Cambrian Explosion

The Whale Story

By Dr. Richard Sternberg

Darwin's Poster Child

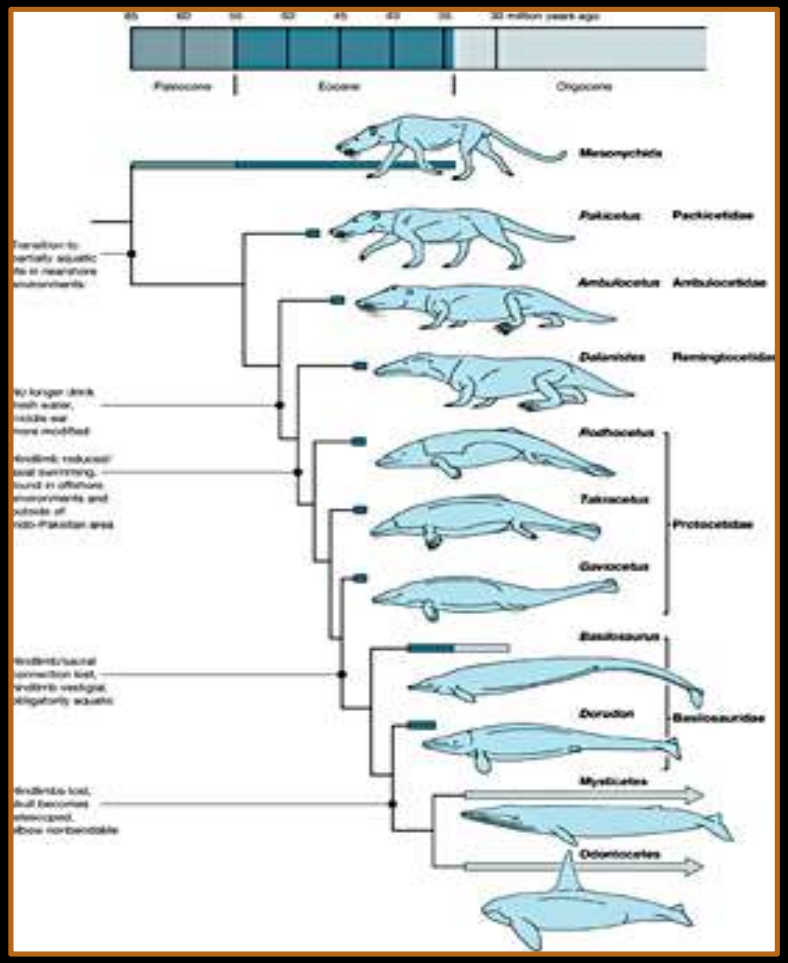
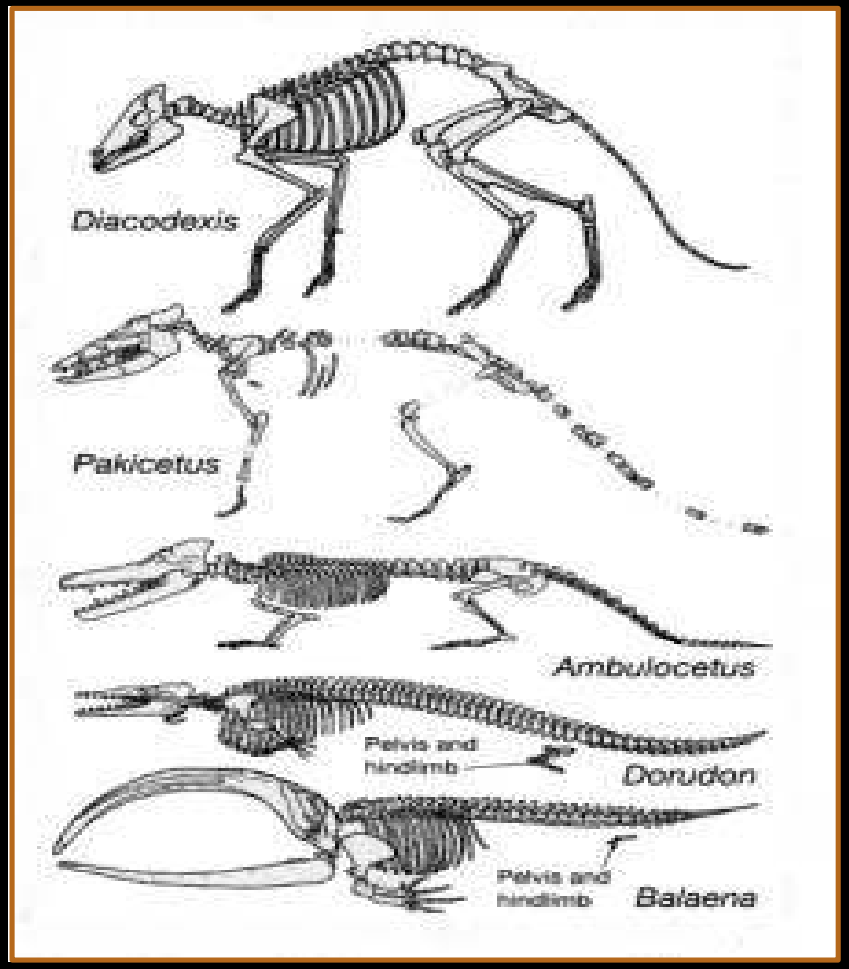


