

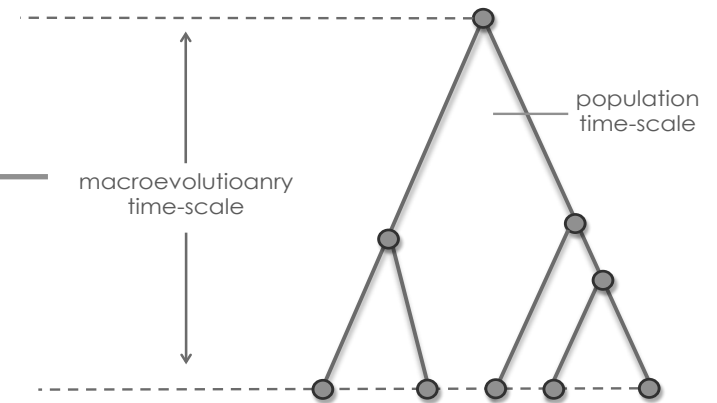
Codon-model based inference of selection pressure

(a very brief review prior to the PAML lab)

an index of selection pressure

rate ratio	mode	example
$dN/dS < 1$	purifying (negative) selection	histones
$dN/dS = 1$	Neutral Evolution	pseudogenes
$dN/dS > 1$	Diversifying (positive) selection	MHC, Lysin

phenomenological
models



“OMEGA MODELS”


$$Q_{ij} = \begin{cases} 0 & \text{if } i \text{ and } j \text{ differ by } > 1 \\ \pi_j & \text{for synonymous tv.} \\ \kappa\pi_j & \text{for synonymous ts.} \\ \omega\pi_j & \text{for non-synonymous tv.} \\ \omega\kappa\pi_j & \text{for non-synonymous ts.} \end{cases}$$

Goldman and Yang (1994)

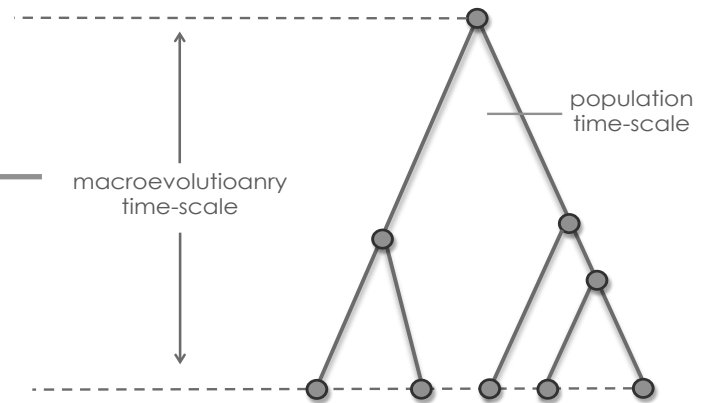
Muse and Gaut (1994)

- phenomenological parameters
- ts/tv ratio: κ
- codon frequencies: π_j
- $\omega = dN/dS$
- parameter estimation via ML
- *stationary process*

3 analytical tasks

- task 1.** parameter estimation (e.g., ω) 
- task 2.** hypothesis testing
- task 3.** make predictions (e.g., sites having $\omega > 1$)

phenomenological
models



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Goldman and Yang (1994)
Muse and Gaut (1994)

- phenomenological parameters
- ts/tv ratio: κ
- **codon frequencies: π_j**
- $\omega = dN/dS$
- parameter estimation via ML
- *stationary process*

task 1: parameter estimation

How to model codon frequencies?

example: A → C

AAA → CAA

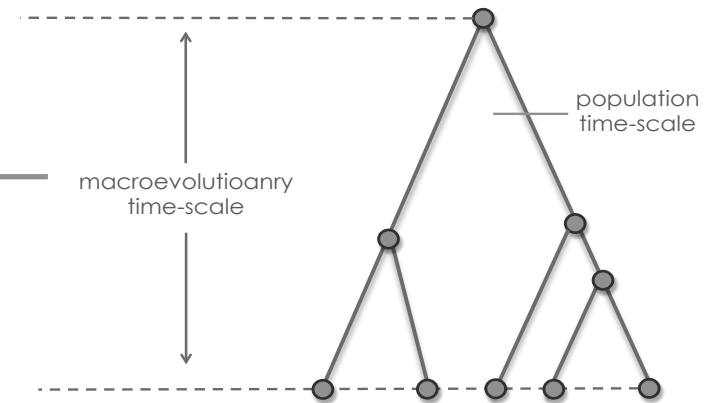
AAA → ACA

AAA → AAC

	Δ at codon position		
	1 st	2 nd	3 rd
GY	π_{CAA}	π_{ACA}	π_{AAC}
MG	π_c^1	π_c^2	π_c^3

} Either way, these are **empirically estimated.**

phenomenological
models



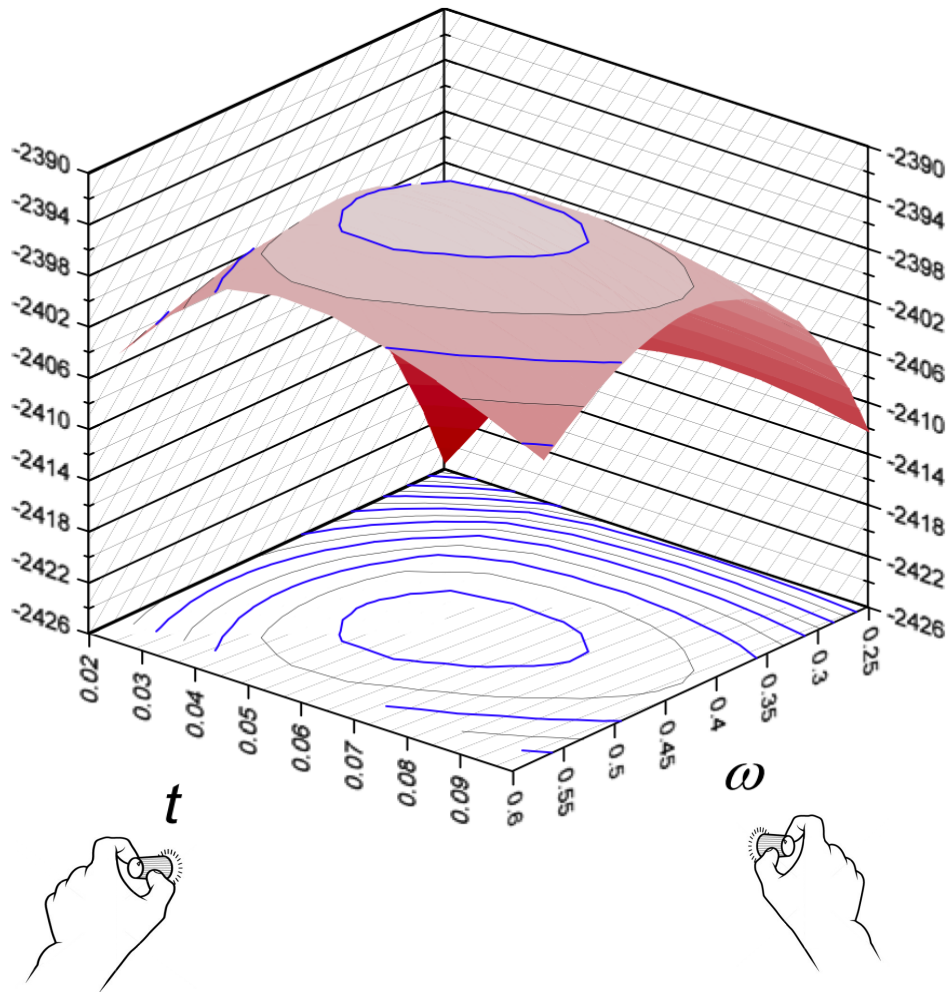
“OMEGA MODELS”

$$Q_{ij} = \begin{cases} 0 & \text{if } i \text{ and } j \text{ differ by } > 1 \\ \pi_j & \text{for synonymous tv.} \\ \kappa\pi_j & \text{for synonymous ts.} \\ \omega\pi_j & \text{for non-synonymous tv.} \\ \omega\kappa\pi_j & \text{for non-synonymous ts.} \end{cases}$$

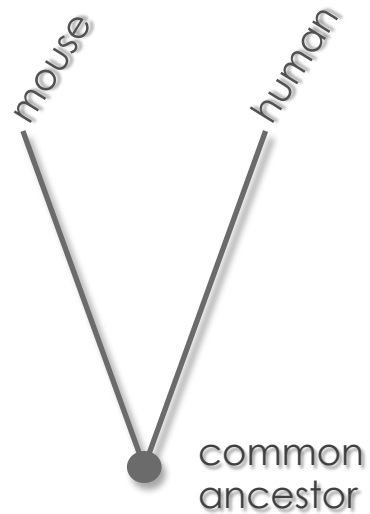
Goldman and Yang (1994)
Muse and Gaut (1994)

- phenomenological parameters
- **ts/tv ratio: κ**
- codon frequencies: π_j
- **$\omega = dN/dS$**
- **parameter estimation via ML**
- *stationary process*

task 1: parameter estimation

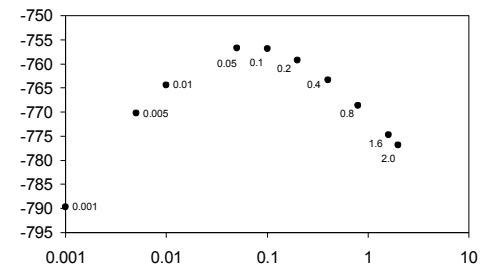
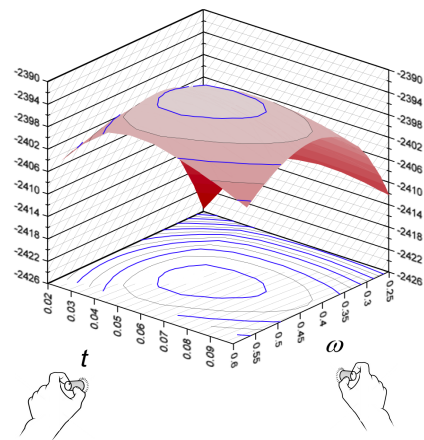


