

Statistical and computational methods for bioinformatics and social network analysis

or how did I learn to stop worrying and love the bomb

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October 8, 2019

Paper 1: Exponential Random Graph Models for Small Networks

Paper 2: On the prediction of gene functions using phylogenetic trees

Future directions

Things that are very interesting but I most probably won't have any time to discuss with the attendees

References

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What are Exponential Random Graph Models

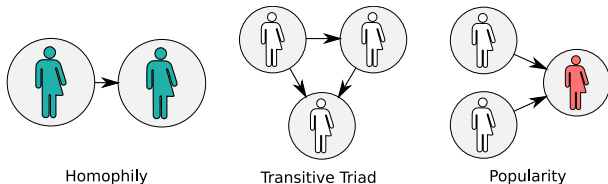
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A vector of
model parameters

A vector of
sufficient statistics

$$\Pr(\mathbf{Y} = \mathbf{y} \mid \theta, \mathbf{X}) = \frac{\exp\{\theta^t \mathbf{s}(\mathbf{y}, \mathbf{X})\}}{\sum_{\mathbf{y}' \in \mathcal{Y}} \exp\{\theta^t \mathbf{s}(\mathbf{y}', \mathbf{X})\}}, \quad \forall \mathbf{y} \in \mathcal{Y}$$

Observed data

The normalizing constant

All possible networks

ERGMs: State of the Art

Small-large (dozens to a couple of thousand vertices) networks

- ▶ Markov Chain Monte Carlo (MCMC) based approaches like MC-MLE or Robbins-Monro Stochastic approximation. [▶ details](#)
- ▶ Maximum Pseudo Likelihood (MPLE)

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large-huge networks (up to the millions of vertices)

- ▶ Semi-parametric bootstrap
- ▶ Conditional joint estimation (like snowball sampling, a.k.a. divide and conquer)
- ▶ Equilibrium Expectation Algorithm (millions of vertices)

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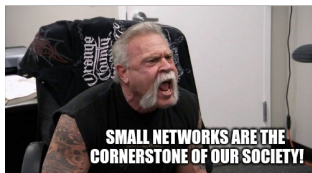
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What about tiny to small networks?

A frame with examples of small networks...



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- ▶ Possible accuracy issues (error rates)
- ▶ Prone to degeneracy problems (sampling and existence of MLE)
- ▶ It is not MLE,

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ERGMs for Small Networks

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We implemented this and more in the `ergm` R package [▶ more](#)

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- ▶ Draw 20,000 samples of groups of small networks
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- ▶ Each group could have from 5 to 300 small networks

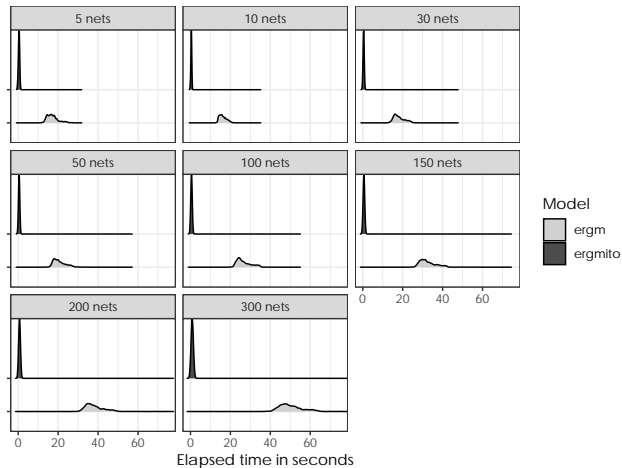
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- ▶ Draw 20,000 samples of groups of small networks
- ▶ Each group had prescribed: (model parameters, number of networks, sizes of the networks)
- ▶ Each group could have from 5 to 300 small networks
- ▶ We estimated the models using MC-MLE and MLE.

Sample size	N. Simulations	P(Type I error)		
		MC-MLE	MLE	chi2
5	2,189	0.084	0.057	11.71 ***
10	2,330	0.070	0.045	12.46 ***
15	2,395	0.084	0.066	5.55 *
20	2,430	0.074	0.060	3.58
30	2,460	0.057	0.052	0.67
50	2,495	0.046	0.044	0.17
100	2,499	0.048	0.048	0.00

Table 1 Empirical Type I error rates. The χ^2 statistic is from a 2-sample test for equality of proportions, and the significance levels are given by *** $p < 0.001$, ** $p < 0.01$, and * $p < 0.05$. The lack of fitted samples in some levels is due to failure of the estimation method.

