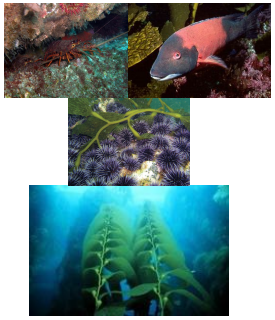
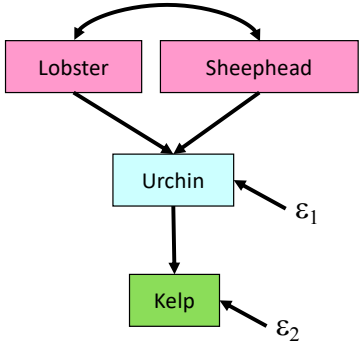
Structural Equation Modeling for Ecology & Evolutionary Biology

Jarrett E. K. Byrnes
University of Massachusetts Boston
http://byrneslab.net/teaching/sem

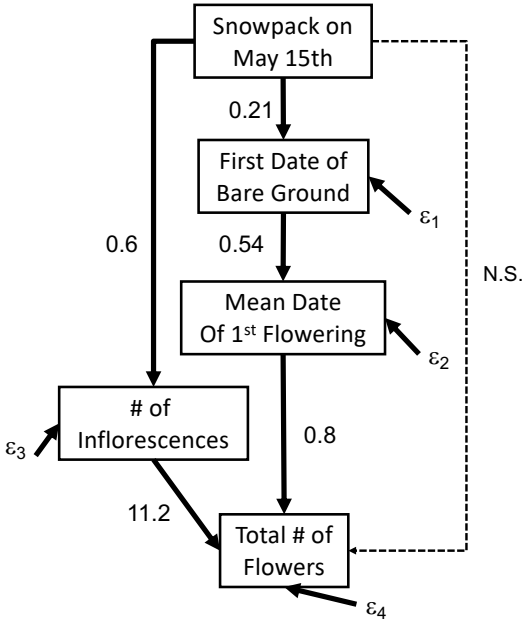




 # Flowers = α + β*Depth of March Snowpack + ε

- Describes a system
- But, implies that if we trim flowers, we change March snowpack, right?
- We assume directionality
- There implicit rules underlying =

Mechanistic Description of a System



Inouye et al 2002 Oecologia

Course Goals

1. Give you a working familiarity with SEM
2. Decide when SEM is right for you
3. Understand the process of model creation, evaluation, and revision
4. Be able to implement SEM in R in whatever framework you choose
5. Build models that incorporate real-world complexity to arrive at new insights to scientific challenges

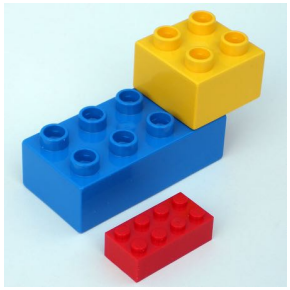
Two Paradigms

Covariance-Based Estimation (lavaan)

$$\hat{\Sigma} = \begin{Bmatrix} \sigma_{11} \\ \sigma_{12}\ \sigma_{22} \\ \sigma_{13}\ \sigma_{23}\ \sigma_{33} \end{Bmatrix}$$

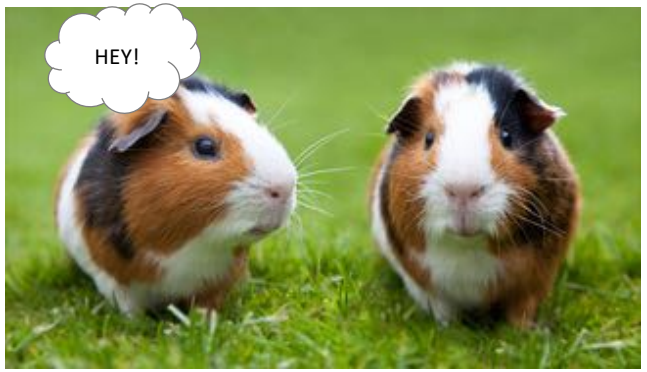
Implied Covariance Matrix

Local Equation Estimation (piecewiseSEM)



Testing *piecewiseSEM*

- Use you to test the new version (2.1) of *piecewiseSEM (which is in development!)*



Typical Day

9:00 – 10:30 Lecture/Lab I

10:30 – 10:45 Break!

10:45 – 12:00 Lecture/Lab II

12:00 – 1:00 Lunch

1:00 – 2:30 Lecture/Lab III

2:30 – 3:00 Break!

3:00 – 4:30 Lecture

4:30 – 5:30 Work with Your Data

Schedule for the Week

Monday -

What is SEM? A Practical and Historical Overview
Building Multivariate Causal Models
Engines of SEM: Covariance-Based Estimation

Tuesday –

Engines of SEM: Covariance-Based Estimation
What does it mean to evaluate a multivariate hypothesis?
Latent Variable models

…

Schedule for the Week

Wednesday -

- Engines of SEM: Local Estimation with piecewiseSEM
- A Nonlinear, Non-normal world
- Mixed Models in SEM
- Categorical Variables and Multigroup Analysis

Thursday -

- Spatial Data in SEM
- Timseries and Temporal Autocorrelation in SEM
- Whole-System Prediction with SEM
- Composite Variables