Parameters: t and ω
Gene: acetylcholine α receptor



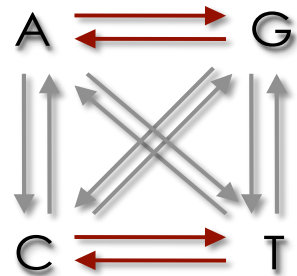
$\ln L = -2399$

Exercise 1: ML estimation of the $d_N/d_S (\omega)$ ratio “by hand” for GstD1



task 1: parameter estimation

transitions vs. **transversions**:



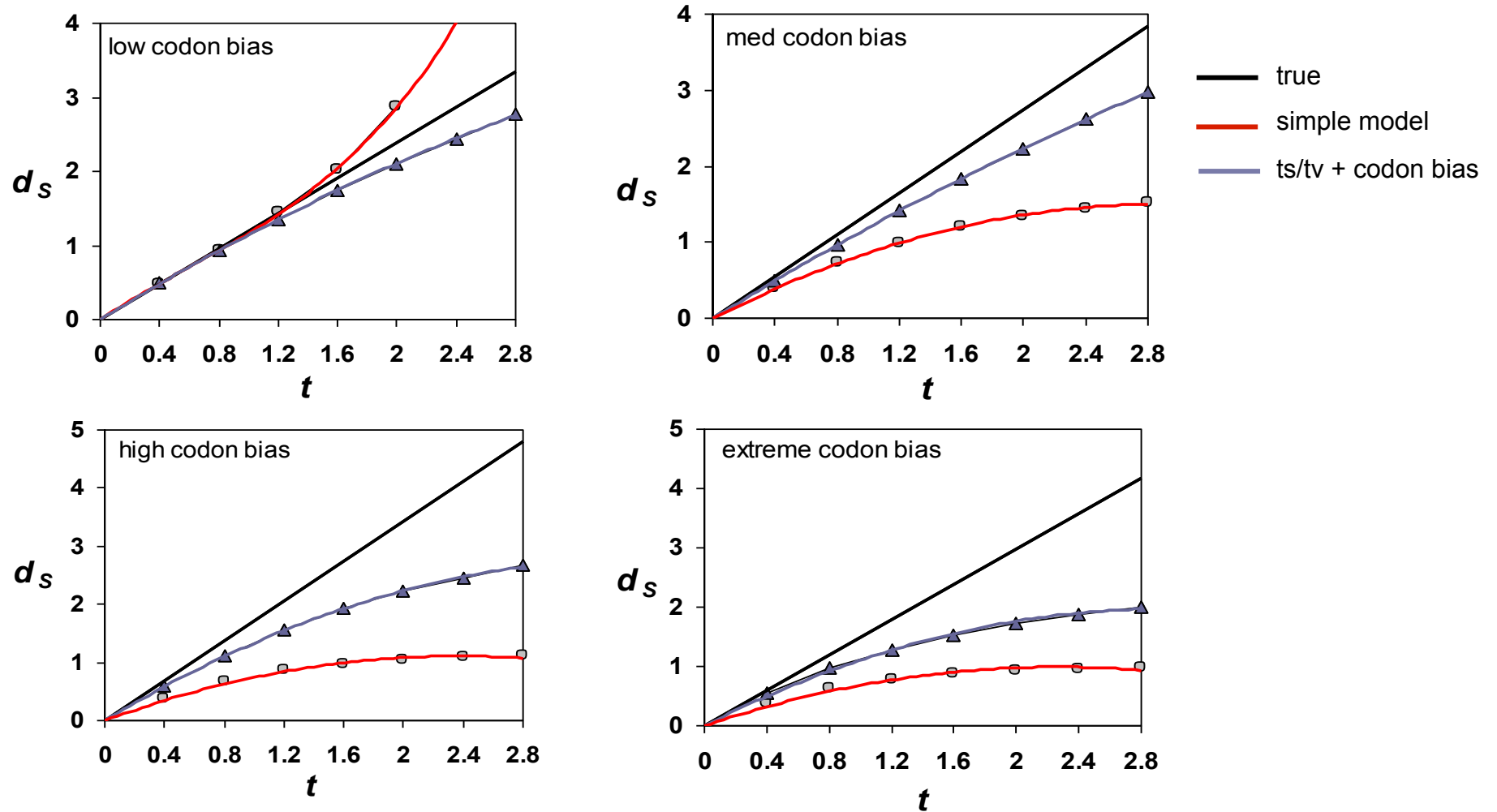
$$t_s/t_v = 2.71$$

preferred vs. **un-preferred** codons:

partial codon usage table for the *GstD* gene of *Drosophila*

Phe F	TTT	0	Ser S	TCT	0	Tyr Y	TAT	1	Cys C	TGT	0
	TTC	27		TCC	15		TAC	22		TGC	6
Leu L	TTA	0		TCA	0	*** *	TAA	0	*** *	TGA	0
	TTG	1		TCG	1		TAG	0	Trp W	TGG	8
Leu L	CTT	2	Pro P	CCT	1	His H	CAT	0	Arg R	CGT	1
	CTC	2		CCC	15		CAC	4		CGC	7
	CTA	0		CCA	3	Gln Q	CAA	0		CGA	0
	CTG	29		CCG	1		CAG	14		CGG	0

uncorrected evolutionary bias leads to estimation bias




data from: Dunn, Bielawski, and Yang (2001) Genetics, 157: 295-305

task 1: parameter estimation

dS and dN must be corrected for BOTH the structure of genetic code and the underlying mutational process of the DNA

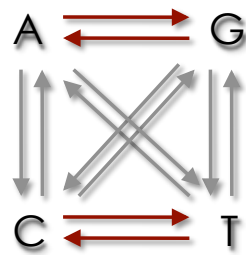
but, this can differ among lineages and genes!



correcting dS and dN for underlying mutational process of the DNA makes them **sensitive to assumptions about the process of evolution!**

Exercise 2: investigate sensitivity of d_N/d_S (ω) to assumptions

transitions vs. transversions



preferred vs. un-preferred codons

partial codon usage table for the *GstD* gene of *Drosophila*

Phe F	TTT	0	|	Ser S	TCT	0	|	Tyr Y	TAT	1	|	Cys C	TGT	0
	TTC	27	|		TCC	15	|		TAC	22	|		TGC	6
Leu L	TTA	0	|		TCA	0	|	***** *	TAA	0	|	***** *	TGA	0
	TTG	1	|		TCG	1	|		TAG	0	|	Trp W	TGG	8
Leu L	CTT	2	|	Pro P	CCT	1	|	His H	CAT	0	|	Arg R	CGT	1
	CTC	2	|		CCC	15	|		CAC	4	|		CGC	7
	CTA	0	|		CCA	3	|	Gln Q	CAA	0	|		CGA	0
	CTG	29	|		CCG	1	|		CAG	14	|		CGG	0

3 analytical tasks

task 1. parameter estimation (e.g., ω)

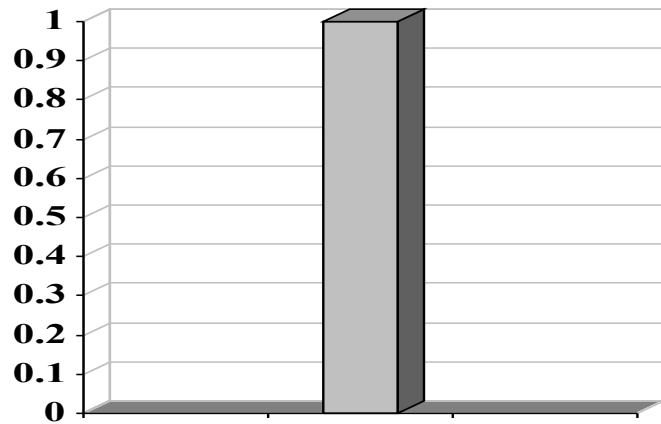
task 2. hypothesis testing 

task 3. make predictions (e.g., sites having $\omega > 1$)

task 2: likelihood ratio test for varied selection among sites

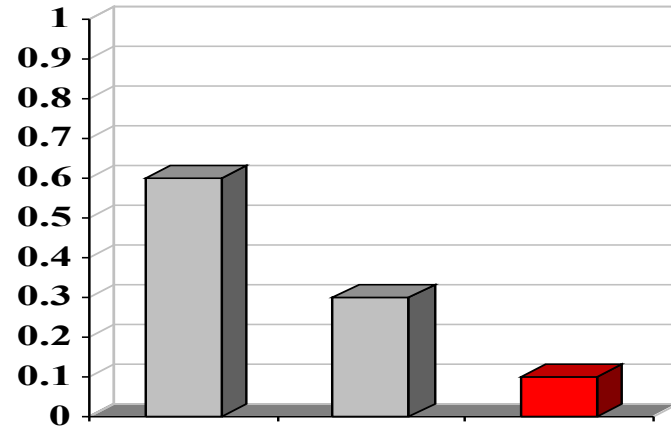
H₀: uniform selective pressure among sites (M0)
H₁: variable selective pressure among sites (M3)
Compare $2\Delta l = 2(l_1 - l_0)$ with a χ^2 distribution

