Time series analyses in Paleobiology

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3.9.2025 (Wednesday)

What are timeseries (TS) data

What are time series analyses?

Timeseries (TS)

- set of values in sequence representing a variable value at different points in time
- measures collected at regular time intervals** …. … resulting in a set of ordered values
- sampling adjacent points in time introduces a **correlation in the data**

- From a **statistical perspective**, the impact of time resulting from **repeated measurements** over time on a single subject or unit, introduce a **dependency among data points** which *prevents the use of some of the most common statistical techniques*

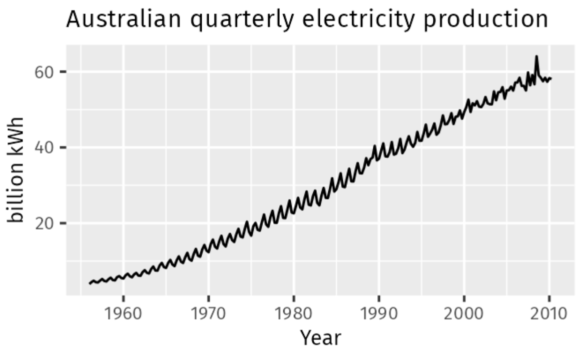
https://nicolarighetti.github.io/Time-Series-Analysis-With-R/basic-concepts.html#time-series

Objectives of time series analyses

- **DESCRIPTION**
  - Temporal trend?
  - Peak at some point?
  - Repeated patterns?

- **EVALUATION** & **EXPLANATION**
  - Impact of a certain event (Before and After)
  - “Drivers” of processes.

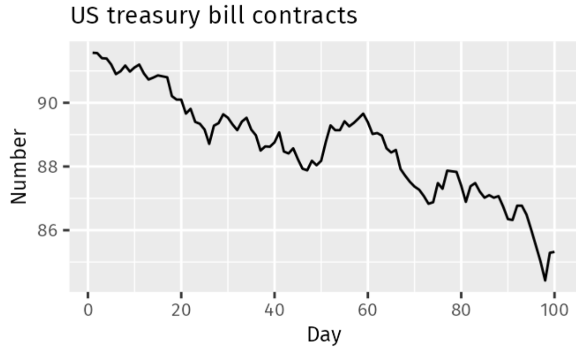
- **FORECASTING**
  - Prediction of the future values of a process

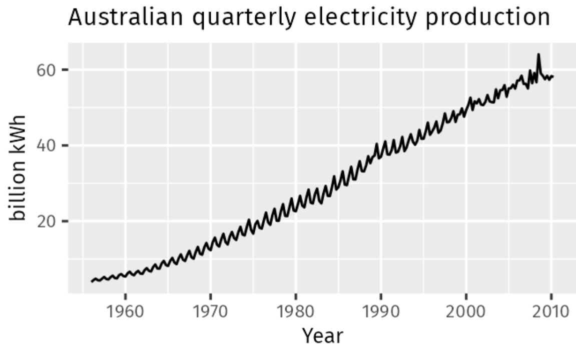


✓ Trend
✓ Seasonanlity
X Cyclicty

https://otexts.com/fpp2/tspatterns.html

✓ Trend
X Seasonanlity
X Cyclicty





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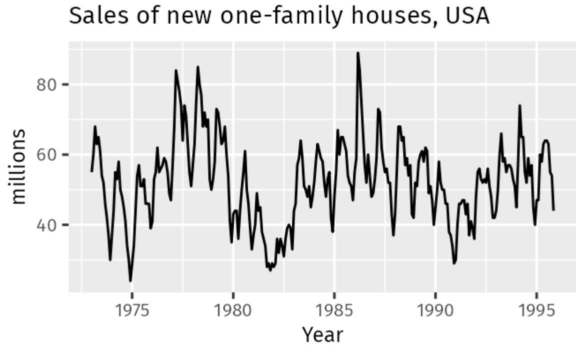

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X Seasonanlity
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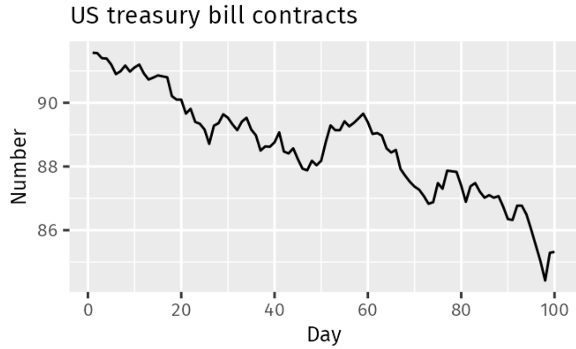
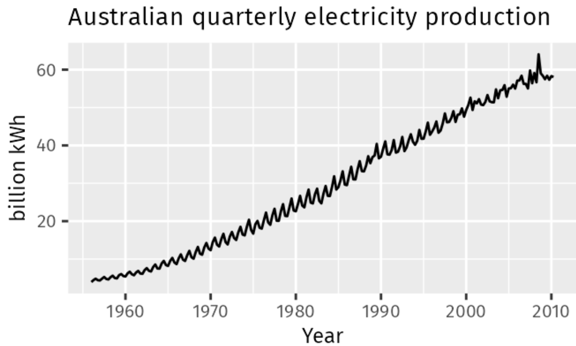




✓ Trend
✓ Seasonanlity
X Cyclicty

https://otexts.com/fpp2/tspatterns.html

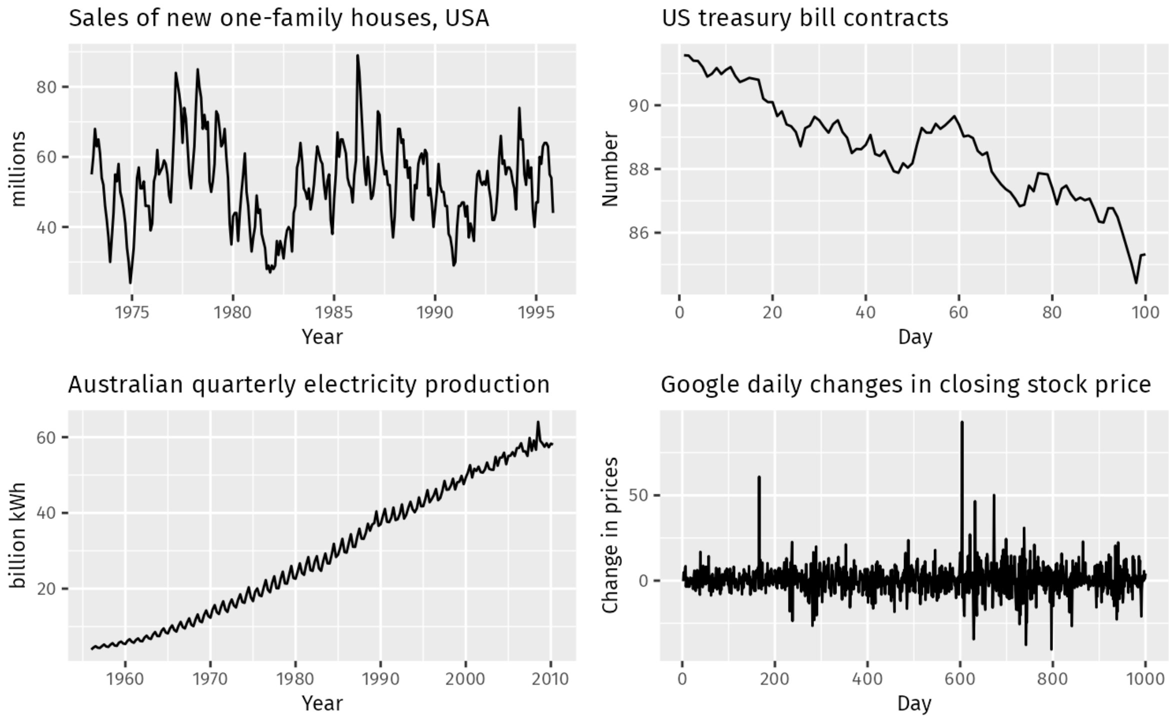
Trends:
long-term increase or decrease in the data

Seasonal:
affected by seasonal factors e.g. time of the year or the day of the week:
always of a fixed and known frequency

Cyclic:
exhibit rises and falls that are not of a fixed frequency

X Trend
✓ Seasonanlity
✓ Cyclicty

✓ Trend
X Seasonanlity
X Cyclicty



✓ Trend
✓ Seasonanlity
X Cyclicty

X Trend
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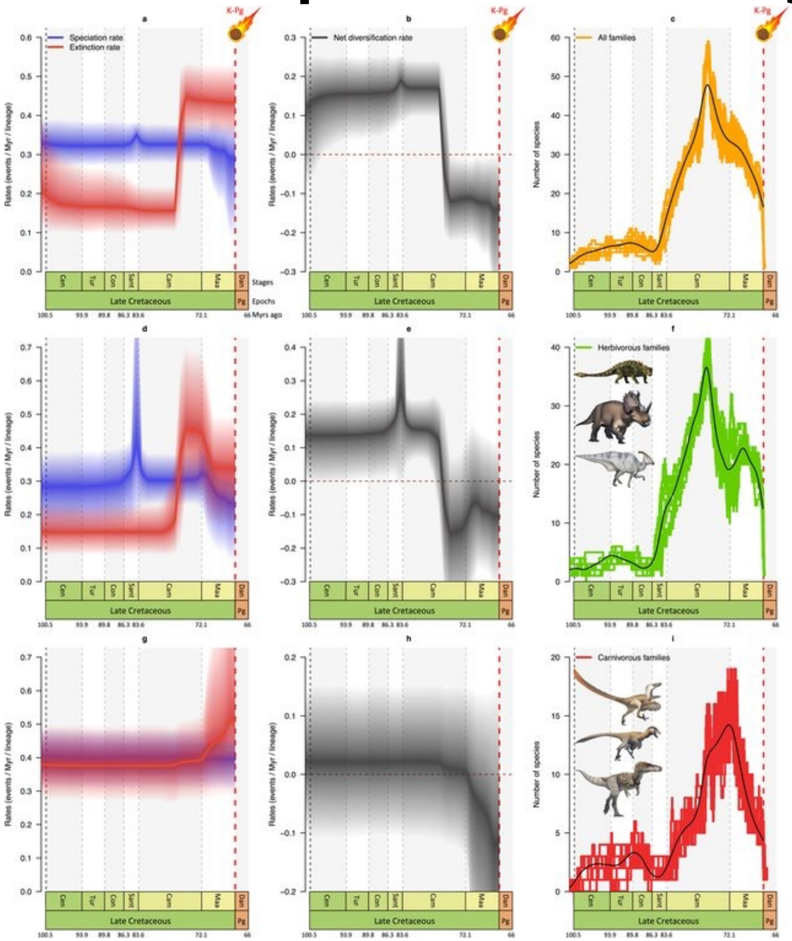
X Cyclicty