Paper 1 Simulation Studies: Elapsed time



► more results

Paper 1: Key takeaway

- Developed a new extension of ERGMs using exact statistics for small networks (families, teams, ego-centered, etc.)

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- ▶ Opens the door the new methods.

Paper 1: Exponential Random Graph Models for Small Networks

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Gene Functional Annotations: The Gene Ontology Project

Accession	GO:0060047
Name	heart contraction
Ontology	biological_process
Synonyms	heart beating, cardiac contraction, hemolymph circulation
Alternate	IDs None
Definition	The multicellular organismal process in which the heart decreases in volume in a characteristic way to propel blood through the body. Source: GOC:dph

Table 2 Heart Contraction Function. source: amigo.geneontology.org



pthr10037



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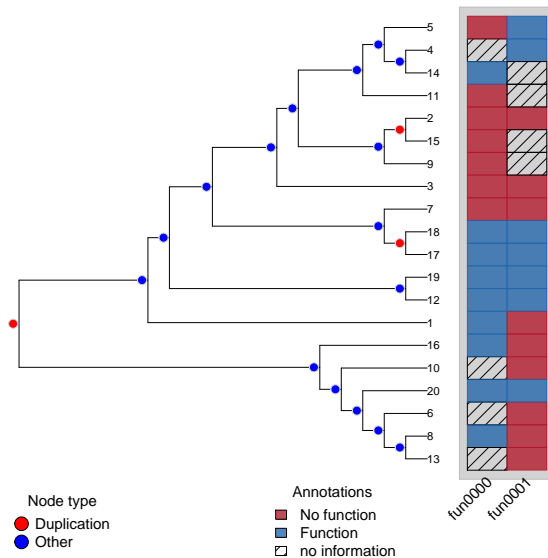
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- It can be very general: think of the tree of life

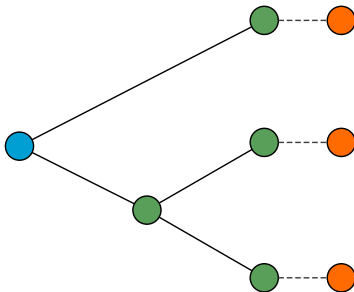
- ▶ It can be very general: think of the tree of life
- ▶ Nowadays, thanks to gene-sequencing techniques, we are building trees at the gene level (using sequence-alignment methods, i.e. comparing gene sequences to see how much similar/different two genes are between and within species (whattt!)).

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- ▶ A single phylogenetic tree can host multiple species

Annotated Phylogenetic Tree

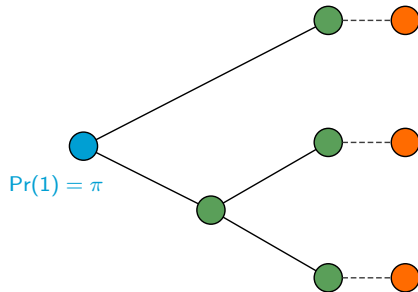


An evolutionary model of gene functions: Formal statement



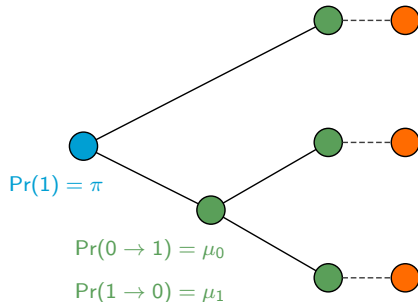
An evolutionary model of gene functions: Formal statement

- Initial (spontaneous) gain of function.



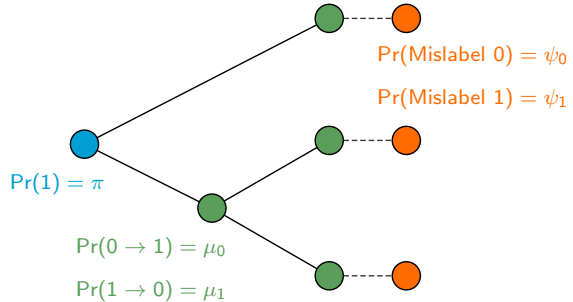
An evolutionary model of gene functions: Formal statement

- Initial (spontaneous) gain of function.
- Loss/gain of offspring depends on the state of its' parents. (**markov process**)

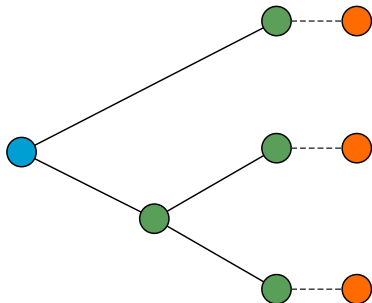


An evolutionary model of gene functions: Formal statement

- ▶ Initial (spontaneous) gain of function.
- ▶ Loss/gain of offspring depends on the state of its' parents. (**markov process**)
- ▶ There's a change of error.