Illustration by Carl Buell in *Vertebrate Life* 7th Edition 2005

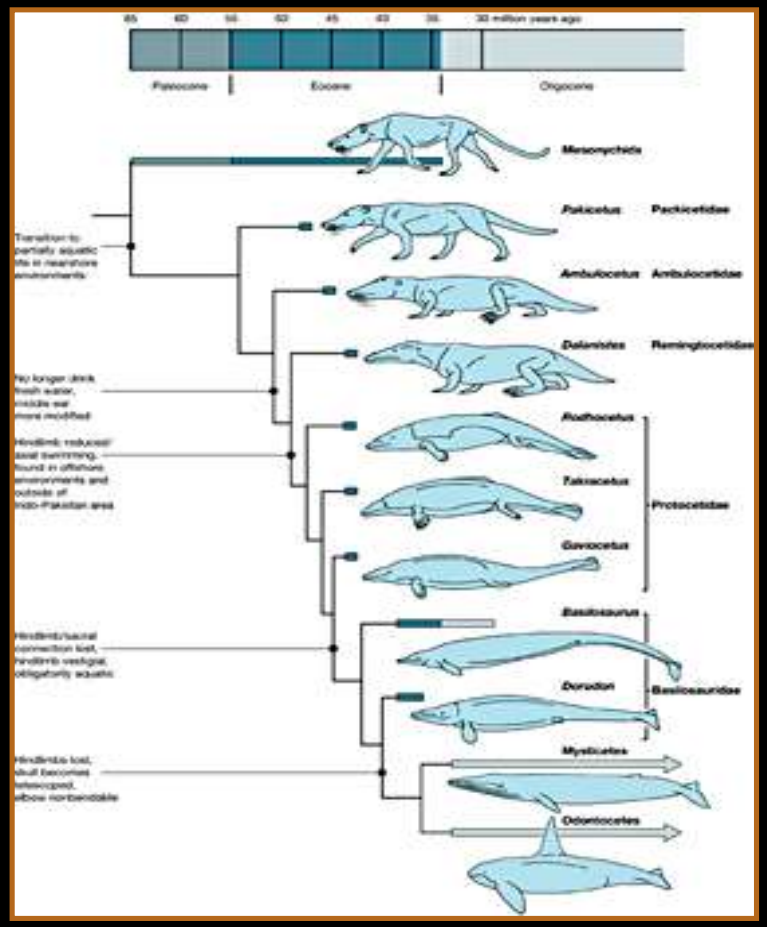
Deer*ish*-Mammal to Whale Transition?