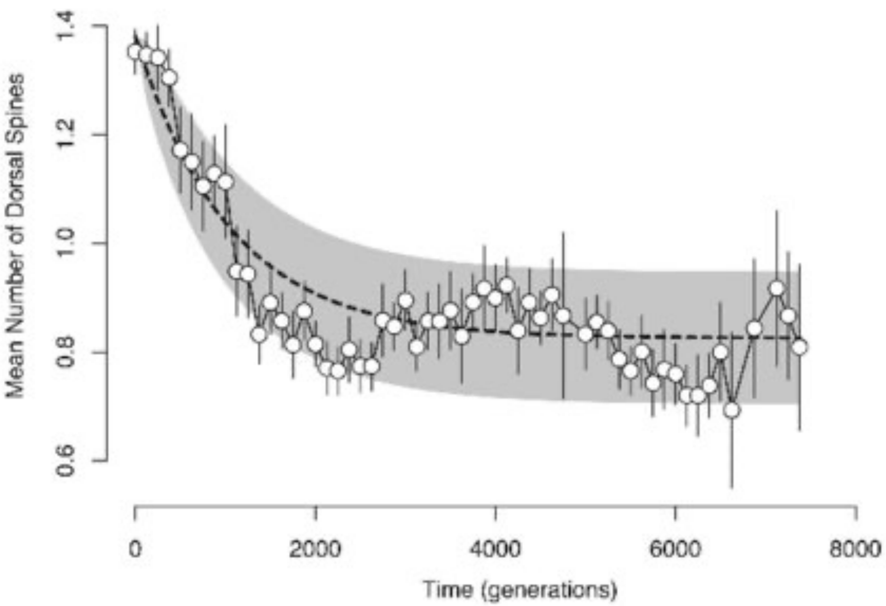
https://otexts.com/fpp2/tspatterns.html

Some paleontological time series



Condamine *et al.* Dinosaur biodiversity declined well before the asteroid impact, influenced by ecological and environmental pressures. *Nat Commun* **12**, 3833 (2021). https://doi.org/10.1038/s41467-021-23754-0

Some paleontological time series



https://earthathome.org/wp-content/uploads/2022/04/Gasterosteus-williamsoni-Quaternary-LahontanFm-Nevada.jpg

Hunt G.2010 Evolution in fossil lineages: paleontology and The Origin of Species. Am Nat.

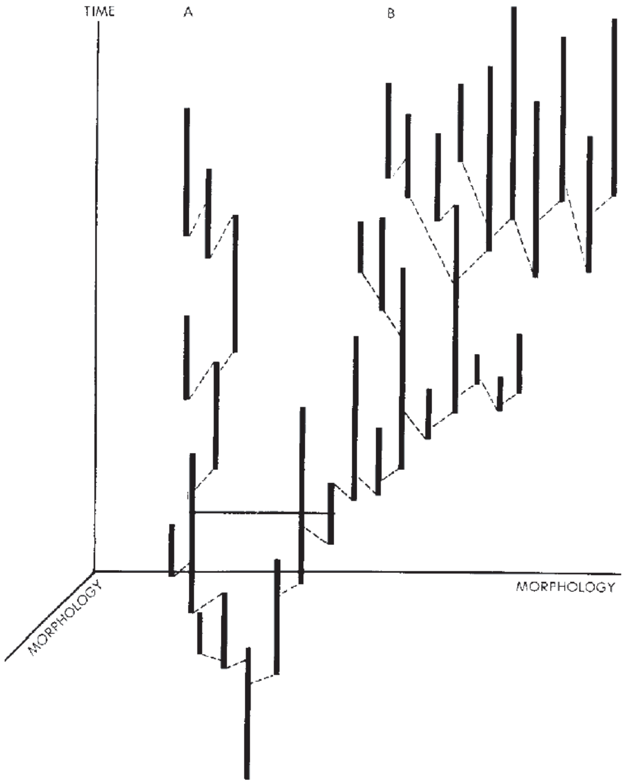
Time series concepts

- Time series data are temporally autocorrelated
- We can study TS in their time or frequency domains (spectral analyses)
- Sometimes folks massage their data so it resembles white noise (WN) so it is easier to analyse (it's a bit like transforming your data so it "behaves well" for standard statistical models that assume that the data are normally distrbuted.
- What is WN? (a TS whose statistical properties like mean, variance and autocorrelation remain constant over time, staionary, looks the same anywhere you look)
- What is a RW (you often hear about this in paleobiology)? Is that WN?
- RW is X(at time t)= X (at time t-1) + white noise (at t)

One major example

- Important historically in paleontology
- Important in time series tool development in both evolutionary biology (comparative phylogenetics) and paleontology

Eldredge and Gould 1972 Punctuated equilibria: an alternative to phyletic gradualism *in* ***Models in Paleobiology.***



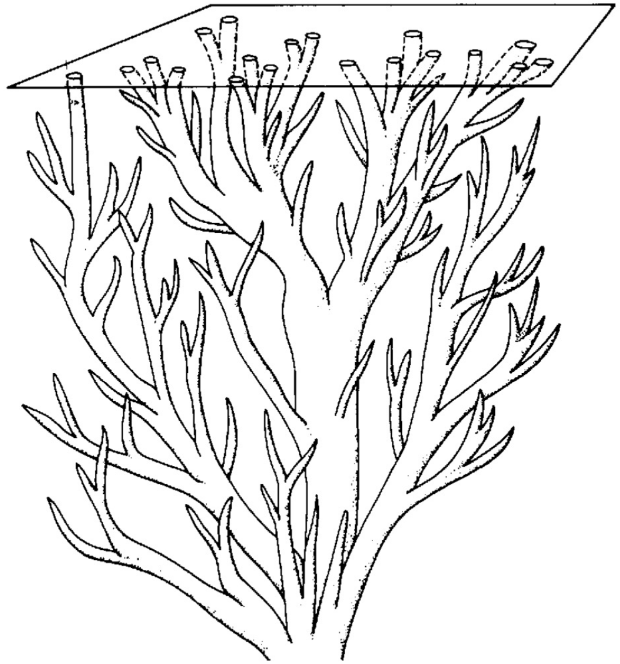
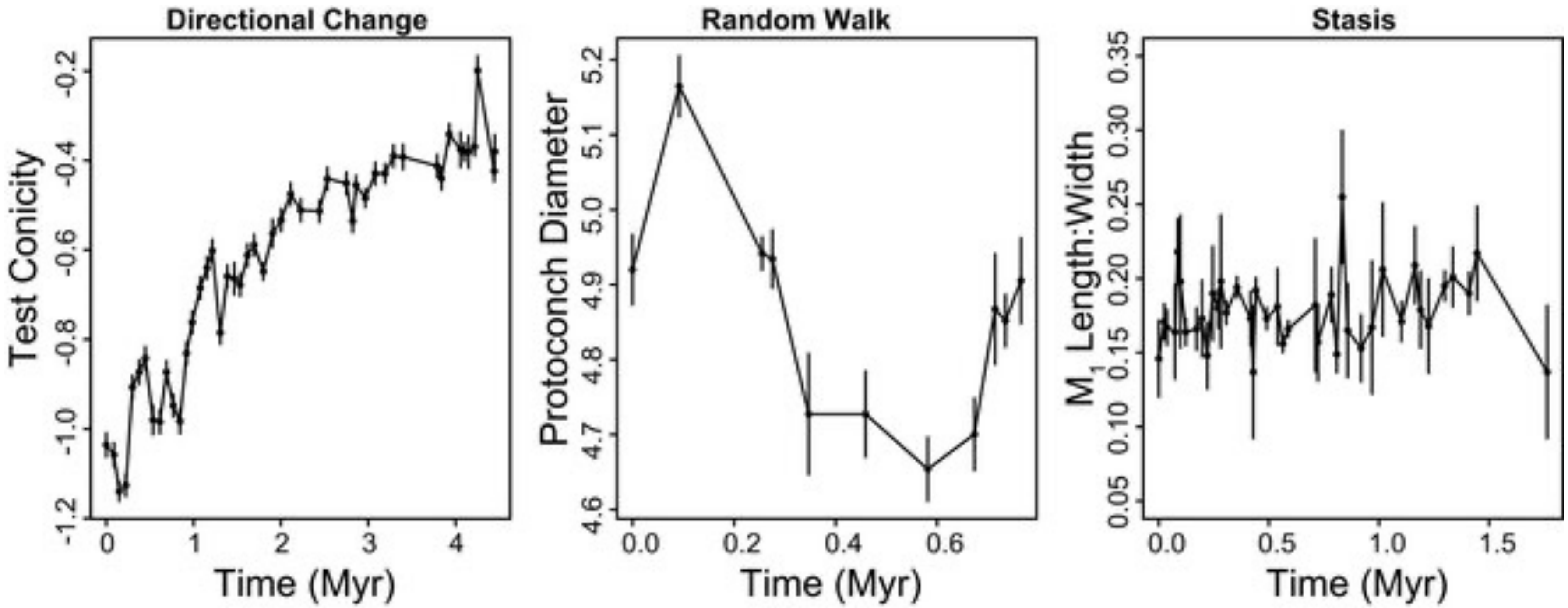


Figure 5–9: The "Tree of Life" viewed from the perspective of phyletic gradualism. Branches diverge gradually one from the other. A slow and relatively equal rate of evolution pervades the system. From Weller, 1969; figure 637.

Punc eq : canonical phenotypic models



Hunt 2010. Evolution in fossil lineages: paleontology and the origin of species. The American Naturalist 176:S61–S76.