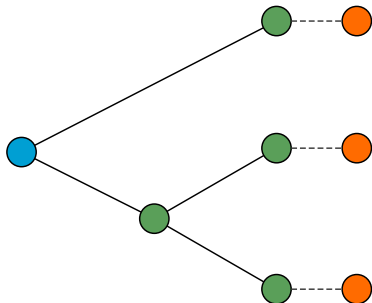


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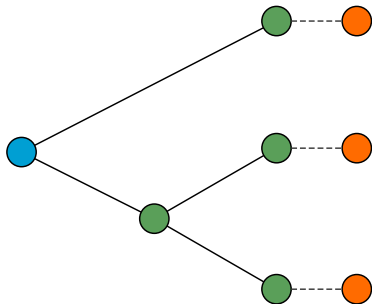
- Gain and loss also depend on the type of the parent node speciation vs duplication

An evolutionary model of gene functions: Formal statement



- ▶ Gain and loss also depend on the type of the parent node **speciation vs duplication**
- ▶ We use Felsensteins' pruning algorithm **algorithmic view** (linear complexity)

An evolutionary model of gene functions: Formal statement

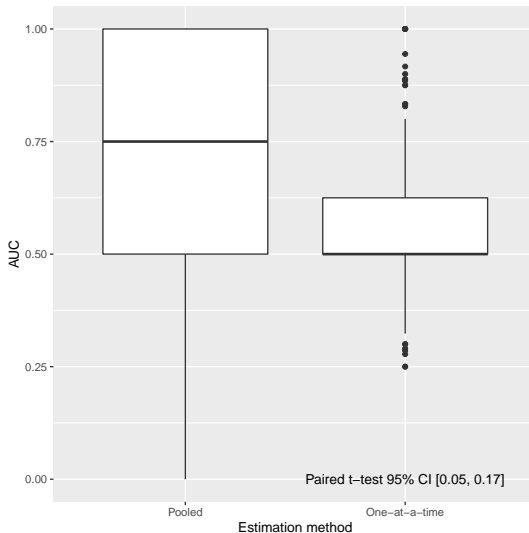


- ▶ Gain and loss also depend on the type of the parent node [speciation vs duplication](#)
- ▶ We use Felsensteins' pruning algorithm [algorithmic view](#) (linear complexity)
- ▶ Full framework has been implemented in the `aphylo` R package [more](#).

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
ψ_0	0.00	0.00	0.23	0.25	0.00	0.00	0.21	0.25
ψ_1	0.00	0.00	0.01	0.01	0.00	0.00	0.00	0.01
μ_{d0}	0.01	0.01	0.97	0.96	1.00	0.01	1.00	0.98
μ_{d1}	0.01	0.02	0.52	0.58	0.25	0.02	0.51	0.58
μ_{s0}	0.00	0.00	0.05	0.06	0.07	0.00	0.05	0.06
μ_{s1}	0.01	0.01	0.01	0.02	0.01	0.01	0.01	0.02
π	0.81	0.91	0.78	0.45	0.82	0.91	0.83	0.49
Tree count	88	88	141	141	88	88	141	141
Method	MCMC	MCMC	MCMC	MCMC	MLE	MLE	MLE	MLE
Prior	Uniform	Beta	Uniform	Beta	Uniform	Beta	Uniform	Beta
Inferred	Yes	Yes	No	No	Yes	Yes	No	No
AUC	1.00	1.00	0.69	0.67	0.98	1.00	0.70	0.67
P. Score (obs)	1.00	1.00	0.81	0.81	0.92	1.00	0.81	0.81
P. Score (random)	0.71	0.71	0.61	0.61	0.71	0.71	0.61	0.61

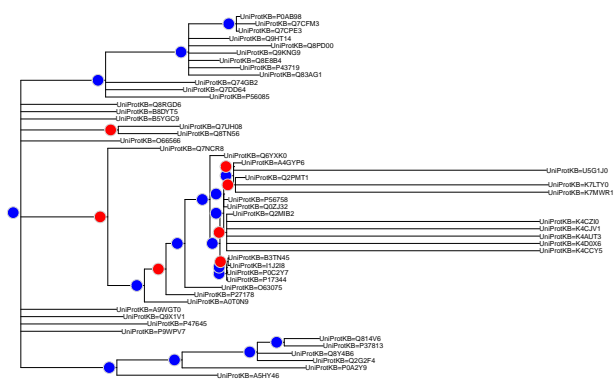
Table 3 Parameter estimates using different estimation methods, priors, and types of annotations.