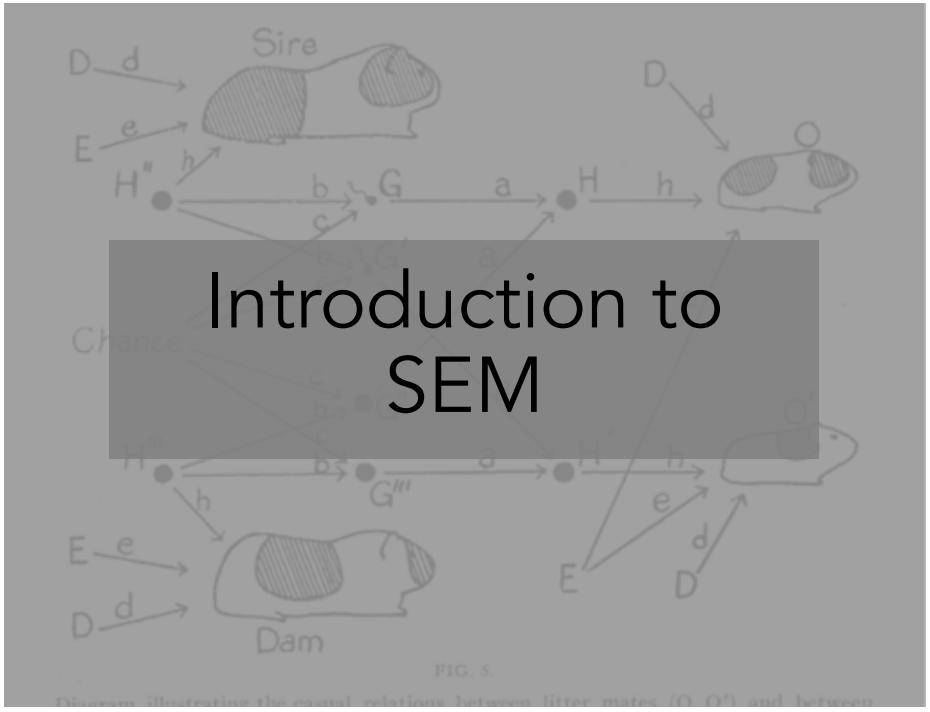
Friday -

- How to Fool Yourself with SEM
- Open Lab & Presentations

Who are you? Why are you here?

Who is Jarrett Byrnes?

- Assistant Professor at University of Massachusetts Boston
- Fields:
  - Biodiversity & ecosystem function
  - Kelp forests and global change
  - Salt marsh food webs
  - Ecological statistics



Introduction to SEM

Overview

1. What is SEM?
2. A History Lesson
3. From ANOVA to SEM

What is SEM?

Structural Equation Modeling

What is SEM?

Structural

There is hypothesized underlying *structure* to nature (a **cause** and an **effect**)…

Equation Modeling

What is SEM?

Structural

There is hypothesized underlying *structure* to nature (a **cause** and an **effect**)…

Equation

…that can be translated to a series of mathematical *equations*…

Modeling

What is SEM?

Structural

There is hypothesized underlying *structure* to nature (a **cause** and an **effect**)…

Equation

…that can be translated to a series of mathematical *equations*…

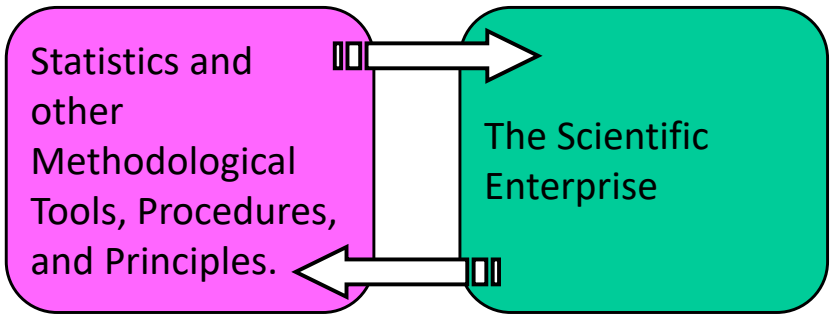
Modeling

…which can be *modeled* against data to support or refute the proposed structure

What is SEM? By any other name …

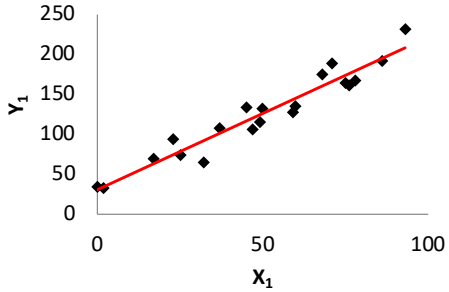
- Structural equation modelling (SEM)
- Path analysis
- Directed acyclic graph models