Model 0



$\hat{\omega} = 0.65$

Model 3



$\hat{\omega} = 0.01$ $\hat{\omega} = 0.90$ $\hat{\omega} = 5.55$

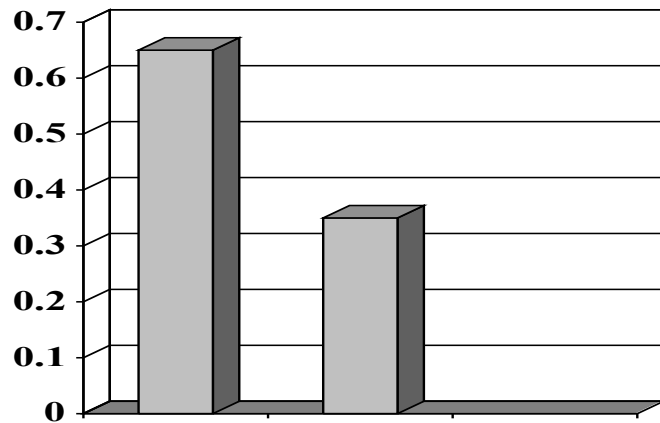
task 2: likelihood ratio test for positive selection

H_0 : variable selective pressure but NO positive selection (M1)

H_1 : variable selective pressure with positive selection (M2)

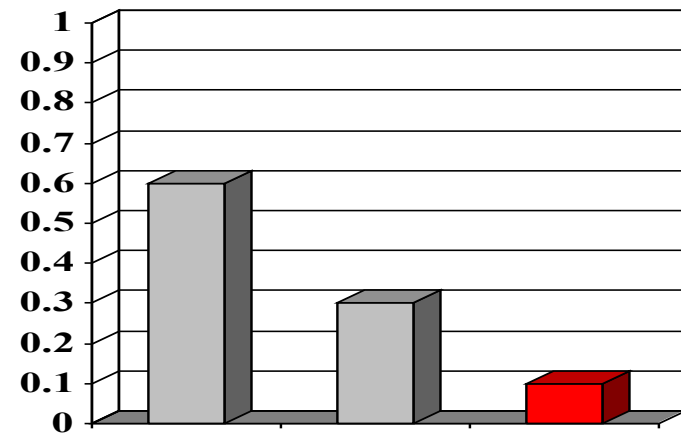
Compare $2\Delta l = 2(l_1 - l_0)$ with a χ^2 distribution

Model 1a



$\hat{\omega} = 0.5$ ($\omega = 1$)

Model 2a



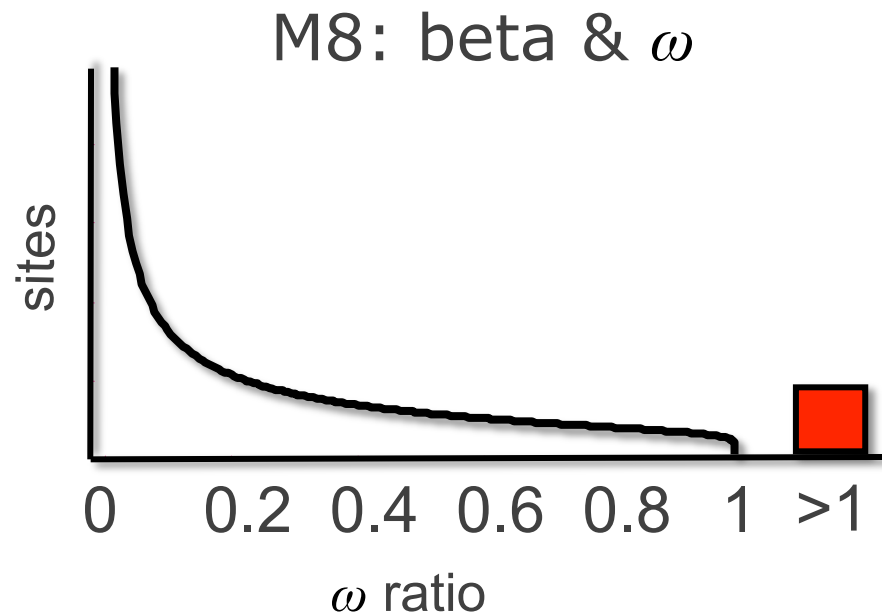
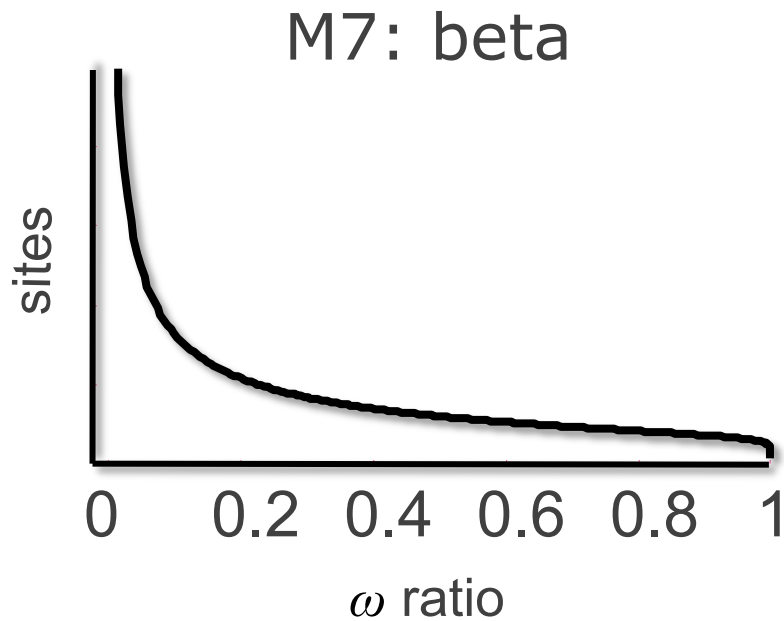
$\hat{\omega} = 0.5$ ($\omega = 1$) $\hat{\omega} = 3.25$

task 2: likelihood ratio test for positive selection

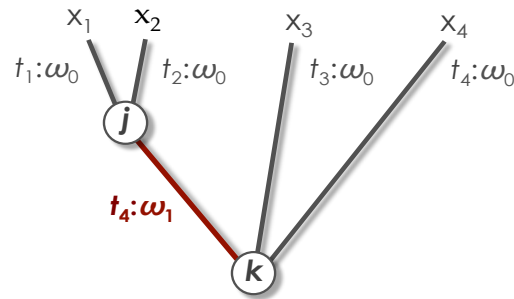
H₀: Beta distributed variable selective pressure (M7)

H₁: Beta plus positive selection (M8)

Compare $2\Delta l = 2(l_1 - l_0)$ with a χ^2 distribution

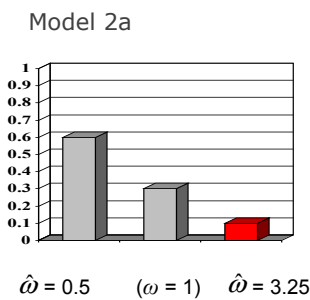
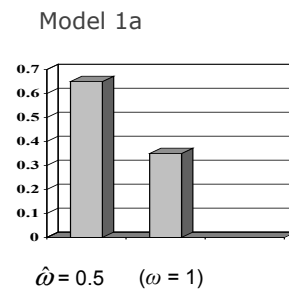


Exercise 3: Test hypotheses about molecular evolution of *Ldh*



branch models
(ω varies among branches)

Exercise 4: Testing for adaptive evolution in the *nef* gene of HIV-2



site models
(ω varies among sites)

3 analytical tasks

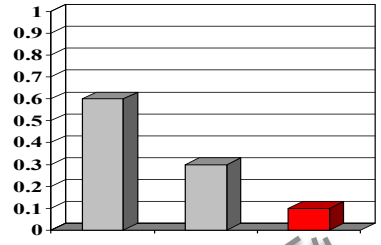
task 1. parameter estimation (e.g., ω)

task 2. hypothesis testing

task 3. make predictions (e.g., sites having $\omega > 1$) 