de Muizon, C. 2001.
Walking with whales. *Nature* 413:259-260

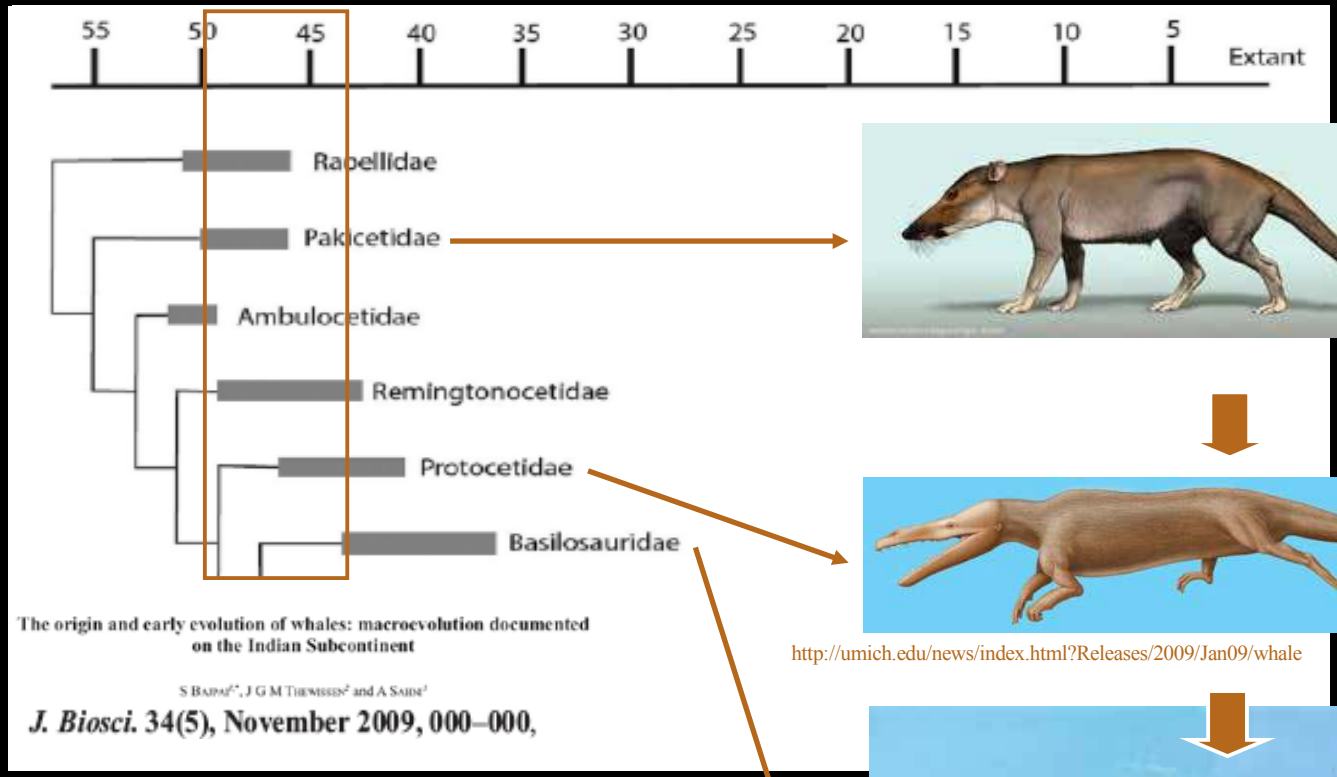
Pattern v. Process Distinction

To be explained…



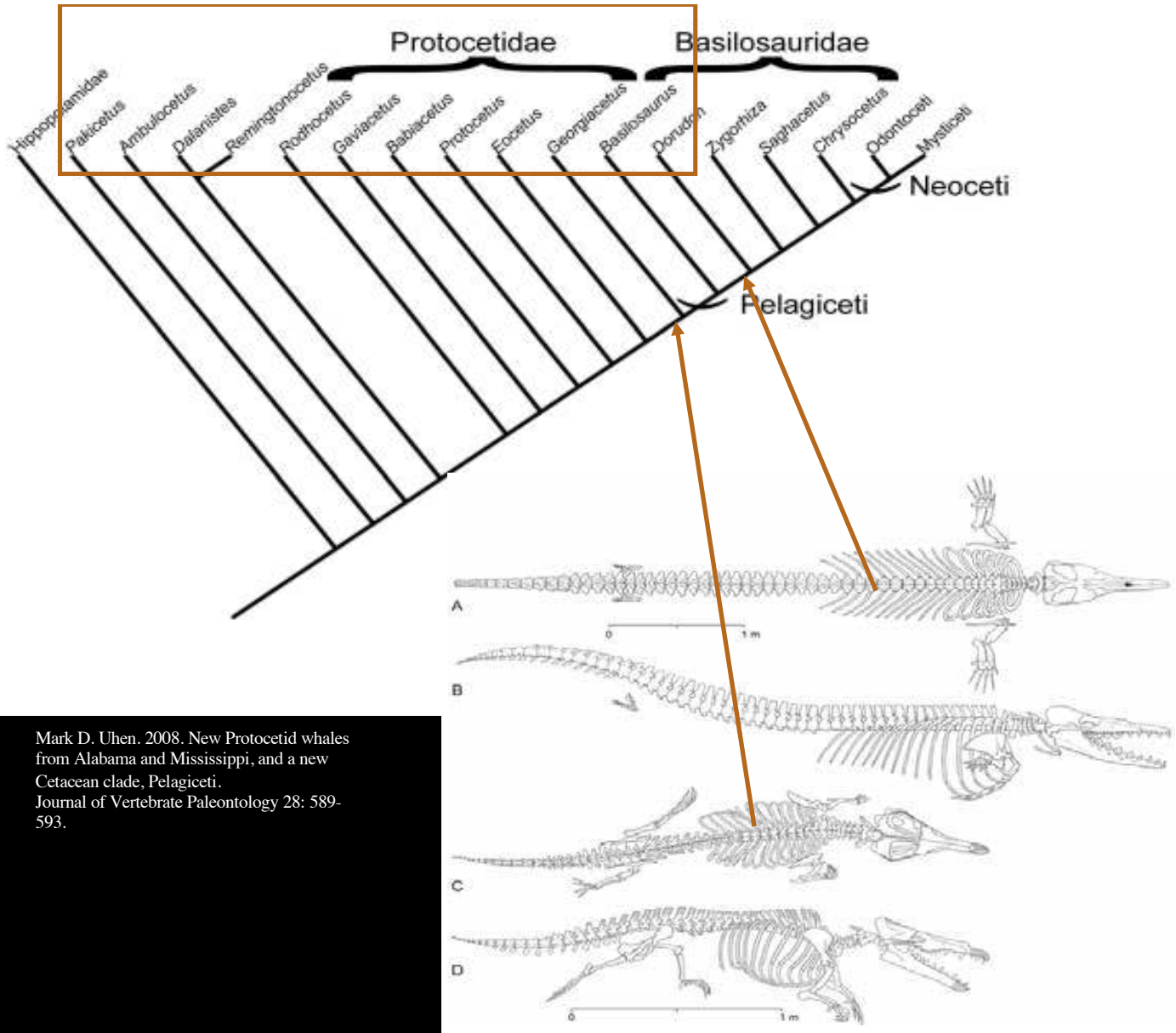
Causal explanation

High random mutation rates + selection coefficients ⇒ Incremental genetic change over time (def. of evolution)



http://umich.edu/news/index.html?Releases/2009/Jan09/whale

www.netheimar.net



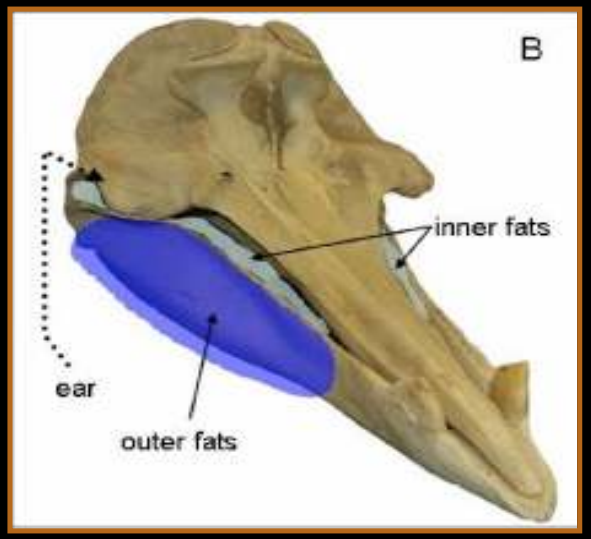
The majority of anatomical novelties unique to aquatic cetaceans (Pelagiceti) appeared during just a few million years, probably within 1-3 myrs.

Mark D. Uhen. 2008. New Protocetid whales from Alabama and Mississippi, and a new Cetacean clade, Pelagiceti. Journal of Vertebrate Paleontology 28: 589-593.

Gingerich PD et al. 2009. New protocetid whale from the middle eocene of pakistan: birth on land, precocial development, and sexual dimorphism. PLoS ONE 4(2): e4366.