Why SEM? The Scientific Enterprise is Influenced by our Statistical Methodology



What is SEM? A graphical approach

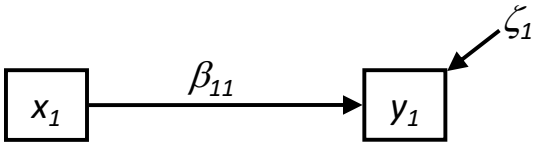
The data



Equation form

$$y_1 = \alpha_{11} + \beta_{11} x_1 + \zeta_1$$

Graphical form



What is SEM? A graphical approach

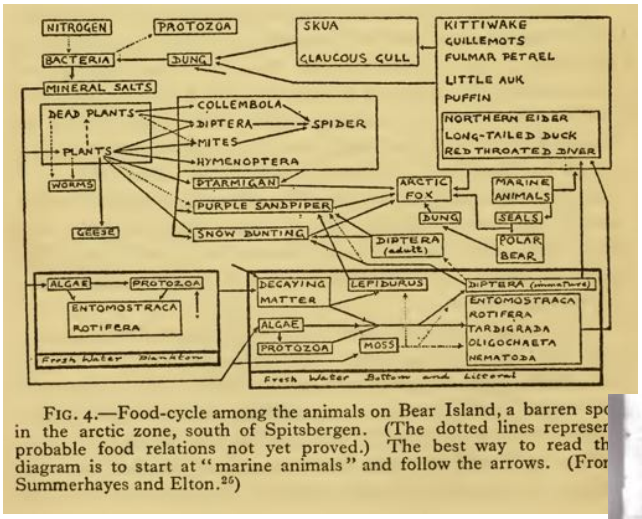


FIG. 4.—Food-cycle among the animals on Bear Island, a barren spo in the arctic zone, south of Spitsbergen. (The dotted lines represer probable food relations not yet proved.) The best way to read th diagram is to start at "marine animals" and follow the arrows. (Fro Summerhayes and Elton.[26])

Charles Elton, "Animal Ecology" (1927, p.58)

What is SEM? A graphical approach

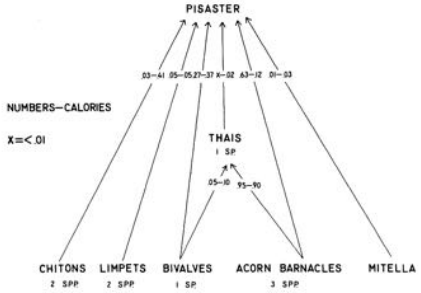
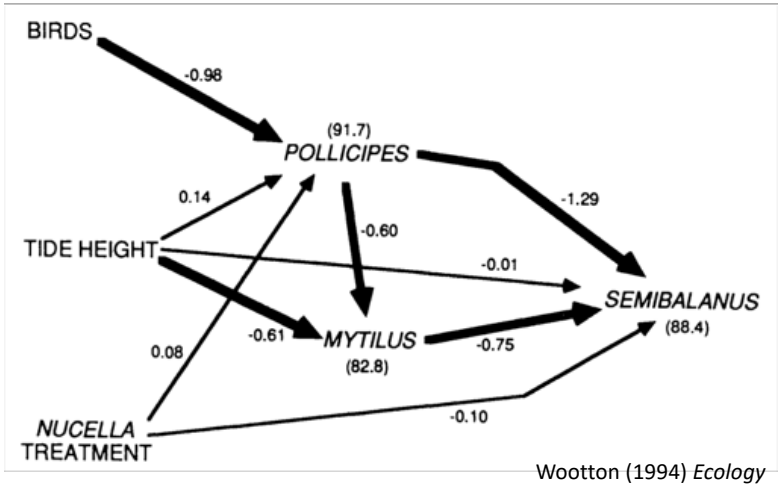


FIG. 1. The feeding relationships by numbers and calories of the *Pisaster* dominated subweb at Mukkaw Bay. *Pisaster*, N = 1049; *Thais*, N = 287. N is the number of food items observed eaten by the predators. The specific composition of each predator's diet is given as a pair of fractions; numbers on the left, calories on the right.

Paine, 1966

What is SEM? A graphical approach

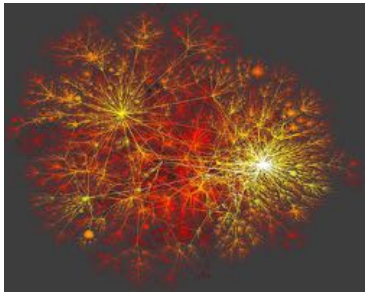


Wootton (1994) *Ecology*

What is SEM? A framework

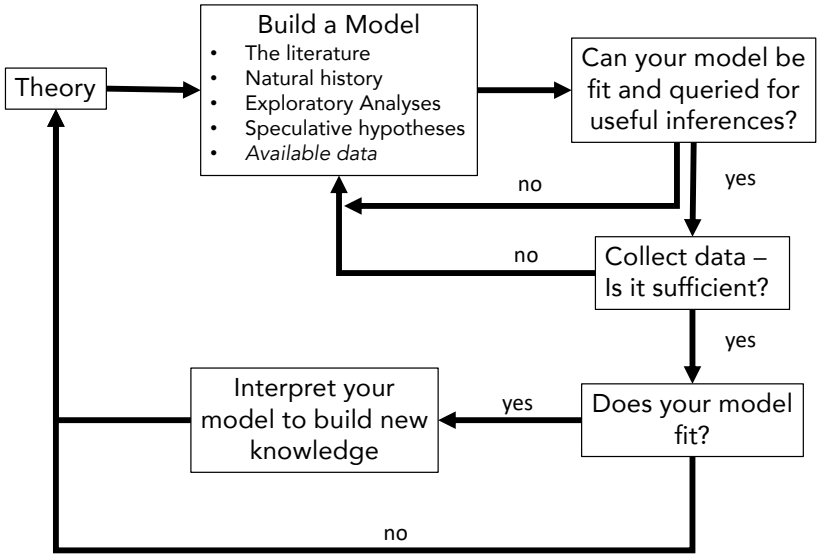
We use statistical and mathematical tools

within the SEM framework



to build scientific understanding about the multiple processes operating in <u>systems</u>