task 3: which sites have $dN/dS > 1$

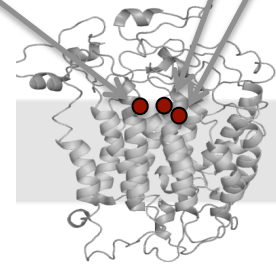
model:
9% have $\omega > 1$



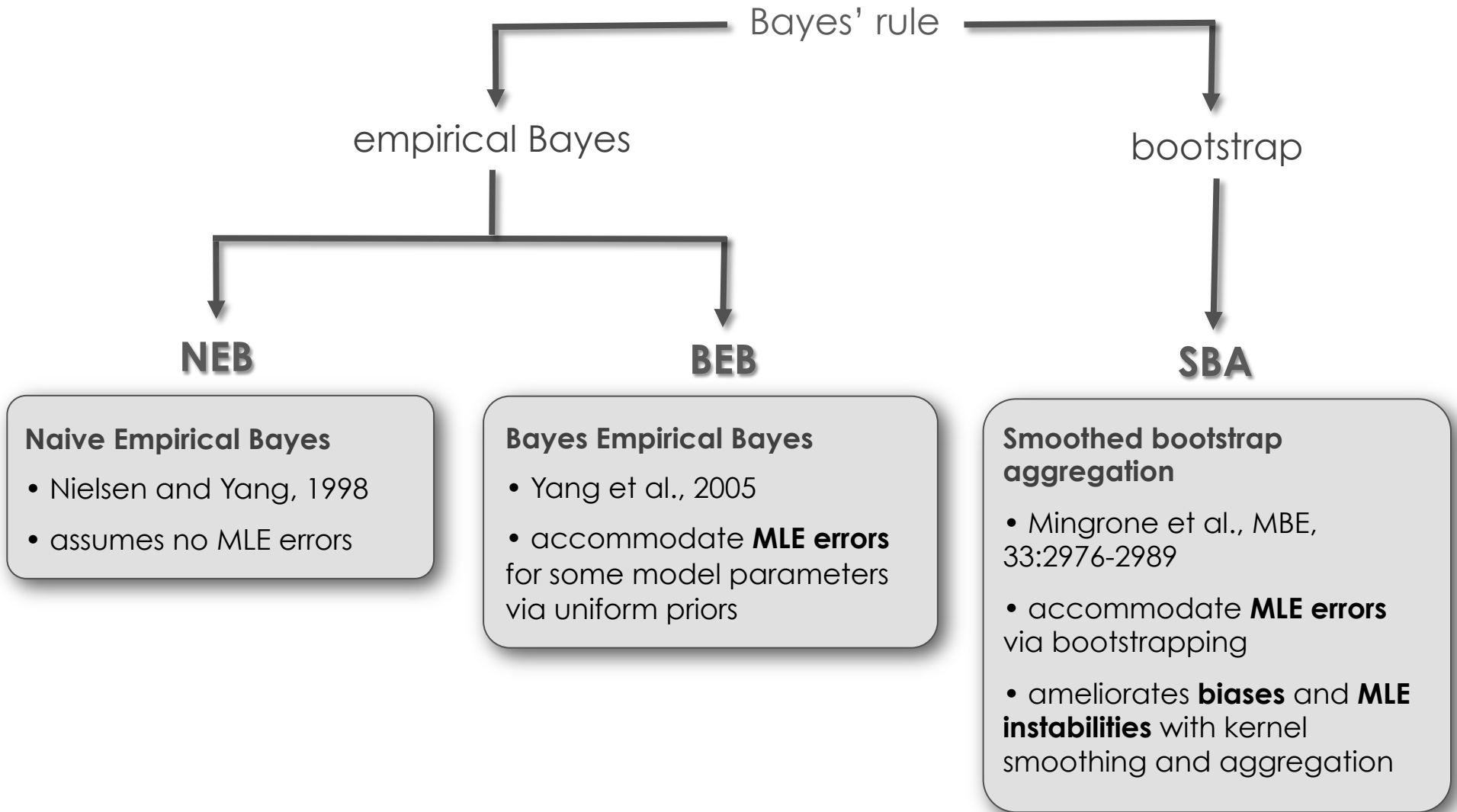
Bayes' rule:
site 4, 12 & 13

GTG	CTG	TCT	CCT	GCC	GAC	AAG	ACC	AAC	GTC	AAG	GCC	GCC	TGG	GGC	AAG	GTT	GGC	GCG	CAC
...	...	...	G.C	...	...	...	T..	..T	...	...	...	...	...	...	...	...	...	..GC	A..
...	...	...	.C	..T	...	...	...	...	A..	...	A.T	...	...	..AA	...	A.C	...	AGC	...
...	..C	...	G.A	..AT	...	..A	...	...	A..	...	AA.	TG.	...	..G	...	A..	..T	..GC	..T
...	..C	..G	GA.	..T	...	...	..T	C..	..G	..A	...	AT.	...	..T	...	..G	..A	..GC	...

structure:
sites are in contact

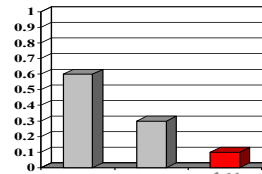


task 3: Bayes rule for which sites have $dN/dS > 1$



Exercise 4: identify adaptive sites in the *nef* gene of HIV-2

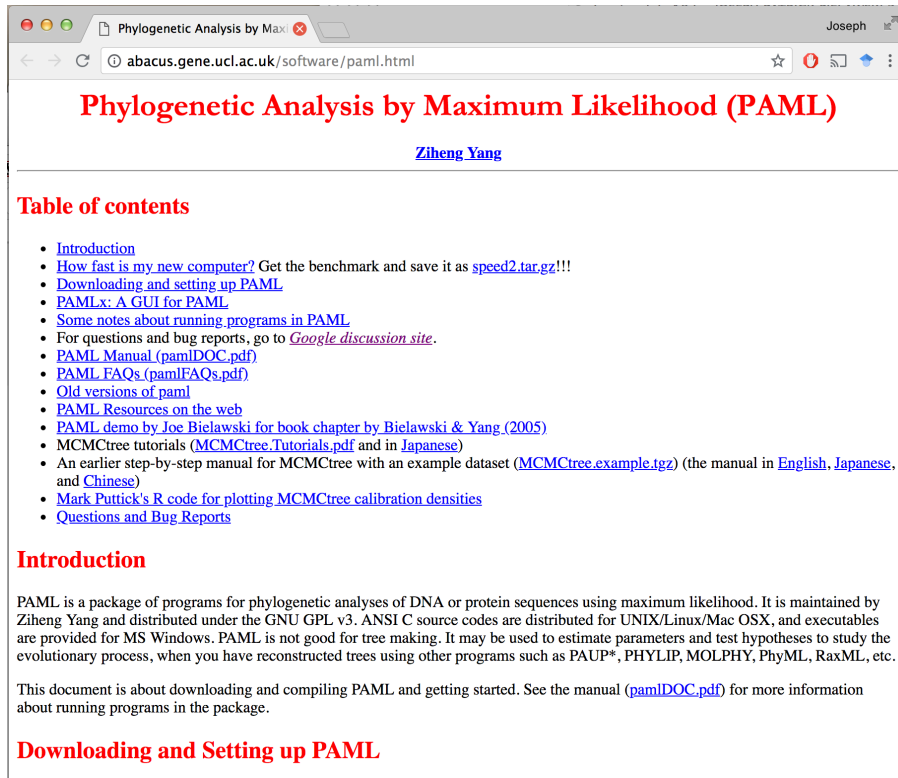
model:
9% have $\omega > 1$



Bayes' rule:
site 4, 12 & 13

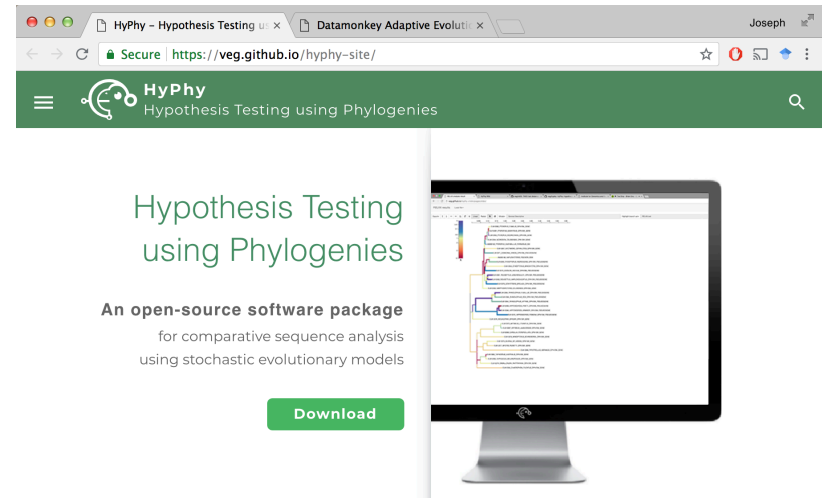
GTG	CTG	TCT	CCT	GCC	GAC	AAG	ACC	AAC	GTC	AAG	GCC	GCC	TGG	GGC	AAG	GTT	GGC	GCG	CAC	
...	G.C	T..	..TAA	...	A.CGC	A..
...C	..T	A..	...	A.TAA	...	A.C	...	AGC	...
...	...	..C	G.A	..AT	...	..A	...	...	A..	...	AA.	TG.	...	..G	...	A..	..T	.GC	..T
...	..C	..G	GA.	..T	...	..T	C..	..G	..A	...	..	AT.	...	..T	...	..G	..A	.GC	...

Software: both **PAML** and **HyPhy** are great choices



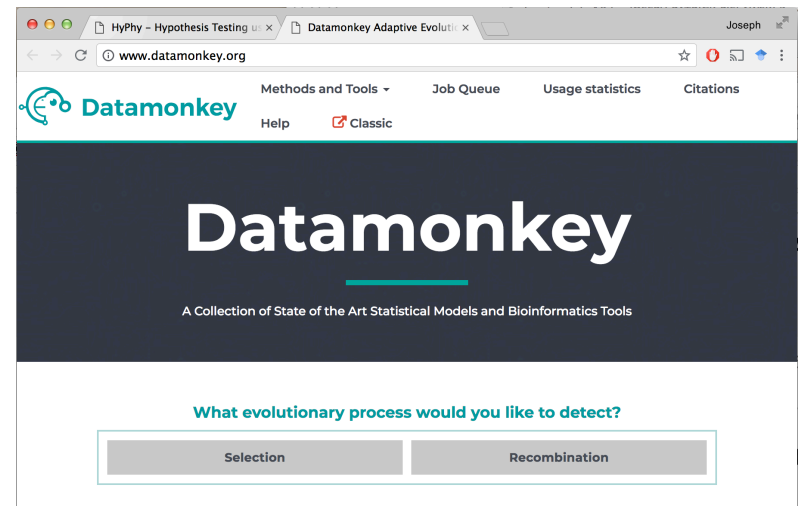
The screenshot shows the website for Phylogenetic Analysis by Maximum Likelihood (PAML). The page title is "Phylogenetic Analysis by Maximum Likelihood (PAML)" by Ziheng Yang. It features a "Table of contents" section with a list of links including "Introduction", "How fast is my new computer?", "Downloading and setting up PAML", "PAMLx: A GUI for PAML", "Some notes about running programs in PAML", "For questions and bug reports, go to Google discussion site.", "PAML Manual (pamDOC.pdf)", "PAML FAQs (pamFAQs.pdf)", "Old versions of paml", "PAML Resources on the web", "PAML demo by Joe Bielawski for book chapter by Bielawski & Yang (2005)", "MCMCtree tutorials (MCMCtree.Tutorials.pdf and in Japanese)", "An earlier step-by-step manual for MCMCtree with an example dataset (MCMCtree.example.tgz) (the manual in English, Japanese, and Chinese)", "Mark Puttick's R code for plotting MCMCtree calibration densities", and "Questions and Bug Reports". Below the table of contents is an "Introduction" section that describes PAML as a package for phylogenetic analyses of DNA or protein sequences using maximum likelihood, maintained by Ziheng Yang. It also mentions that PAML is not good for tree making and can be used to estimate parameters and test hypotheses. The "Introduction" section concludes with a note about downloading and compiling PAML, referring to the manual (pamDOC.pdf) for more information. At the bottom of the screenshot, the "Downloading and Setting up PAML" section is visible.