R package PaleoTS

Hunt 2008 Gradual or pulsed evolution: when should punctuational explanations be preferred? **Paleobiology** 34:60-377

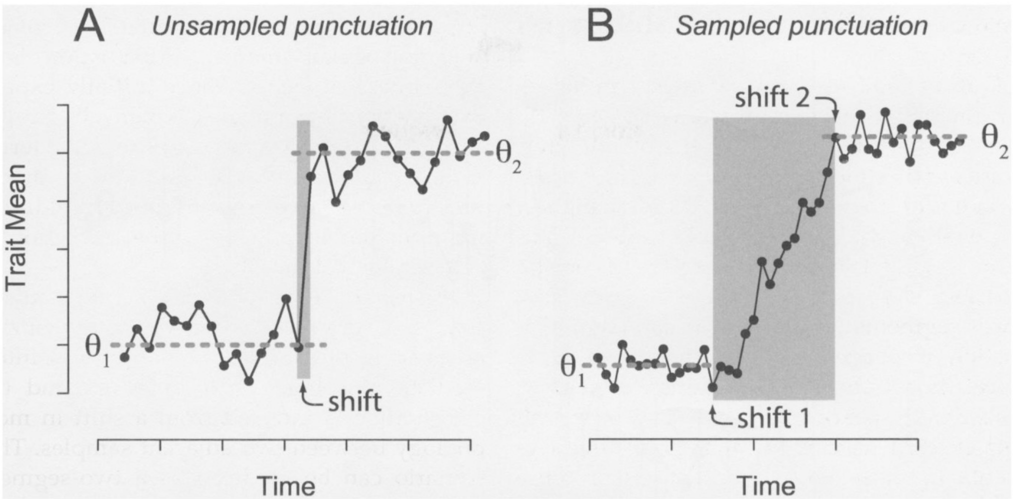
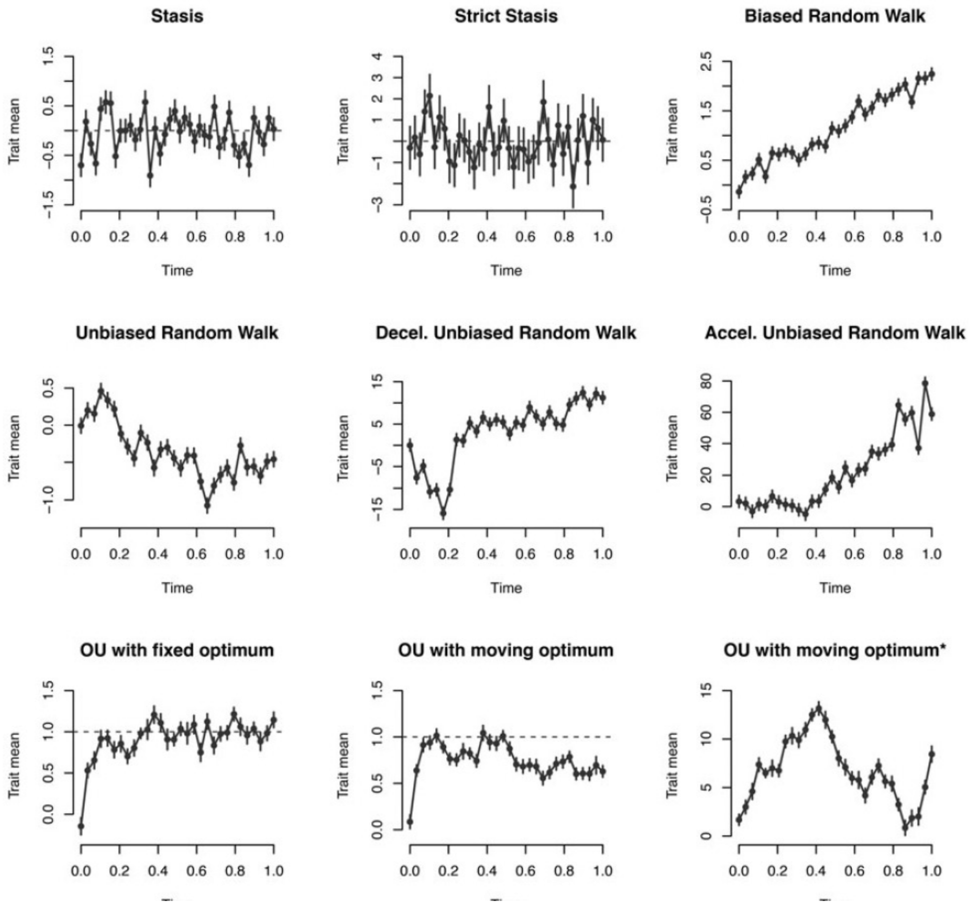


FIGURE 1. Illustrations of two kinds of punctuated change: unsampled punctuations (A), in which few or no intermediate populations are captured; and sampled punctuations (B), in which multiple populations from the transition interval are observed. Unsampled punctuations can be modeled effectively as two intervals of stasis with different optima (θ_1 and θ_2); the magnitude of punctuated change is determined by the difference in the two optimal values. For sampled punctuations, the interval of directional change is modeled explicitly as a general random walk inserted between two periods of stasis.

More models (evoTS)



Voje, K. L. 2023. Fitting and evaluating univariate and multivariate models of within-lineage evolution. Paleobiology 49:747–764.

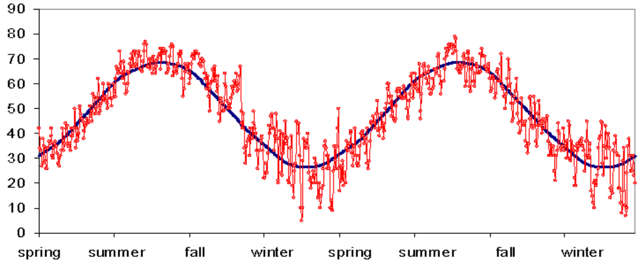
Objectives of time series analyses

- **DESCRIPTION**
  - Temporal trend?
  - Peak at some point?
  - Repeated patterns?
  - Tipping points, break points

- **EVALUATION** & **EXPLANATION**
  - Impact of a certain event (Before and After)
  - "Drivers" of processes.

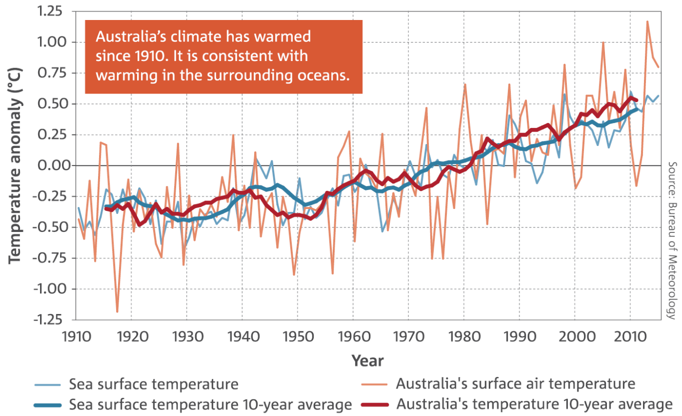
- **FORECASTING**
  - Prediction of the future values of a process

- Study one time series by itself
    - Patterns
    - Structure
    - Parameters

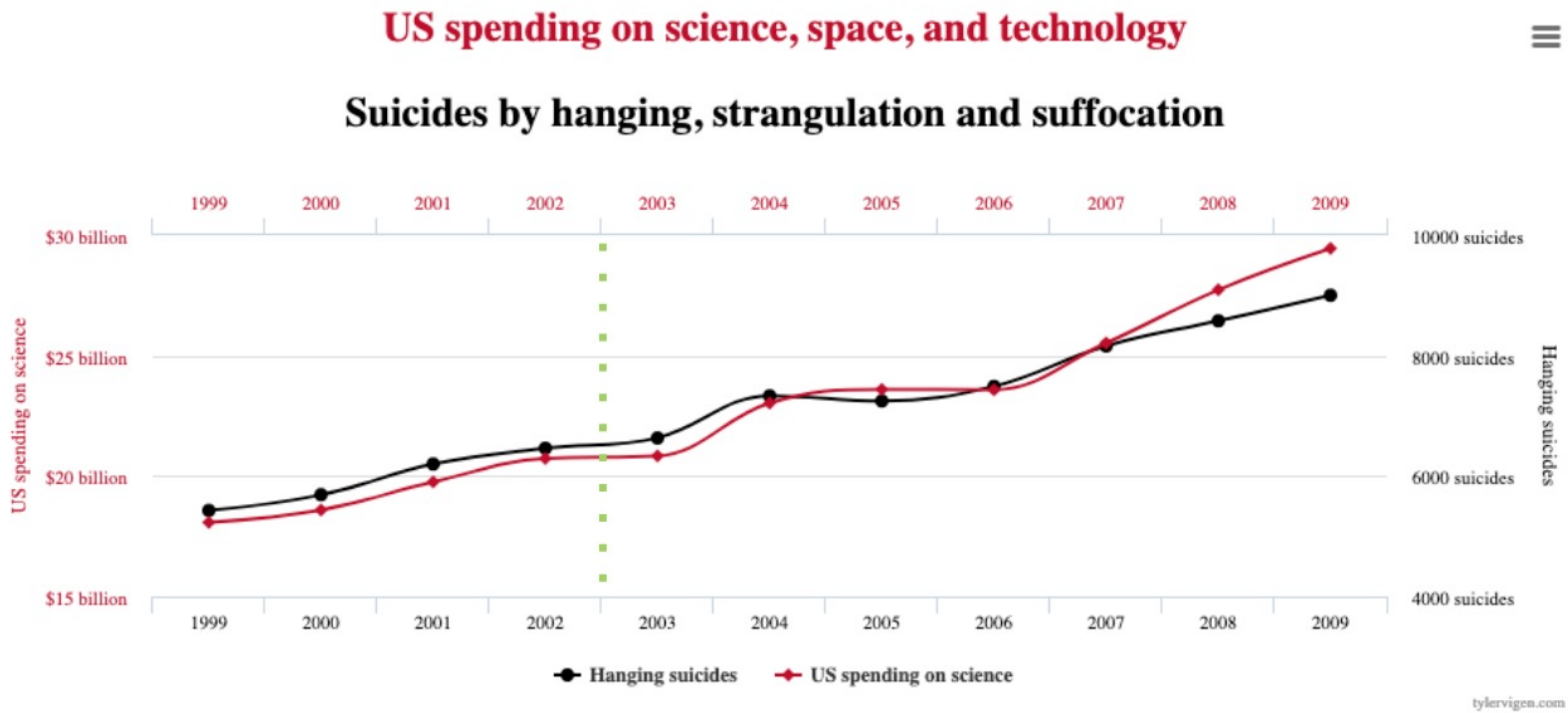


https://training.weather.gov/pds/climate/pcu2/statistics/Stats/part1/CTS_PFtmin.png