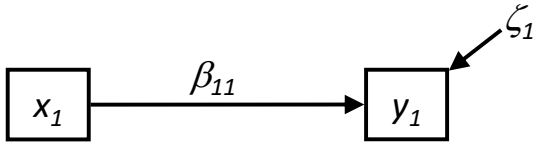
What is SEM? A unifying process



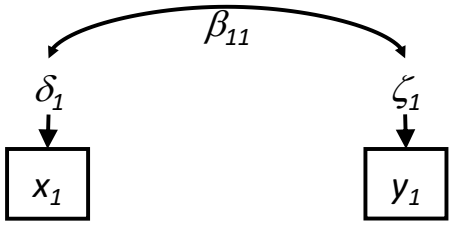
What is SEM? Implies directionality

equation form $y_1 = \beta_{11}x_1 + \zeta_1$

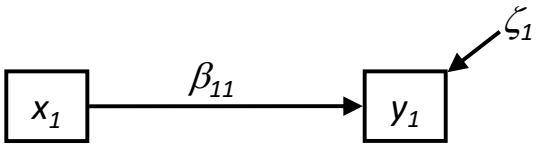
graphical form with causality



graphical form "without" causality



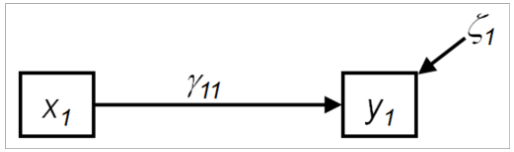
What is SEM? The elephant in the room



"An equation…can be said to be *structural* if there exists sufficient evidence from all available sources to support the interpretation that x_1 has a causal effect on y_1."

(Grace, 2006)

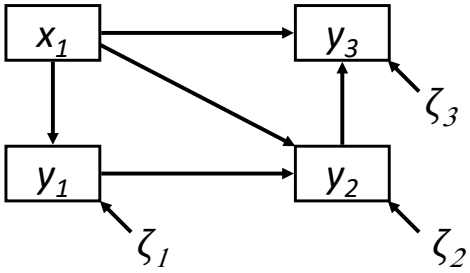
What is SEM? What is *causation*?



- **Key Point #1:** SEM assumes that *x* causes *y*
  - Prior observation
  - Prior statistical models
  - Prior experimentation
  - Some or all of the above
- Does not assume ultimate causation

What is SEM? Incorporating complexity

Hypothesis involving indirect effects



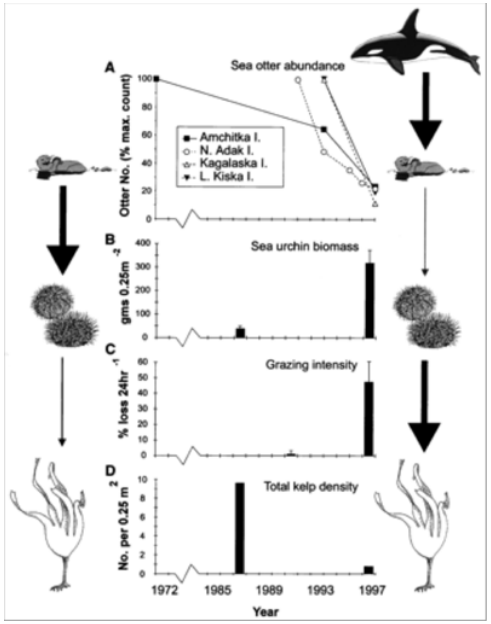
Corresponding Equations

e.g.

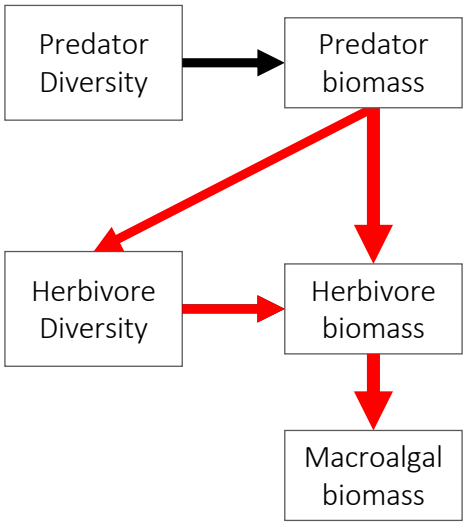
$$y_1 = \gamma_{11} x_1 + \zeta_1$$
$$y_2 = \beta_{21} y_1 + \gamma_{21} x_1 + \zeta_2$$
$$y_3 = \beta_{32} y_2 + \gamma_{31} x_1 + \zeta_3$$

What is SEM? A complicated network

- **Key Point #2:** By combining inferences across multiple equations, SEM addresses both direct and indirect effects in a system



What is SEM? Indirect effects



What is SEM? Putting it all together

- **Key Point #1:** SEM assumes that *x* causes *y*
- **Key Point #2:** By combining inferences across multiple equations, SEM addresses both direct (proximate) and indirect (ultimate) effects in a system