Structures necessary to produce a fully marine whale

- Counter-current heat exchanger for intra-abdominal testes
- Ball vertebra
- Tail flukes and musculature
- Blubber for temperature insulation
- Ability to drink sea water (reorganization of kidney tissues)
- Fetus in breech position (for labor underwater)
- Nurse young underwater (modified mammae)
- Forelimbs transformed into flippers
- Reduction of hindlimbs
- Reduction/loss of pelvis and sacral vertebrae
- Reorganization of the musculature for the reproductive organs
- Hydrodynamic properties of the skin
- Special lung surfactants
- Novel muscle systems for the blowhole
- Modification of the teeth
- Modification of the eye for underwater vision
- Emergence and expansion of the mandibular fat pad with complex lipid distribution



Topographical Distribution of Lipids Inside the Mandibular Fat Bodies of Odontocetes: Remarkable Complexity and Consistency

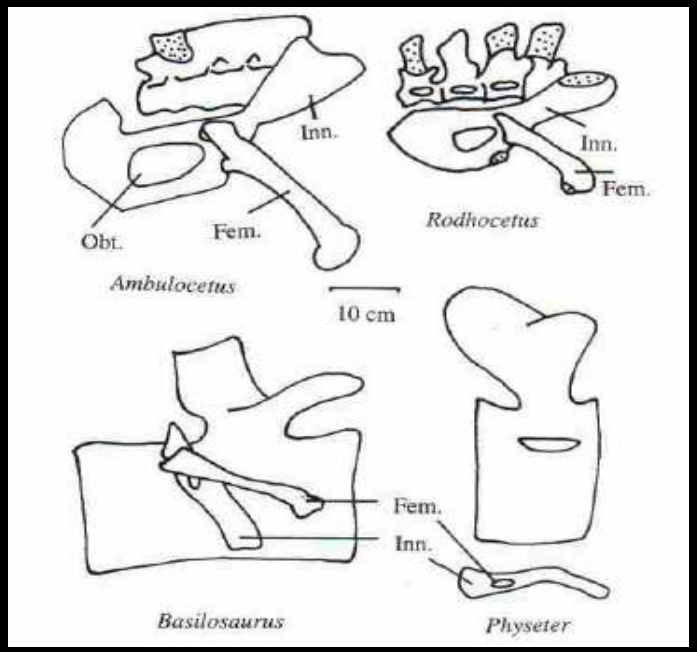
Heather N. Koopman, Suzanne M. Budge, Darlene R. Ketten, and Sara J. Iverson

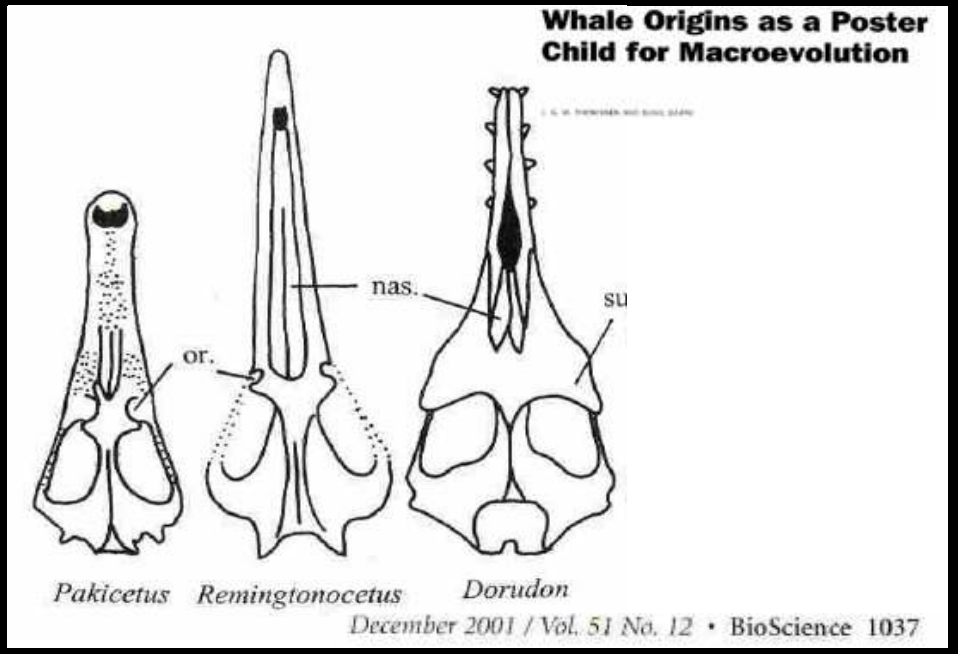
IEEE JOURNAL OF OCEANIC ENGINEERING, VOL. 31, NO. 1, JANUARY 2006

Structures necessary to produce a fully marine whale

- Reorganization of skull bones and musculature
- Modification of the ear bones
- Decoupling of esophagus and trachea
- Synthesis and metabolism of isovaleric acid (toxic to terrestrial mammals)
- Emergence of blowhole musculature and their neurological control

