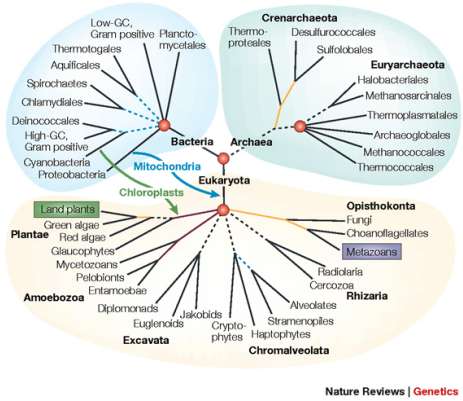


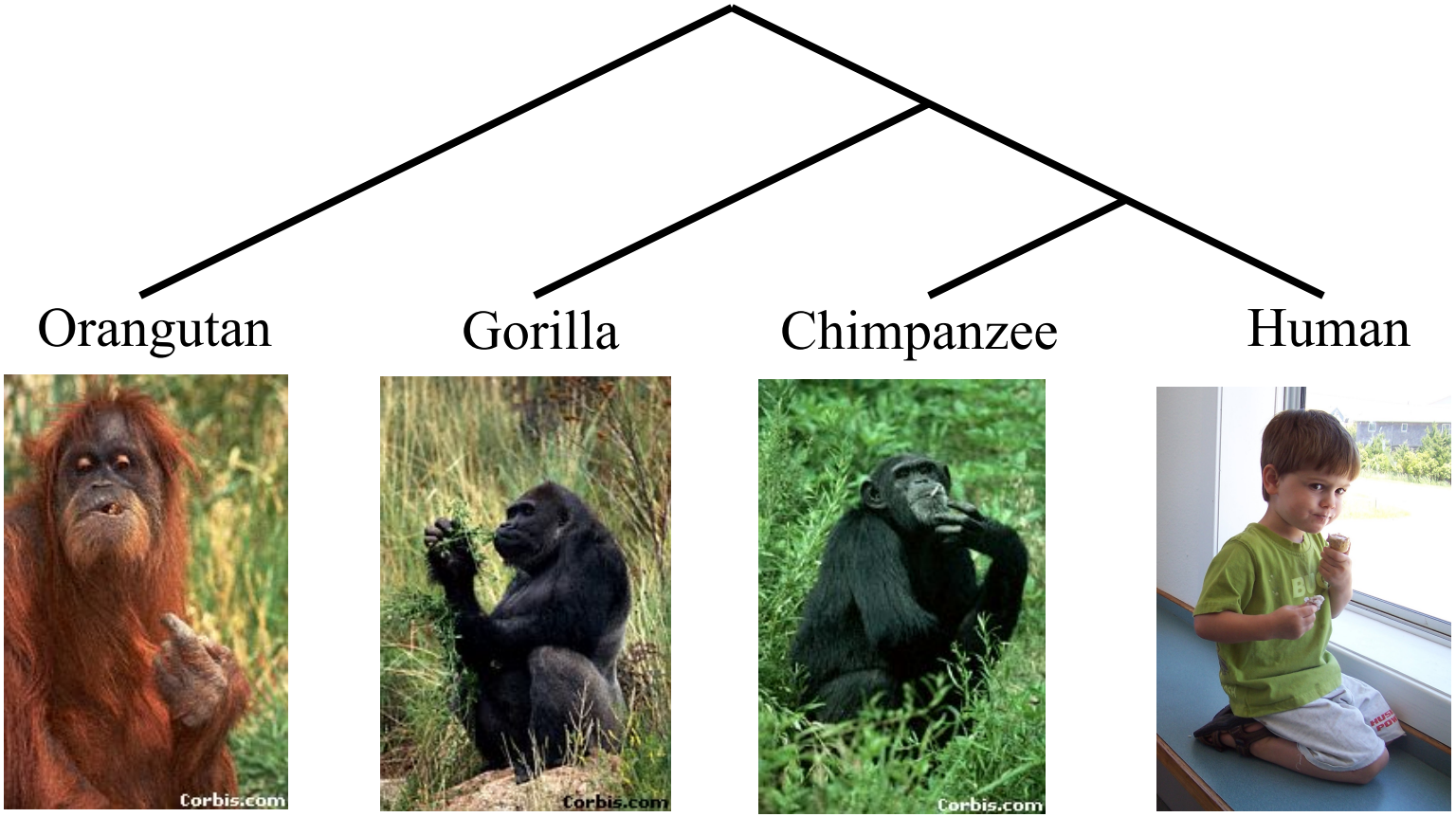
Nature Reviews | Genetics

From Gene Trees to Species Trees

Tandy Warnow

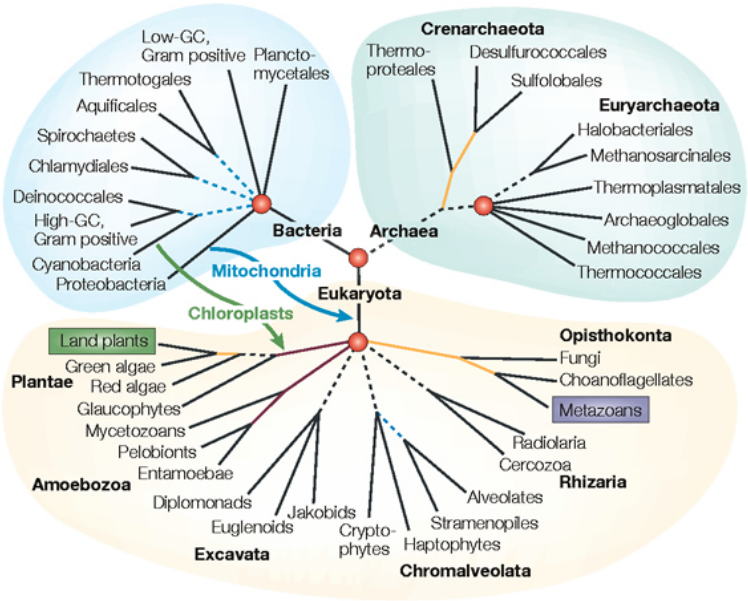
The University of Texas at Austin

Phylogeny
(evolutionary tree)



From the Tree of the Life Website,
University of Arizona

Estimating The Tree of Life: a *Grand Challenge*



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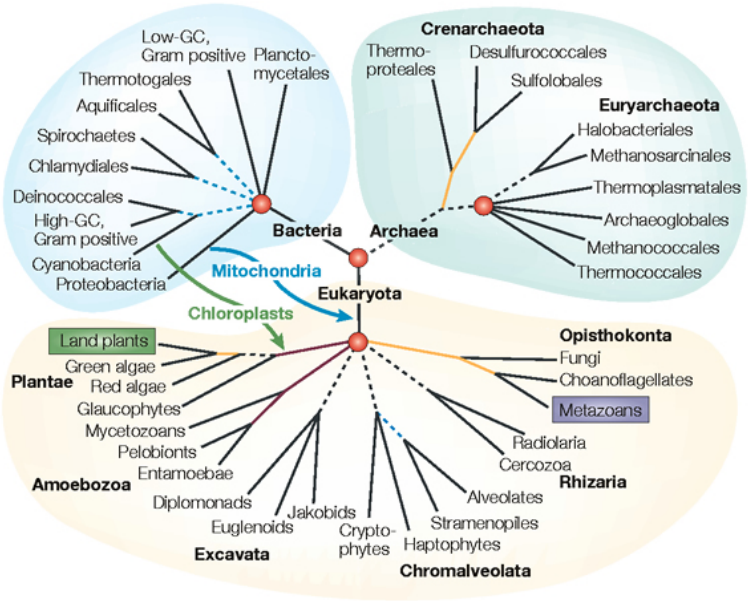
Most well studied problem:

Given DNA sequences, find the Maximum Likelihood Tree

NP-hard, lots of software (RAxML, FastTree-2, GARLI, etc.)

Estimating The Tree of Life: a *Grand Challenge*



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Novel techniques needed for scalability and accuracy:

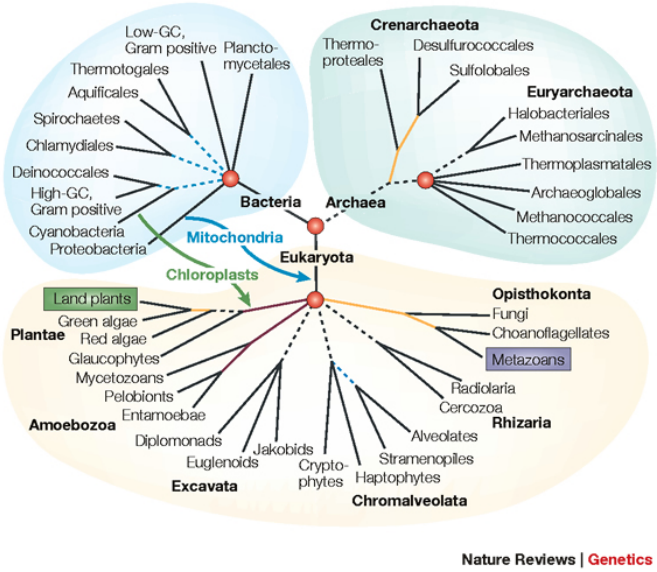
NP-hard problems and large datasets

Current methods not good enough on large datasets

HPC is necessary but not sufficient

Phylogenomics

(Phylogenetic estimation from whole genomes)



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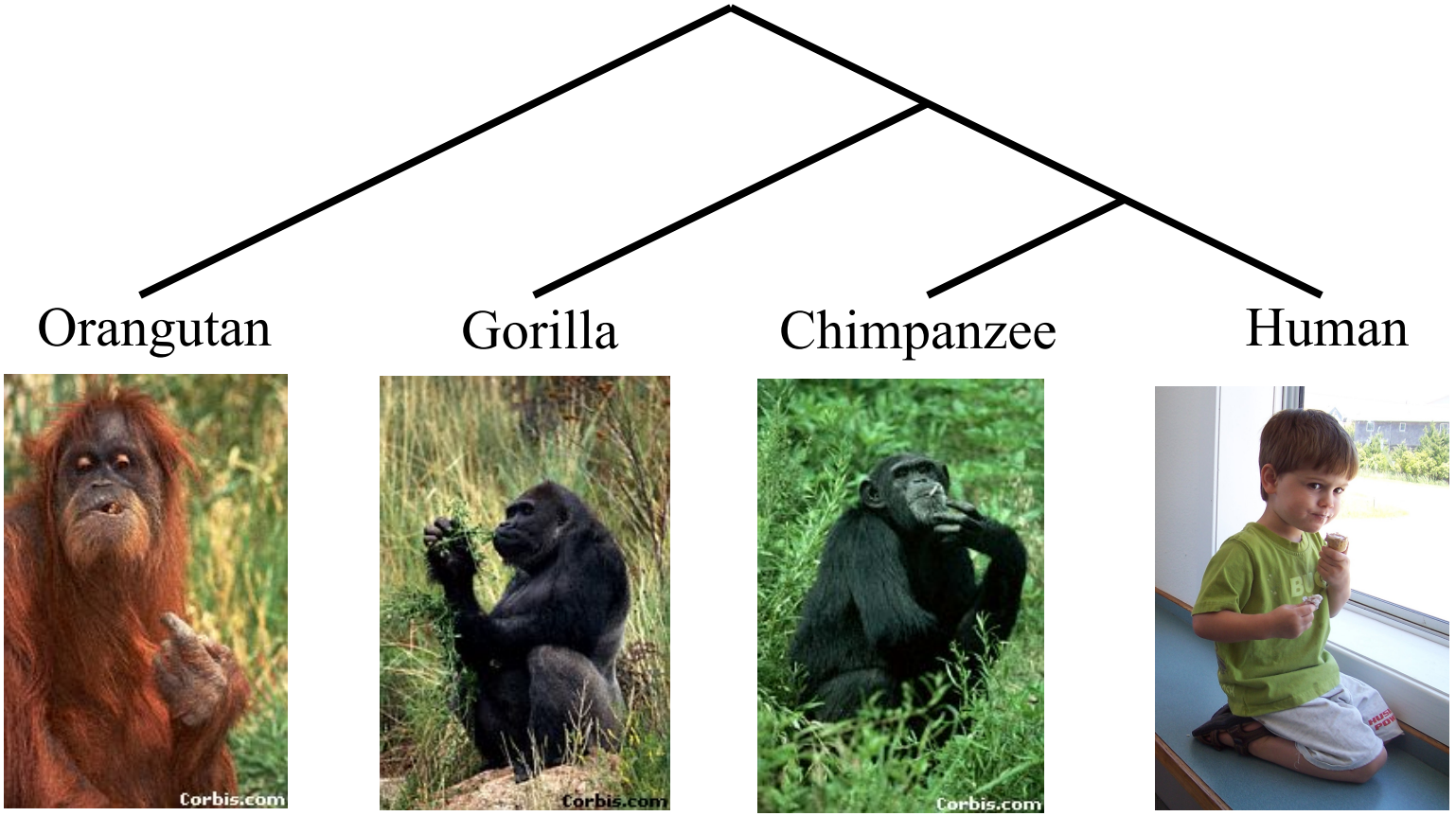
Sampling multiple genes from multiple species



From the Tree of the Life Website,
University of Arizona

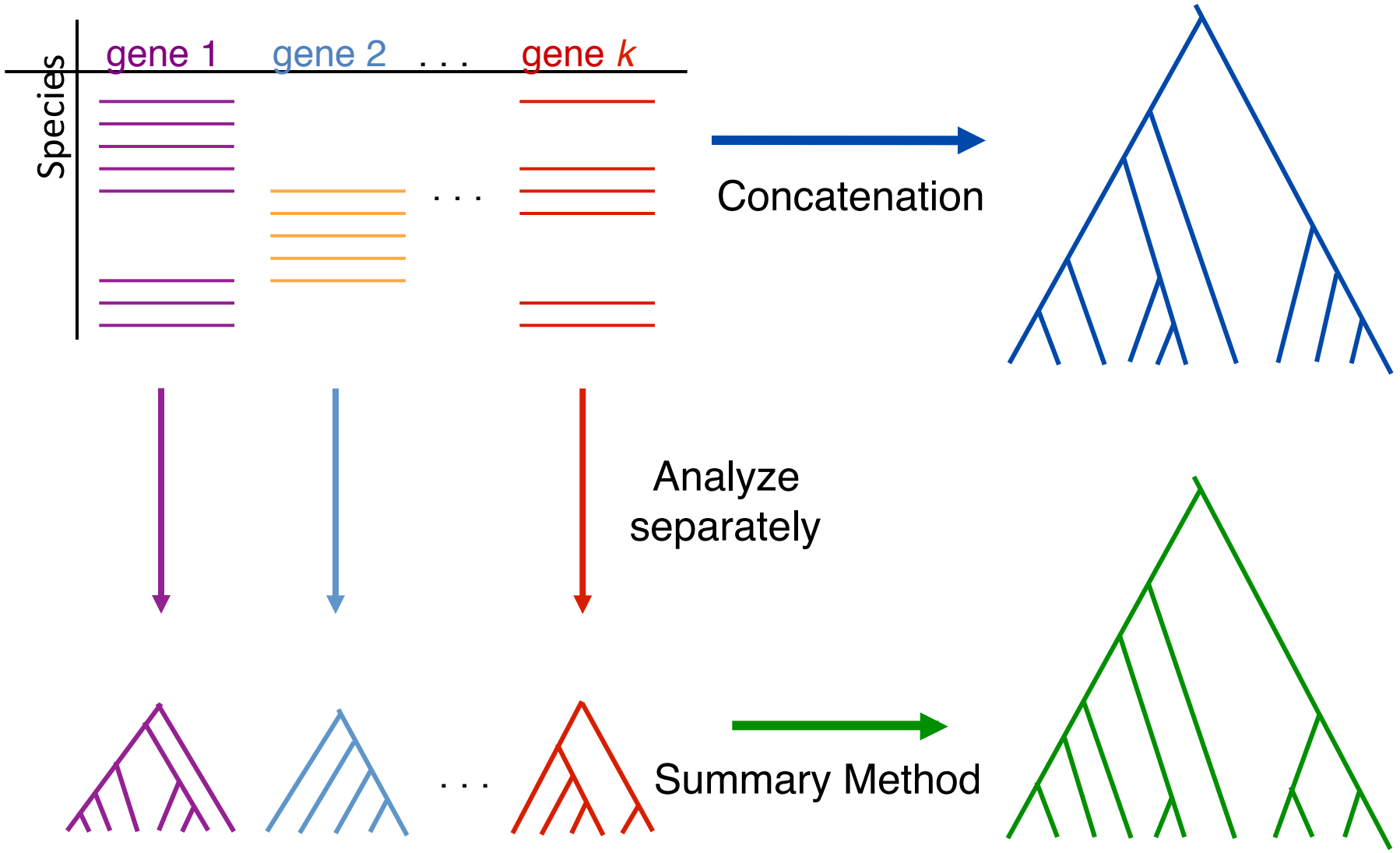
Using multiple genes

	gene 1
S_1	TCTAATGGAA
S_2	GCTAAGGGAA
S_3	TCTAAGGGAA
S_4	TCTAACGGAA
S_7	TCTAATGGAC
S_8	TATAACGGAA

	gene 2
S_4	GGTAACCCTC
S_5	GCTAAACCTC
S_6	GGTGACCATC
S_7	GCTAAACCTC

	gene 3
S_1	TATTGATACA
S_3	TCTTGATACC
S_4	TAGTGATGCA
S_7	TAGTGATGCA
S_8	CATTCATACC

Two competing approaches



1kp: Thousand Transcriptome Project

G. Ka-Shu Wong
U Alberta

J. Leebens-Mack
U Georgia

N. Wickett
Northwestern

N. Matasci
iPlant

T. Warnow,
UT-Austin

S. Mirarab,
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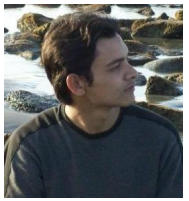


Plus many many other people…

- Plant Tree of Life based on transcriptomes of ~1200 species
- More than 13,000 gene families (most not single copy)
- Gene sequence alignments and trees computed using SATé (Liu et al., Science 2009 and Systematic Biology 2012)

Challenges:

Multiple sequence alignments of > 100,000 sequences

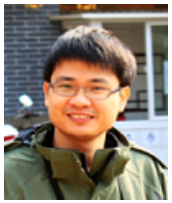
Gene tree incongruence

Avian Phylogenomics Project

Erich Jarvis, HHMI

MTP Gilbert, Copenhagen

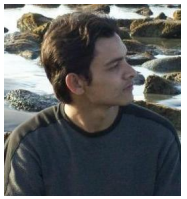
G Zhang, BGI



T. Warnow UT-Austin

S. Mirarab UT-Austin

Md. S. Bayzid, UT-Austin



Plus many many other people…

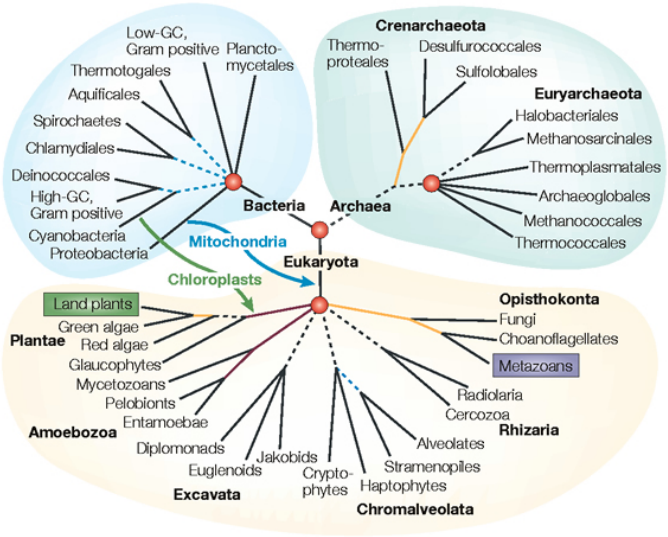
- Approx. 50 species, whole genomes
- 8000+ genes, UCEs
- Gene sequence alignments and trees computed using SATé (Liu et al., Science 2009 and Systematic Biology 2012)