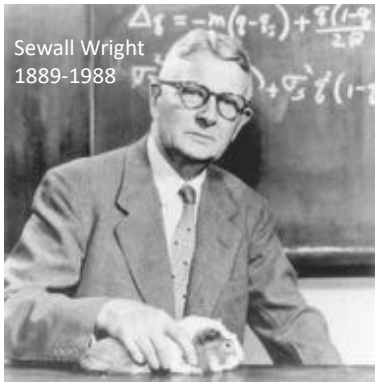
Overview

1. What is SEM?

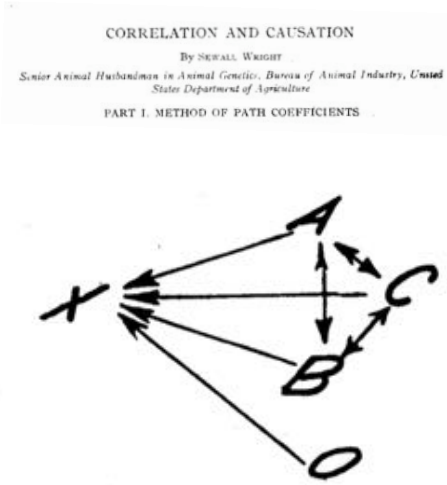
2. A History Lesson

3. From ANOVA to SEM

History. Causation vs. correlation



Path analysis



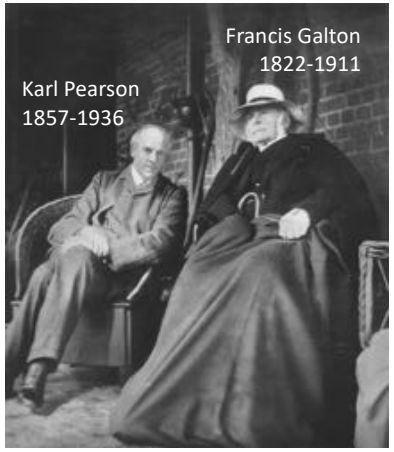
CORRELATION AND CAUSATION

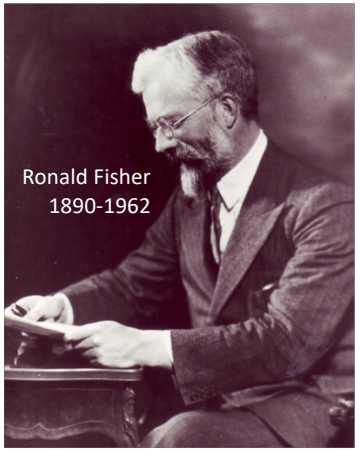
By SEWALL WRIGHT

Senior Animal Husbandman in Animal Genetics, Bureau of Animal Industry, United States Department of Agriculture

PART I. METHOD OF PATH COEFFICIENTS

History. Fit, correlation, and testing models





Numerical strength of association (Pearson product moment correlation, *r)*
Evaluate model fit (Chi-squared goodness of fit, $\chi^{2)}$

Test hypotheses (ANOVA)
Derive effect sizes (maximum likelihood estimation)

The First Path Diagram?

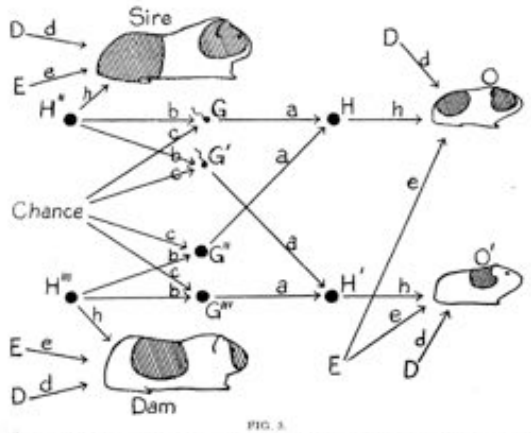


FIG. 3.

Diagram illustrating the causal relations between litter mates (O, O') and between each of them and their parents. H, H', H'', H''' represent the genetic constitutions of the four individuals, G, G', G'', and G''' that of four germ cells. E represents such environmental factors as are common to litter mates. D represents other factors, largely ontogenetic irregularity. The small letters stand for the various path coefficients.

Wright 1920 PNAS

History. Causation vs. correlation

"The **basic fallacy of the method appears to be the assumption that it is possible to set up *a priori* a comparatively simple graphic system which will truly represent the lines of action of several variables upon each other**, and upon a common result. . . . The pure mathematics by which this is shown is apparently faultless in the sense of algebraic manipulation, but it is based upon assumptions which are wholly without warrant from the standpoint of concrete, phenomenal actuality." (Niles, 1922)

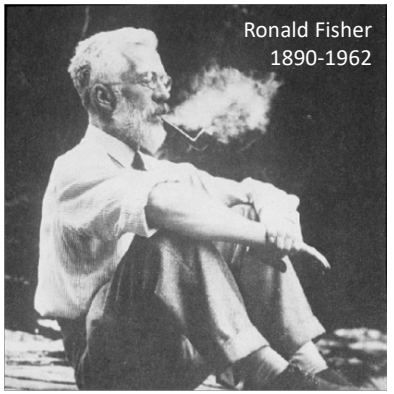
"The writer has never made the preposterous claim that **the theory of path coefficients provides a general formula for the deduction of causal relations**. He wishes to submit that the ***combination* of knowledge of correlations with knowledge of causal relations, to obtain certain results**, is a different thing from the *deduction* of causal relations from correlations implied by Niles's statement. Prior knowledge of the causal relations is assumed as a prerequisite in the former case. Whether such knowledge is ever possible seems to be the subject of Niles's philosophical discussion of the nature of causation." (Wright, 1923)