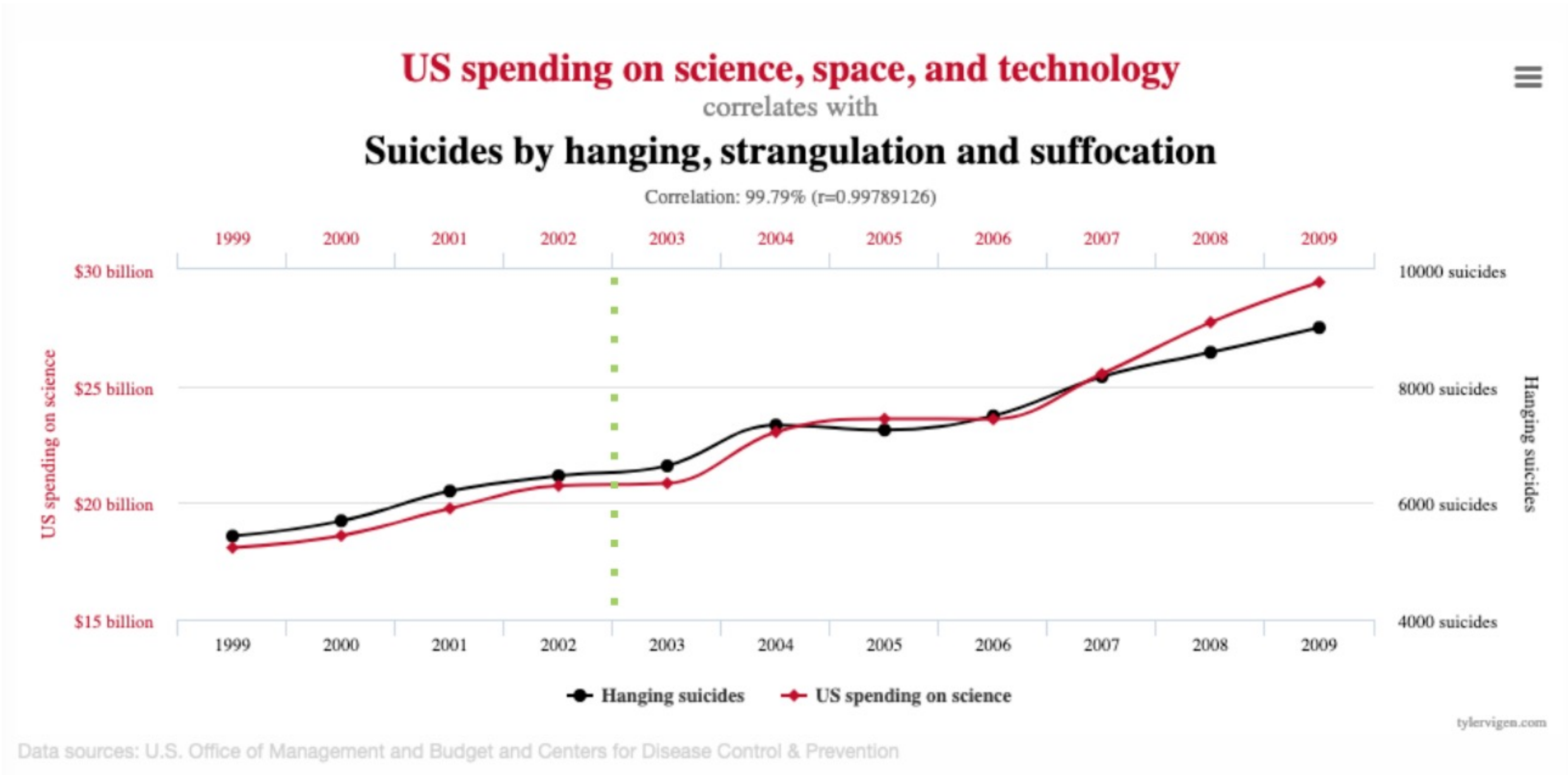
- Relationship(s) between 2 or more time series



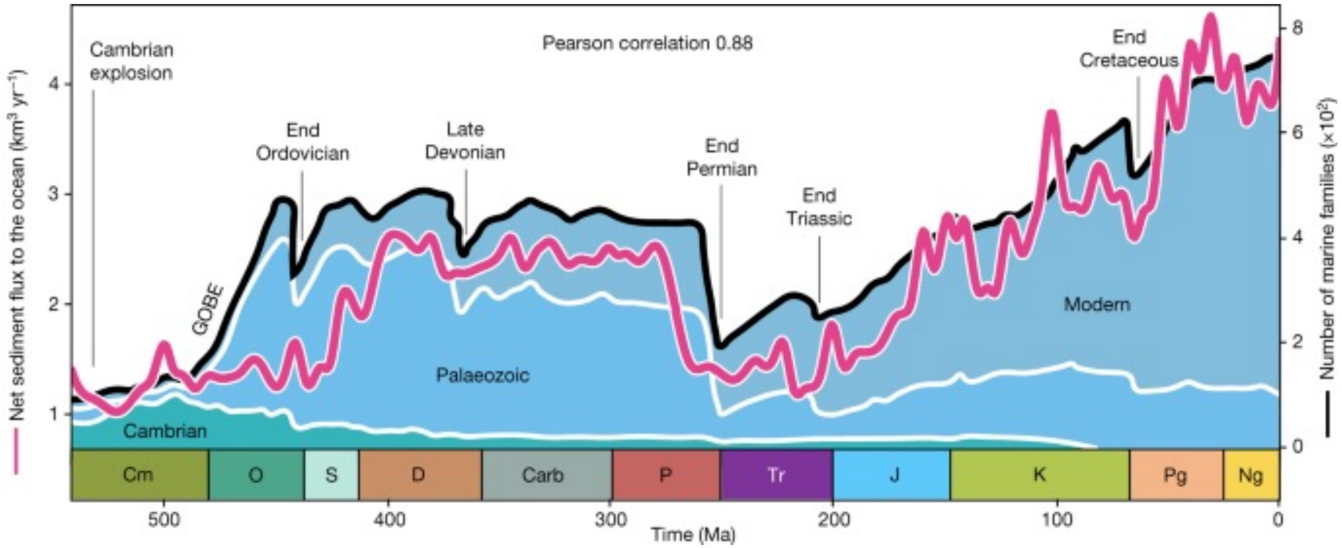
http://www.bom.gov.au/state-of-the-climate/images/2016-03_p4.png



Data sources: U.S. Office of Management and Budget and Centers for Disease Control & Prevention



https://www.michaeldiamond.com/beware-spurious-correlations/

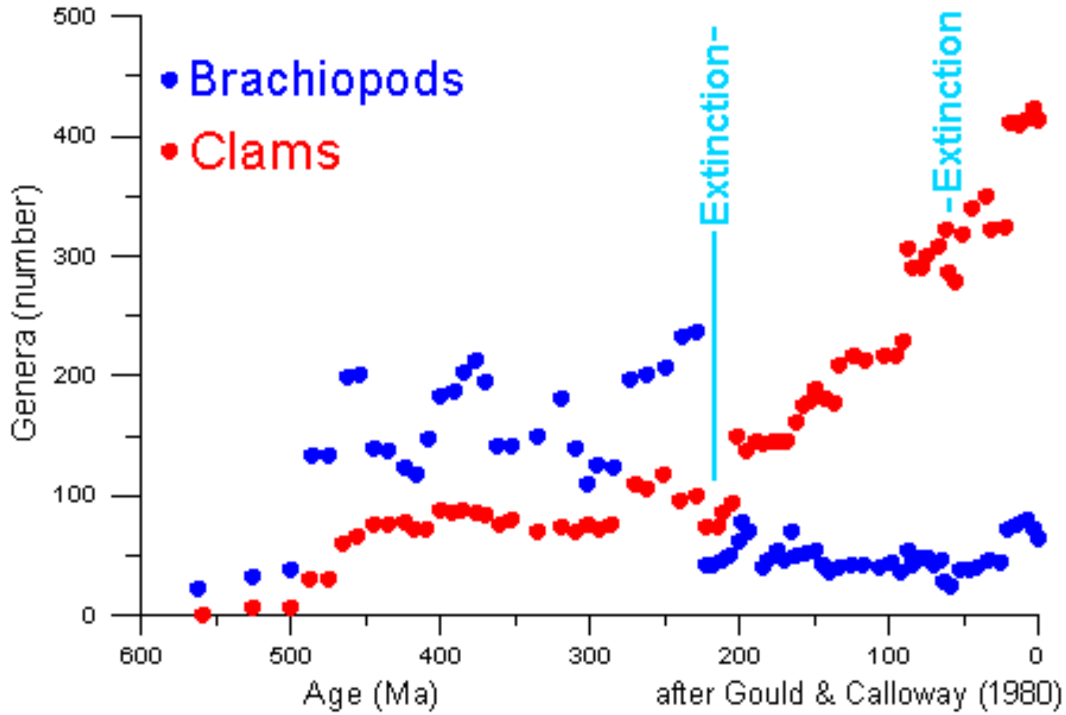


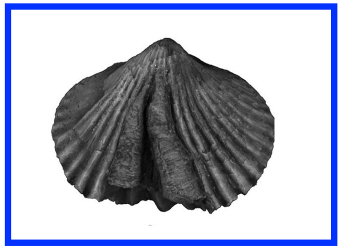
[redacted] Landscape dynamics and the Phanerozoic diversification of the biosphere Nature 624: 115–121

“The reconstructed net sediment flux to the ocean and the total number of marine families are strongly correlated (Pearson coefficient 0.88) and sediment flux variation markedly matches the three main phases that span the Phanerozoic eon (Fig. 3 and Extended Data Fig. 10a). This suggests that nutrient availability is a prime control on marine diversity.”