Challenges:

Maximum likelihood on multi-million-site sequence alignments

Massive gene tree incongruence

The Tree of Life: *Multiple Challenges*



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Large datasets:

100,000+ sequences

10,000+ genes

"BigData" complexity

Also:

Ultra-large multiple-sequence alignment

Estimating species trees from incongruent gene trees

Supertree estimation

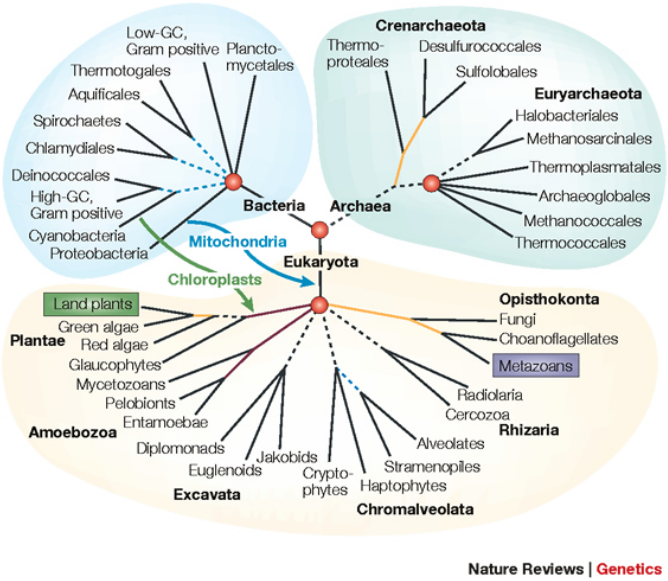
Genome rearrangement phylogeny

Reticulate evolution

Visualization of large trees and alignments

Data mining techniques to explore multiple optima

The Tree of Life: *Multiple Challenges*



Nature Reviews | Genetics

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Also:

Tomorrow's talk

Ultra-large multiple-sequence alignment

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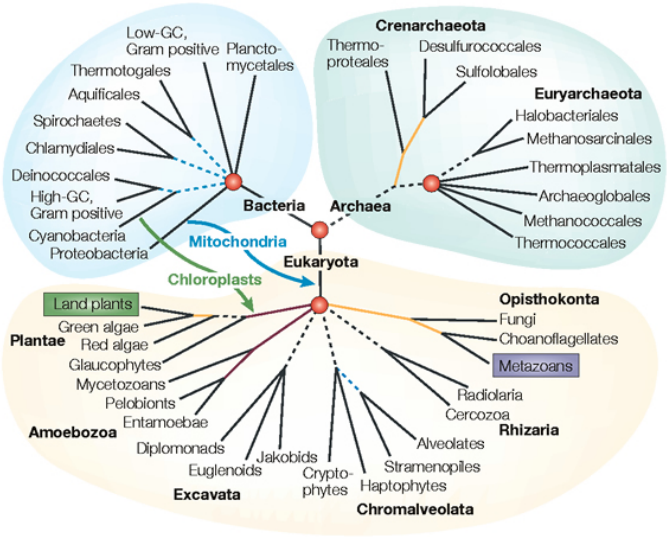

Nature Reviews | Genetics

Large datasets:

100,000+ sequences

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This talk

Also:

Ultra-large multiple-sequence alignment

Estimating species trees from incongruent gene trees

Supertree estimation

Genome rearrangement phylogeny

Reticulate evolution

Visualization of large trees and alignments

Data mining techniques to explore multiple optima

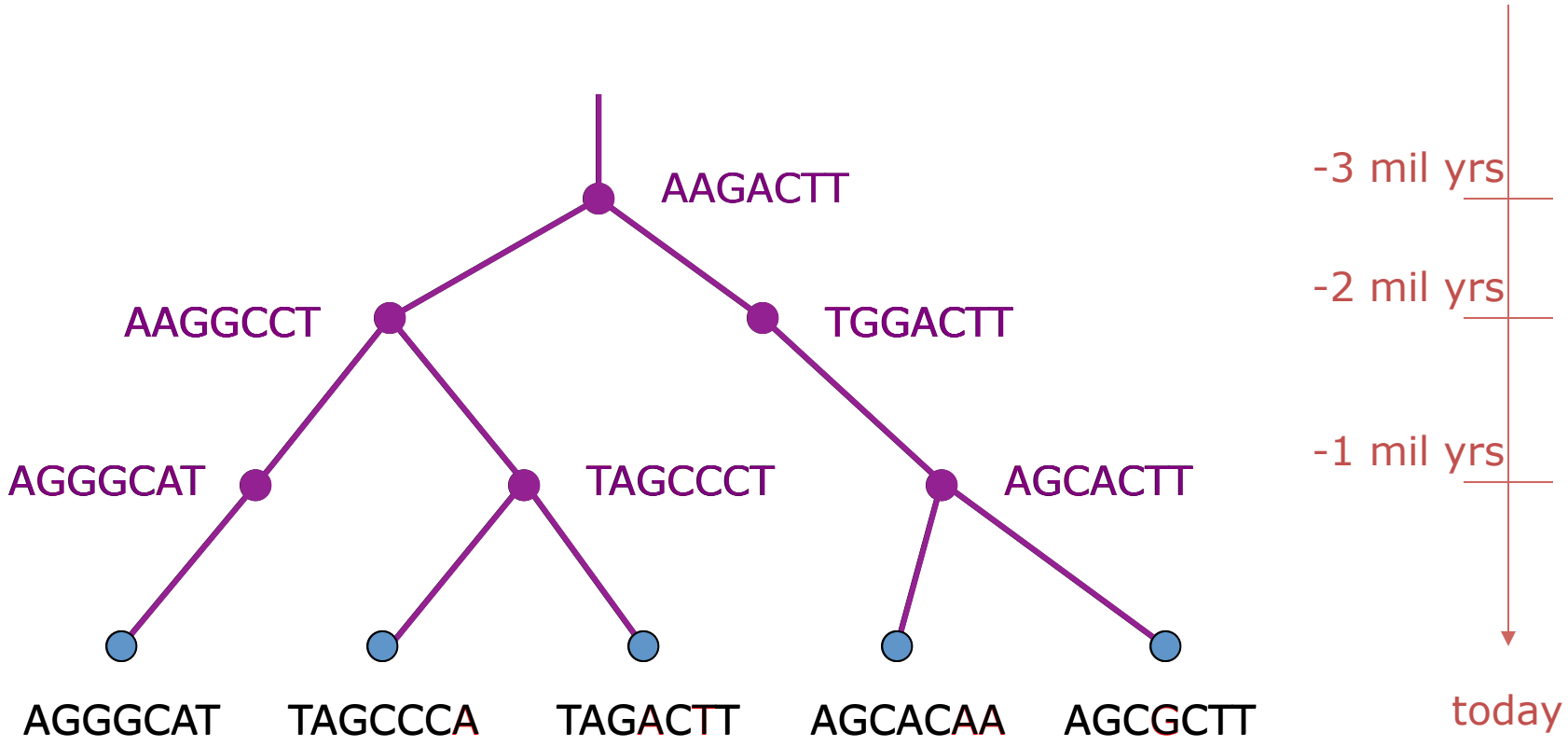
This talk

Species tree estimation from multiple genes

- Mathematical foundations
- Algorithms
- Data challenges
- New statistical questions
- Avian Phylogenomics

Part I: Gene Tree Estimation

DNA Sequence Evolution (Idealized)

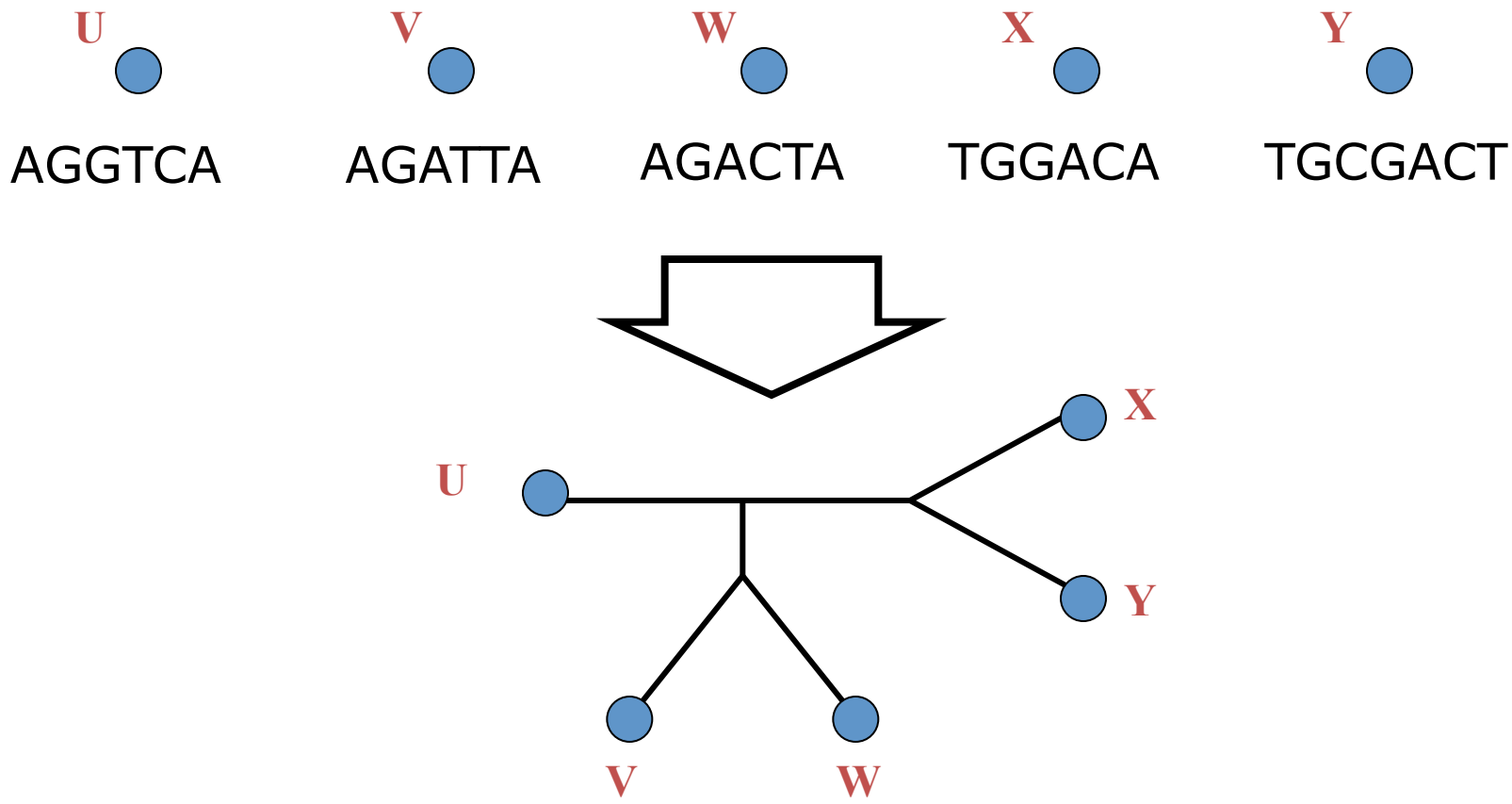


Markov Model of Site Evolution

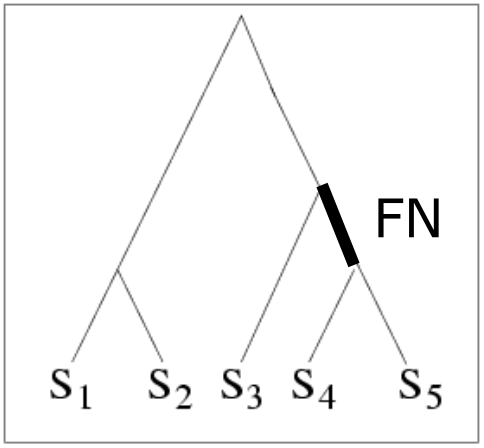
Simplest (Jukes-Cantor, 1969):

- The model tree T is binary and has substitution probabilities p(e) on each edge e.
- The state at the root is randomly drawn from {A,C,T,G} (nucleotides)
- If a site (position) changes on an edge, it changes with equal probability to each of the remaining states.
- The evolutionary process is Markovian.

More complex models (such as the General Markov model) are also considered, often with little change to the theory.


U
V
W
X
Y
AGGTCA
AGATTA
AGACTA
TGGACA
TGCGACT
X
U
Y
V
W

Quantifying Error



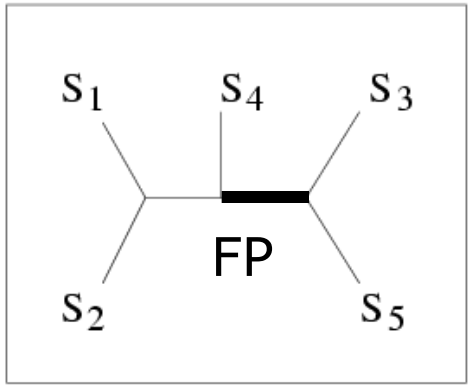
TRUE TREE

S_1	ACAATTAGAAC
S_2	ACCCTTAGAAC
S_3	ACCATTCCAAC
S_4	ACCAGACCAAC
S_5	ACCAGACCGGA

DNA SEQUENCES

FN: false negative
(missing edge)
FP: false positive
(incorrect edge)

50% error rate

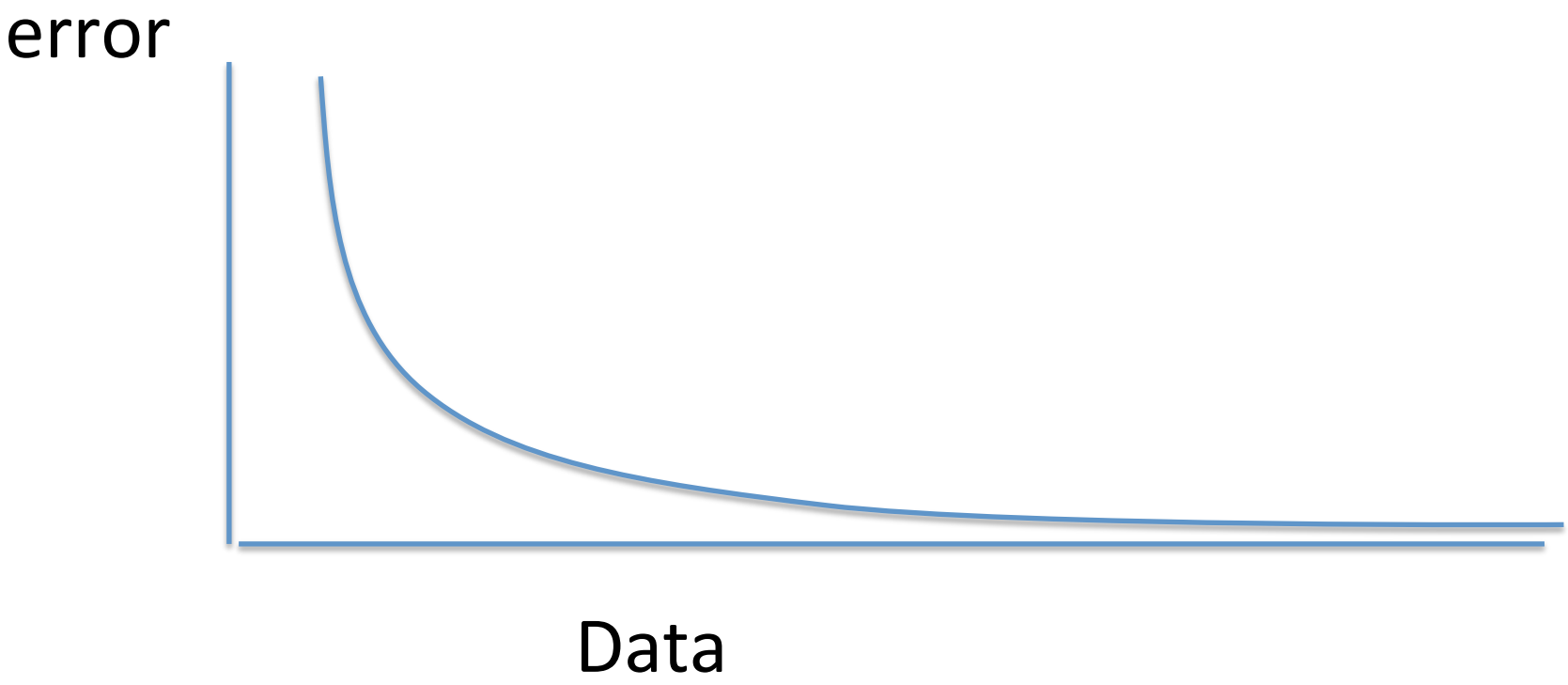


INFERRED TREE

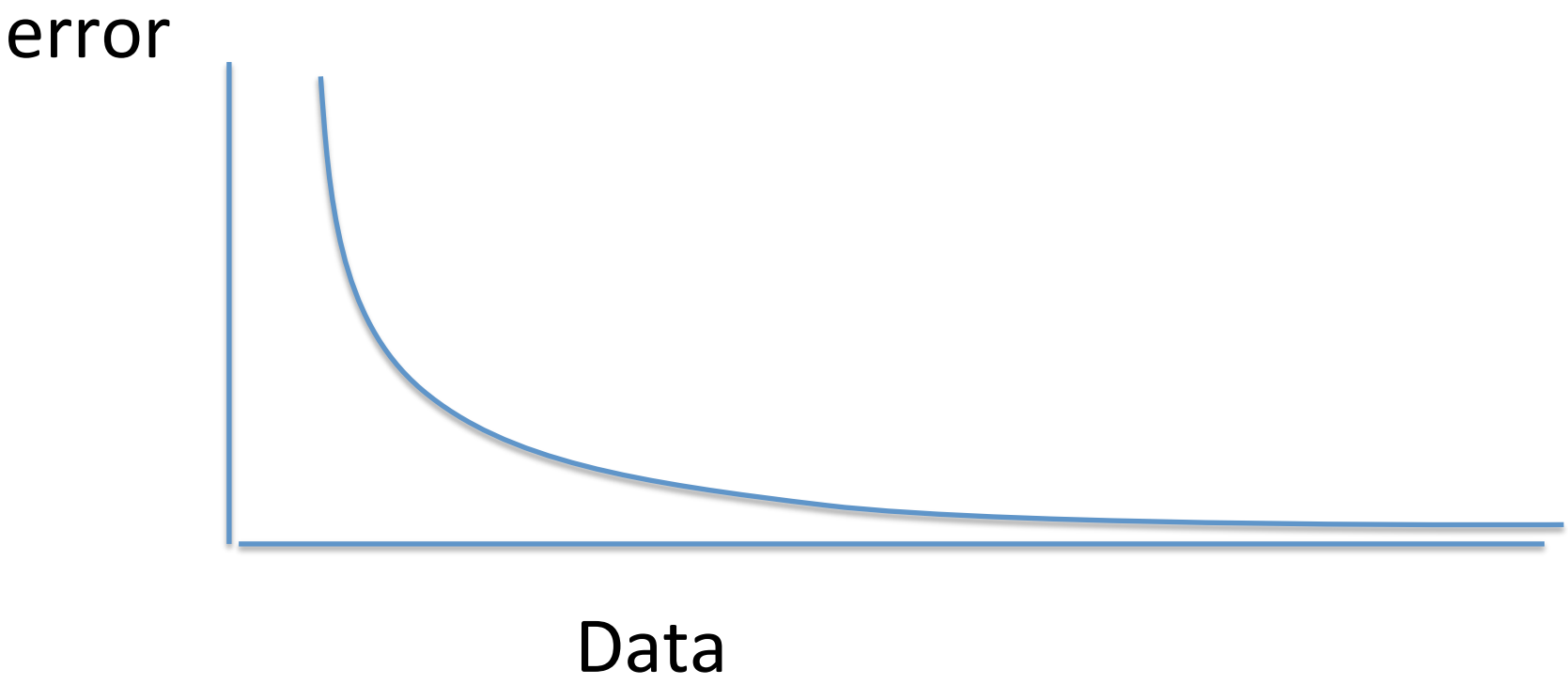
Questions

- Is the model tree identifiable?
- Which estimation methods are statistically consistent under this model?
- How much data does the method need to estimate the model tree correctly (with high probability)?
- What is the computational complexity of an estimation problem?