History. Causation vs. correlation

Smoking → Cancer

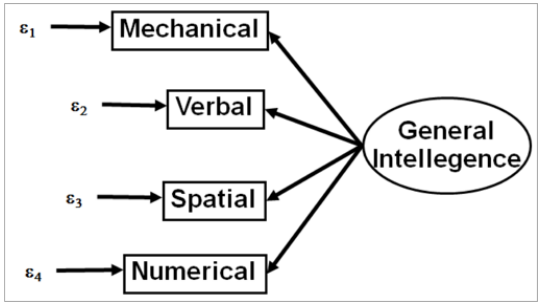
Cancer → Smoking

Smoking ← Gene → Cancer



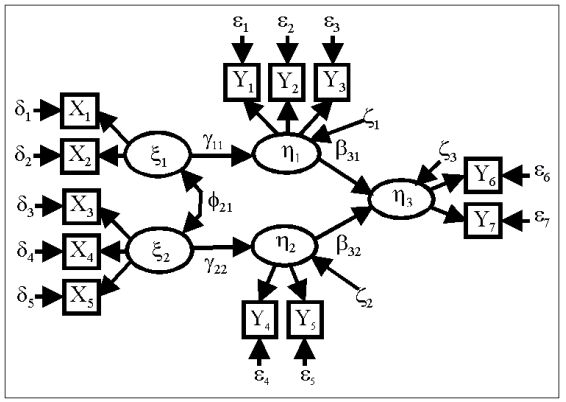
History. Factor Analysis

Charles Spearman
1863-1945



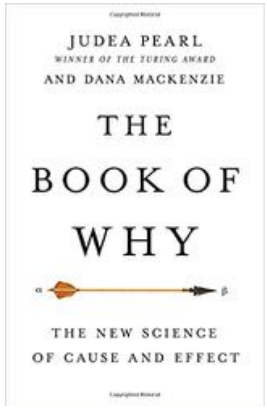
This is the basis of your SAT and GRE score!

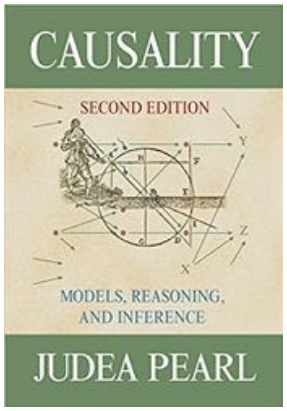
History. 2nd Generation SEM



- LISREL = combine path and factor analysis
- Model fit using covariance and ML estimation
- Assess and compare fit of multivariate model

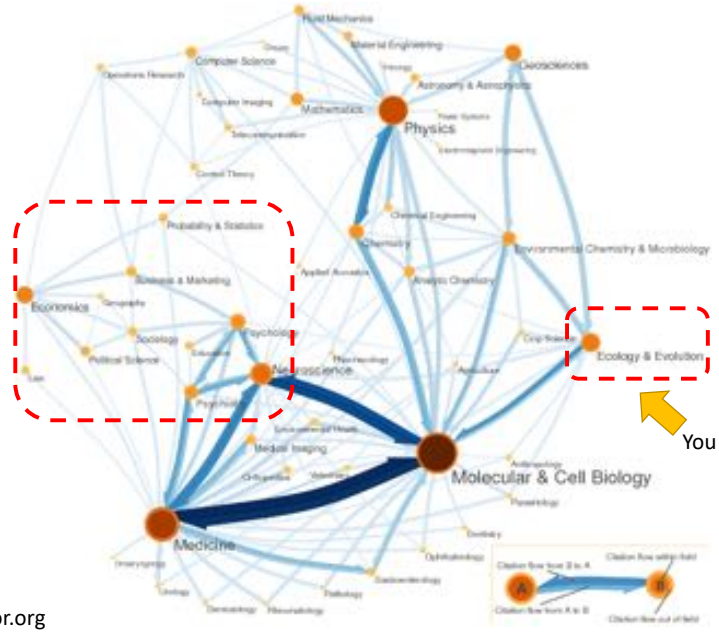
History. 3rd Generation SEM





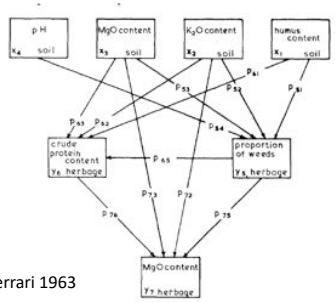
- Unite SEM with graph theory
- Causality is central
- Flexible methods with piecewise approach

History. SEM and Ecology

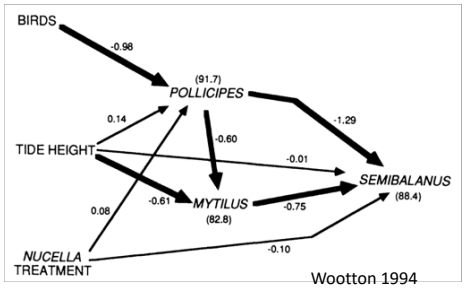


eigenfactor.org

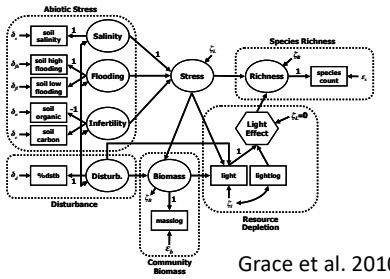
History. SEM and Ecology



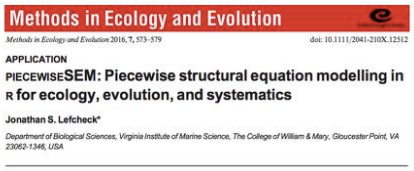
Ferrari 1963



Wootton 1994



Grace et al. 2010


Methods in Ecology and Evolution

APPLICATION

PIECEWISESEM: Piecewise structural equation modelling in R for ecology, evolution, and systematics