and hundreds if not thousands of other trait changes

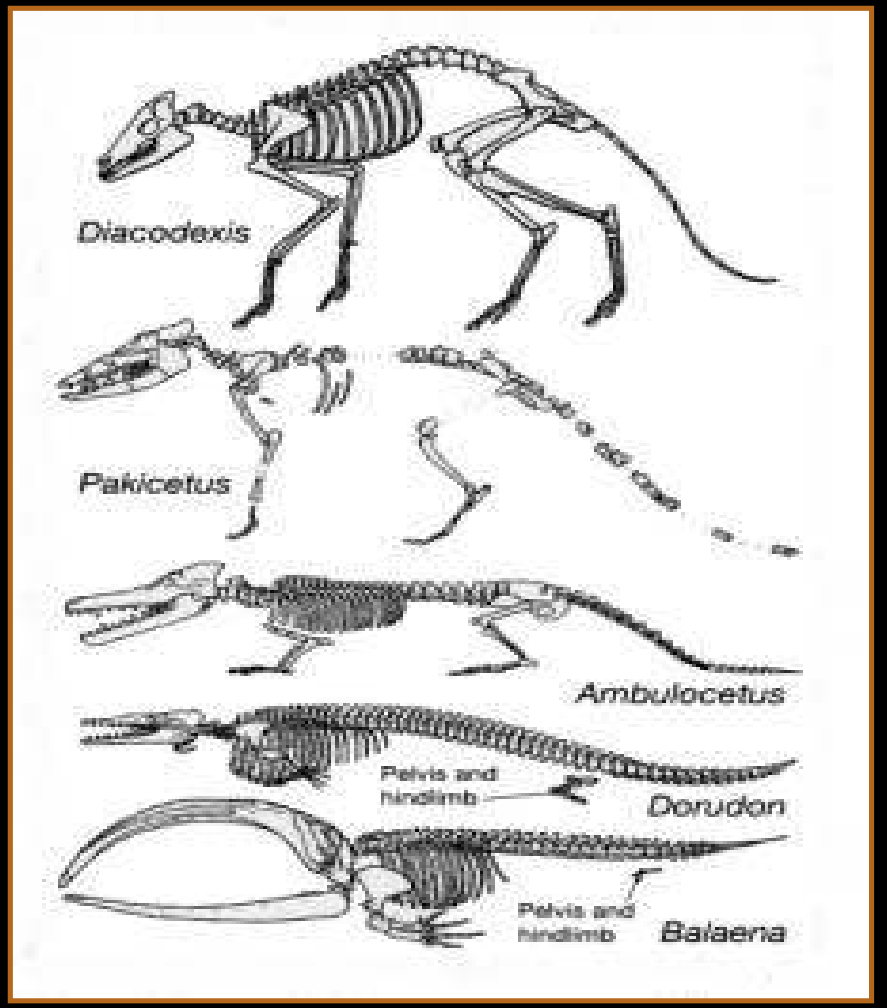




Deer*ish* Mammal to Whale Transition?

Can this geological *pattern* or *progression* of forms be explained by the *processes* of population genetics?

Does neo-Darwinism provide a *causal explanation* for the origin of these new traits and structures?



According to neo-Darwinian evolutionary theory:

Mutations generate variation (the source of new traits).

Natural selection just preserves the successful variations.

Therefore, if many new traits are necessary to produce a new biological form, *many* adaptive mutations must arise and be preserved.

Evolutionary Theory & Population Genetics

The equations of population genetics determine the plausibility of evolutionary transitions by determining the mutational resources available to a given population in a given window of time.

A large number of traits require a large number of mutations.

A Numbers Game. . . …three necessary factors:

Getting enough mutations to produce significant morphological change requires either:

(a) many generations and/or

(b) rapid mutation rates and/or

(c) large population sizes.

One more requirement:

The new adaptive gene variants must become *fixed* in a population (takes even more time).

Without these…

- Variation would have been exhausted in the "walking whale" lineage (e.g., inbreeding depression), or

- Genetic drift would have applied, meaning the entire evolutionary process was random or nearly-random.

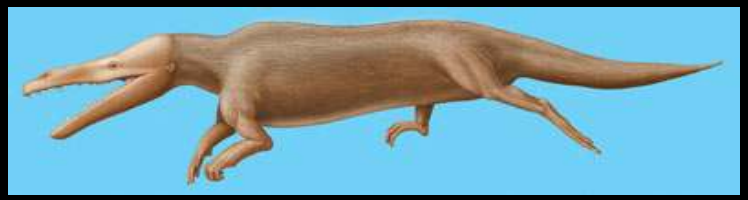
The Transition to Whales: Three Problems

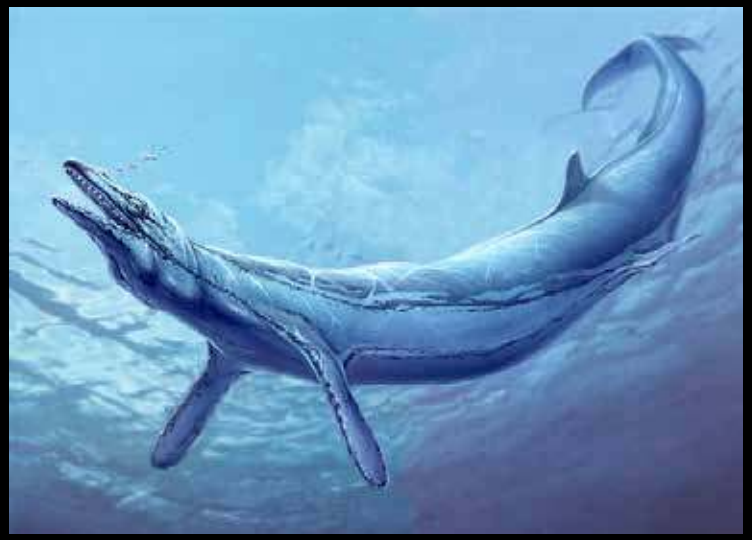
1. Too few generations involved in the transition.