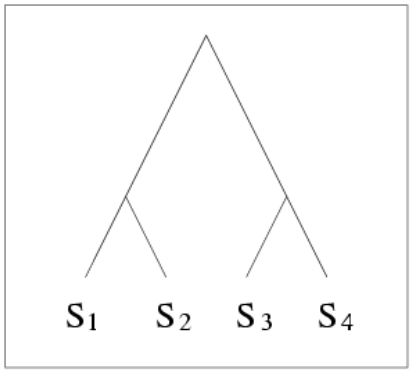
Statistical Consistency



Statistical Consistency



Data are sites in an alignment



TRUE TREE

S_1	ACAATTAGAAC
S_2	ACCCTTAGAAC
S_3	ACCATTCCAAC
S_4	ACCAGACCAAC

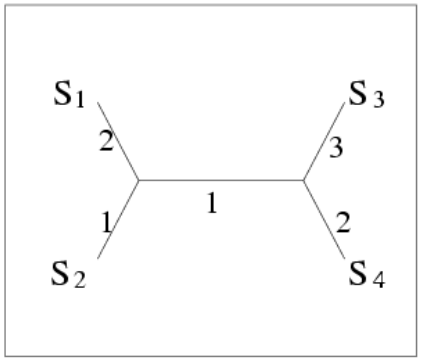
DNA SEQUENCES

STATISTICAL ESTIMATION OF PAIRWISE DISTANCES

	S_1	S_2	S_3	S_4
S_1	0	3	6	5
S_2		0	5	4
S_3			0	5
S_4				0

DISTANCE MATRIX

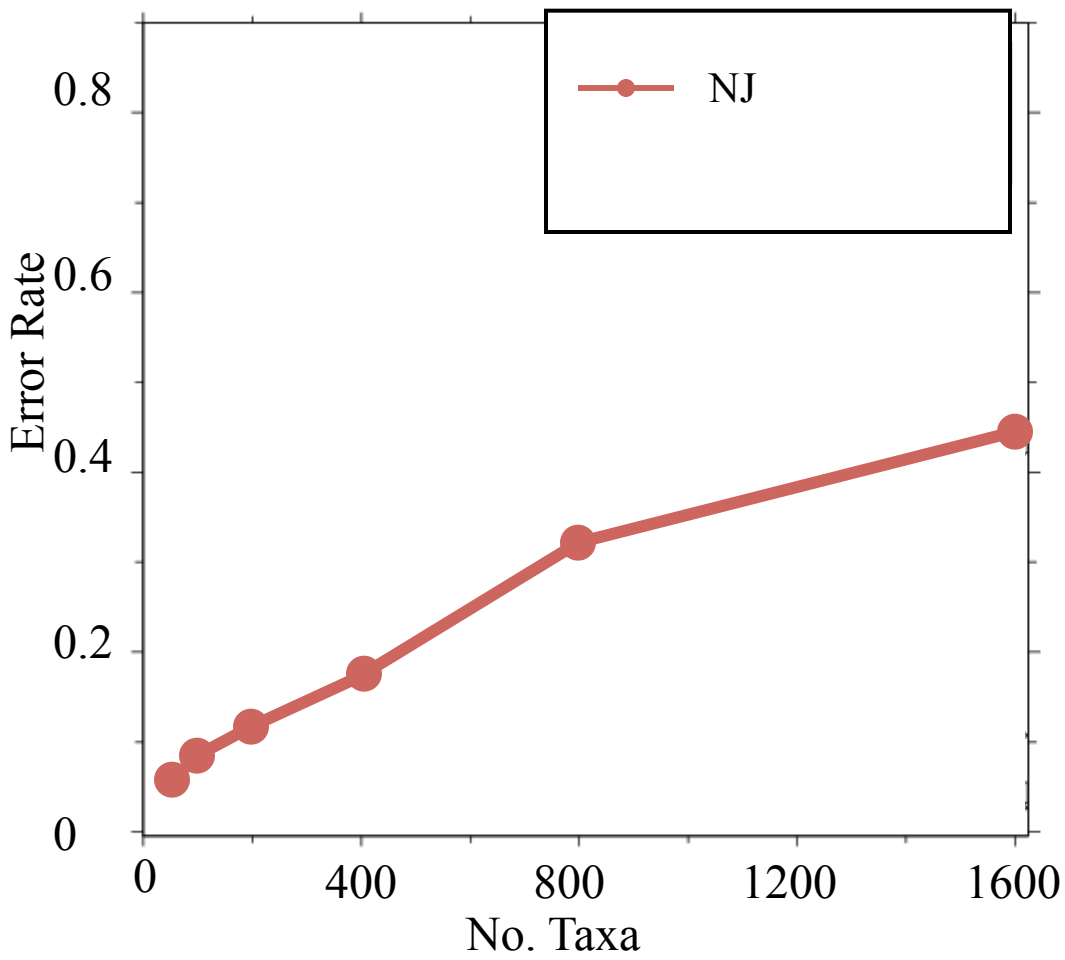
METHODS SUCH AS NEIGHBOR JOINING



INFERRED TREE

Neighbor Joining (and many other distance-based methods) are statistically consistent under Jukes-Cantor

Neighbor Joining on large diameter trees



Simulation study based upon fixed edge lengths, K2P model of evolution, sequence lengths fixed to 1000 nucleotides.

Error rates reflect proportion of incorrect edges in inferred trees.

[Nakhleh et al. ISMB 2001]

"Convergence rate" or sequence length requirement

The sequence length (number of sites) that a phylogeny reconstruction method M needs to reconstruct the true tree with probability at least $1-\varepsilon$ depends on

- M (the method)
- ε
- f = min p(e),
- g = max p(e), and
- n = the number of leaves

We fix everything but n.

Theorem (Erdos et al. 1999, Atteson 1999):

Various distance-based methods (including Neighbor joining) will return the true tree with high probability given sequence lengths that are *exponential* in the evolutionary diameter of the tree (hence, exponential in n).

Proof:

- the method returns the true tree if the estimated distance matrix is close to the model tree distance matrix
- the sequence lengths that suffice to achieve bounded error are exponential in the evolutionary diameter.

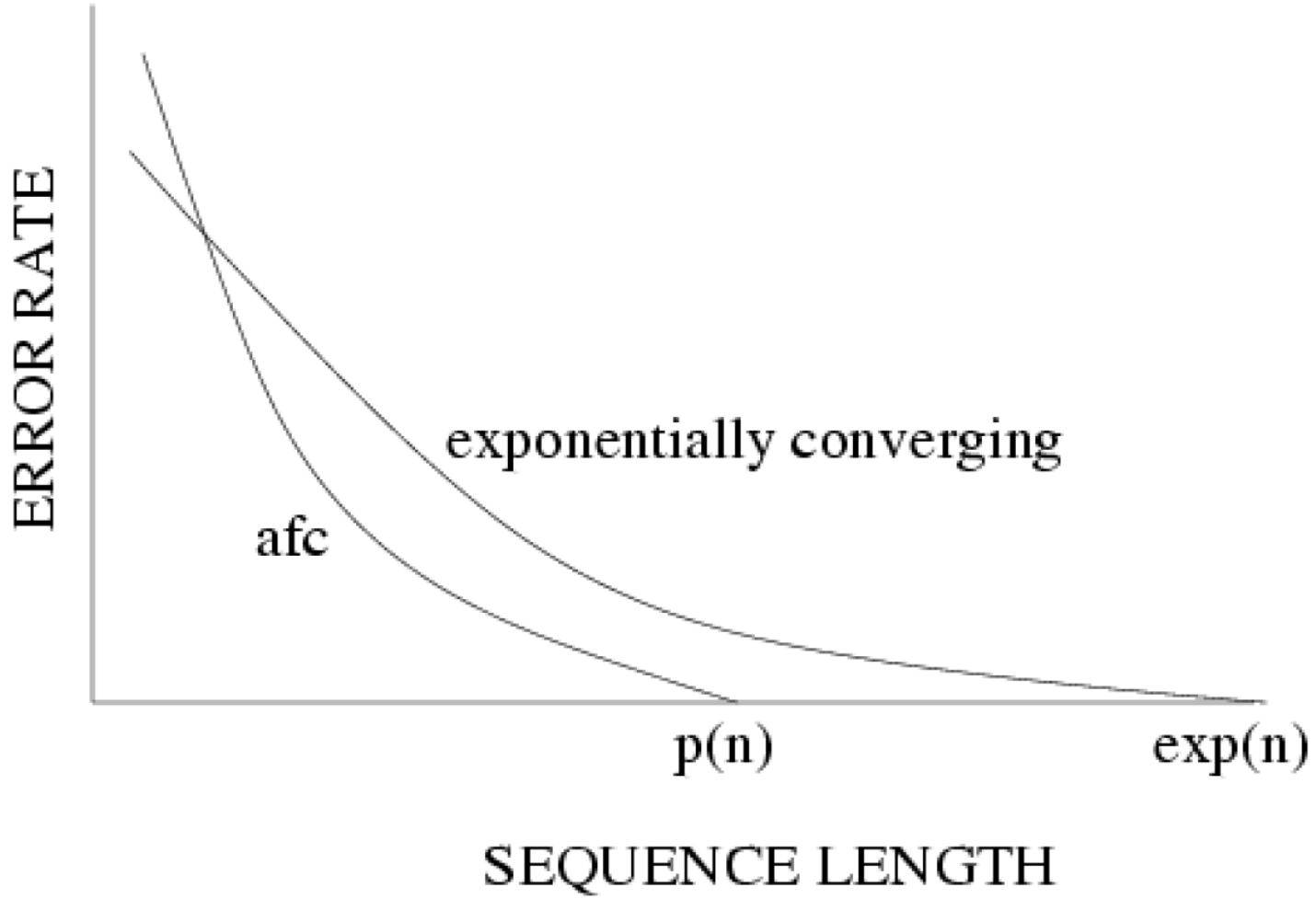
Afc methods (Warnow et al., 1999)

A method M is "absolute fast converging", or afc, if for all positive f, g, and ε, there is a polynomial p(n) s.t. $Pr(M(S)=T) > 1-\varepsilon$, when S is a set of sequences generated on T of length at least p(n).

Notes:

1. The polynomial p(n) will depend upon M, f, g, and ε.
2. The method M is not "told" the values of f and g.

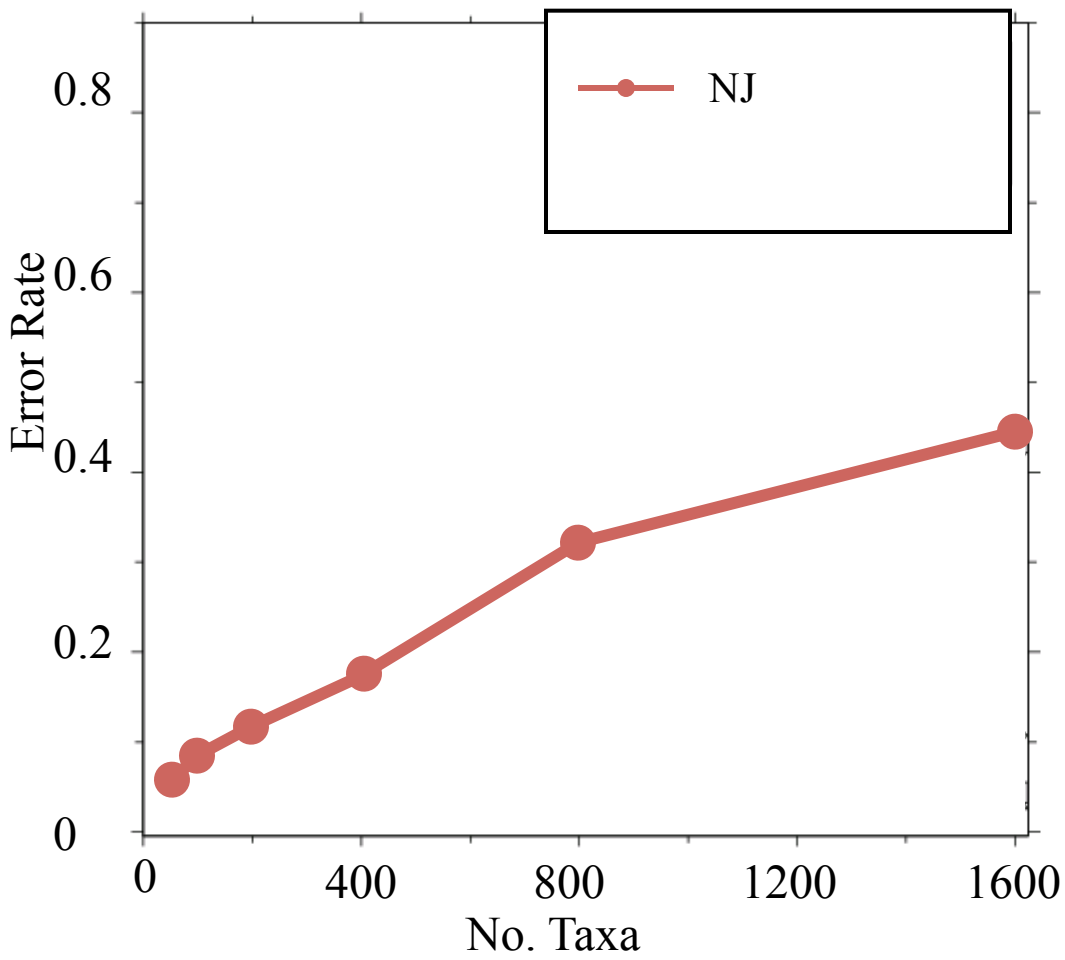
Statistical consistency, exponential convergence, and absolute fast convergence (afc)



Fast-converging methods (and related work)

- 1997: Erdos, Steel, Szekely, and Warnow (ICALP).
- 1999: Erdos, Steel, Szekely, and Warnow (RSA, TCS);
  Huson, Nettles and Warnow (J. Comp Bio.)
- 2001: Warnow, St. John, and Moret (SODA);
  Nakhleh, St. John, Roshan, Sun, and Warnow (ISMB)
  Cryan, Goldberg, and Goldberg (SICOMP);
  Csuros and Kao (SODA);
- 2002: Csuros (J. Comp. Bio.)
- 2006: Daskalakis, Mossel, Roch (STOC),
  Daskalakis, Hill, Jaffe, Mihaescu, Mossel, and Rao (RECOMB)
- 2007: Mossel (IEEE TCBB)
- 2008: Gronau, Moran and Snir (SODA)
- 2010: Roch (Science)
- 2013: Roch (in preparation)

Neighbor Joining on large diameter trees



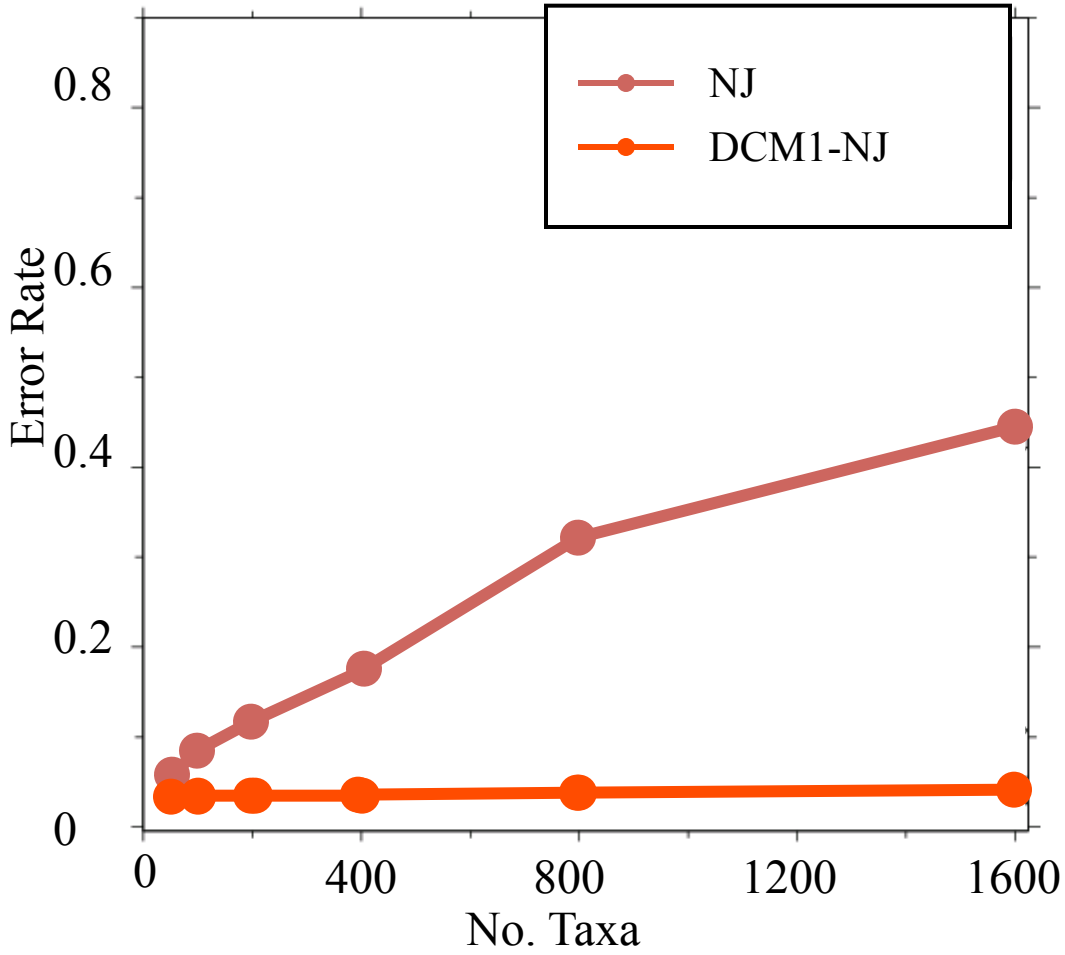
Simulation study based upon fixed edge lengths, K2P model of evolution, sequence lengths fixed to 1000 nucleotides.

Error rates reflect proportion of incorrect edges in inferred trees.

[Nakhleh et al. ISMB 2001]

DCM1-boosting distance-based methods

[Nakhleh et al. ISMB 2001]



Theorem (Warnow et al., SODA 2001): DCM1-NJ converges to the true tree from polynomial length sequences. Hence DCM1-NJ is afc.

Proof: uses chordal graph theory and probabilistic analysis of algorithms

Questions

- Is the model tree identifiable?
- Which estimation methods are statistically consistent under this model?
- How much data does the method need to estimate the model tree correctly (with high probability)?
- What is the computational complexity of an estimation problem?

Answers?

- We know a lot about which site evolution models are identifiable, and which methods are statistically consistent.

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- We know a lot about which site evolution models are identifiable, and which methods are statistically consistent.
- Some polynomial time afc methods have been developed, and we know a little bit about the sequence length requirements for standard methods.

Answers?