<http://abacus.gene.ucl.ac.uk/software/paml.html>



The screenshot shows the website for HyPhy: Hypothesis Testing using Phylogenies. The page title is "Hypothesis Testing using Phylogenies" and it is described as "An open-source software package for comparative sequence analysis using stochastic evolutionary models". There is a prominent "Download" button. To the right of the text is a computer monitor displaying a phylogenetic tree. The website is hosted on <https://veg.github.io/hyphy-site/>.

<https://veg.github.io/hyphy-site/>



The screenshot shows the website for Datamonkey. The page title is "Datamonkey" and it is described as "A Collection of State of the Art Statistical Models and Bioinformatics Tools". The website features a navigation menu with "Methods and Tools", "Job Queue", "Usage statistics", and "Citations". There is a "Help" link and a "Classic" link. Below the navigation menu is a large heading "Datamonkey" and a sub-heading "A Collection of State of the Art Statistical Models and Bioinformatics Tools". At the bottom of the screenshot, there is a section titled "What evolutionary process would you like to detect?" with two buttons: "Selection" and "Recombination".

<http://www.datamonkey.org/>

PAML (Phylogenetic Analysis by Maximum Likelihood)

A program package by Ziheng Yang
(Demonstration by Joseph Bielawski)

What does PAML do?

Features include:

- estimating synonymous and nonsynonymous rates
- testing hypotheses concerning d_N/d_S rate ratios
- various amino acid-based likelihood analysis
- ancestral sequence reconstruction (DNA, codon, or AAs)
- various clock models
- simulating nucleotide, codon, or AA sequence data sets
- and more

Programs in the package

baseml	for bases
basemlg	continuous-gamma for bases
codeml	aaml (for amino acids) & codonml (for codons)
evolver	simulation, tree distances
yn00	d_N and d_S by YN00
chi2	chi square table
pamp	parsimony (Yang and Kumar 1996)
mcmctree	Bayes MCMC tree (Yang & Rannala 1997). Slow

Running PAML programs

1. Sequence data file
2. Tree file
3. Control file (*.ctl)

Running PAML programs: the sequence file

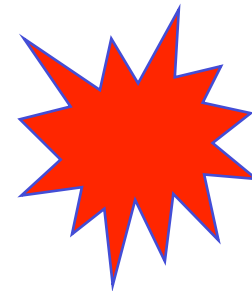
4 20

```
sequence_1 TCATT CTATC TATCG TGATG  
sequence_2 TCATT CTATC TATCG TGATG  
sequence_3 TCATT CTATC TATCG TGATG  
sequence_4 TCATT CTATC TATCG TGATG
```



4 20

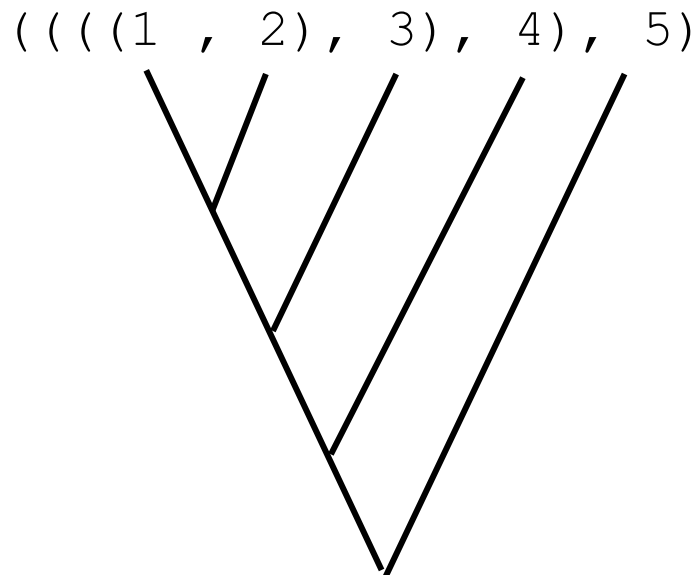
```
sequence_1TCATTCTATCTATCGTGATG  
sequence_2TCATTCTATCTATCGTGATG  
sequence_3TCATTCTATCTATCGTGATG  
sequence_4TCATTCTATCTATCGTGATG
```



Format = plain text in “PHYLIP” format

Running PAML programs: the tree file

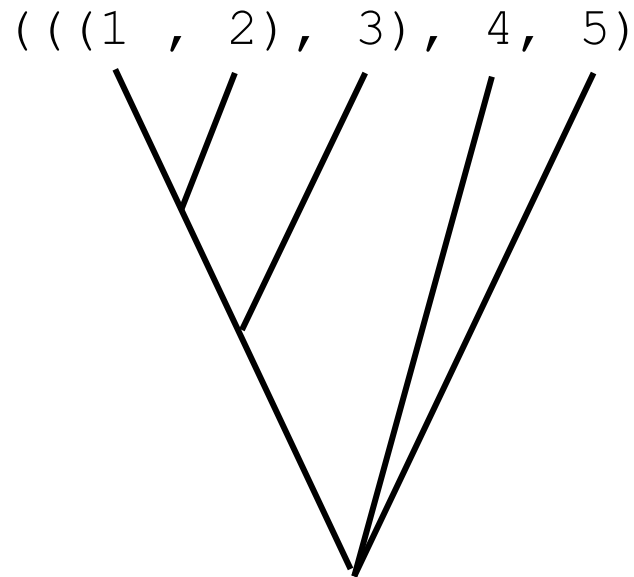
Format = parenthetical notation



This is a rooted tree (root is degree = 2)

Running PAML programs: the tree file

Format = parenthetical notation



This is an **unrooted** tree (basal node is degree = 3)

Running PAML programs: the “*.ctl” file

codeml.ctl

```

seqfile = seqfile.txt      * sequence data filename
treefile = tree.txt       * tree structure file name
outfile = results.txt     * main result file name

    noisy = 9             * 0,1,2,3,9: how much rubbish on the screen
    verbose = 1          * 1:detailed output
    runmode = 0          * 0:user defined tree

    seqtype = 1          * 1:codons
    CodonFreq = 2        * 0:equal, 1:F1X4, 2:F3X4, 3:F61

    model = 0            * 0:one omega ratio for all branches

    NSsites = 0          * 0:one omega ratio (M0 in Tables 2 and 4)
                        * 1:neutral (M1 in Tables 2 and 4)
                        * 2:selection (M2 in Tables 2 and 4)
                        * 3:discrete (M3 in Tables 2 and 4)
                        * 7:beta (M7 in Tables 2 and 4)
                        * 8:beta&w; (M8 in Tables 2 and 4)

    icode = 0            * 0:universal code

    fix_kappa = 0        * 1:kappa fixed, 0:kappa to be estimated
    kappa = 2            * initial or fixed kappa

    fix_omega = 0        * 1:omega fixed, 0:omega to be estimated
    omega = 5            * initial omega

                        *set ncatG for models M3, M7, and M8!!!
    *ncatG = 3           * # of site categories for M3 in Table 4
    *ncatG = 10         * # of site categories for M7 and M8 in Table 4

```


Exercises:

Rasmus Nielsen
Editor

Statistical Methods in Molecular Evolution

 Springer

5

Maximum Likelihood Methods for Detecting Adaptive Protein Evolution

Joseph P. Bielawski¹ and Ziheng Yang²

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² Department of Biology, University College London, Gower Street, London WC1E 6BT, United Kingdom, z.yang@ucl.ac.uk

5.1 Introduction

Proteins evolve; the genes encoding them undergo mutation, and the evolutionary fate of the new mutation is determined by random genetic drift as well as purifying or positive (Darwinian) selection. The ability to analyze this process was realized in the late 1970s when techniques to measure genetic variation at the sequence level were developed. The arrival of molecular sequence data also intensified the debate concerning the relative importance of neutral drift and positive selection to the process of molecular evolution [17]. Ever since, there has been considerable interest in documenting cases of molecular adaptation. Despite a spectacular increase in the amount of available nucleotide sequence data since the 1970s, the number of such well-established cases is still relatively small [9, 38]. This is largely due to the difficulty in developing powerful statistical tests for adaptive molecular evolution. Although several powerful tests for nonneutral evolution have been developed [33], significant results under such tests do not necessarily indicate evolution by positive selection.

A powerful approach to detecting molecular evolution by positive selection derives from comparison of the relative rates of synonymous and nonsynonymous substitutions [22]. Synonymous mutations do not change the amino acid sequence; hence their substitution rate (d_S) is neutral with respect to selective pressure on the protein product of a gene. Nonsynonymous mutations do change the amino acid sequence, so their substitution rate (d_N) is a function of selective pressure on the protein. The ratio of these rates ($\omega = d_N/d_S$) is a measure of selective pressure. For example, if nonsynonymous mutations are deleterious, purifying selection will reduce their fixation rate and d_N/d_S will be less than 1, whereas if nonsynonymous mutations are advantageous, they will be fixed at a higher rate than synonymous mutations, and d_N/d_S will be greater than 1. A d_N/d_S ratio equal to one is consistent with neutral evolution.

Exercises:

	Method/model	program	dataset
1	Pair-wise ML method	codeml	<i>Drosophila GstD1</i>
2	Pair-wise ML method	codeml	<i>Drosophila GstD1</i>
3	M0 and “branch models”	codeml	<i>Ldh</i> gene family
4	M0 and “site models”	codeml	HIV-2 <i>nef</i> genes

Exercise 1: ML estimation of the d_N/d_S (ω) ratio “by hand” for *GstD1*

Dataset: *GstD1* genes of *Drosophila melanogaster* and *D. simulans* (600 codons).