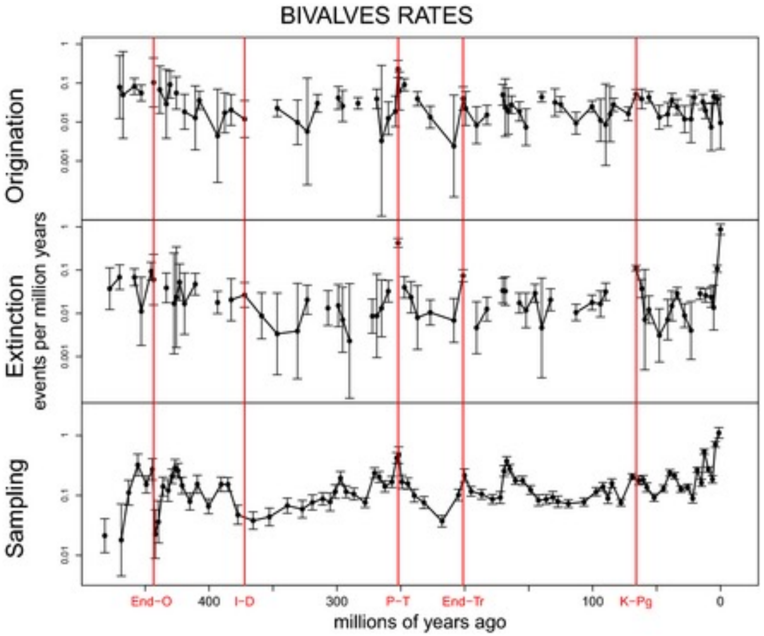
Gould & Calloway 1980 Clams and Brachiopods-Ships That Pass in the Night. Paleobiology

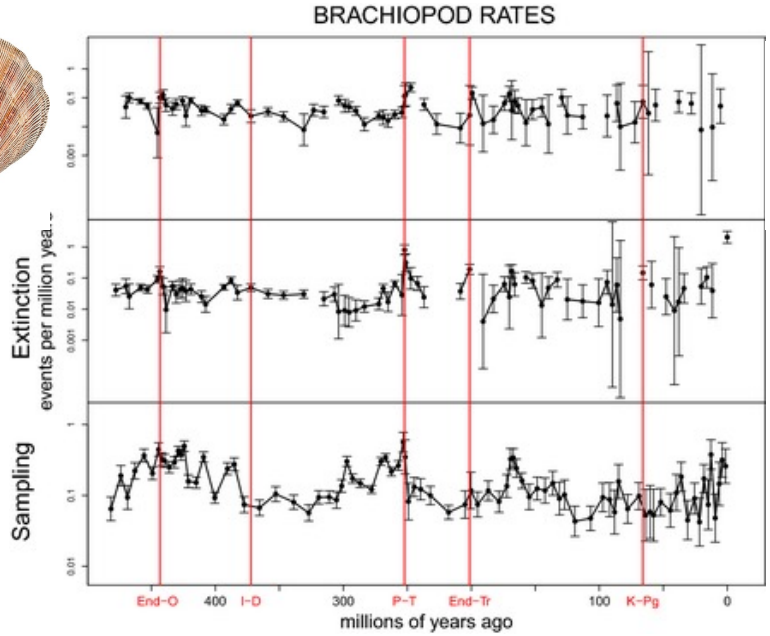
“The supposed replacement of brachiopods by clams is not gradual and sequential. It is a product of one event: the Permian extinction (which affected brachiopods profoundly and clams relatively little).”



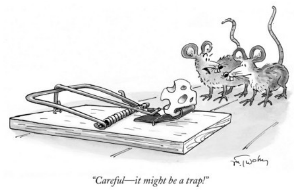


https://www.geo.arizona.edu/Antevs/ecol438/clambrac.html

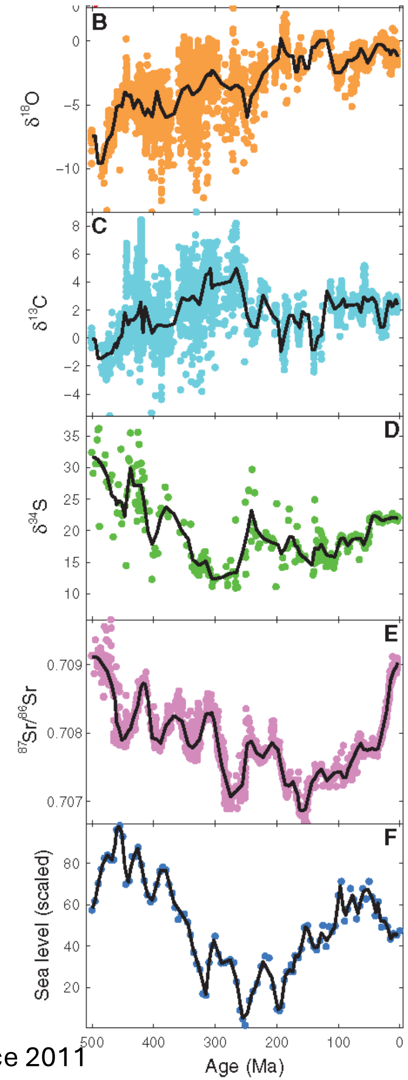


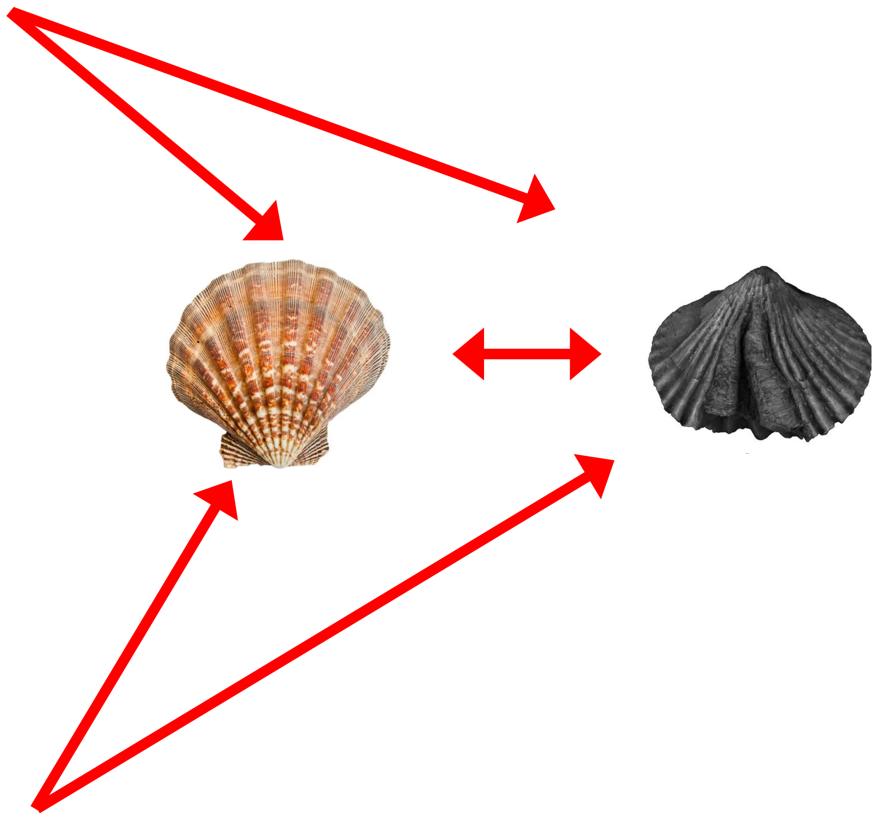


Liow, Reitan & Harnik 2015 Ecological interactions on macroevolutionary time scales: clams and brachiopods are more than ships that pass in the night. Ecology Letters

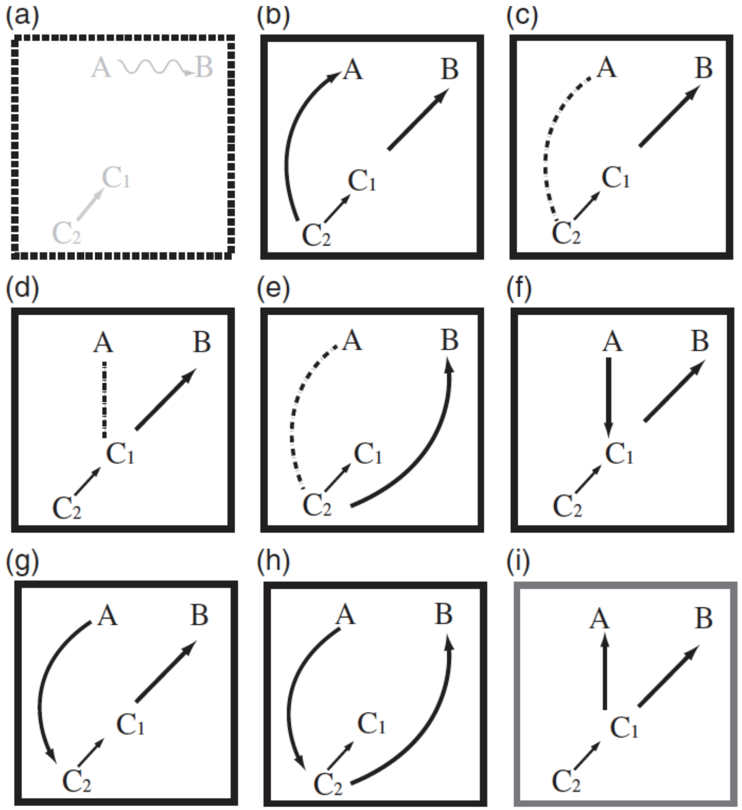


Hypotheses





Data from Hannisdal and Peters Science 2011



Reitan, T. and Liow, L.H. (2019) layeranalyzer: Inferring correlative and causal connections from time series data in R. *Methods Ecol. Evol.* 10, 2183–2188

Granger causality via linear Stochastic Differential Equations (SDEs)