Paper 2: Pooled estimation (worth it?)



Paper 2: Leave-one-out predictions

Annotated Phylogenetic Tree

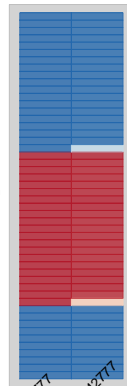


Node type

- Duplication
- Other

Annotations

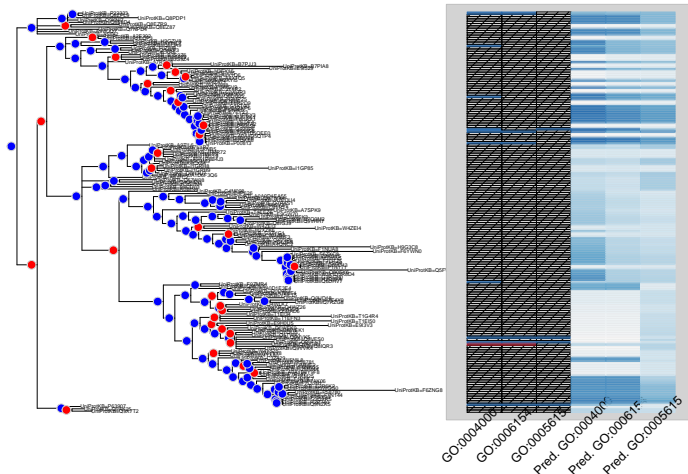
- No function
- Function
- no information



Paper 2: Out-of-sample-predictions

Adenosine Deaminase (PTHR11409)

AUCs:={0.80, 0.67, -}



Paper 2: Key takeaways

- ▶ (Yet another) model for predicting gene functions using phylogenetics

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- ▶ Meaningful biological results
- ▶ Preliminary accuracy results comparable to state-of-the-art phylo-based models

Possible venues to continue

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- Identify an adequate test for goodness-of-fit assesment

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- ▶ Identify an adequate test for goodness-of-fit assesment
- ▶ Extend to estimation of large graphs by splitting the networks in induced-subgraphs

Future directions: Gene functional prediction

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


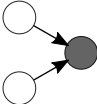

- ▶ Make the model hierarchical when pooling trees: different mutation rates.

Here are some by-products of my research here at USC

- ▶ The slurmR R package
- ▶ The pruner C++ library
- ▶ The fmcmc R package

Dodd, D. M. B. (1989). Reproductive isolation as a consequence of adaptive divergence in *Drosophila pseudoobscura*. *Evolution*, 43(6), 1308–1311. Retrieved from <http://www.jstor.org/stable/2409365>

Sufficient statistics have various forms

Representation	Description
	Mutual Ties (Reciprocity) $\sum_{i \neq j} y_{ij} y_{ji}$
	Transitive Triad (Balance) $\sum_{i \neq j \neq k} y_{ij} y_{jk} y_{ik}$
	Homophily $\sum_{i \neq j} y_{ij} \mathbf{1}(x_i = x_j)$
	Covariate Effect for Incoming Ties $\sum_{i \neq j} y_{ij} x_j$
	Four Cycle $\sum_{i \neq j \neq k \neq l} y_{ij} y_{jk} y_{kl} y_{li}$

One of the most popular methods for estimating ERGMs is the MC-MLE approach (citations here)

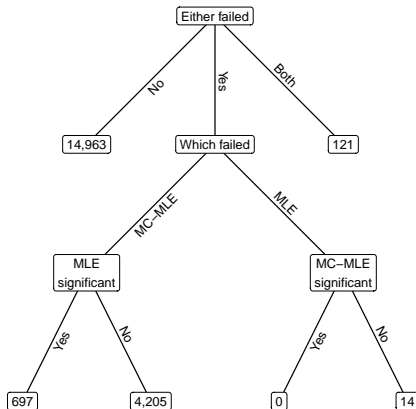
This consists on the following steps

1. Start from a sensible guess on what should be the population parameters (usually done using pseudo-MLE estimation)
2. While the algorithm doesn't converge, do:
 - 2.1 Simulate a stream of networks with the current state of the parameter, θ_t
 - 2.2 Using the law of large numbers, approximate the ratio of likelihoods based on the parameter θ_t , this is the objective function
 - 2.3 Update the parameter by a Newton-Raphson step
 - 2.4 Next iteration