2. Adaptive mutation rates are far too low.

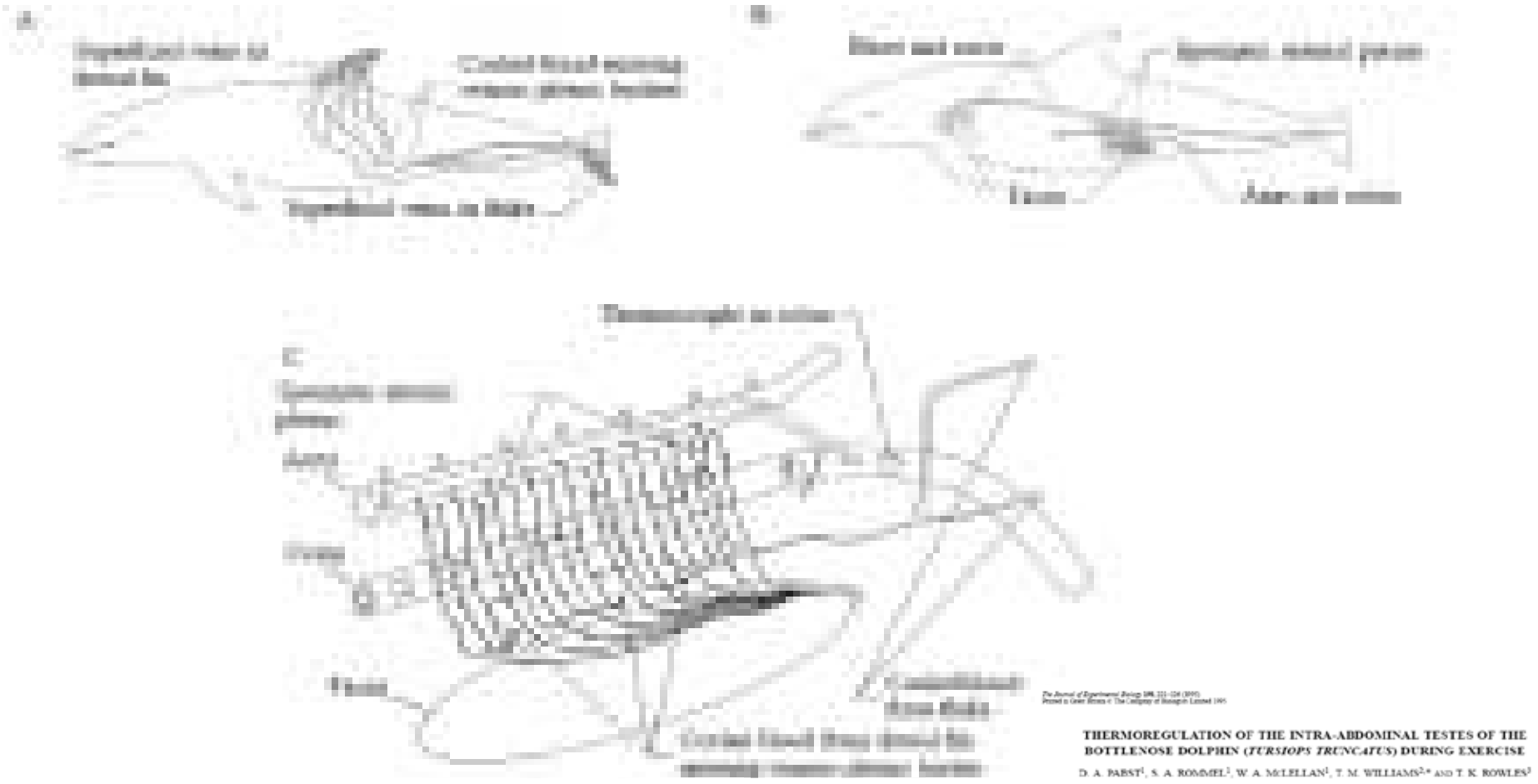
3. Mammalian breeding population sizes are far too small.

Let's think about transitions that had to involve *multiple, coordinated changes* in genes





Intra-abdominal Counter-Current Heat Exchange System



THERMOREGULATION OF THE INTRA-ABDOMINAL TESTES OF THE BOTTLENOSE DOLPHIN (*TURSIOPS TRUNCATUS*) DURING EXERCISE

D. A. PABST[1], S. A. ROMMEL[1], W. A. McLELLAN[1], T. M. WILLIAMS[2,*] AND T. K. ROWLES[3]

The Transition to Whales: Three Problems

1. Too few generations involved in the transition.

2. The numbers of mutations needed are prohibitive.

3. Mammalian breeding population sizes are far too small.

Generating Two Coordinated Beneficial Mutations

Durrett and Schmidt (2008) *("refuting" Michael Behe)* calculated that two simple coordinated mutations would have arisen in the hominid lineage every 216 million years *(chimp/human divergence was ~5.5 million years)*.

For walking whales the equivalent is:

Breeding Population Size	Generations (5 years per)	Years
100,000	8,660,000	43,300,000

Two Coordinated Beneficial Mutations

Documentation of the Math

DOI: 10.1534/genetics.107.082610

Waiting for Two Mutations: With Applications to Regulatory Sequence Evolution and the Limits of Darwinian Evolution

Rick Durrett[*,1] **and Deena Schmidt**[†]

[*]Department of Mathematics and [†]Center for Applied Mathematics, Cornell University, Ithaca, New York 14853

Humans: We now show that two coordinated changes that turn off one regulatory sequence and turn on another without either mutant becoming fixed are unlikely to occur in the human population. We assume

is not satisfied, Theorem 1 predicts a mean waiting time of

$$\frac{1}{2Nu_1\sqrt{u_2}} = \frac{1.73}{2} \times 10^7 = 8.66 \times 10^6 \text{ generations.}$$

Multiplying by 25 years per generation gives 216 million years.

The Nub of The Issue

If the evolutionary process would typically produce only two coordinated mutations in 216 million years in a hominids lineage, and if in aquatic mammals the evolutionary process would only produced two such mutations in 43 million years, how could it have produced fully aquatic whales (with their *multiple* anatomical novelties requiring many hundreds or thousands of coordinated adaptive mutations) in less than 2 million years? Or even less than nine million?

But the Durrett & Schmidt model assumes that the first mutation decreases fitness, so a second one is needed for an adaptive benefit.