Deterministic part

Stochastic part

$$dX_1(t) = -\alpha_1(X_1(t) - \mu_1)dt + \sigma_1 dB_1(t)$$

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Tore Schweder
University of Oslo, Norway

Deterministic part

Stochastic
part

$$dX_1(t)=-\alpha_1(X_1(t)-\mu_1)dt+\sigma_1 dB_1(t)$$

X_2 is correlated with X_1

$$dX_2(t)=-\alpha_2(X_2(t)-\mu_2)dt+\sigma_2(1-\boxed{\rho^2})^{0.5}dB_2(t)+\boxed{\rho}\sigma_2 dB_1(t)$$

Deterministic part

Stochastic part

$$dX_1(t)=-\alpha_1(X_1(t)-\mu_1)dt+\sigma_1 dB_1(t)$$

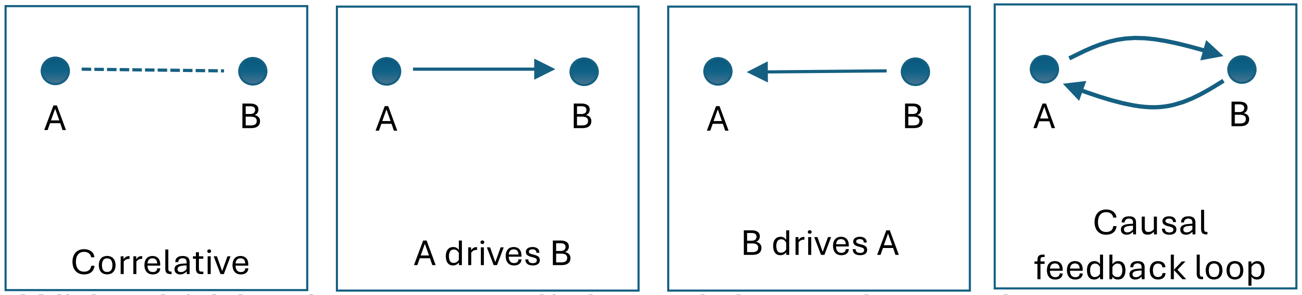
X_2 is correlated with X_1

$$dX_2(t)=-\alpha_2(X_2(t)-\mu_2)dt+\sigma_2(1-\boxed{\rho^2})^{0.5}dB_2(t)+\boxed{\rho}\sigma_2 dB_1(t)$$

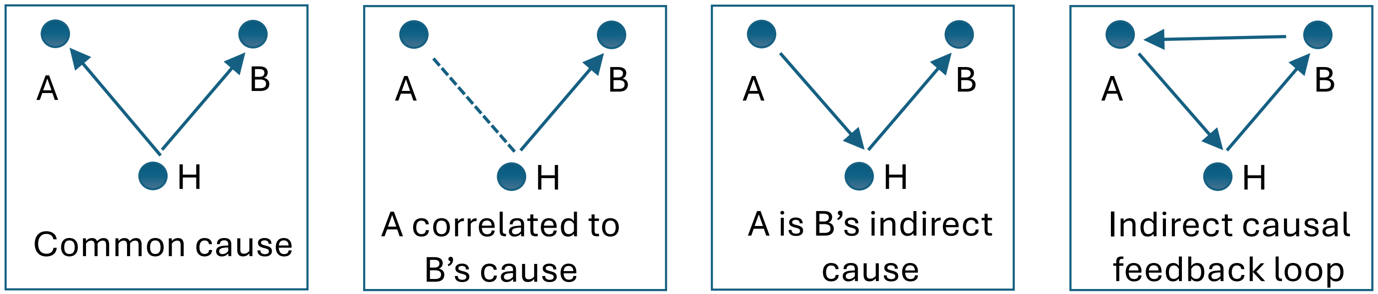
X_2 is driven by X_1

$$dX_2(t) = -\alpha_2(X_2(t)-\mu_2-\boxed{\beta}[X_1(t) -\mu_1])dt)+\sigma_2 dB_2(t)dt$$

Link models that can be built using linear SDEs



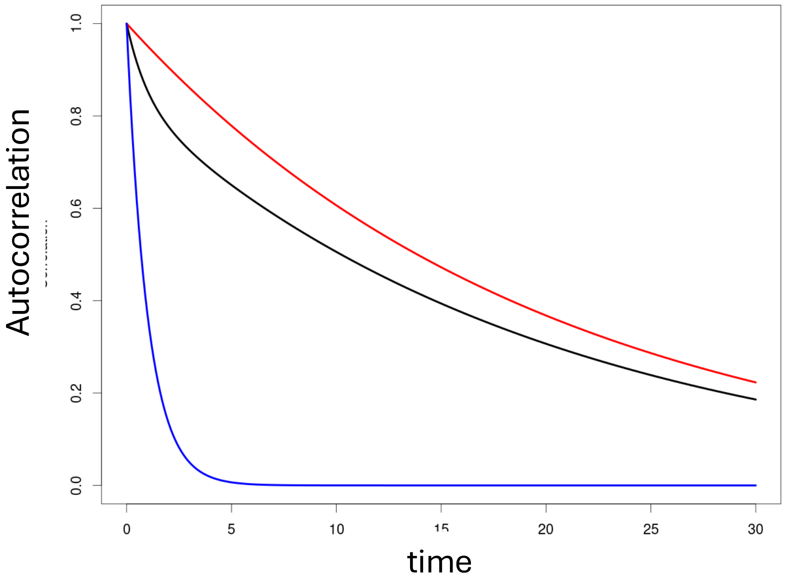
With a hidden layer, more link models can be made



etc!

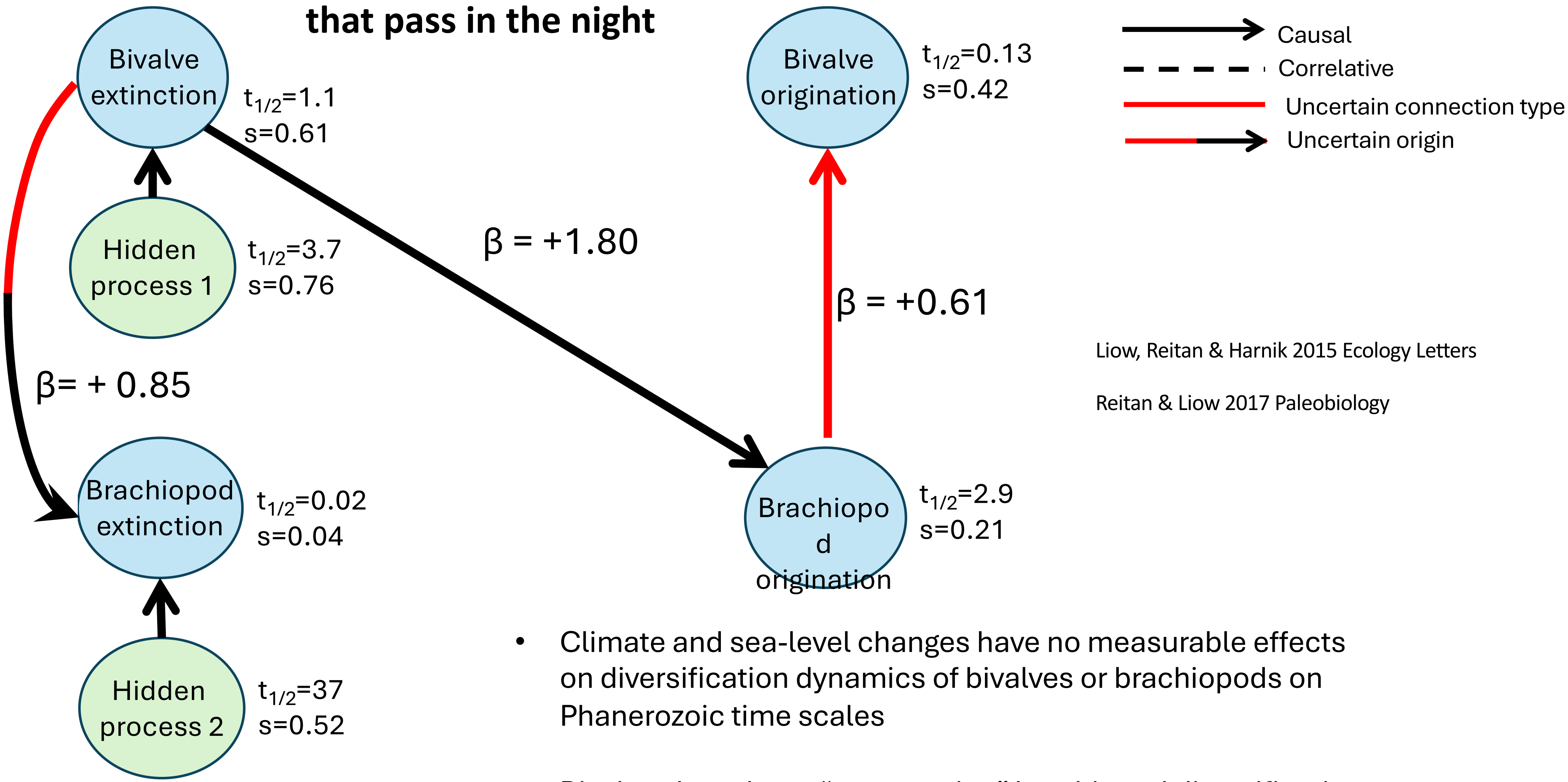
Hidden layers – not black magic

The hidden (bottom) layer can be found by its imprint on the observed (top) layer.