Objective: Use codeml to evaluate the likelihood the *GstD1* sequences for a variety of fixed ω values.

- 1- Plot log-likelihood scores against the values of ω and determine the maximum likelihood estimate of ω .
- 2- Check your finding by running codeml's hill-climbing algorithm.

Exercise 1

```
seqfile = seqfile.txt * sequence data filename
outfile = results.txt * main result file name

noisy = 9 * 0,1,2,3,9: how much rubbish on the screen
verbose = 1 * 1:detailed output
runmode = -2 * -2:pairwise

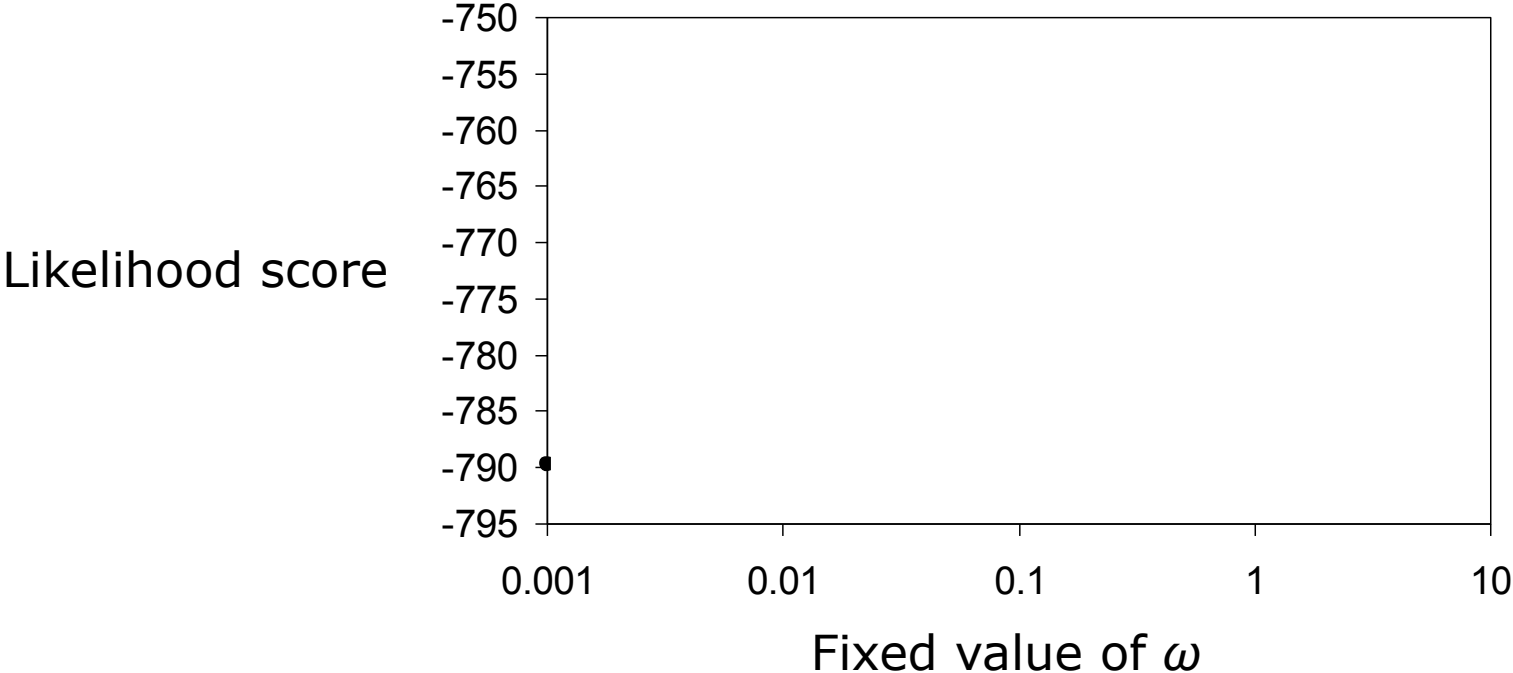
seqtype = 1 * 1:codons
CodonFreq = 3 * 0:equal, 1:F1X4, 2:F3X4, 3:F61
model = 0 *
NSsites = 0 *
icode = 0 * 0:universal code

fix_kappa = 0 * 1:kappa fixed, 0:kappa to be estimated
kappa = 2 * initial or fixed kappa

fix_omega = 1 * 1:omega fixed, 0:omega to be estimated
omega = 0.001 * 1st fixed omega value [CHANGE THIS]

*alternate fixed omega values
*omega = 0.005 * 2nd fixed value
*omega = 0.01 * 3rd fixed value
*omega = 0.05 * 4th fixed value
*omega = 0.10 * 5th fixed value
*omega = 0.20 * 6th fixed value
*omega = 0.40 * 7th fixed value
*omega = 0.80 * 8th fixed value
*omega = 1.60 * 9th fixed value
*omega = 2.00 * 10th fixed value
```

Plot results: likelihood score vs. omega (log scale)



Exercise 1

If you forget what to do, there is a “step-by-step” guide on the course web site.

There is also a “HelpFile” to help you to get what you need from the output of `codeml`

Exercise 2: Investigating the sensitivity of the d_N/d_S ratio to assumptions

Dataset: *GstD1* genes of *Drosophila melanogaster* and *D. simulans* (600 codons).

Objective:

- 1- Test effect of transition / transversion ratio (κ)
- 2- Test effect of codon frequencies (π_i 's)
- 3- Determine which assumptions yield the largest and smallest values of S , and what is the effect on ω

"CodonFreq=" is used to specify the equilibrium codon frequencies

Fequal: - 1/61 each for the standard genetic code

- `CodonFreq = 0`
- number of parameters in the model = 0

F3x4: - calculated from the average nucleotide frequencies at the three codon positions

- `CodonFreq = 2`
- number of parameters in the model = 9

F61 - also called "ftable"; empirical estimate of each codon frequency

- `CodonFreq = 3`
- number of parameters in the model = 61

Example: A → C

AAA → CAA

AAA → ACA

AAA → AAC

	Target codon (nucleotide)			NP
	CAA	ACA	AAC	
No bias	1/61	1/61	1/61	0
MG	π_C^1	π_C^2	π_C^3	9
F3×4 (GY)	$\pi_C^1 \pi_A^2 \pi_A^3$	$\pi_A^1 \pi_C^2 \pi_A^3$	$\pi_A^1 \pi_A^2 \pi_C^3$	9
F61 (GY)	π_{CAA}	π_{ACA}	π_{AAC}	61

NOTE: There are **even more ways** to model frequencies; but these are the only one we will deal with in this lab.

```
seqfile = seqfile.txt    * sequence data filename
outfile = results.txt    * main result file name

    noisy = 9            * 0,1,2,3,9: how much rubbish on the screen
verbose = 1             * 1:detailed output
runmode = -2            * -2:pairwise

seqtype = 1            * 1:codons
CodonFreq = 0          * 0:equal, 1:F1X4, 2:F3X4, 3:F61 [CHANGE THIS]
    model = 0           *
NSsites = 0           *
    icode = 0          * 0:universal code

fix_kappa = 1          * 1:kappa fixed, 0:kappa to be estimated [CHANGE THIS]
    kappa = 1          * fixed or initial value

fix_omega = 0          * 1:omega fixed, 0:omega to be estimated
    omega = 0.5        * initial omega value
```

Further details for about the assumptions tested in ACTIVITY 2

- Assumption set 1:** (Codon bias = none; Ts/Tv bias = none)
CodonFreq=0; kappa=1; fix_kappa=1
- Assumption set 2:** (Codon bias = none; Ts/Tv bias = Yes)
CodonFreq=0; kappa=1; fix_kappa=0
- Assumption set 3:** (Codon bias = yes [F3x4]; Ts/Tv bias = none)
CodonFreq=2; kappa=1; fix_kappa=1
- Assumption set 4:** (Codon bias = yes [F3x4]; Ts/Tv bias = Yes)
CodonFreq=2; kappa=1; fix_kappa=0
- Assumption set 5:** (Codon bias = yes [F61]; Ts/Tv bias = none)
CodonFreq=3; kappa=1; fix_kappa=1
- Assumption set 6:** (Codon bias = yes [F61]; Ts/Tv bias = Yes)
CodonFreq=3; kappa=1; fix_kappa=0

Complete this table (If you forget what to do, there is a “step-by-step” guide on the course web-site.)

Table E2: Estimation of d_S and d_N between *Drosophila melanogaster* and *D. simulans* *GstD1* genes

Assumptions	κ	S	N	d_S	d_N	ω	ℓ
Fequal + $\kappa = 1$	1.0	?	?	?	?	?	?
Fequal + $\kappa = \text{estimated}$?	?	?	?	?	?	?
F3×4 + $\kappa = 1$	1.0	?	?	?	?	?	?
F3×4 + $\kappa = \text{estimated}$?	?	?	?	?	?	?
F61 + $\kappa = 1$	1.0	?	?	?	?	?	?
F61 + $\kappa = \text{estimated}$?	?	?	?	?	?	?