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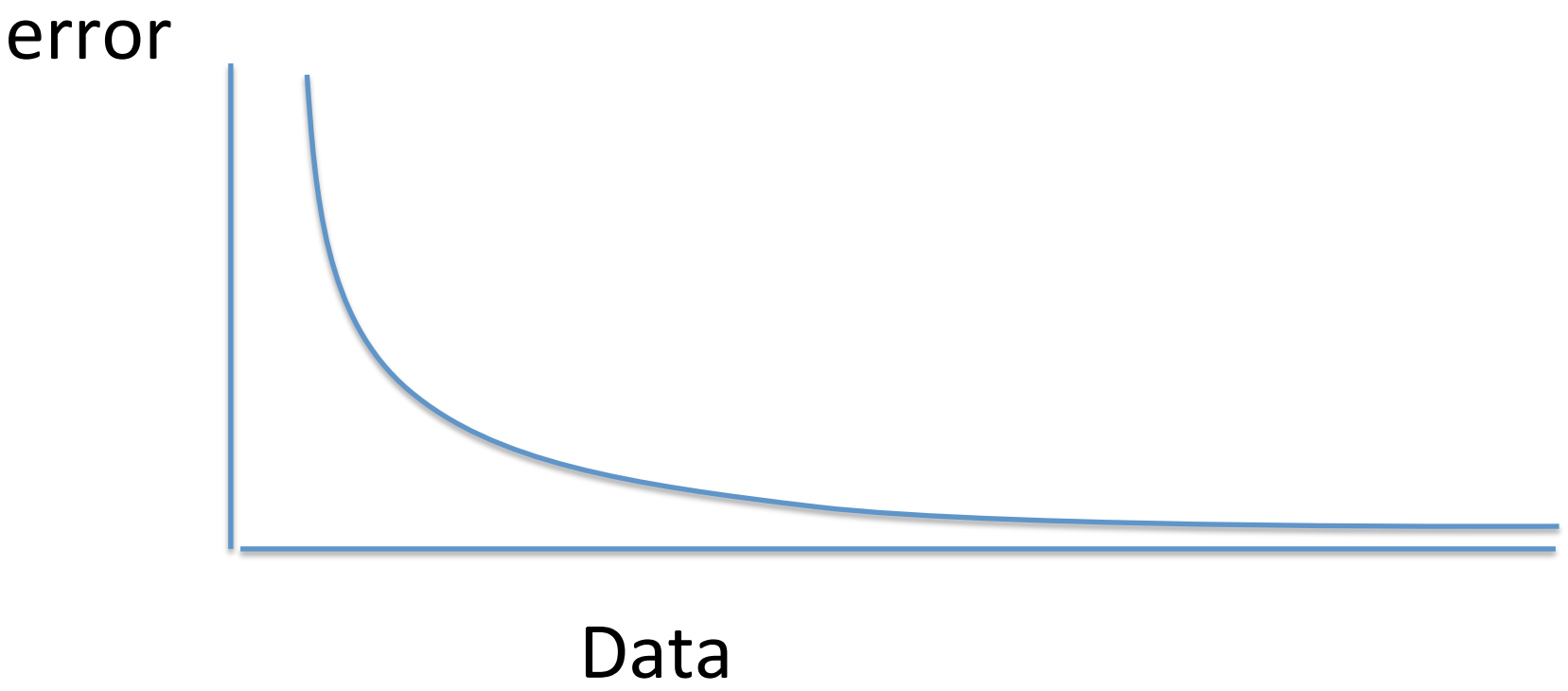
- Just about everything is NP-hard, and the datasets are big.

Answers?

- We know a lot about which site evolution models are identifiable, and which methods are statistically consistent.
- Some polynomial time afc methods have been developed, and we know a little bit about the sequence length requirements for standard methods.
- Just about everything is NP-hard, and the datasets are big.
- Extensive studies show that even the best methods produce gene trees with some error.

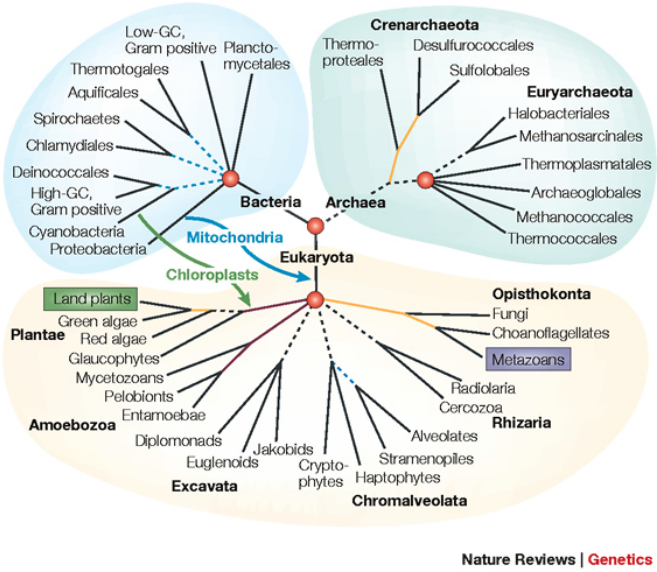
In other words…



Statistical consistency doesn't guarantee accuracy w.h.p. unless the sequences ***are long enough.***

Phylogenomics

(Phylogenetic estimation from whole genomes)



Nature Reviews | Genetics

Using multiple genes

	gene 1
S_1	TCTAATGGAA
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S_4	TCTAACGGAA
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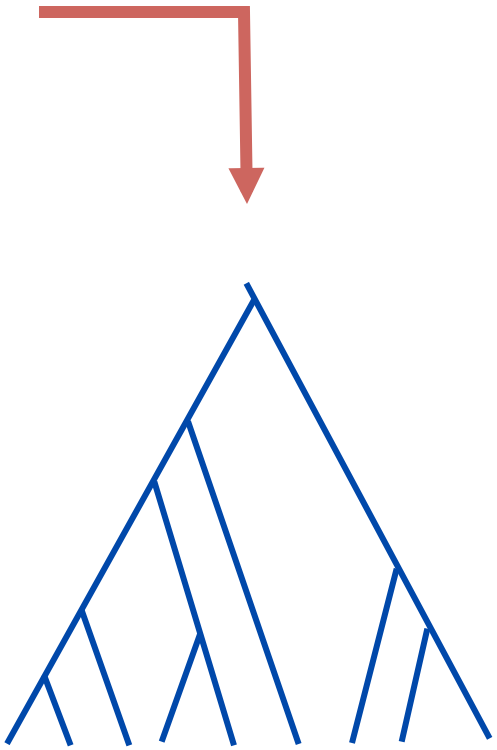
S_7	GCTAAACCTC

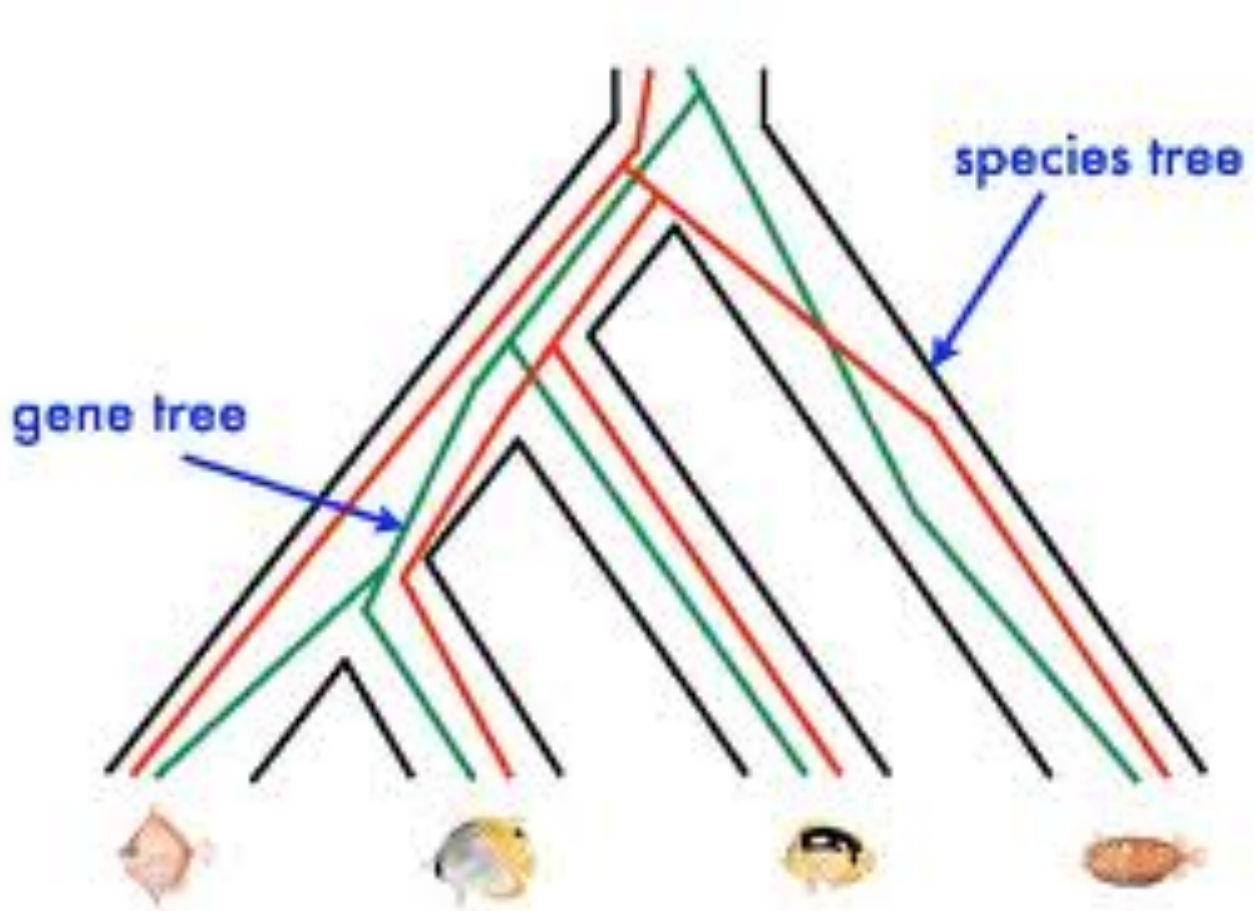
	gene 3
S_1	TATTGATACA
S_3	TCTTGATACC
S_4	TAGTGATGCA
S_7	TAGTGATGCA
S_8	CATTCATACC

Concatenation

	gene 1	gene 2	gene 3
S_1	TCTAATGGAA	? ? ? ? ? ? ? ? ? ?	TATTGATACA
S_2	GCTAAGGGAA	? ? ? ? ? ? ? ? ? ?	? ? ? ? ? ? ? ? ? ?
S_3	TCTAAGGGAA	? ? ? ? ? ? ? ? ? ?	TCTTGATACC
S_4	TCTAACGGAA	GGTAACCCTC	TAGTGATGCA
S_5	? ? ? ? ? ? ? ? ? ?	GCTAAACCTC	? ? ? ? ? ? ? ? ? ?
S_6	? ? ? ? ? ? ? ? ? ?	GGTGACCATC	? ? ? ? ? ? ? ? ? ?
S_7	TCTAATGGAC	GCTAAACCTC	TAGTGATGCA
S_8	TATAACGGAA	? ? ? ? ? ? ? ? ? ?	CATTCATACC



Red gene tree ≠ species tree (green gene tree okay)

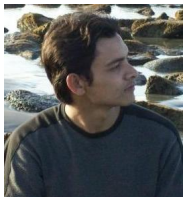


1KP: Thousand Transcriptome Project







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- 1200 plant transcriptomes
- More than 13,000 gene families (most not single copy)
- Multi-institutional project (10+ universities)
- iPLANT (NSF-funded cooperative)
- Gene sequence alignments and trees computed using SATe (Liu et al., Science 2009 and Systematic Biology 2012)

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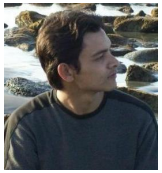


Gene Tree Incongruence

Plus many many other people…

- Approx. 50 species, whole genomes
- 8000+ genes, UCEs
- Gene sequence alignments computed using SATé (Liu et al., Science 2009 and Systematic Biology 2012)

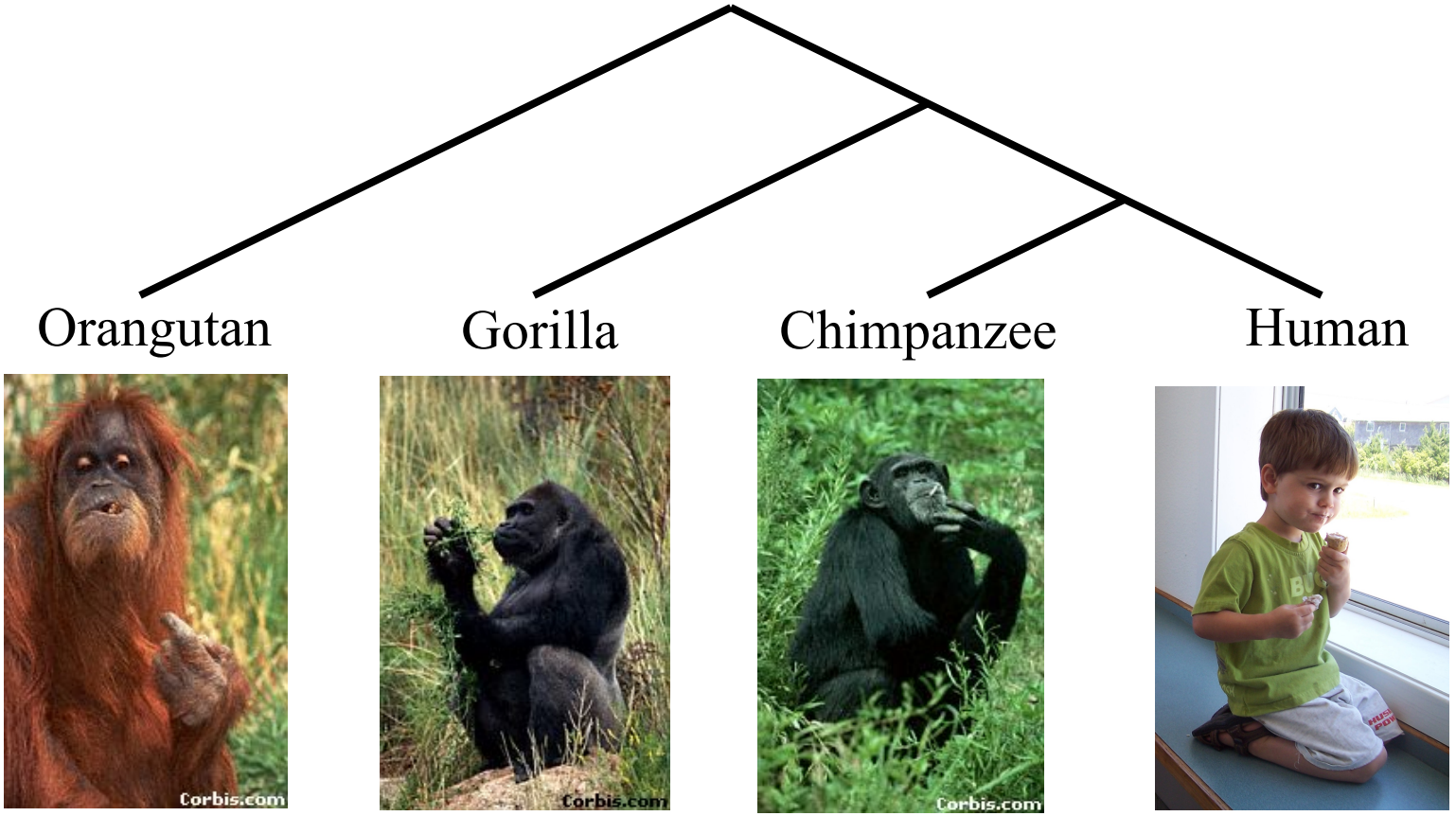
Gene Tree Incongruence

- Gene trees can differ from the species tree due to:
  - Duplication and loss
  - Horizontal gene transfer
  - Incomplete lineage sorting (ILS)

Part II: Species Tree Estimation in the presence of ILS

- Mathematical model: Kingman's coalescent
- "Coalescent-based" species tree estimation methods
- Simulation studies evaluating methods
- New techniques to improve methods
- Application to the Avian Tree of Life

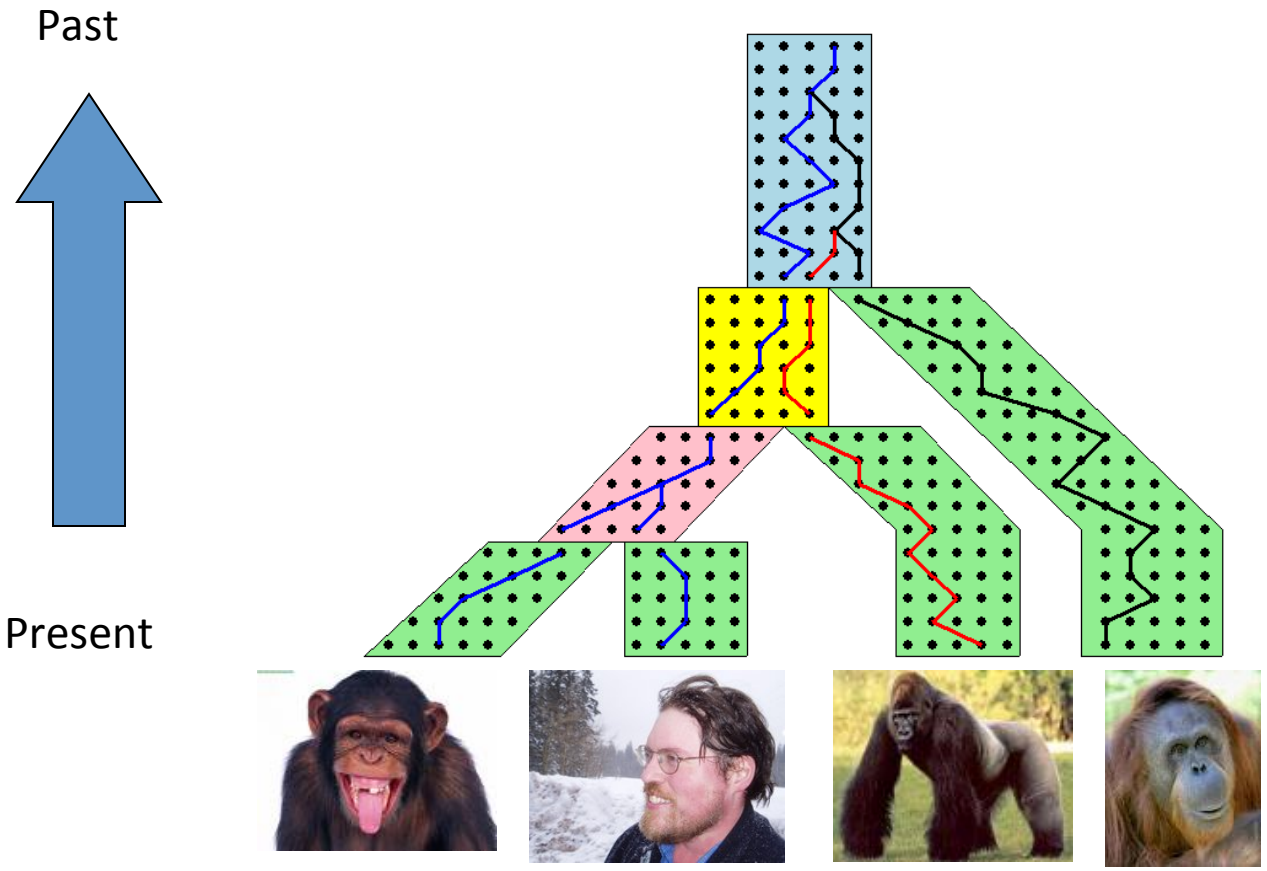
Species tree estimation: difficult, even for small datasets!