Jonathan S. Lefcheck*

Overview

1. What is SEM?

2. A History Lesson

3. From ANOVA to SEM

From ANOVA to SEM. Whalen et al. 2013

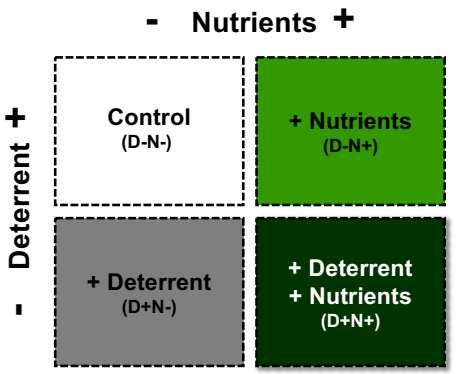
Ecology, 94(2), 2013, pp. 510–520

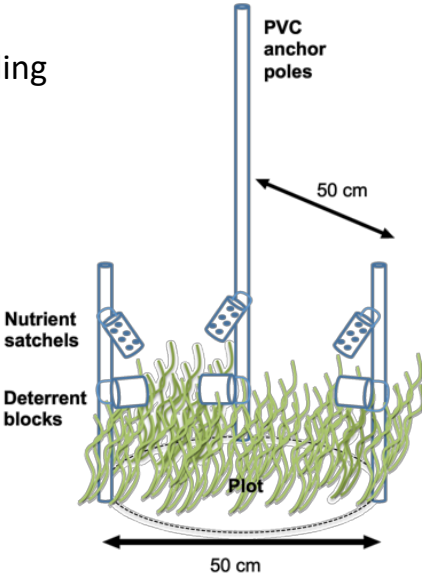
Temporal shifts in top-down vs. bottom-up control of epiphytic algae in a seagrass ecosystem

MATTHEW A. WHALEN,[1,3] J. EMMETT DUFFY,[1] AND JAMES B. GRACE[2]

From ANOVA to SEM. Experimental Design

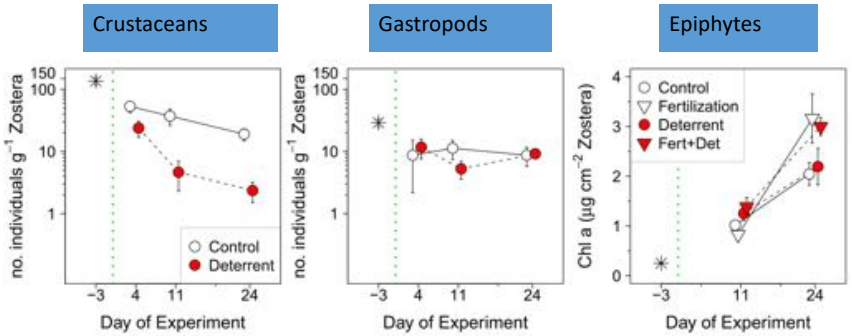
What are the relative influence of top-down vs. bottom-up control in controlling seagrass ecosystems?





From ANOVA to SEM. Whalen et al. 2013

From ANOVA to SEM. Graphing results



From ANOVA to SEM. Whalen et al. 2013

TABLE 1. Univariate analyses of mesograzer densities and epiphyte biomass from (A) fall and (B) summer experiments in an eelgrass (*Zostera marina*) bed in the York River, Virginia, USA.

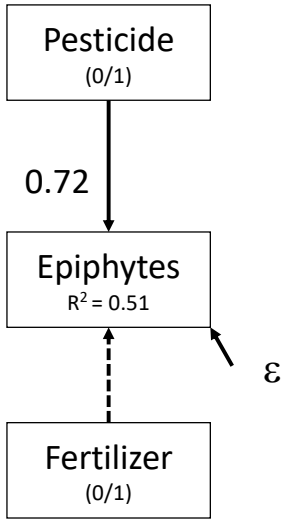
Experiment and response source	Crustaceans df	Crustaceans F	Crustaceans P	Gastropods df	Gastropods F	Gastropods P	Epiphytes df	Epiphytes F	Epiphytes P
A) Fall									
Deterrent	1	42.84	**<0.001**	1	0.33	0.574	1	3.97	0.052
Fertilization							1	3.10	0.084
Sampling date	2	13.77	**<0.001**	2	0.12	0.887	1	78.24	**<0.001**
Det. × fert.							1	0.86	0.358
Det. × date	2	2.48	0.108	2	1.27	0.301	1	3.72	0.059
Fert. × date							1	7.00	**0.011**
Det. × fert. × date							1	0.81	0.371
Residual	21			51			51		
B) Summer									
Deterrent	1	129.24	**<0.001**	1	1.07	0.306	1	66.22	**<0.001**
Fertilization	1	0.00	0.958	1	0.01	0.920	1	2.19	0.145
Sampling date	1	0.89	0.349	1	11.00	**0.002**	1	0.83	0.367
Det. × fert.	1	0.10	0.756	1	2.00	0.163	1	1.00	0.322
Det. × date	1	0.58	0.448	1	2.96	0.091	1	6.21	**0.016**
Fert. × date	1	2.90	0.094	1	0.71	0.403	1	0.53	0.468
Det. × fert. × date	1	1.57	0.216	1	0.27	0.606	1	1.14	0.290
Residual	56			56			56		

DEATH BY F-TABLES!