So what if we instead assume that all the mutations required were neutral?

So let's suppose that…

1. There is a gene duplicate that is evolving neutrally.

2. Anywhere from one to 10 neutral DNA base changes can convert the extra gene into a sequence that is adaptive.

3. Since mammalian breeding population sizes are on the order of only 10^4-10^5 individuals per generation, let's use both estimates to re-run the math.

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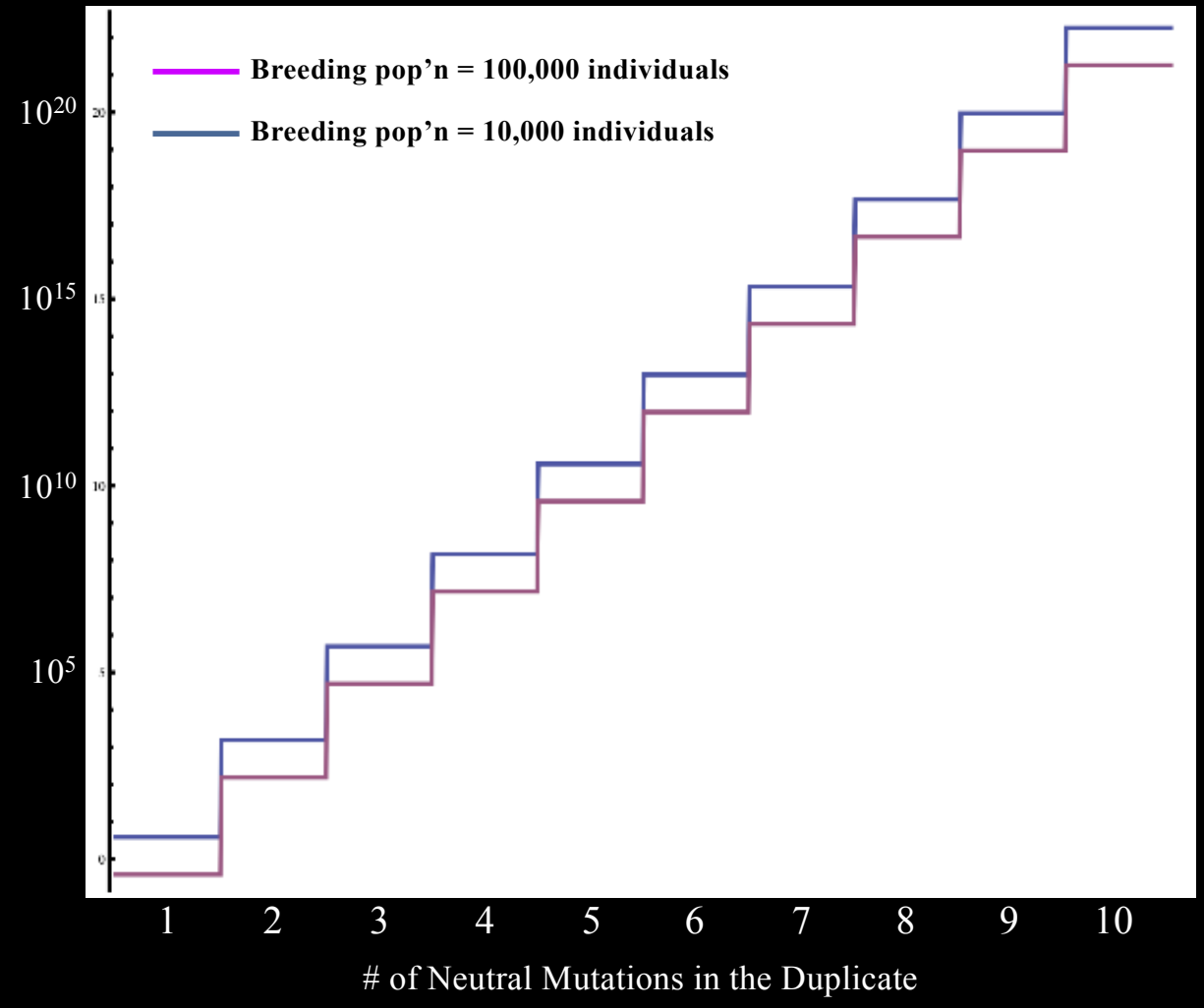
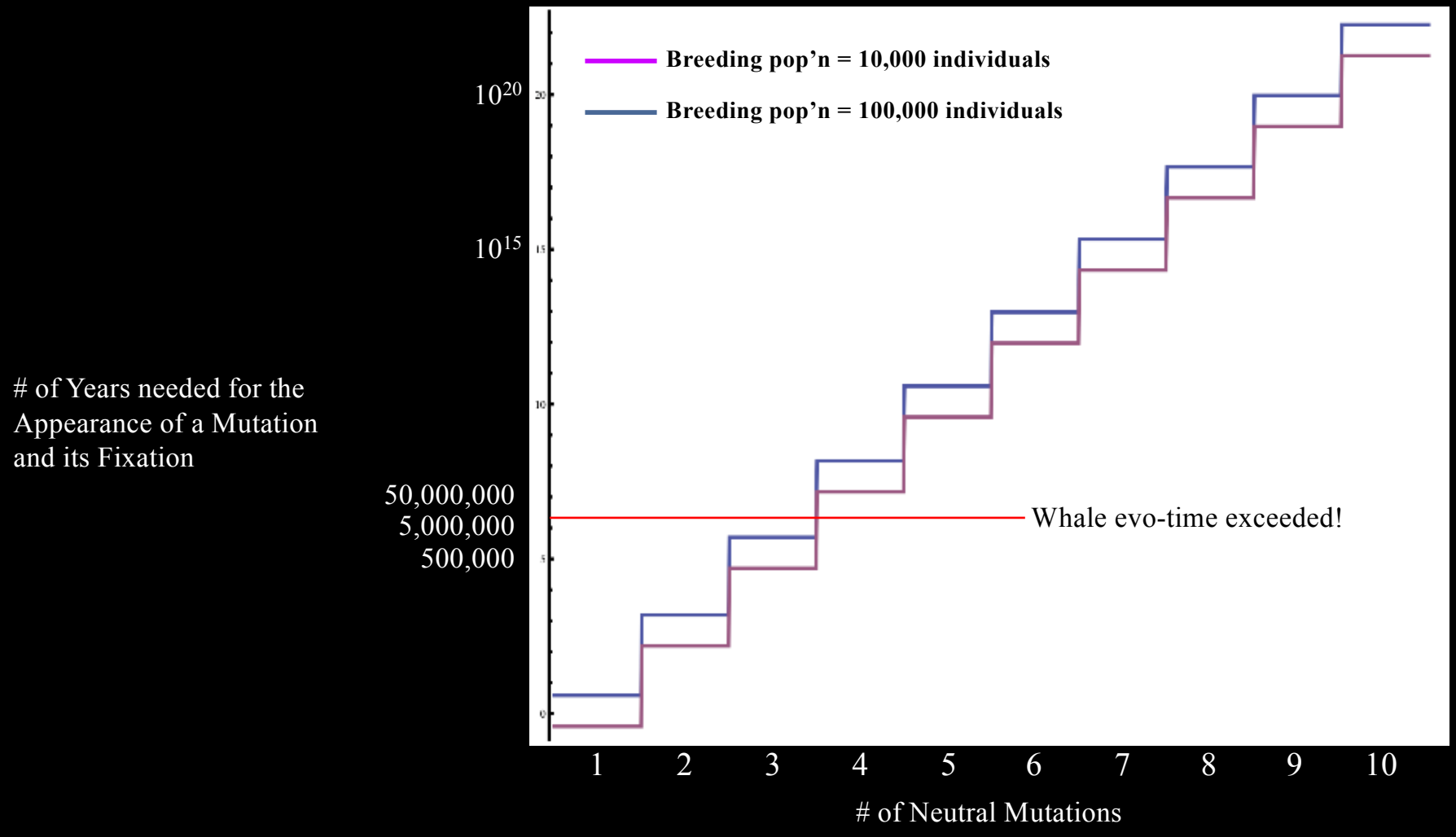
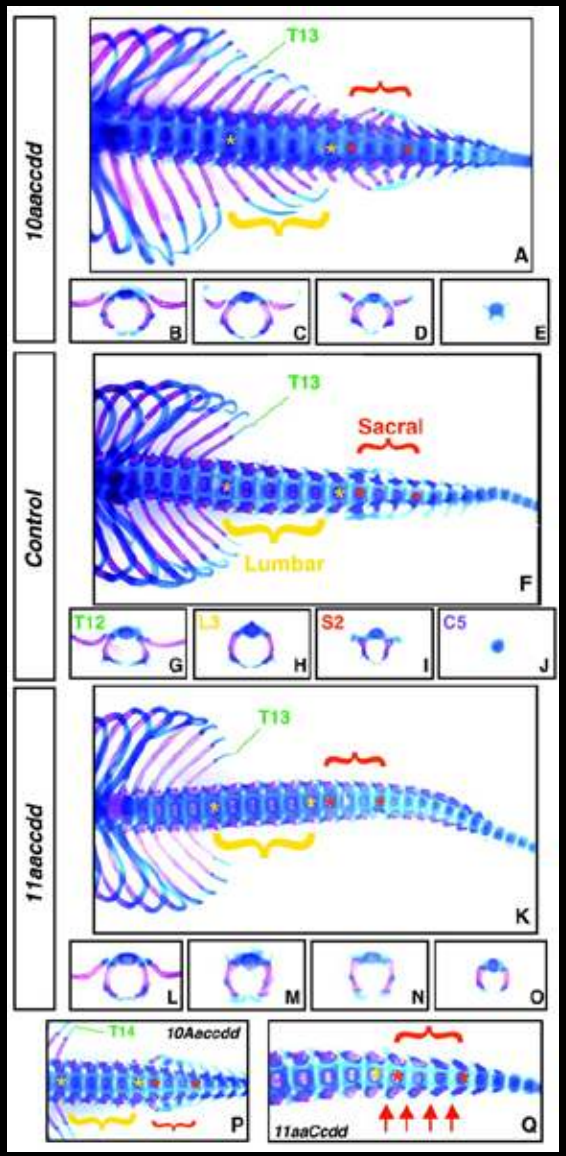
Neutral Mutations



# of Generations needed for the Appearance of a Mutation and its Fixation

Neutral Mutations





So “large developmental mutations” are now being considered…but these don’t turn out so well in mammals.

The Nub of The Issue (Again)

If a neutral evolutionary process would typically need four or more mutations in a duplicate before an adaptive novelty could arise, then there simply was not enough generations or years for this to happen.

But when we look at the number of gene changes required for new functionality, far more than four neutral mutations are needed.

And There are Other Obstacles….

‘[D]irect transition between different "types" is only possible if the transitional forms have all the characters that the ancestral and the derived types have and are thus compatible with the factorization of both types. Transitional forms thus have to go over a "complexity hump" where they have more quasi-independent characters than either the ancestral as well as the derived type. The only logical, but biologically unlikely, alternative is a "hopeful monster" that transforms in a single step from the ancestral type to the derived type.’

Wagner GP, Stadler PF. 2003. Quasi-independence, homology and the unity of type: a topological theory of characters. J Theor Biol. 220(4):505-527.

Too many genetic re-wirings, too little time