From the Tree of the Life Website, University of Arizona

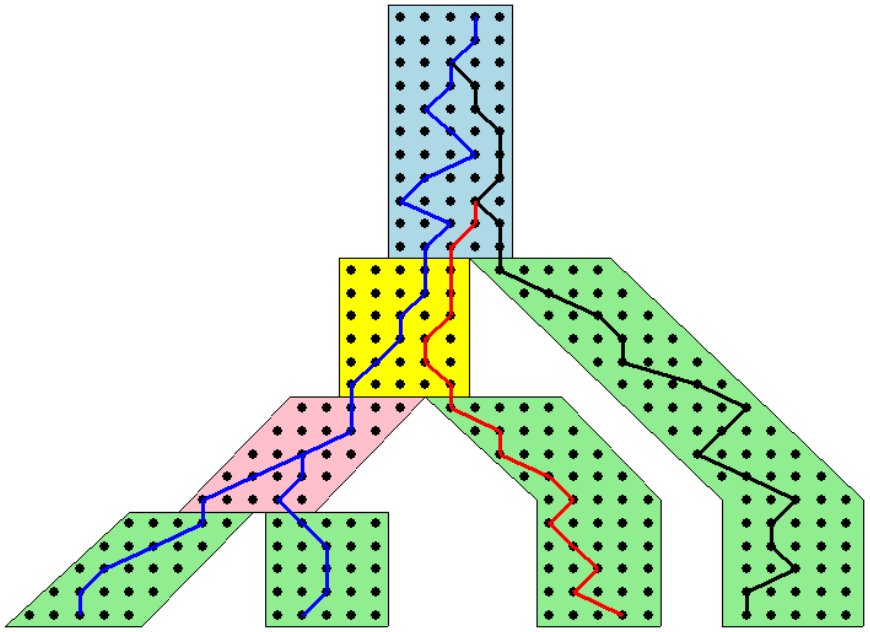
The Coalescent

Courtesy James Degnan



Gene tree in a species tree

Courtesy James Degnan

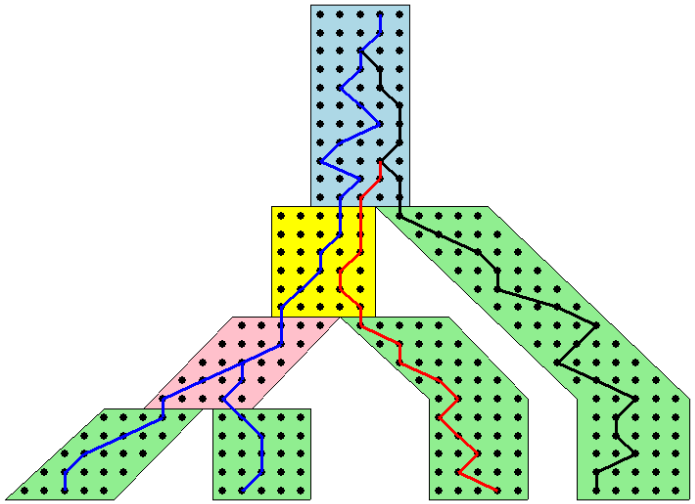


Lineage Sorting

- Population-level process, also called the "Multi-species coalescent" (Kingman, 1982)
- Gene trees can differ from species trees due to short times between speciation events or large population size; this is called "Incomplete Lineage Sorting" or "Deep Coalescence".

Key observation:

Under the multi-species coalescent model, the species tree defines a *probability distribution on the gene trees*

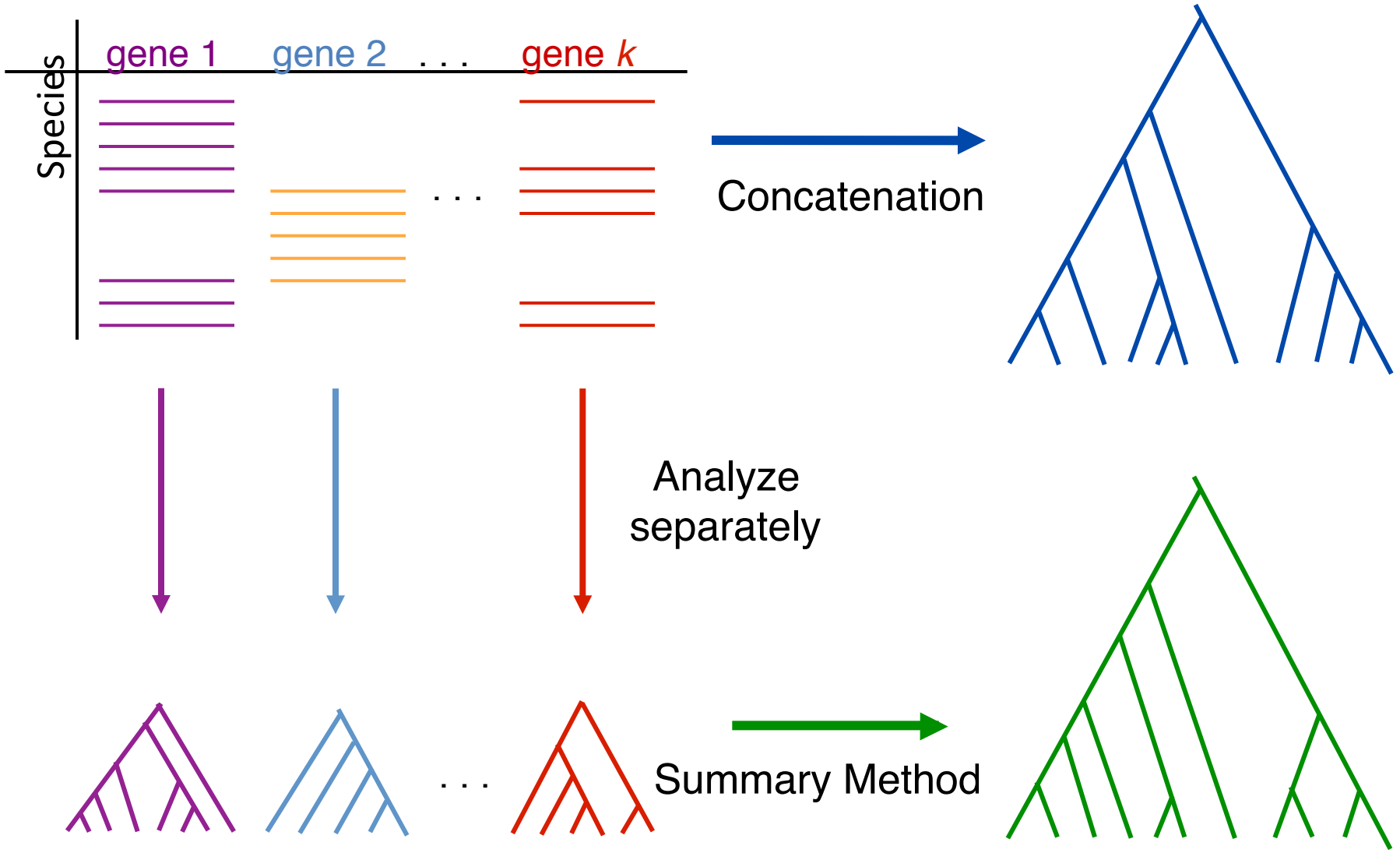


Courtesy James Degnan

Incomplete Lineage Sorting (ILS)

- 2000+ papers in 2013 alone
- Confounds phylogenetic analysis for many groups:
  - Hominids
  - Birds
  - Yeast
  - Animals
  - Toads
  - Fish
  - Fungi
- There is substantial debate about how to analyze phylogenomic datasets in the presence of ILS.

Two competing approaches

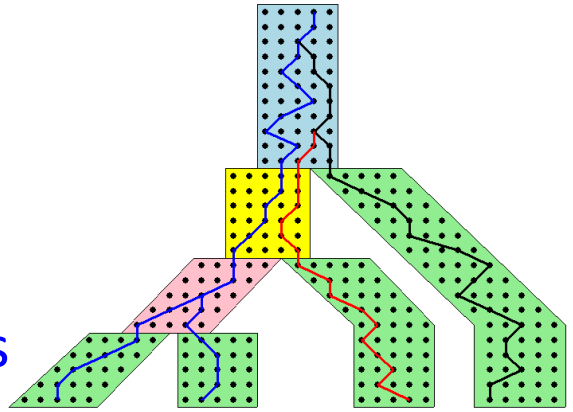


How to compute a species tree?

Under the multi-species coalescent model, the species tree defines a probability distribution on the gene trees

Courtesy James Degnan

Theorem (Degnan et al., 2006, 2009): Under the multi-species coalescent model, for any three taxa A, B, and C, the most probable rooted gene tree on {A,B,C} is identical to the rooted species tree induced on {A,B,C}.



How to compute a species tree?

Techniques:

- MDC?
- Most frequent gene tree?
- Consensus of gene trees?
- Other?

How to compute a species tree?

Theorem (Degnan et al., 2006, 2009): Under the multi-species coalescent model, for any three taxa A, B, and C, the most probable rooted gene tree on {A,B,C} is identical to the rooted species tree induced on {A,B,C}.

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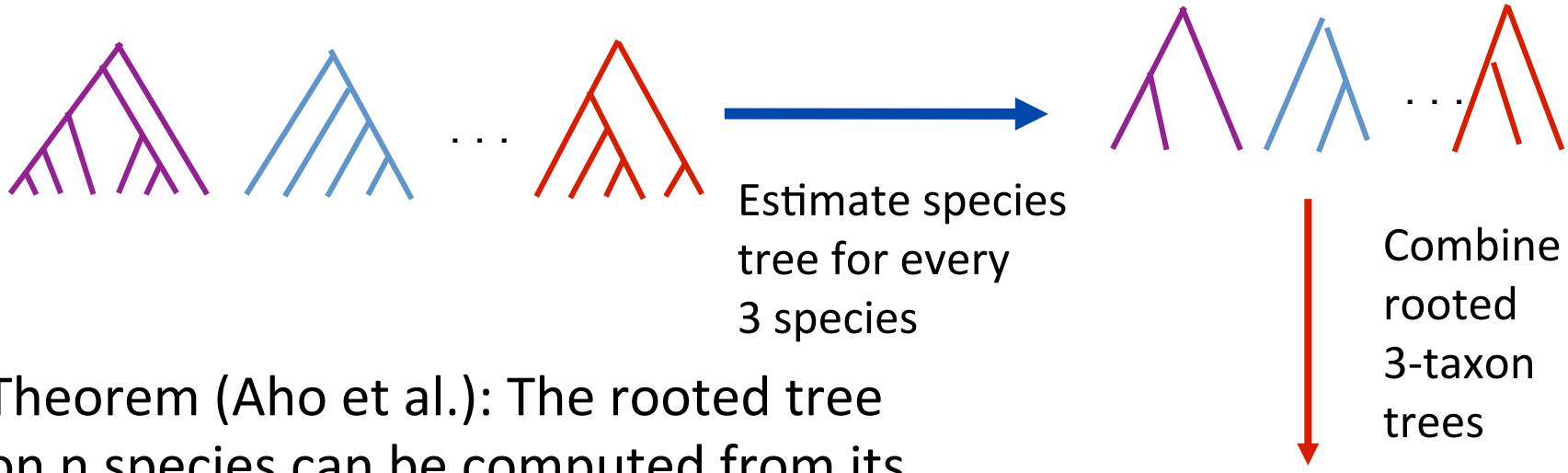
How to compute a species tree?

Estimate species tree for every 3 species

Theorem (Aho et al.): The rooted tree on n species can be computed from its set of 3-taxon rooted subtrees in polynomial time.

How to compute a species tree?



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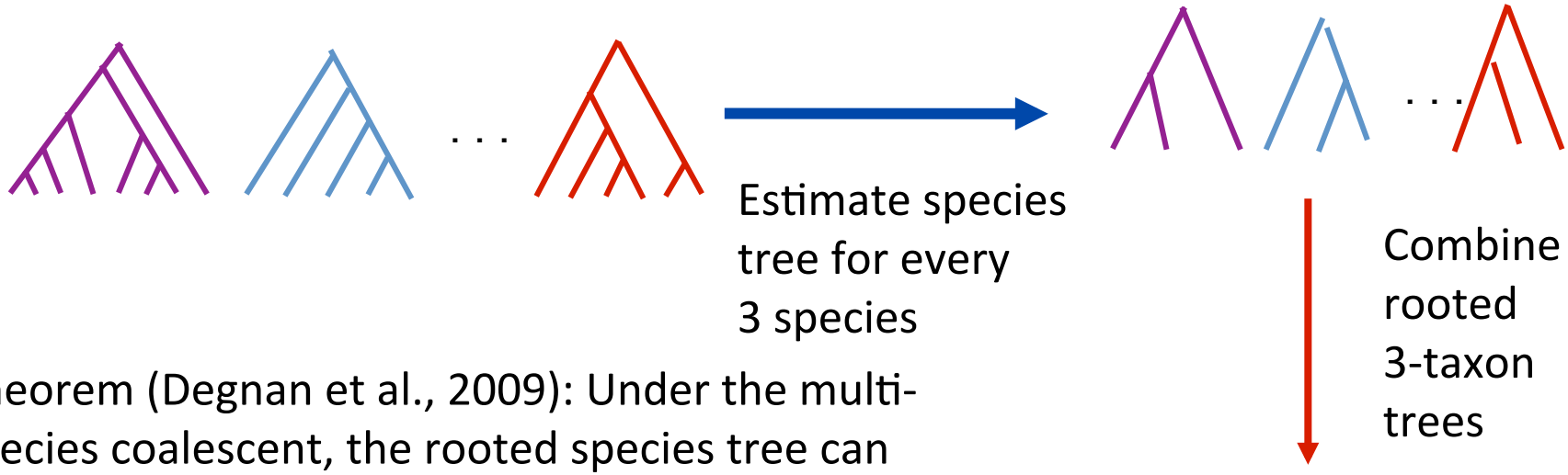
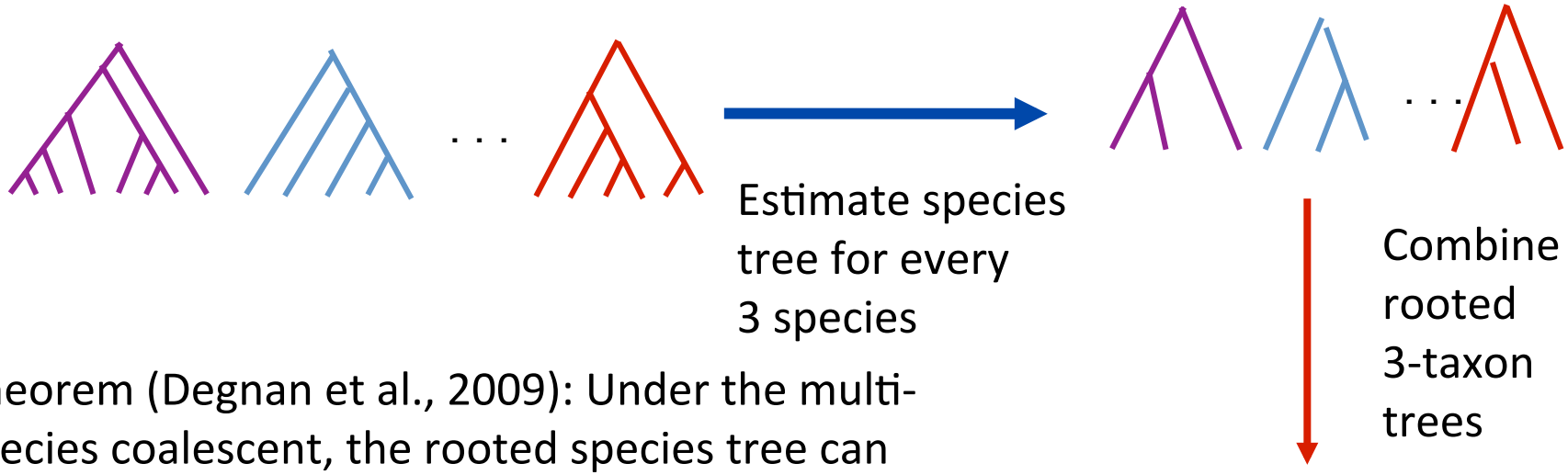


Theorem (Degnan et al., 2009): Under the multi-species coalescent, the rooted species tree can be estimated correctly (with high probability) given a large enough number of true rooted gene trees.

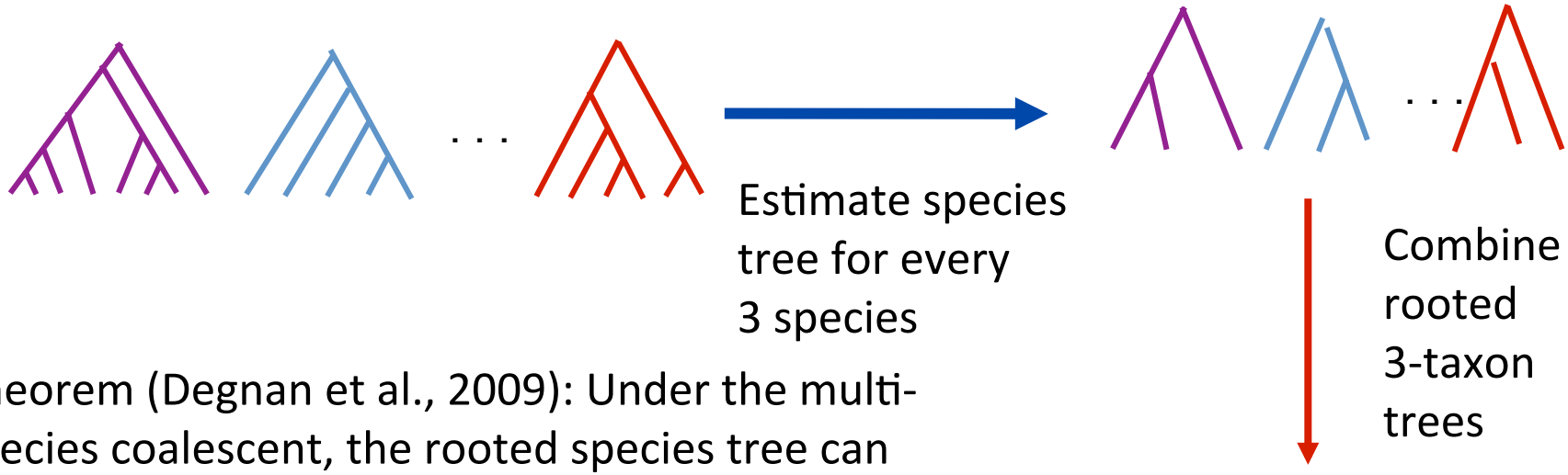
How to compute a species tree?



Theorem (Degnan et al., 2009): Under the multi-species coalescent, the rooted species tree can be estimated correctly (with high probability) given a large enough number of true rooted gene trees.

Theorem (Allman et al., 2011): the unrooted species tree can be estimated from a large enough number of true unrooted gene trees.

How to compute a species tree?