κ = transition/transversion rate ratio

S = number of synonymous sites

N = number of nonsynonymous sites

$\omega = d_N/d_S$

ℓ = log likelihood score

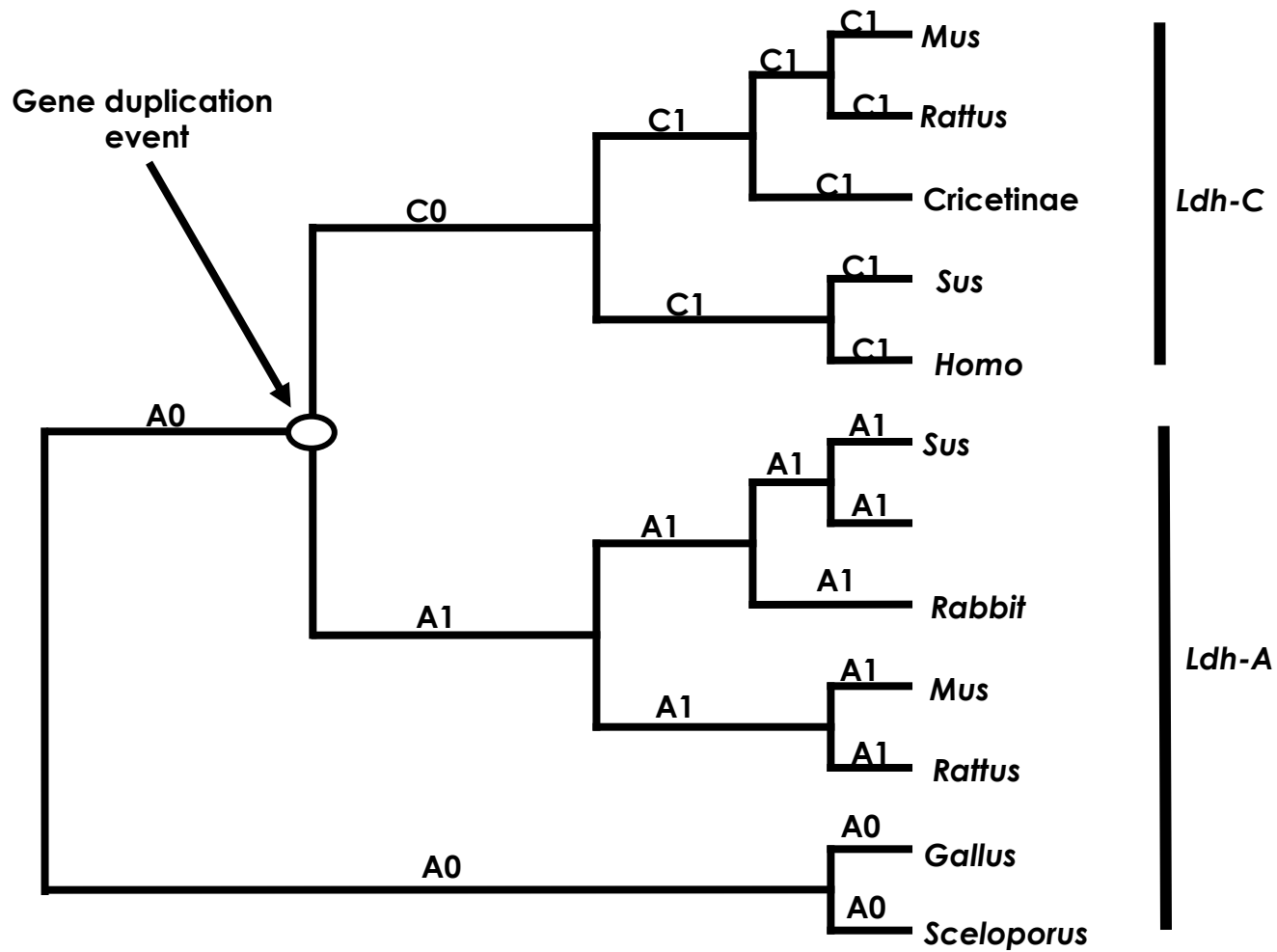
Exercise 3: Test hypotheses about molecular evolution of *Ldh*

Dataset: The *Ldh* gene family is an important model system for molecular evolution of isozyme multigene families. The rate of evolution is known to have increased in *Ldh-C* following the gene duplication event

Objective: Use LRTs to evaluate the following hypotheses:

- 1- The mutation rate of *Ldh-C* has increased relative to *Ldh-A*,
- 2- A burst of positive selection for functional divergence occurred following the duplication event that gave rise to *Ldh-C*
- 3- There was a long term shift in selective constraints following the duplication event that gave rise to *Ldh-C*

Exercise 3



$$H_0: \omega_{A0} = \omega_{A1} = \omega_{C1} = \omega_{C0}$$

$$H_1: \omega_{A0} = \omega_{A1} = \omega_{C1} \neq \omega_{C0}$$

$$H_2: \omega_{A0} = \omega_{A1} \neq \omega_{C1} = \omega_{C0}$$

$$H_3: \omega_{A0} \neq \omega_{A1} \neq \omega_{C1} = \omega_{C0}$$

```

seqfile = seqfile.txt      * sequence data filename
treefile = tree.H0.txt    * tree structure file name [CHANGE THIS]
outfile = results.txt     * main result file name

noisy = 9                 * 0,1,2,3,9: how much rubbish on the screen
verbose = 1              * 1:detailed output
runmode = 0              * 0:user defined tree

seqtype = 1              * 1:codons
CodonFreq = 2           * 0:equal, 1:F1X4, 2:F3X4, 3:F61

model = 0                * 0:one omega ratio for all branches [FOR MODEL H0]
                        * 1:separate omega for each branch
                        * 2:user specified dN/dS ratios for branches [FOR MODELS H1-H3]

NSsites = 0             *

icode = 0               * 0:universal code

fix_kappa = 0          * 1:kappa fixed, 0:kappa to be estimated
kappa = 2              * initial or fixed kappa

fix_omega = 0          * 1:omega fixed, 0:omega to be estimated
omega = 0.2            * initial omega

*H0 in Table 3:
*model = 0
*(X02152Hom,U07178Sus,(M22585rab,((NM017025Rat,U13687Mus),
*((AF070995C,(X04752Mus,U07177Rat)),(U95378Sus,U13680Hom)),(X53828OG1,
* U28410OG2)))));

*H1 in Table 3:
*model = 2
*(X02152Hom,U07178Sus,(M22585rab,((NM017025Rat,U13687Mus),((AF070995C,
*(X04752Mus,U07177Rat)),(U95378Sus,U13680Hom))#1,(X53828OG1,U28410OG2))
* ));

*H2 in Table 3:
*model = 2
*(X02152Hom,U07178Sus,(M22585rab,((NM017025Rat,U13687Mus),((AF070995C
* #1,(X04752Mus #1,U07177Rat #1)#1)#1,(U95378Sus #1,U13680Hom #1)
* #1)#1,(X53828OG1,U28410OG2)))));

*H3 in Table 3:
*model = 2
*(X02152Hom,U07178Sus,(M22585rab,((NM017025Rat,U13687Mus),((AF070995C
* #1,(X04752Mus #1,U07177Rat #1)#1)#1,(U95378Sus #1,U13680Hom #1)
* #1)#1,(X53828OG1 #2,U28410OG2 #2)#2)))));

```

Complete this table (If you forget what to do, there is a “step-by-step” guide on the course web-site.)

Table E3: Parameter estimates under models of variable ω ratios among lineages and LRTs of their fit to the *Ldh-A* and *Ldh-C* gene family.

Models	ω_{A0}	ω_{A1}	ω_{C1}	ω_{C0}	ℓ	LRT
$H_0: \omega_{A0} = \omega_{A1} = \omega_{C1} = \omega_{C0}$	?	$= \omega_{A.0}$	$= \omega_{A.0}$	$= \omega_{A.0}$?	?
$H_1: \omega_{A0} = \omega_{A1} = \omega_{C1} \neq \omega_{C0}$	?	$= \omega_{A.0}$	$= \omega_{A.0}$?	?	?
$H_2: \omega_{A0} = \omega_{A1} \neq \omega_{C1} = \omega_{C0}$	?	$= \omega_{A.0}$	?	$= \omega_{C.1}$?	?
$H_3: \omega_{A0} \neq \omega_{A1} \neq \omega_{C1} = \omega_{C0}$	?	?	?	$= \omega_{C.1}$?	?

The topology and branch specific ω ratios are presented in Figure 5.

$$H_0 \vee H_1: df = 1$$

$$H_0 \vee H_2: df = 1$$

$$H_2 \vee H_3: df = 1$$

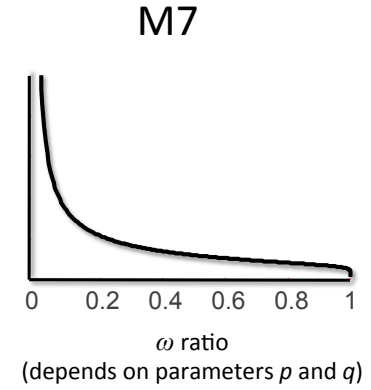
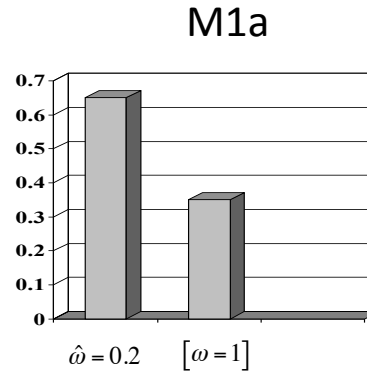
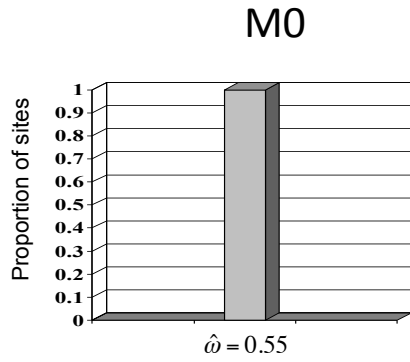
$$\chi^2_{df=1, \alpha=0.05} = 3.841$$

Exercise 4: Testing for adaptive evolution in the *nef* gene of human HIV-2 (Start tonight, but finish as homework)