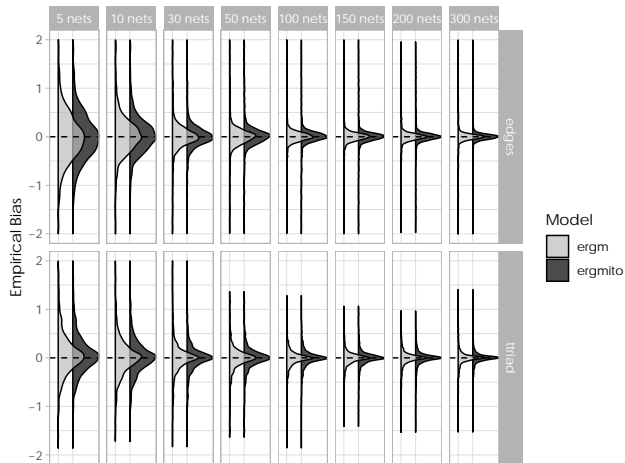
- ▶ Implements estimation of ERGMs using exact statistics for small networks
- ▶ Metaprogramming allows specifying likelihood (and gradient) functions for joint models
- ▶ Includes tools for simulating, and postestimation checks
- ▶ Getting ready for CRAN!

◀ go back

Paper 1 Simulation Studies: Error rate



Paper 1 Simulation Studies: Empirical Bias



An evolutionary model of gene functions (algorithmic view)

Data: A phylogenetic tree, $\{\pi, \mu, \psi\}$ (Model probabilities)

Result: An annotated tree

for $n \in \text{PostOrder}(N)$ do

Nodes gain/loss function depending on their parent;

 switch *class of n* do

 case *root node* do

 Gain function with probability π ;

 case *interior node* do

 if *Parent has the function* then Keep it with prob. $(1 - \mu_1)$;

 else Gain it with prob. μ_0 ;

 end

Finally, we allow for mislabeling;

 if *n is leaf* then

 if *has the function* then Mislabel with prob. ψ_1 ;

 else Mislabel with prob. ψ_0 ;

end

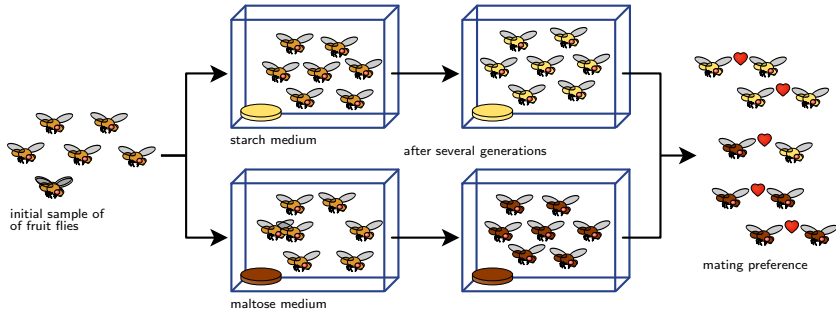


Figure 1 Dodd (1989): After one year of isolation, flies showed a significant level of assortativity in mating (wikimedia)

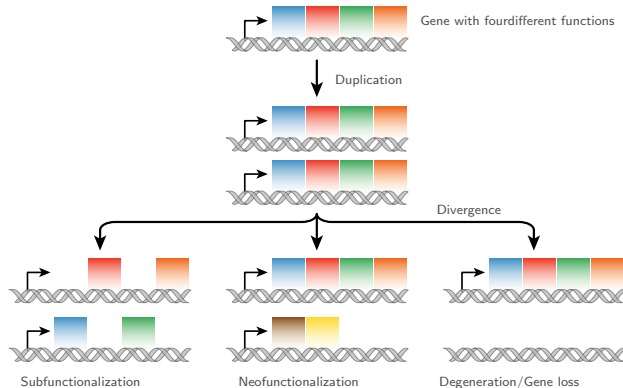


Figure 2 A key part of molecular innovation, gene duplication provides opportunity for new functions to emerge (wikimedia)

- ▶ Pruning algorithm implemented in C++ using the `pruner` template library (implemented in this project).
- ▶ The estimation is done using either Maximum Likelihood, Maximum A Posteriory, or MCMC.
- ▶ The MCMC estimation is done via the `fmcmc` R package using adaptive MCMC (also implemented as part of this project)

◀ go back