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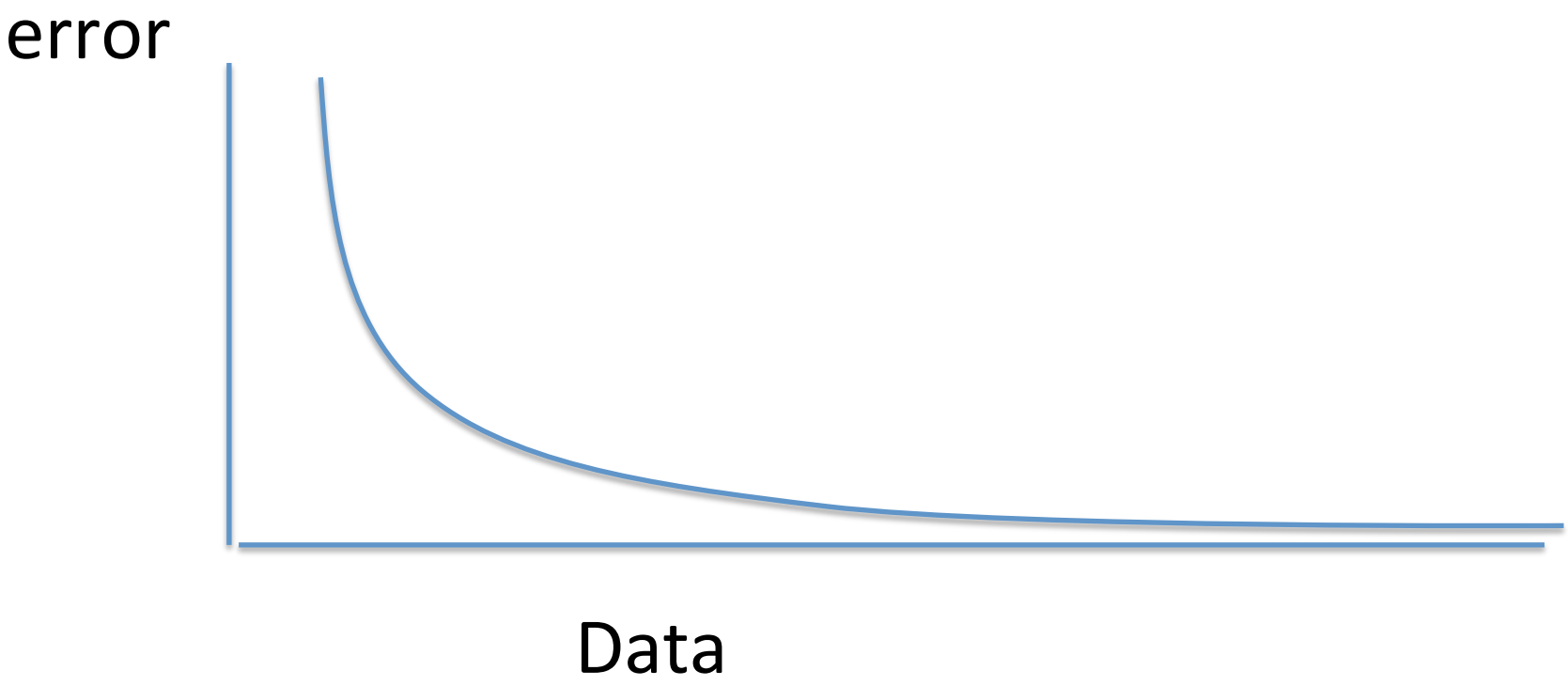
Statistical Consistency



Data are gene trees, presumed to be randomly sampled <u>true gene trees.</u>

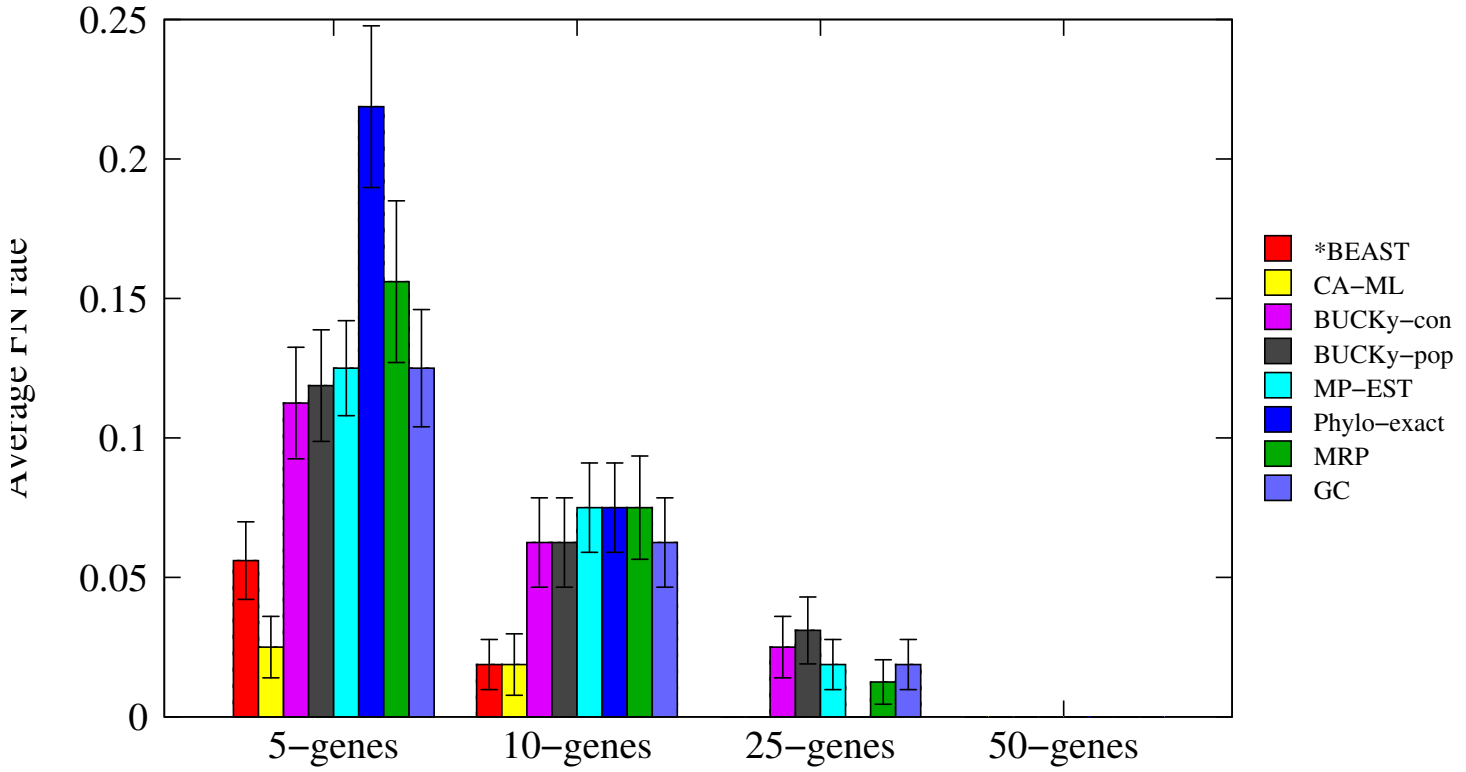
Questions

- Is the model tree identifiable?
- Which estimation methods are statistically consistent under this model?
- How much data does the method need to estimate the model tree correctly (with high probability)?
- What is the computational complexity of an estimation problem?

Statistically consistent under ILS?

- MP-EST (Liu et al. 2010): maximum likelihood estimation of rooted species tree – YES
- BUCKy-pop (Ané and Larget 2010): quartet-based Bayesian species tree estimation –YES
- MDC – NO
- Greedy – NO
- Concatenation under maximum likelihood – open
- MRP (supertree method) – open

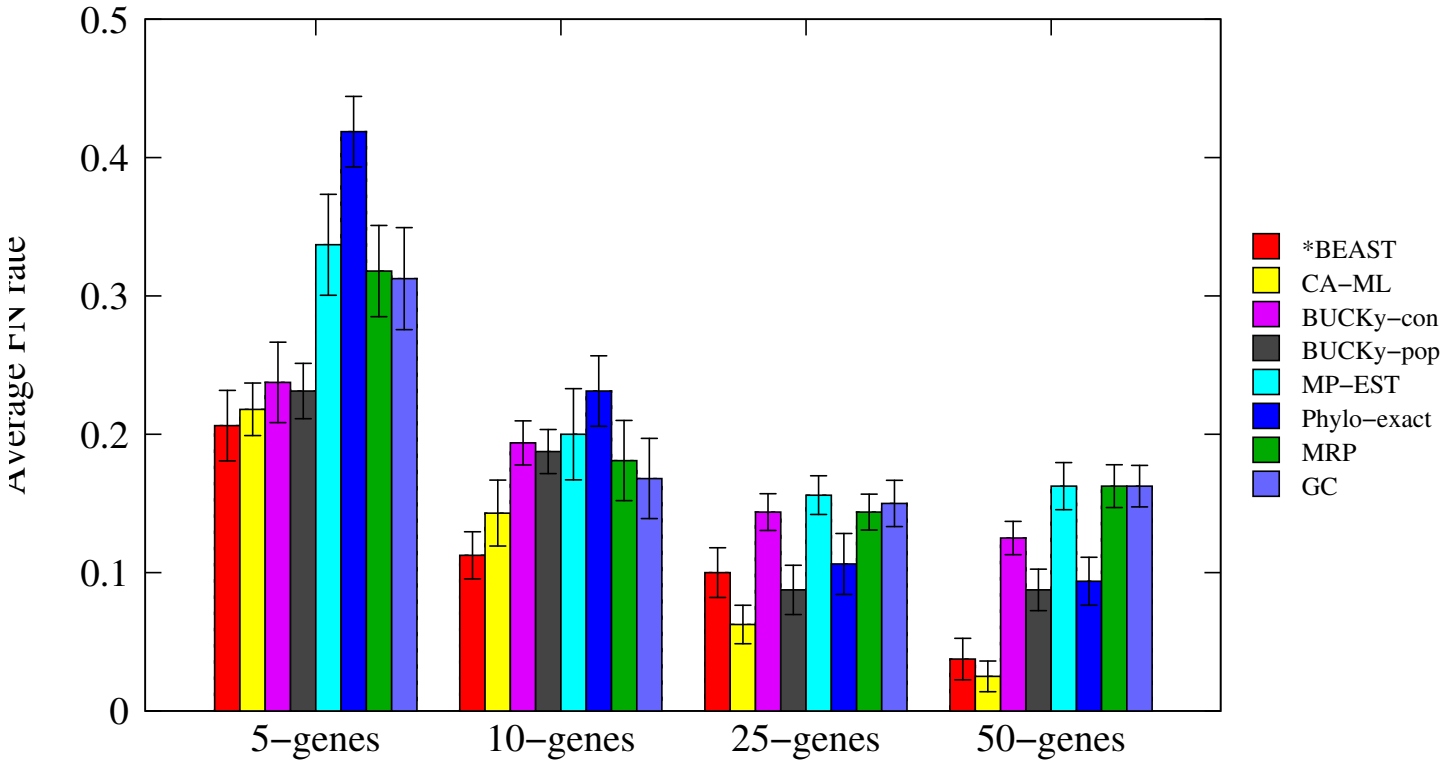
Results on 11-taxon datasets with weak ILS



***BEAST** more accurate than summary methods (MP-EST, BUCKy, etc)
CA-ML: (concatenated analysis) most accurate

Datasets from Chung and Ané, 2011
Bayzid & Warnow, Bioinformatics 2013

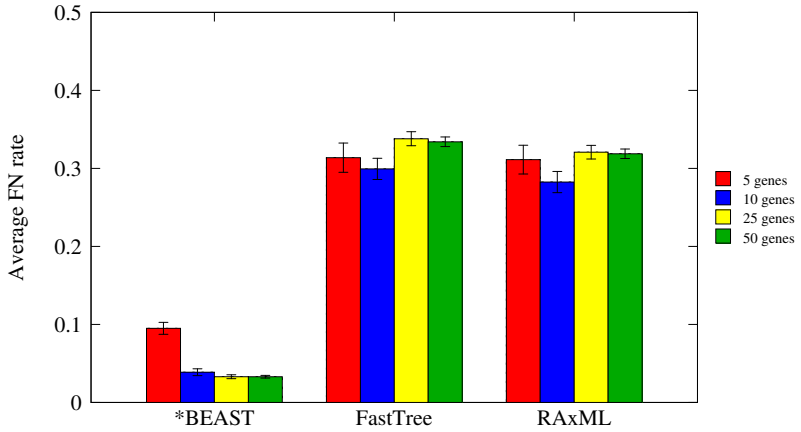
Results on 11-taxon datasets with strongILS



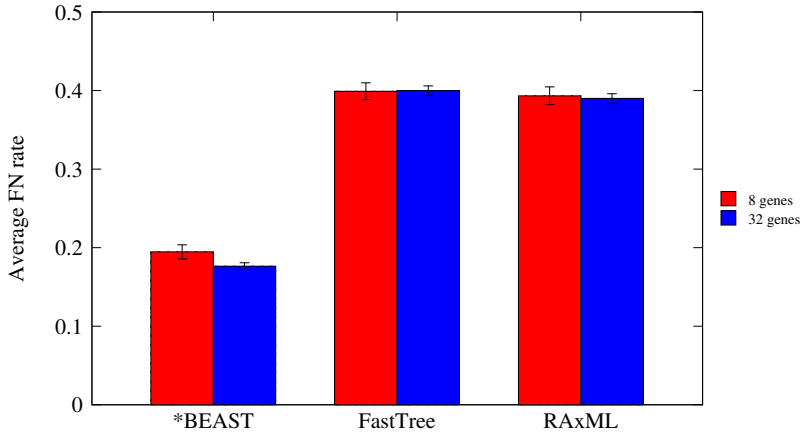
***BEAST** more accurate than summary methods (MP-EST, BUCKy, etc)
CA-ML: (concatenated analysis) also very accurate

Datasets from Chung and Ané, 2011
Bayzid & Warnow, Bioinformatics 2013

Gene Tree Estimation:
*BEAST vs. Maximum Likelihood



11-taxon weakILS datasets

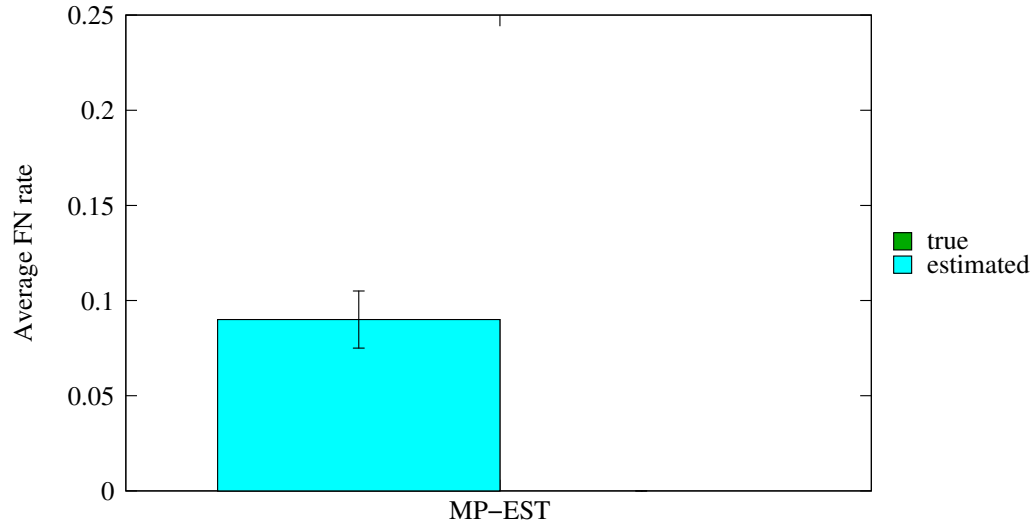


17-taxon (very high ILS) datasets

*BEAST produces more accurate gene trees than ML on gene sequence alignments

11-taxon datasets from Chung and Ané, Syst Biol 2012
17-taxon datasets from Yu, Warnow, and Nakhleh, JCB 2011

Impact of Gene Tree Estimation Error on MP-EST



MP-EST has no error on true gene trees, but
MP-EST has 9% error on estimated gene trees

Datasets: 11-taxon strongILS conditions with 50 genes

Similar results for other summary methods (MDC, Greedy, etc.).

Problem: poor gene trees

- Summary methods combine estimated gene trees, not true gene trees.

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TYPICAL PHYLOGENOMICS PROBLEM: many poor gene trees

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- Which estimation methods are statistically consistent under this model?
- How much data does the method need to estimate the model species tree correctly (with high probability)?
- What is the computational complexity of an estimation problem?
- What is the impact of error in the input data on the estimation of the model species tree?

Addressing gene tree estimation error

- Get better estimates of the gene trees
- Restrict to subset of estimated gene trees
- Model error in the estimated gene trees
- Modify gene trees to reduce error
- “Bin-and-conquer”

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Technique #2: Bin-and-Conquer?

1. Assign genes to "bins", creating "supergene alignments"
2. Estimate trees on each supergene alignment using maximum likelihood
3. Combine the supergene trees together using a summary method

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Variants:

- Naïve binning (Bayzid and Warnow, Bioinformatics 2013)
- Statistical binning (Mirarab, Bayzid, and Warnow, in preparation)

Statistical binning

Input: estimated gene trees with bootstrap support, and minimum support threshold t

Output: partition of the estimated gene trees into sets, so that no two gene trees in the same set are strongly incompatible.

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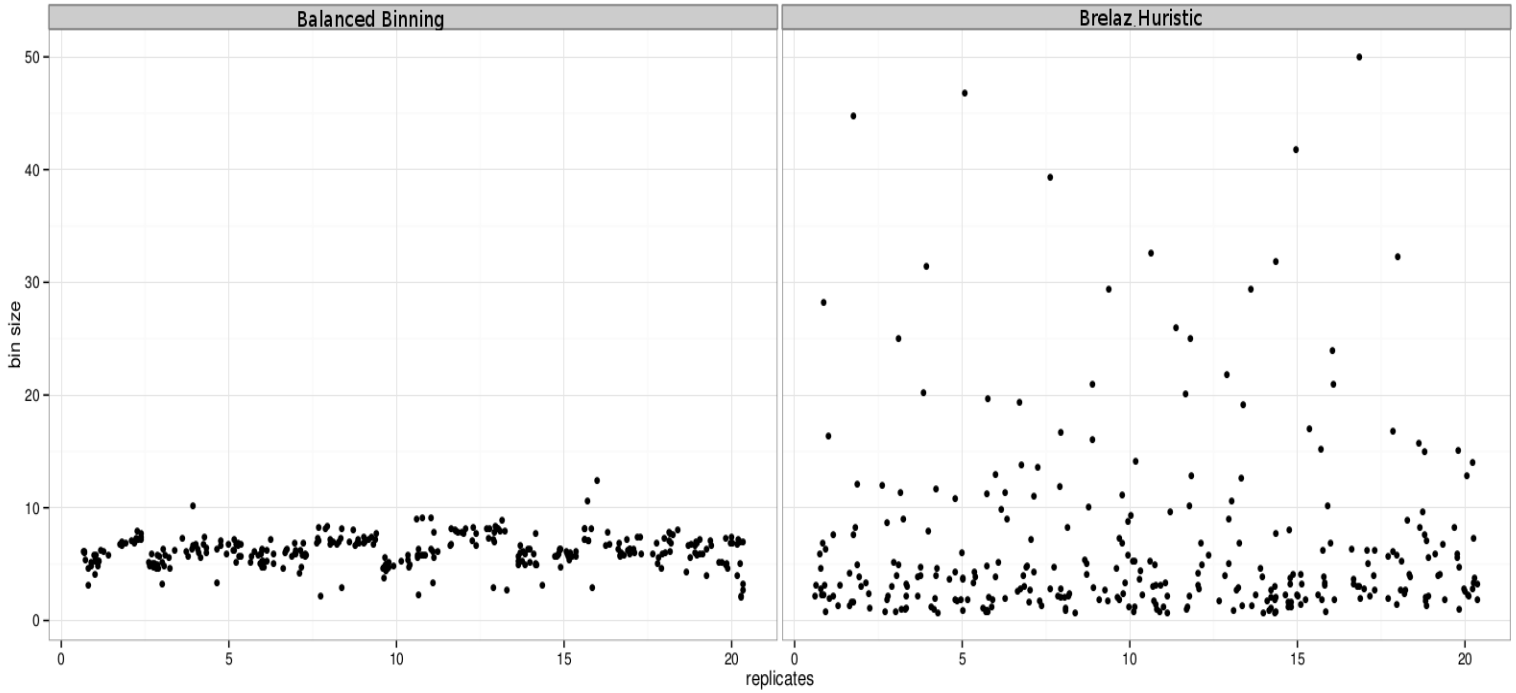
Vertex coloring problem (NP-hard),

but good heuristics are available (e.g., Brelaz 1979)