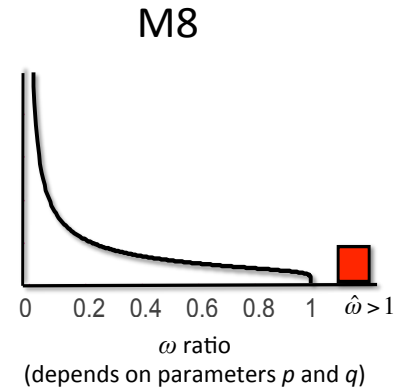
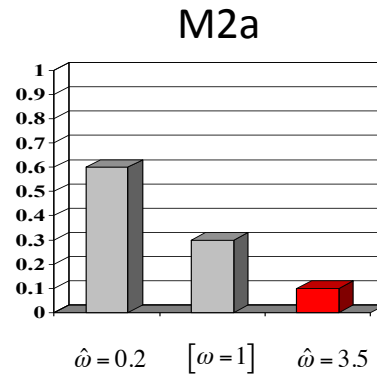
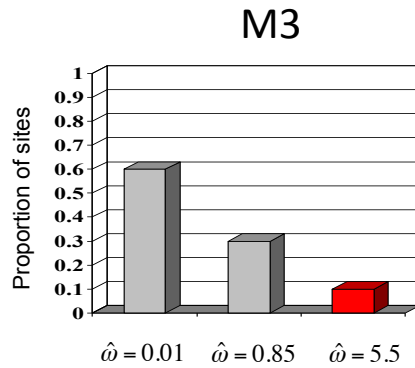
- Dataset:** 44 *nef* sequences from a study population of 37 HIV-2 infected people living in Lisbon, Portugal. The *nef* gene in HIV-2 has received less attention than HIV-1, presumably because HIV-2 is associated with reduced virulence and pathogenicity relative to HIV-1
- Objectives:**
- 1- Learn to use LRTs to test for sites evolving under positive selection in the *nef* gene.
 - 2- If you find significant evidence for positive selection, then identify the involved sites by using empirical Bayes methods.

Exercise 4

H_0



H_a



LRT

1: M0 vs. M3 test for variable selection pressure among sites

2: M1a vs. M2a tests for sites subject to positive selection

3: M7 vs. M8 tests for sites subject to positive selection

Exercise 4

```
seqfile = seqfile.txt

* treefile = treefile_M0.txt
* treefile = treefile_M1.txt
* treefile = treefile_M2.txt
* treefile = treefile_M3.txt
* treefile = treefile_M7.txt
* treefile = treefile_M8.txt

outfile = results.txt
  noisy = 9
  verbose = 1
  runmode = 0
  seqtype = 1
CodonFreq = 2
  model = 0

* NSsites = 0
* NSsites = 1
* NSsites = 2
* NSsites = 3
* NSsites = 7
* NSsites = 8

  icode = 0
fix_kappa = 1
  * kappa = 4.43491
  * kappa = 4.39117
  * kappa = 5.08964
  * kappa = 4.89033
  * kappa = 4.22750
  * kappa = 4.87827

fix_omega = 0
  omega = 5

  * ncatG = 3
  * ncatG = 10

fix_blength = 2

* sequence data filename

* SET THIS for tree file with ML branch lengths under M0
* SET THIS for tree file with ML branch lengths under M1
* SET THIS for tree file with ML branch lengths under M2
* SET THIS for tree file with ML branch lengths under M3
* SET THIS for tree file with ML branch lengths under M7
* SET THIS for tree file with ML branch lengths under M8

* main result file name
* lots of rubbish on the screen
* detailed output
* user defined tree
* codons
* F3X4 for codon frequencies
* one omega ratio for all branches

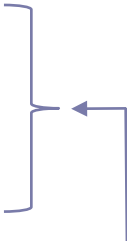
* SET THIS for M0
* SET THIS for M1
* SET THIS for M2
* SET THIS for M3
* SET THIS for M7
* SET THIS for M8

* universal code
* kappa fixed
* SET THIS to fix kappa at MLE under M0
* SET THIS to fix kappa at MLE under M1
* SET THIS to fix kappa at MLE under M2
* SET THIS to fix kappa at MLE under M3
* SET THIS to fix kappa at MLE under M7
* SET THIS to fix kappa at MLE under M8

* omega to be estimated
* initial omega

* SET THIS for 3 site categories under M3
* SET THIS for 10 of site categories under M7 and M8

* fixed branch lengths from tree file
```



These trees contain **pre-computed MLEs for branch lengths** to speed the analyses.

You will want to estimate all the branch lengths via ML when you analyze your own data!

Complete this table (If you forget what to do, there is a “step-by-step” guide on the course web-site.)

Table E4: Parameter estimates and likelihood scores under models of variable ω ratios among sites for HIV-2 *nef* genes.

Nested model pairs	d_N/d_S^b	Parameter estimates ^c	PSS ^d	ℓ
M0: one-ratio (1) ^a	?	$\omega = ?$	N.A.	?
M3: discrete (5)	?	$p_0 = ?, p_1 = ?, (p_2 = ?)$ $\omega_0 = ?, \omega_1 = ?, \omega_2 = ?$? (?)	?
M1: neutral (1)	?	$p_0 = ?, (p_1 = ?)$ $\omega_0 = ?, (\omega_1 = 1)$	N.A.	?
M2: selection (3)	?	$p_0 = ?, p_1 = ?, (p_2 = ?)$ $\omega_0 = ?, (\omega_1 = 1), \omega_2 = ?$? (?)	?
M7: beta (2)	?	$p = ?, q = ?$	N.A.	?
M8: beta& ω (4)	?	$p_0 = ? (p_1 = ?)$ $p = ?, q = ?, \omega = ?$? (?)	?

^a The number after the model code, in parentheses, is the number of free parameters in the ω distribution.

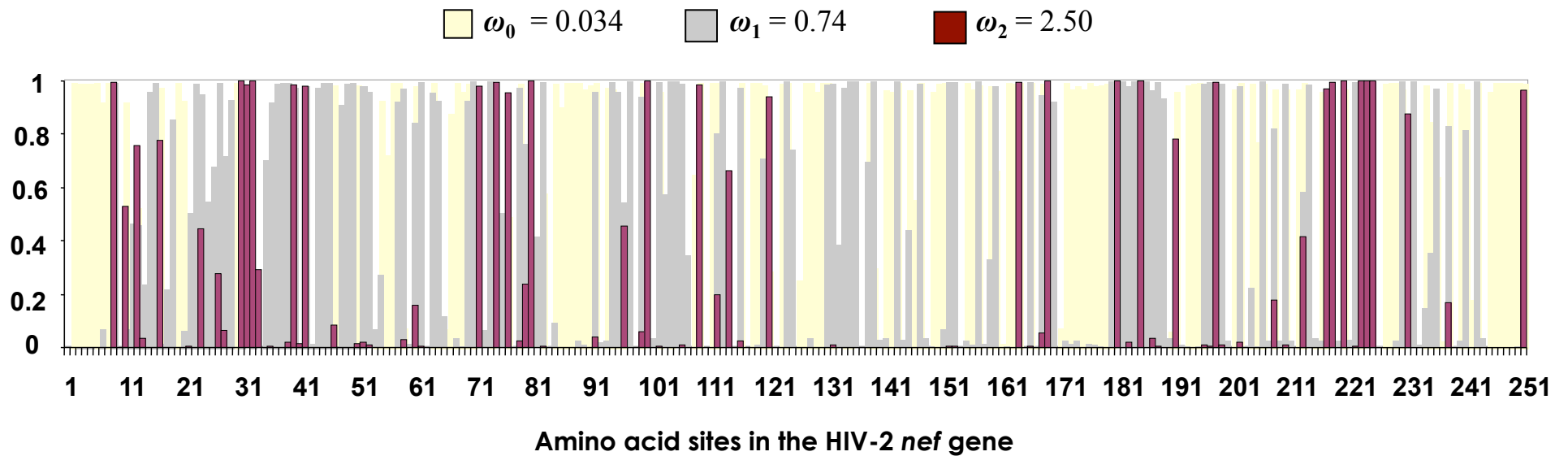
^b This d_N/d_S ratio is an average over all sites in the HIV-2 *nef* gene alignment.

^c Parameters in parentheses are not free parameters.

^d PSS is the number of positive selection sites (NEB). The first number is the PSS with posterior probabilities > 50%. The second number (in parentheses) is the PSS with posterior probabilities > 95%.

NOTE: Codeml now implements models M1a and M2a !

Reproduce this plot (use the "rst" file generated by M3)



Rasmus Nielsen
Editor

Statistical Methods in Molecular Evolution

 Springer

5

Maximum Likelihood Methods for Detecting Adaptive Protein Evolution

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5.1 Introduction

Proteins evolve; the genes encoding them undergo mutation, and the evolutionary fate of the new mutation is determined by random genetic drift as well as purifying or positive (Darwinian) selection. The ability to analyze this process was realized in the late 1970s when techniques to measure genetic variation at the sequence level were developed. The arrival of molecular sequence data also intensified the debate concerning the relative importance of neutral drift and positive selection to the process of molecular evolution [17]. Ever since, there has been considerable interest in documenting cases of molecular adaptation. Despite a spectacular increase in the amount of available nucleotide sequence data since the 1970s, the number of such well-established cases is still relatively small [9, 38]. This is largely due to the difficulty in developing powerful statistical tests for adaptive molecular evolution. Although several powerful tests for nonneutral evolution have been developed [33], significant results under such tests do not necessarily indicate evolution by positive selection.

A powerful approach to detecting molecular evolution by positive selection derives from comparison of the relative rates of synonymous and nonsynonymous substitutions [22]. Synonymous mutations do not change the amino acid sequence; hence their substitution rate (d_S) is neutral with respect to selective pressure on the protein product of a gene. Nonsynonymous mutations do change the amino acid sequence, so their substitution rate (d_N) is a function of selective pressure on the protein. The ratio of these rates ($\omega = d_N/d_S$) is a measure of selective pressure. For example, if nonsynonymous mutations are deleterious, purifying selection will reduce their fixation rate and d_N/d_S will be less than 1, whereas if nonsynonymous mutations are advantageous, they will be fixed at a higher rate than synonymous mutations, and d_N/d_S will be greater than 1. A d_N/d_S ratio equal to one is consistent with neutral evolution.