϕ, ψ) there is one finest π^* with the largest $N(\pi^*)$ and every other π that $(\phi, \psi) \in A_\pi$ is coarser than π^*. We get the results of theorem 4 by lemma 4.

□

1

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