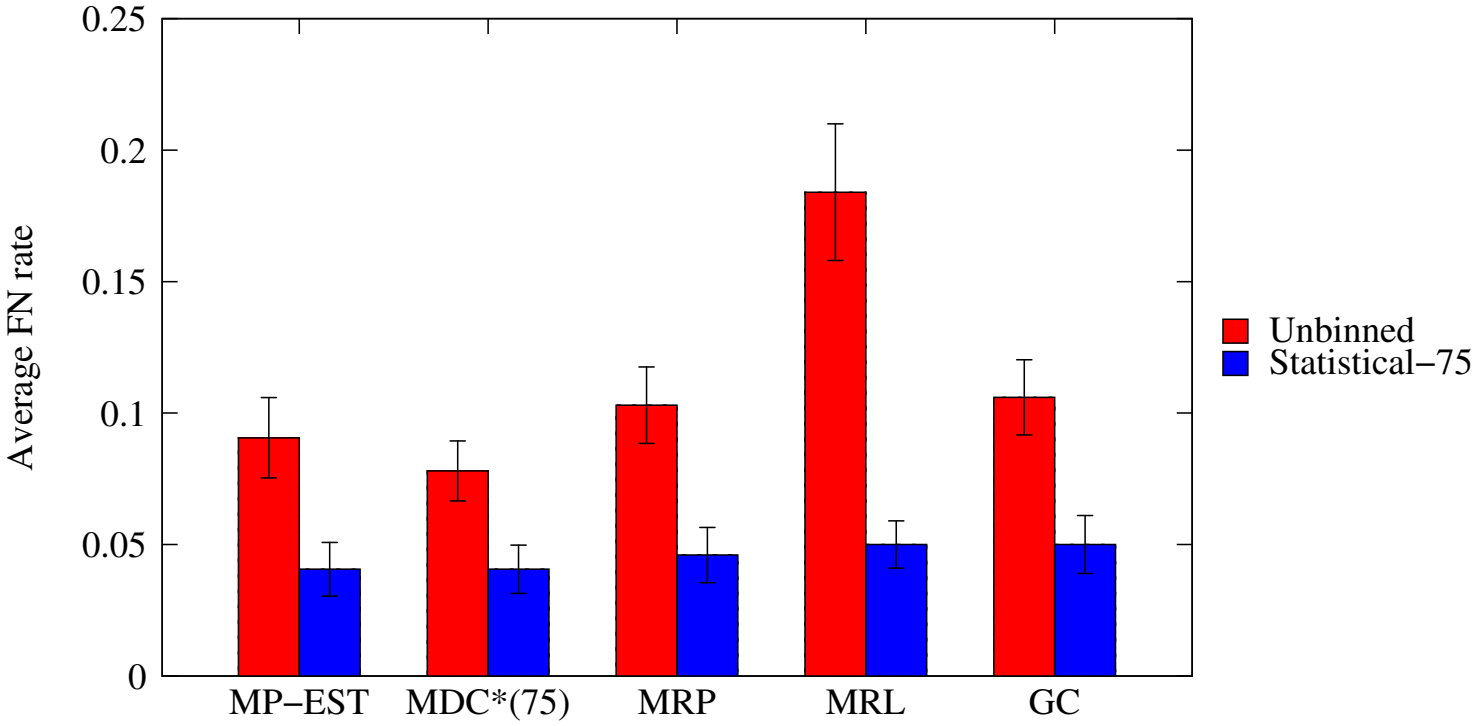
However, for statistical inference reasons, we need balanced vertex color classes

Balanced Statistical Binning



Mirarab, Bayzid, and Warnow, in preparation
Modification of Brelaz Heuristic for minimum vertex coloring.

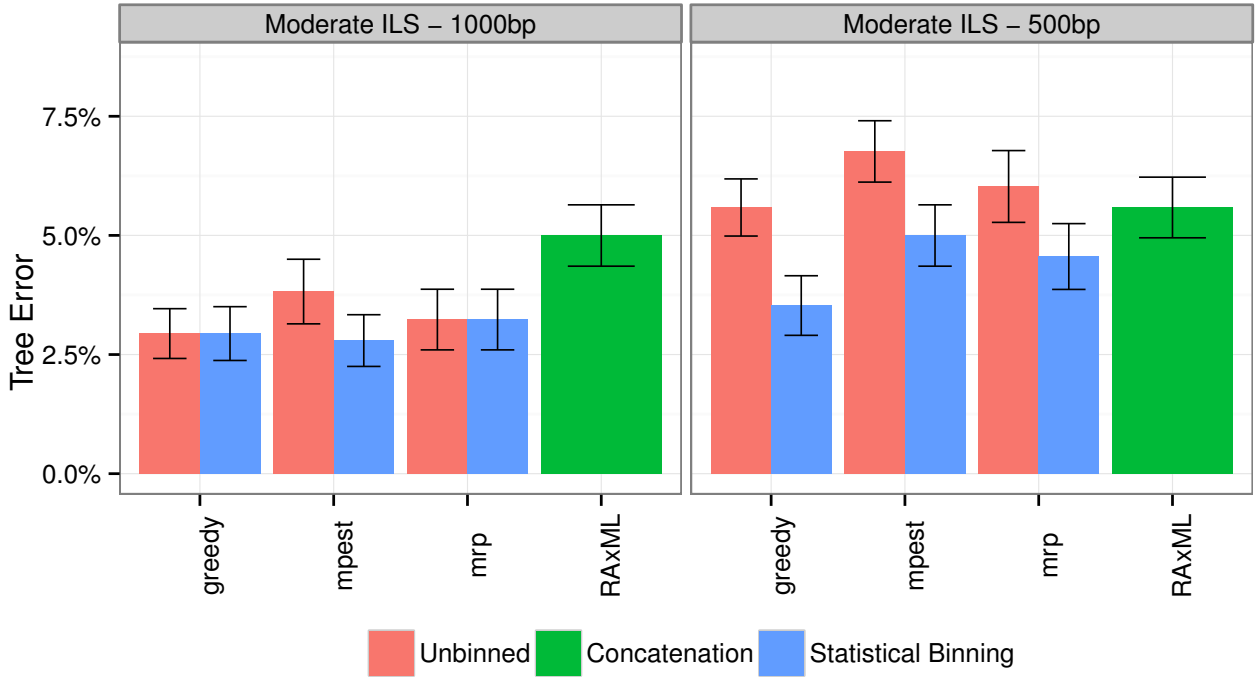
Statistical binning vs. unbinned



Mirarab, et al. in preparation

Datasets: 11-taxon strongILS datasets with 50 genes, Chung and Ané, Systematic Biology

Mammalian Simulation Study



Observations:

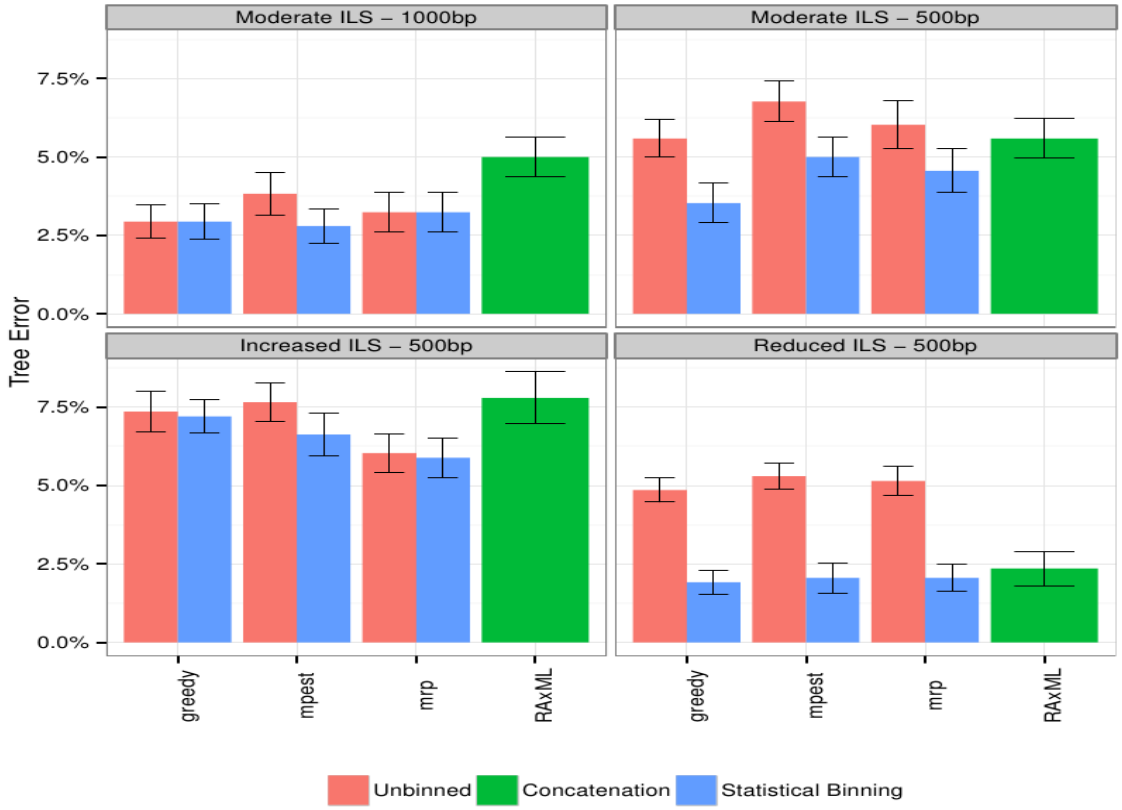
Binning can improve accuracy, but impact depends on accuracy of estimated gene trees and phylogenetic estimation method.

Binned methods can be more accurate than RAxML (maximum likelihood), even when unbinned methods are less accurate.

Data: 200 genes, 20 replicate datasets, based on Song et al. PNAS 2012

Mirarab et al., in preparation

Mammalian simulation



Binning can improve summary methods, but amount of improvement depends on: method, amount of ILS, and accuracy of gene trees.

MP-EST is statistically consistent in the presence of ILS; Greedy is not, unknown for MRP and RAxML.

Data (200 genes, 20 replicate datasets) based on Song et al. PNAS 2012

Avian Phylogenomics Project

E Jarvis, HHMI

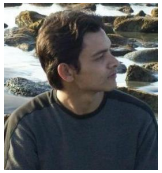
MTP Gilbert, Copenhagen

G Zhang, BGI

T. Warnow UT-Austin

S. Mirarab UT-Austin

Md. S. Bayzid, UT-Austin



Gene Tree Incongruence

Plus many many other people…

Avian Phylogeny

- GTRGAMMA Maximum likelihood analysis (RAxML) of 37 million basepair alignment (exons, introns, UCEs) – highly resolved tree with near 100% bootstrap support.

- More than 17 years of compute time, and used 256 GB. Run at HPC centers.

Avian Phylogenomics Project, in preparation

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- Unbinned MP-EST on 14000+ genes: highly incongruent with the concatenated maximum likelihood analysis, poor bootstrap support.

Avian Phylogenomics Project, in preparation

Avian Simulation – 14,000 genes

- **MP-EST:**
  - Unbinned ~ 11.1% error
  -
- **Greedy:**
  - Unbinned ~ 26.6% error
  -

- 8250 exon-like genes (27% avg. bootstrap support)
- 3600 UCE-like genes (37% avg. bootstrap support)
- 2500 intron-like genes (51% avg. bootstrap support)

Avian Simulation – 14,000 genes

- **MP-EST:**
  - Unbinned ~ 11.1% error
  - Binned ~ 6.6% error
- **Greedy:**
  - Unbinned ~ 26.6% error
  - Binned ~ 13.3% error

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- More than 17 years of compute time, and used 256 GB. Run at HPC centers.
- Unbinned MP-EST on 14000+ genes: highly incongruent with the concatenated maximum likelihood analysis, poor bootstrap support.
- Statistical binning version of MP-EST on 14000+ gene trees – highly resolved tree, largely congruent with the concatenated analysis, good bootstrap support

Avian Phylogenomics Project, in preparation

To consider

- Binning *reduces the amount* of data (number of gene trees) but can improve the accuracy of individual "supergene trees". The response to binning differs between methods. Thus, there is a trade-off between data *quantity* and *quality, and not all methods respond the same to the trade-off*.

- We know very little about the impact of data *error* on methods. We do not even have proofs of statistical consistency in the presence of data error.

Basic Questions

- Is the model tree identifiable?
- Which estimation methods are statistically consistent under this model?
- How much data does the method need to estimate the model tree correctly (with high probability)?
- What is the computational complexity of an estimation problem?

Additional Statistical Questions

- Trade-off between data quality and quantity
- Impact of data selection
- Impact of data error
- Performance guarantees on finite data (e.g., prediction of error rates as a function of the input data and method)

We need a solid mathematical framework for these problems.

Summary

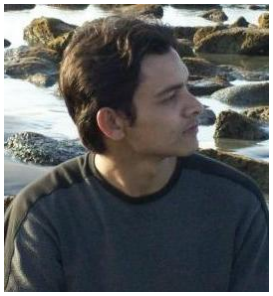
- DCM1-NJ: an absolute fast converging (afc) method, uses chordal graph theory and probabilistic analysis of algorithms to prove performance guarantees

- Binning: species tree estimation from multiple genes, can improve coalescent-based species tree estimation methods.

- New questions in phylogenetic estimation about impact of error in input data.

Warnow Laboratory





PhD students: Siavash Mirarab*, Nam Nguyen, and Md. S. Bayzid**
Undergrad: Keerthana Kumar
Lab Website: http://www.cs.utexas.edu/users/phylo

Funding: Guggenheim Foundation, Packard, NSF, Microsoft Research New England, David Bruton Jr. Centennial Professorship, and TACC (Texas Advanced Computing Center)

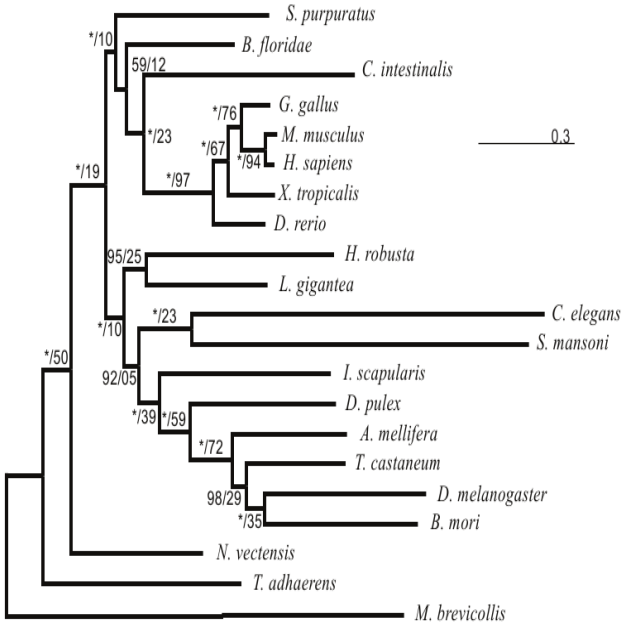
TACC and UTCS computational resources

* Supported by HHMI Predoctoral Fellowship

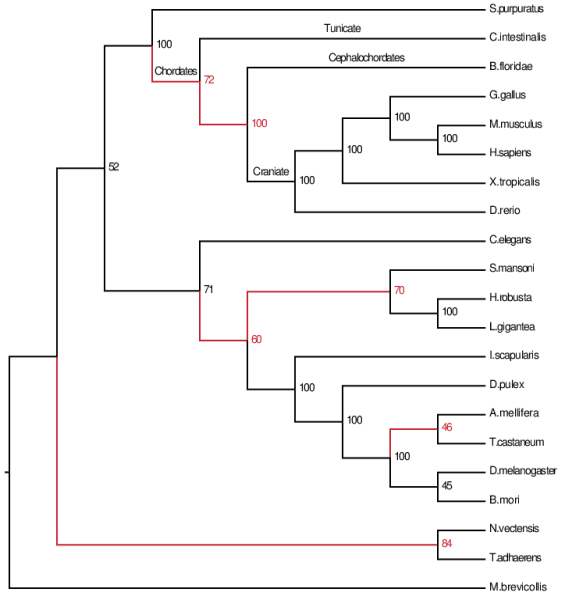
** Supported by Fulbright Foundation Predoctoral Fellowship

Metazoa Dataset from Salichos & Rokas - Nature 2013 225 genes and 21 species

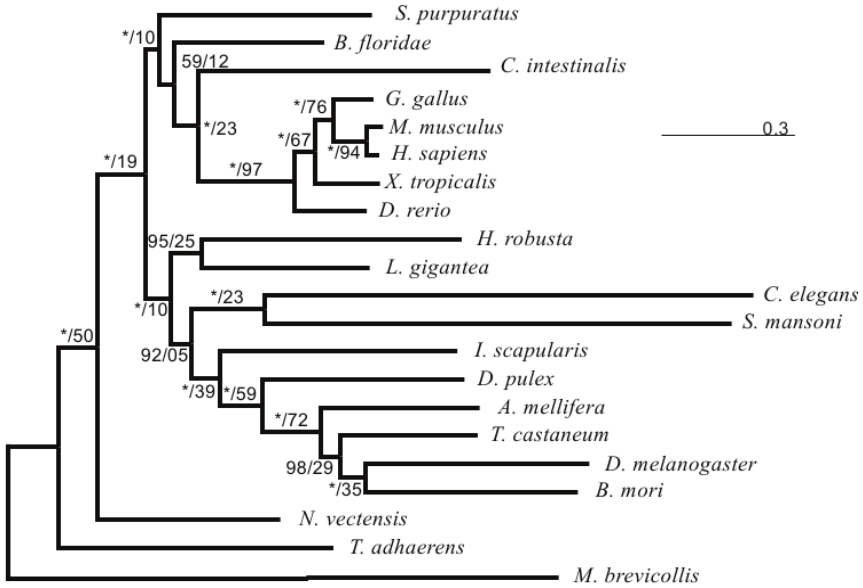
- UnBinned MP-EST compared to Concatenation using RAxML
  - Poor bootstrap support
  - Substantial conflict with concatenation (red is conflict - green/black is congruence)
  - Strongly rejects (Tunicate,Craniate), a subgroup that is strongly supported in the literature [Bourlat, Sarah J., et al *Nature* 444.7115 (2006); Delsuc, Frédéric, et al. *Genesis* 46.11 (2008); Singh, Tiratha R., et al. *BMC genomics* 10.1 (2009): 534.]