Red=autocorr. of only bottom layer
Black=autocorrelation of 2-layered system
Blue=autocorrelation of only top layer

Clams and brachiopods are more than ships that pass in the night

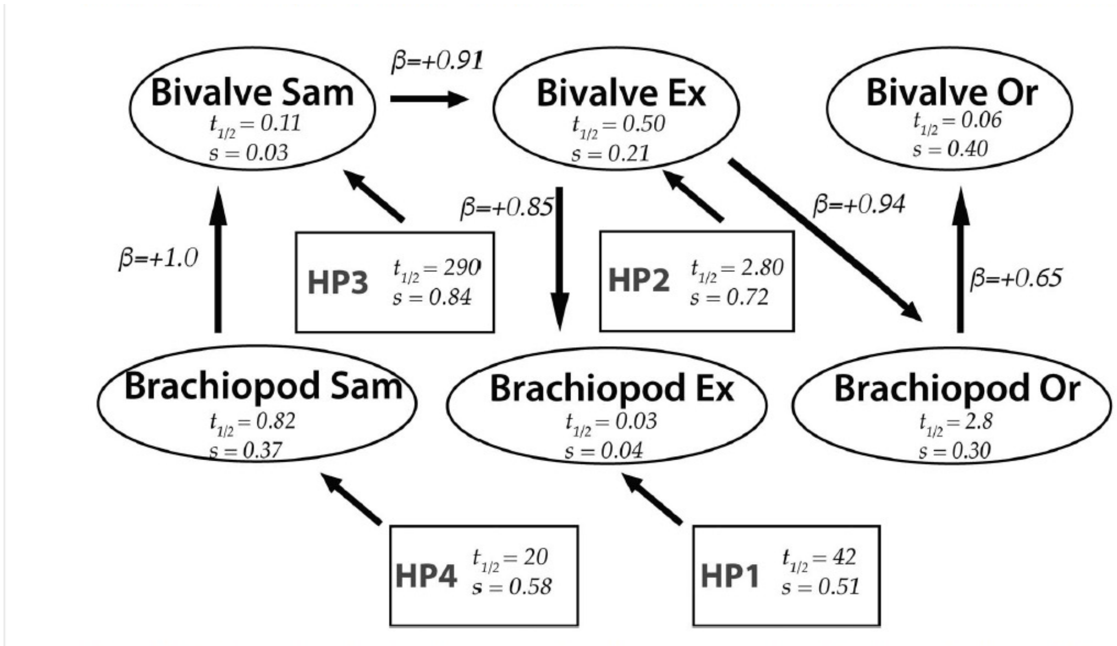


Liow, Reitan & Harnik 2015 Ecology Letters

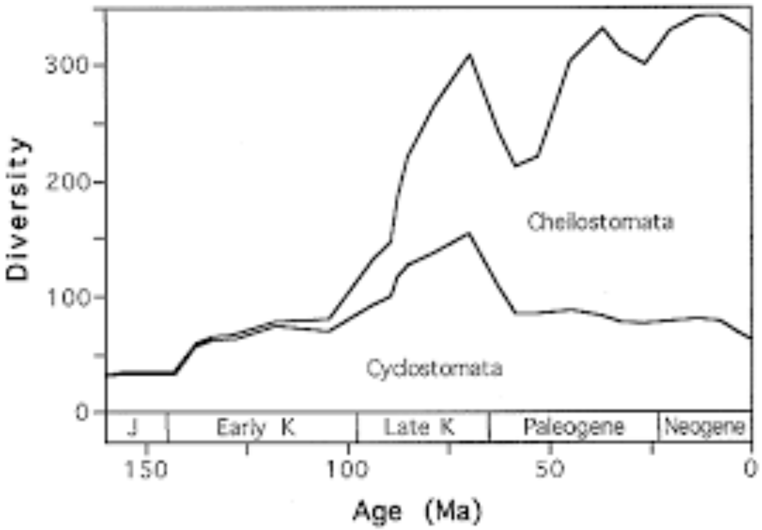
Reitan & Liow 2017 Paleobiology

- Climate and sea-level changes have no measurable effects on diversification dynamics of bivalves or brachiopods on Phanerozoic time scales

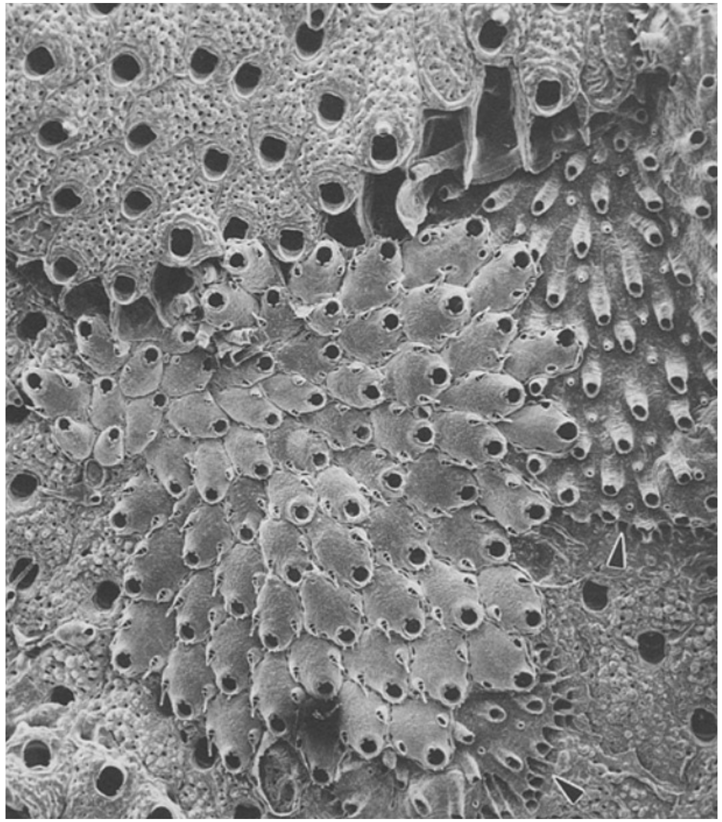
- Bivalves have been “suppressing” brachiopod diversification

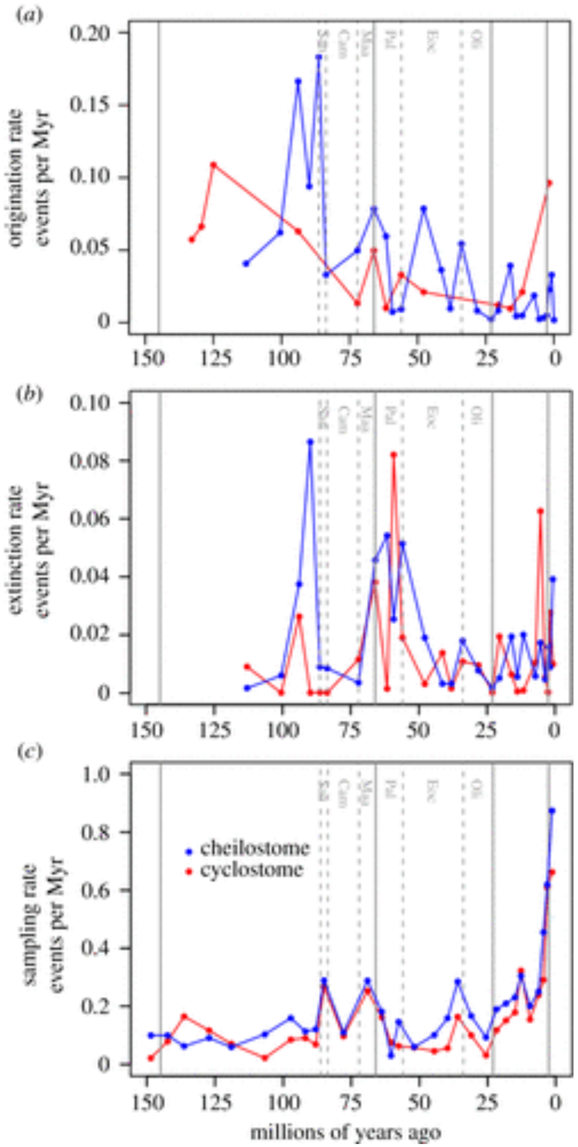


Reitan, T. and Liow, L.H. (2017) An unknown Phanerozoic driver of brachiopod extinction rates unveiled by multivariate linear stochastic differential equations. *Paleobiology* DOI: 10.1017/pab.2017.11



Sepkoski, McKinney &Lidgard. 2000. Competitive displacement among post-Paleozoic cyclostome and cheilostome bryozoans. Paleobiology 26:7–18.





Lidgard, Di Martino, Zágoršek & Liow 2021 When fossil clades 'compete': local dominance, global diversification dynamics and causation. *Proc Biol Sci*.

Cheilostomes and cyclostomes are also more than ships that pass in the night

models	time series 1. cheil orig 2. cycl orig	1. cheil ext 2. cycl ext	1. cheil orig 2. cycl ext	1. cheil ext 2. cycl orig
A. no relationship between time series	41.8	11.4	49.2	24.1
B. 1st time-series drives 2nd	10.5	22.9	11.4	9.8
C. 2nd time-series drives 1st	20.4	13.4	14.5	24.4
D. temporal feedback between time series	17.9	44.0	14.6	31.2
E. correlation between time series	9.4	8.3	10.2	10.5
	1. cheil orig 2. proportion	1. cheil ext 2. proportion	1. cycl orig 2. proportion	1. cycl ext 2. proportion
A. no relationship between time series	34.9	73	44.4	38.2
B. 1st time-series drives 2nd	18.5	11.8	14.4	12.1
C. 2nd time-series drives 1st	14.7	10.6	15	16.9
D. temporal feedback between time series	25.2	0	18.4	24.9
E. correlation between time series	6.6	4.6	7.8	7.9

Cheilostomes and cyclostomes are also more than ships that pass in the night

models	time series 1. cheil orig 2. cycl orig	1. cheil ext 2. cycl ext	1. cheil orig 2. cycl ext	1. cheil ext 2. cycl orig
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E. correlation between time series	9.4	8.3	10.2	10.5

Model D	Mean	Median	Lower 5%	Upper 95%
μ.cheilostome.extinction	-2.126	-2.088	-3.641	-0.605
$t_{1/2}$cheilostome.extinction	30.3445	14.1167	0.719	136.945
σ.cheilostome.extinction	0.288	0.294	0.002	0.623
μ.cyclostome.extinction	-2.459	-2.527	-3.728	-0.939
$t_{1/2}$.cyclostome.extinction	13.710	3.474	0.460	77.983
σ.cyclostome.extinction	0.195	0.152	0.002	0.6467
β.cheilostome.extinction.to.cyclostome.extinction	0.522	0.572	-0.345	1.212
β.cyclostome.extinction.to.cheilostome.extinction	0.326	0.442	-1.017	1.315
Model B				