Notes: ANOVA tables for linear models describe the effects of chemical deterrent, nutrient fertilization, and sampling date on crustacean mesograzer density, gastropod mesograzer density, and epiphyte biomass. All data were natural-log-transformed except summer gastropods (square-root transformed). Model terms were tested using *F* tests and type III sums of squares. Note that the analyses presented for the summer experiment are balanced. *P* values <0.05 are shown in boldface.

From ANOVA to SEM. ANOVA

Epiphytes ~ Pesticide



Pesticide increases epiphytes

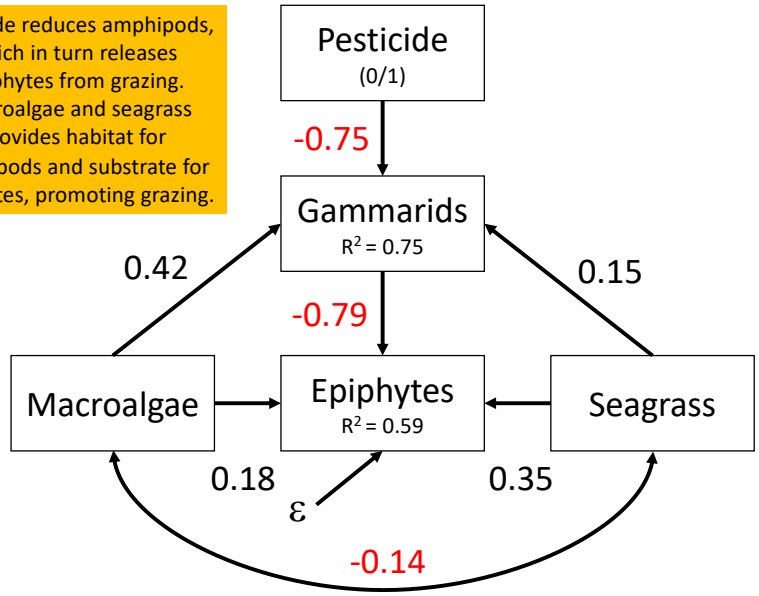
From ANOVA to SEM. ANCOVA

Epiphytes ~ Pesticide + Macroalgae + Seagrass

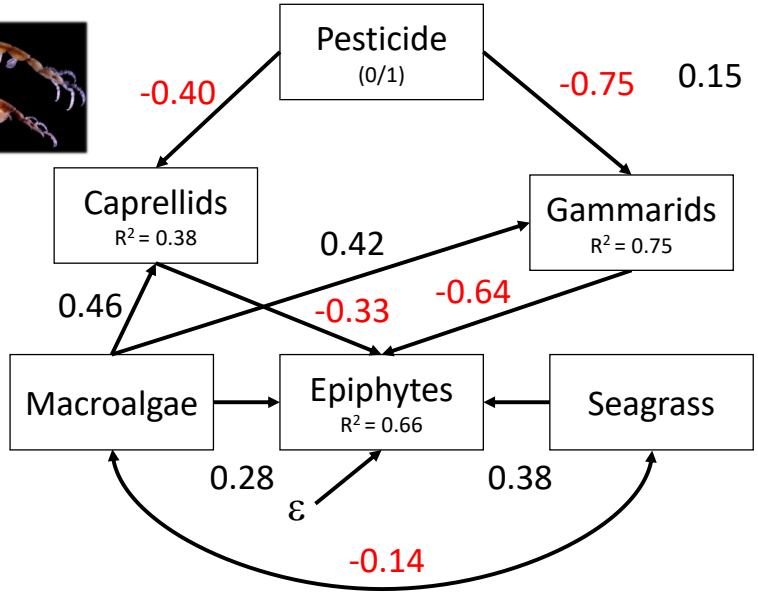
Pesticide increases epiphytes more than habitat (substrate) increases them

From ANOVA to SEM. Mediation

Pesticide reduces amphipods, which in turn releases epiphytes from grazing. Macroalgae and seagrass provides habitat for amphipods and substrate for epiphytes, promoting grazing.

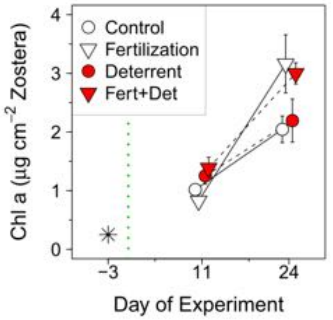


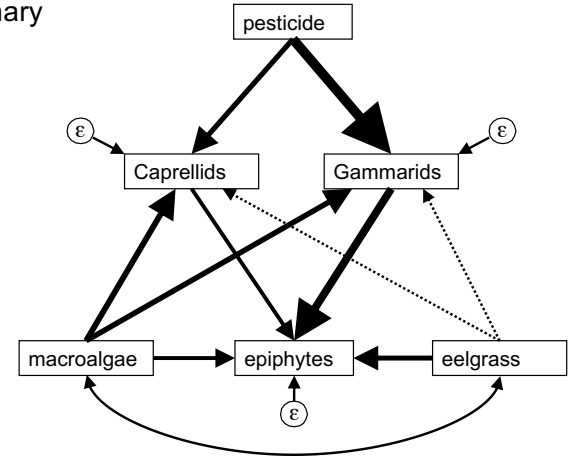
From ANOVA to SEM. Mediation x2



From ANOVA to SEM. Increasing inference

Our model results imply that behind this summary of mean responses…





…is a network of effects like this.

From ANOVA to SEM. Increasing inference

- Teases out *complex relationships*
- Identification and comparison of di*rect vs. indirect effects* & potential mediators
- Precise *mechanistic* explanations