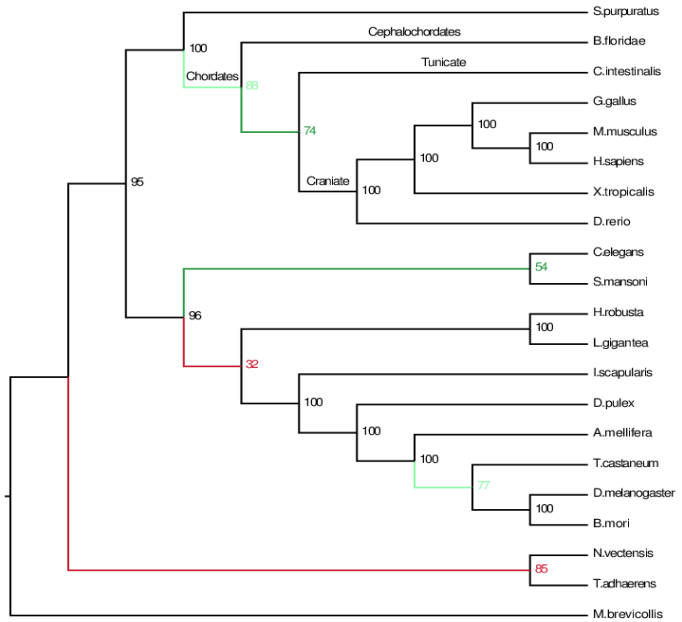
Concatenation



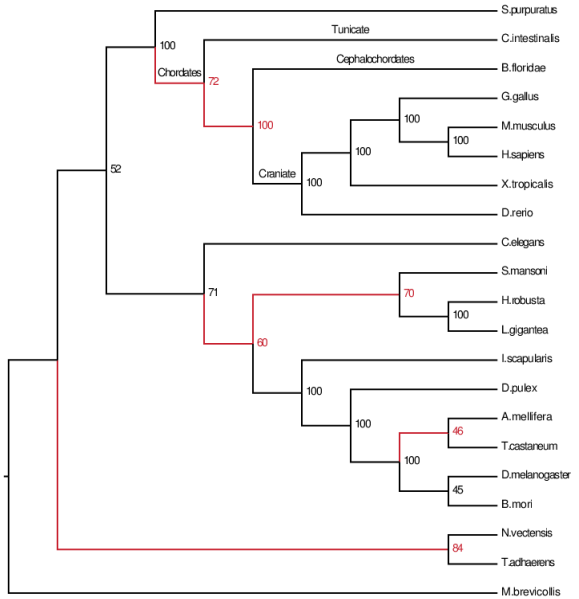
Unbinned MPEST



RAxML on combined datamatrix



Binned MP-EST

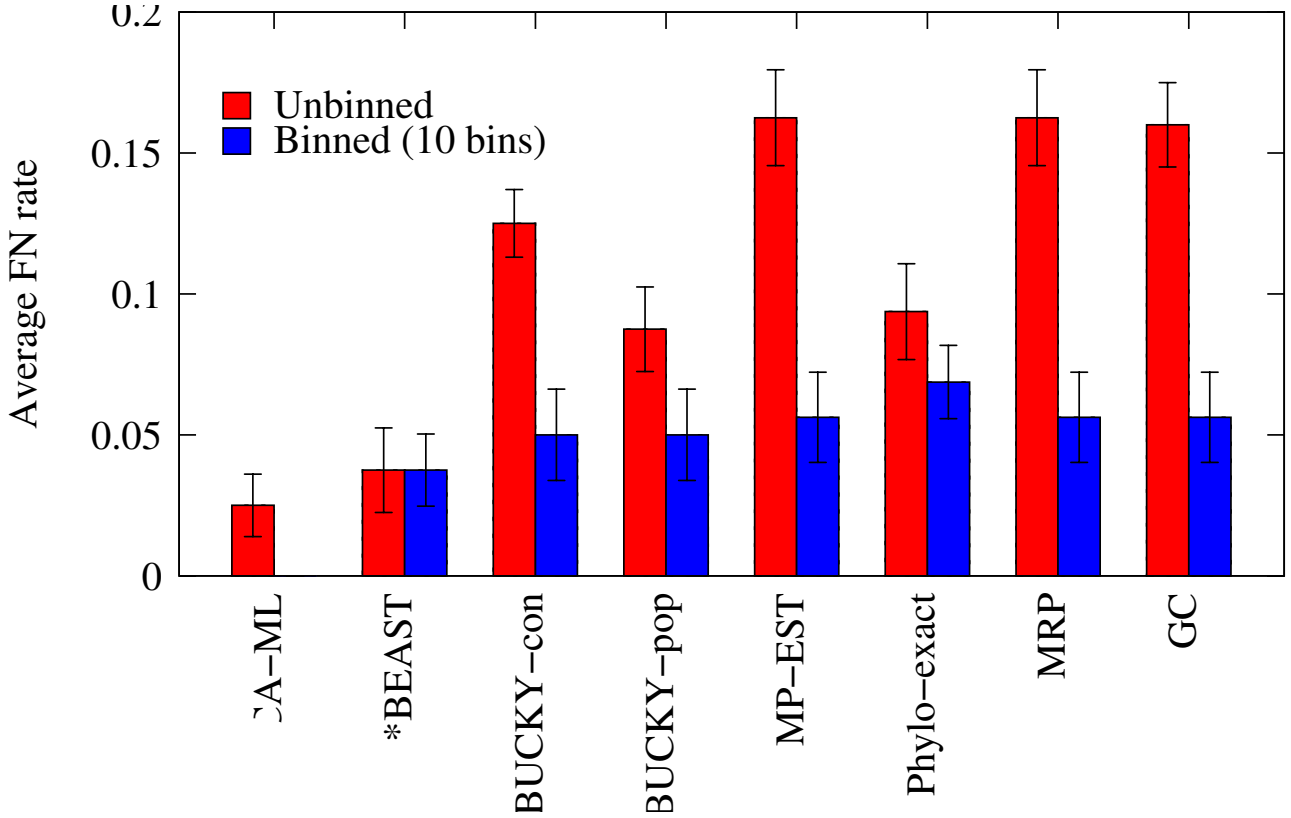


MP-EST unbinned

Binned vs. unbinned analyses

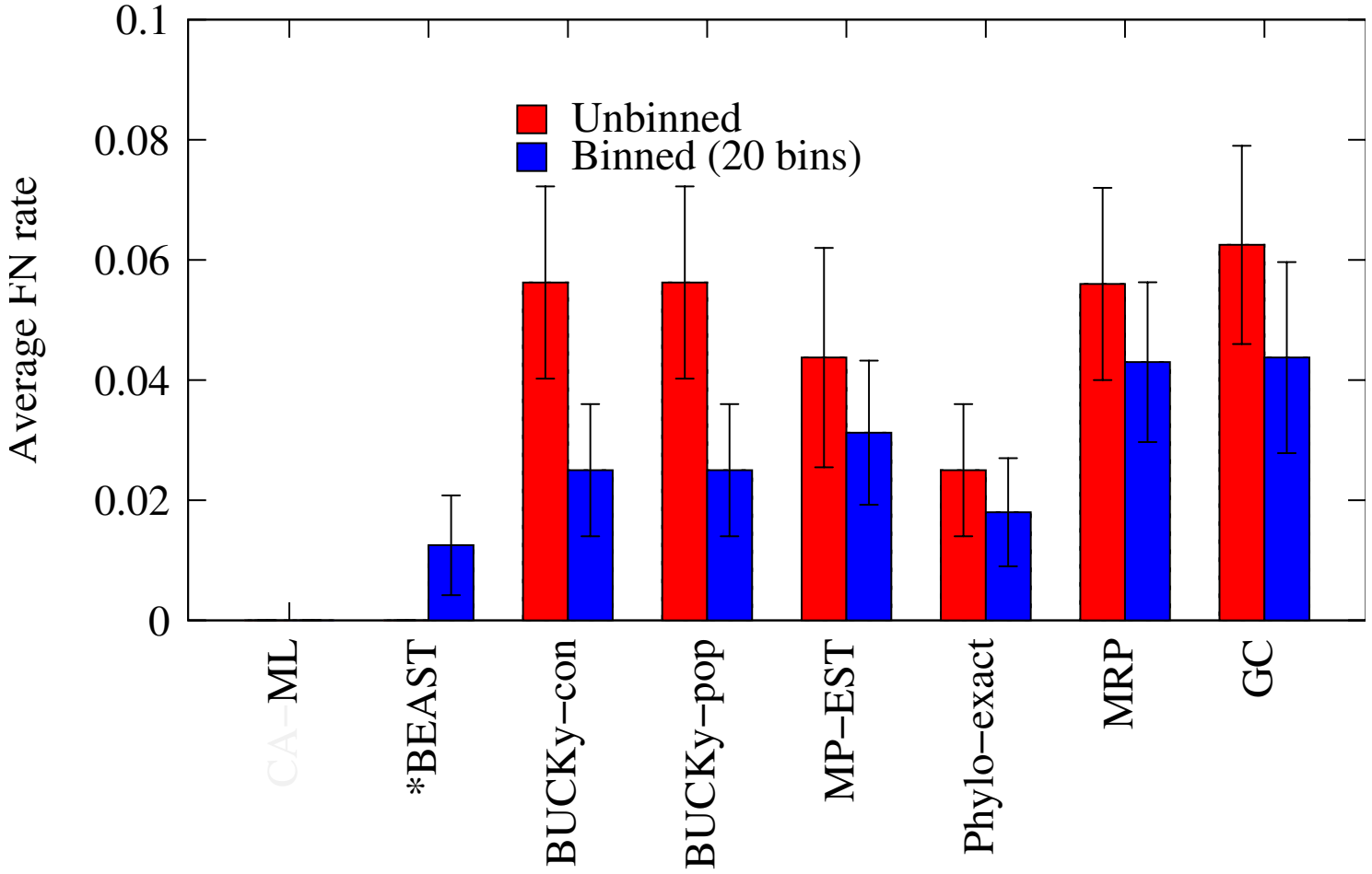
- 75%-threshold for binning
- Number of species: 21 for both
- Number of “genes”
  - Unbinned: 225 genes
  - Binned:17 supergenes
- Gene tree average bootstrap support
  - Unbinned: 47%
  - Binned: 78%
- Species tree bootstrap support
  - Unbinned: avg 83%, 11 above 75%, 10 above 90%
  - Binned: avg 89%, 15 above 75%, 12 above 90%

Naïve binning vs. unbinned: 50 genes



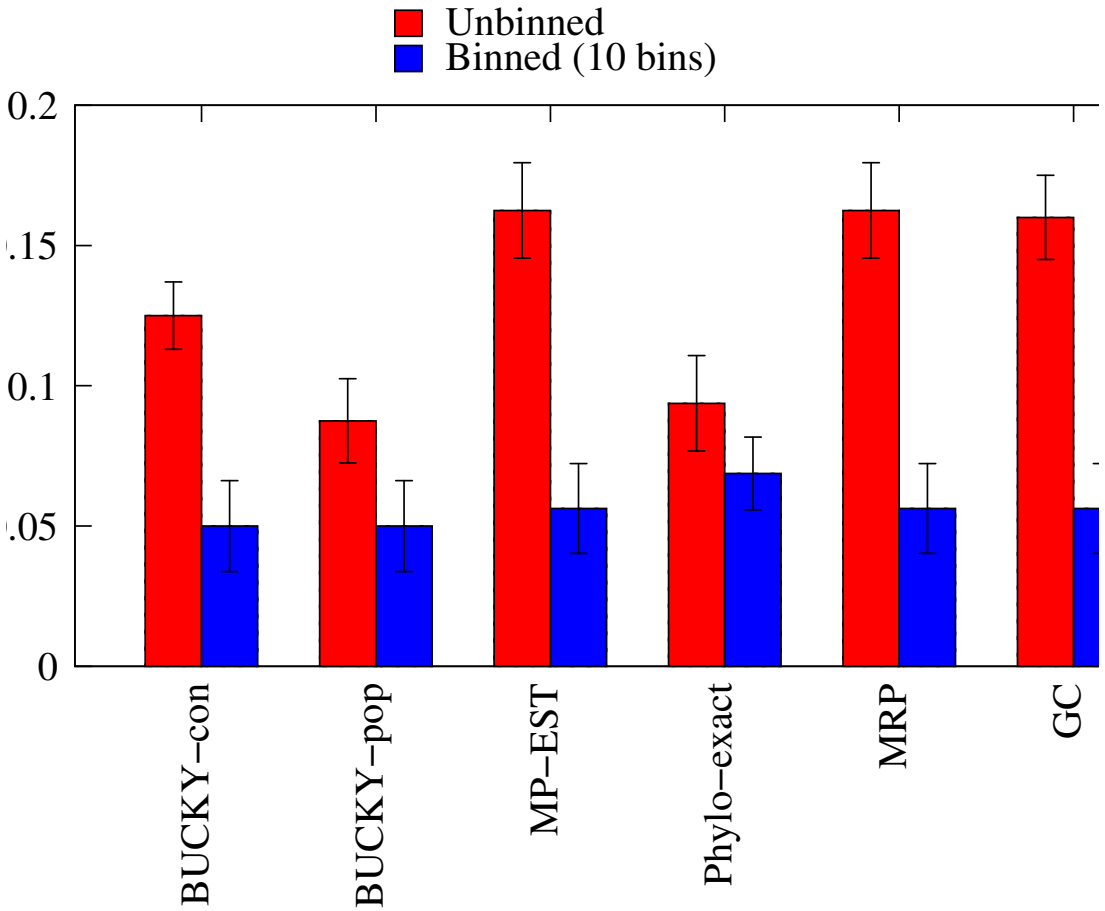
Bayzid and Warnow, Bioinformatics 2013
11-taxon strongILS datasets with 50 genes, 5 genes per bin

Naïve binning vs. unbinned, 100 genes



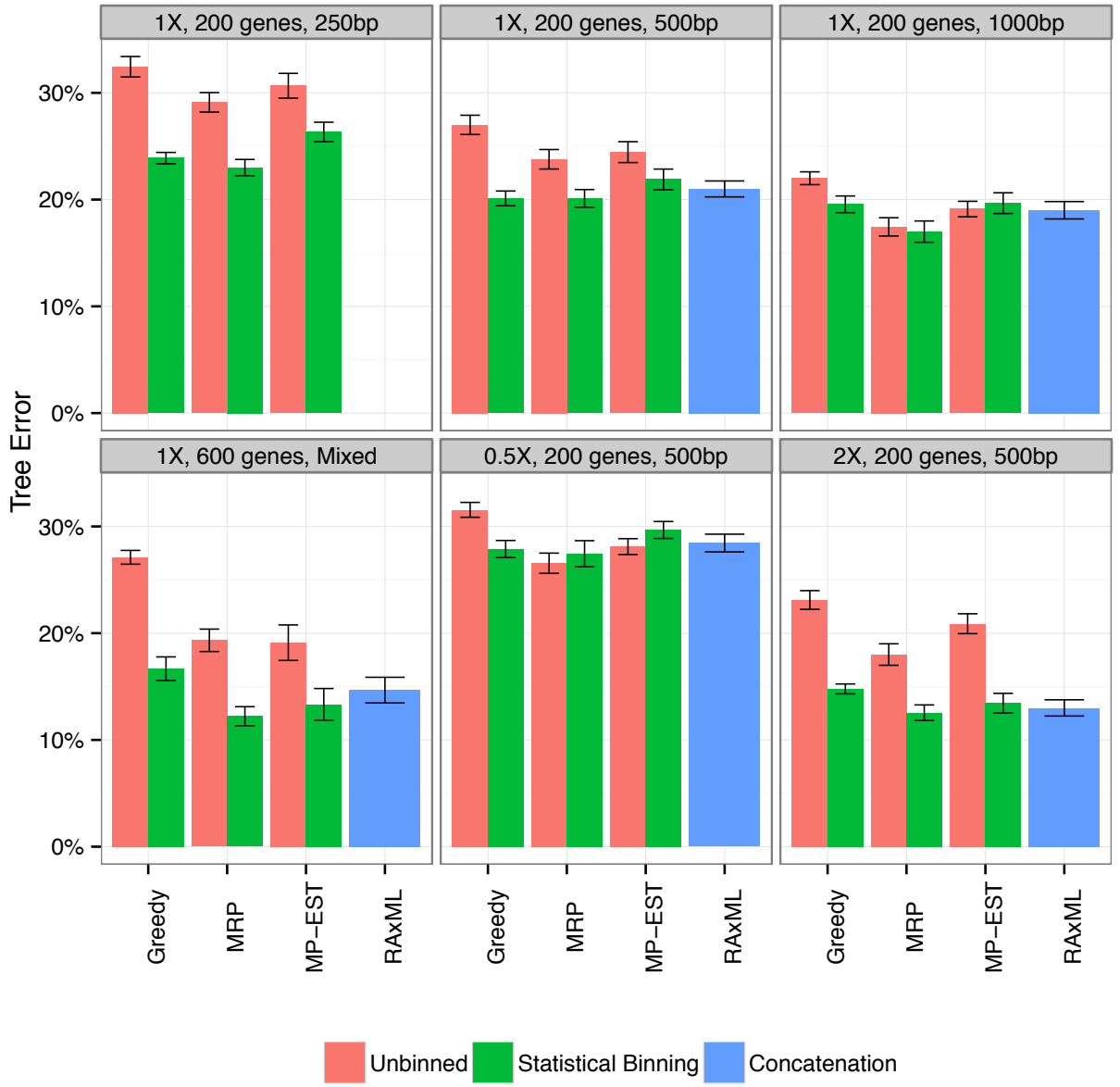
*BEAST did not converge on these datasets, even with 150 hours.
With binning, it converged in 10 hours.

Naïve binning vs. unbinned: 50 genes

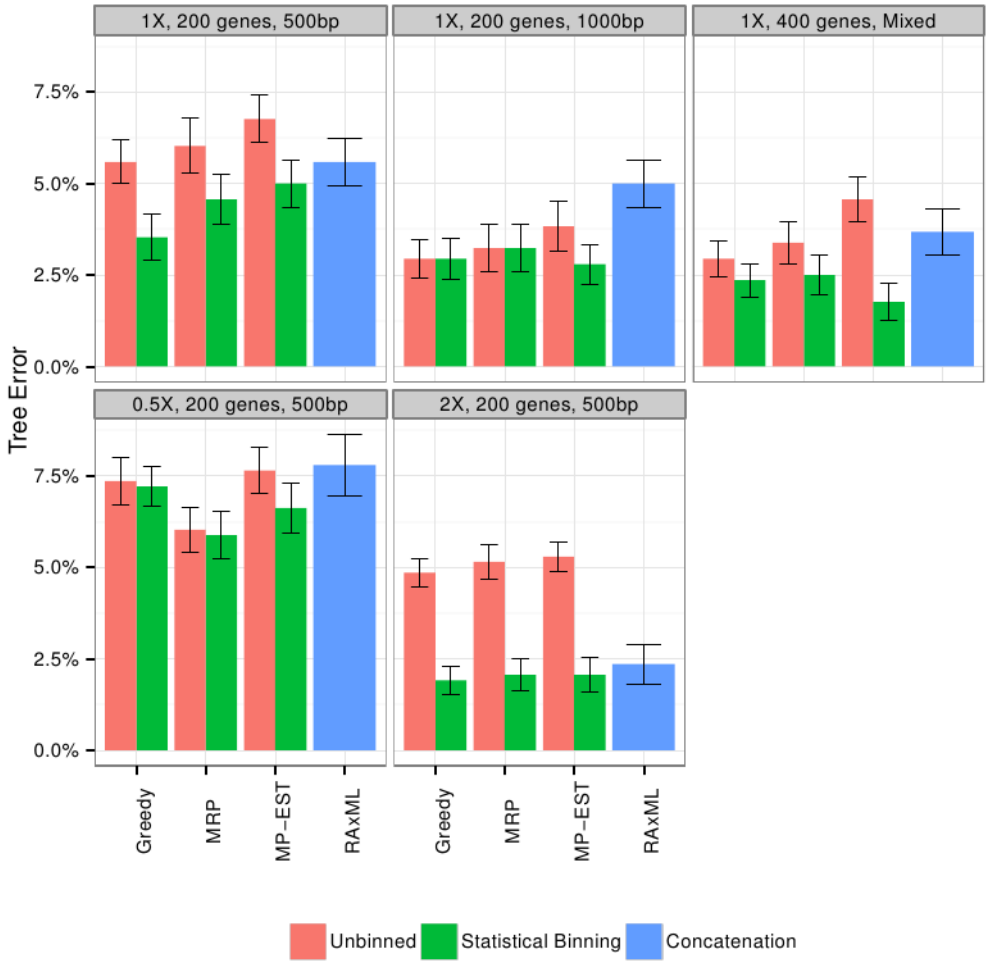


Bayzid and Warnow, Bioinformatics 2013
11-taxon strongILS datasets with 50 genes, 5 genes per bin

Avian Simulation study – binned vs. unbinned, and RAxML



Mammals Simulation



Avian Simulation