Cheilostomes and cyclostomes are also more than ships that pass in the night

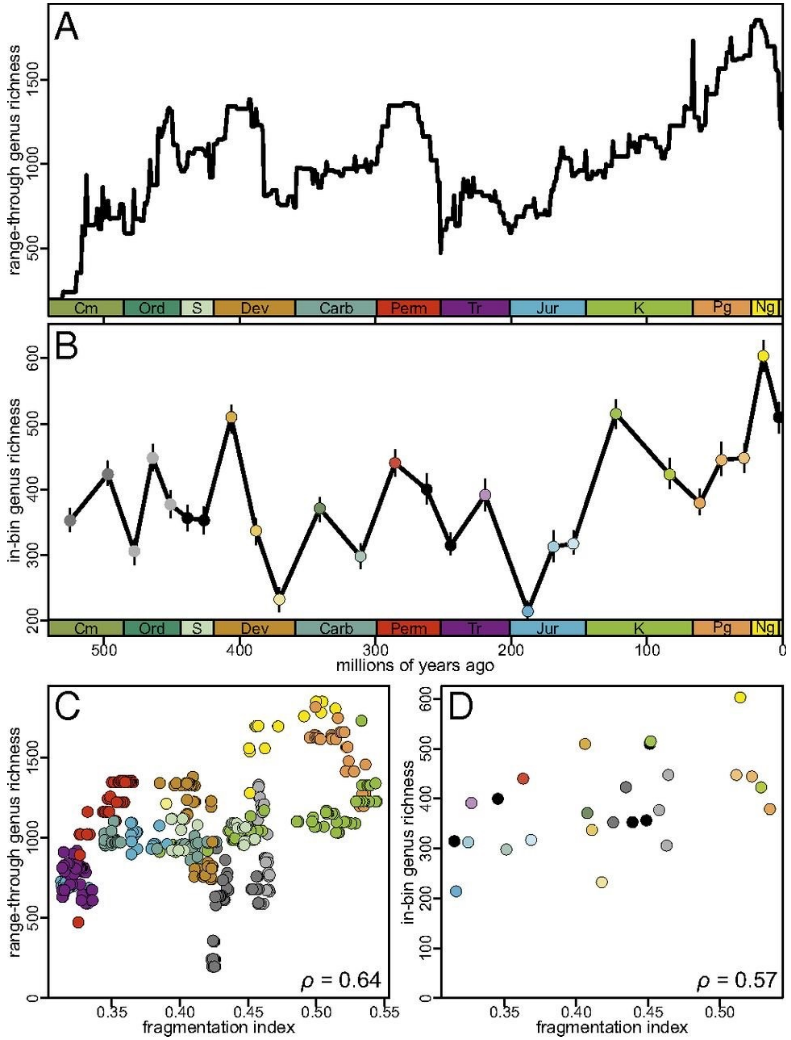
models	time series			
	1. cheil orig 2. cycl orig	1. cheil ext 2. cycl ext	1. cheil orig 2. cycl ext	1. cheil ext 2. cycl orig
A. no relationship between time series	41.8	11.4	49.2	24.1
B. 1st time-series drives 2nd	10.5	22.9	11.4	9.8
C. 2nd time-series drives 1st	20.4	13.4	14.5	24.4
D. temporal feedback between time series	17.9	44.0	14.6	31.2
E. correlation between time series	9.4	8.3	10.2	10.5

Model D	Mean	Median	Lower 95%	Upper 95%
μ.cheilostome.extinction	-2.482	-2.493	-3.795	-1.070
$t_{1/2}$.cheilostome.extinction	14.674	6.600	0.641	80.398
σ.cheilostome.extinction	0.197	0.168	0.002	0.577
μ.cyclostome. origination	-2.026	-2.036	-3.268	-0.472
$t_{1/2}$.cyclostome. origination	29.319	18.183	0.709	121.259
σ.cyclostome.origination	0.275	0.252	0.009	0.658
β.cheilostome.extinction.to.cyclostome.origination	0.275	0.303	-0.915	1.185
β.cyclostome.origination.to.cheilostome.extinction	0.563	0.637	-0.773	1.314

Do tectonics regulate marine diversity at Phanerozoic time scales?

Connor Wilson
(Post bac Fulbright in Oslo, now U of Arizona grad student)

Zaffos et al. 2017. Plate tectonic regulation of global marine animal diversity. PNAS

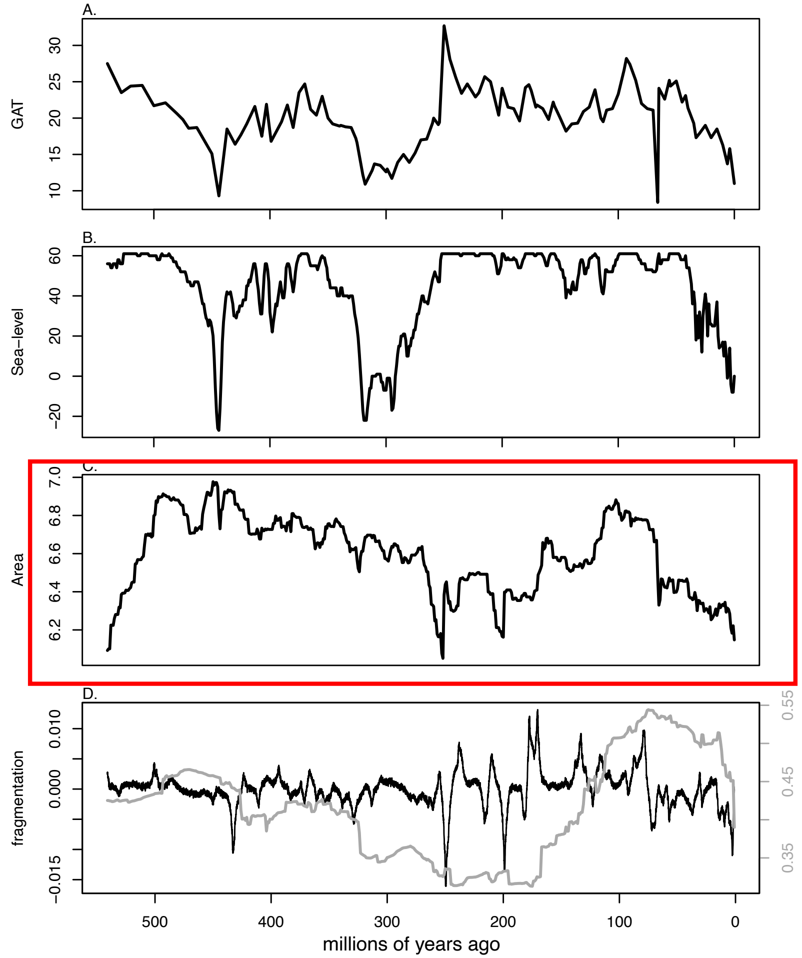


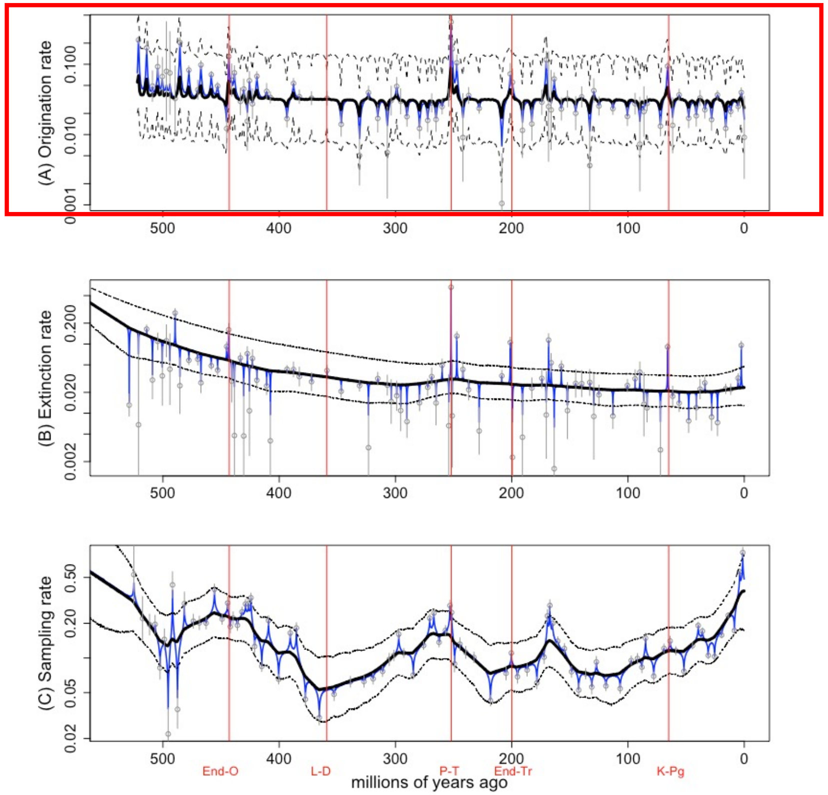
Other causal, and “causal” inference approaches

- Break point analyses
- First differencing
- Structural equation modelling and path analyses

Do tectonics regulate marine diversity at Phanerozoic time scales? - Nope

Wilson et al. 2024 unveiling the underlying drivers of Phanerozoic marine diversification (Proc B Roy Soc)





Received: 15 March 2019 | Accepted: 2 September 2019
DOI: 10.1111/2041-210X.13299

APPLICATION

Methods in Ecology and Evolution

`layeranalyzer`: Inferring correlative and causal connections from time series data in R

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Funding information
H2020 European Research Council, Grant/Award Number: 724324; Norges Forskningsråd, Grant/Award Number: 235073/F20

Handling Editor: Samantha Price

Abstract

1. Distinguishing correlative and causal connections among time series is an important challenge in evolutionary biology, ecology, macroevolution and palaeobiology.
2. Here, we present `layeranalyzer`, an R package that uses linear stochastic differential equations as a tool for parametrically describing evolutionary and ecological processes and for modelling temporal correlation and Granger causality between two or more time series.
3. We describe the basic functions in `layeranalyzer` and briefly discuss modelling strategies by demonstrating our tool with three disparate case studies. First, we model a single time series of phenotypic evolution in a bird species; second, we extract cyclical connections in the well-known hare-lynx dataset; third, we infer

Take home:

Remember: Software are “blind”!!!

And numbers with no units cannot usually be interpreted!