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SEM Essentials: Summary Points

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1. This module provides a general summary of some of the main features of SEM and tries to set the stage for learning more technical information.
2. This set of “Summary Points” is the first in a sequence of modules that address essential features of SEM.
3. Citation that can be used for the information included in this module is:

Grace, J.B. (2006) Structural Equation Modeling and Natural Systems. Cambridge University Press.

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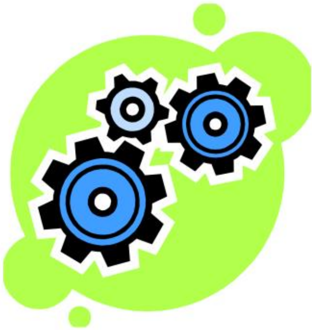
1. SEM is a <u>scientific framework</u> for building and evaluating hypotheses about cause-effect connections in systems.

we use statistical and mathematical tools

within the SEM framework, using the methods of causal analysis.



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

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2

1. In SEM, we use statistical and mathematical tools, along with SEM principles, to learn about systems.
2. Strictly speaking, SEM is not a purely statistical method, but rather, a modeling framework. The literature often equates the methodology of SEM with particular implementations of SEM. So, sometimes you hear people say, for example, “SEM involves the analysis of covariances” or ask, “What are the statistical assumptions of the method?” The proper replies are, “That depends on how a particular model is represented and estimated.” In other words, SEM is a framework for representing and evaluating causal hypotheses, not a particular statistical technique.
3. The contrast being established here is very important. Most scientists’ training about quantitative analysis comes solely from the field of statistics. However, there is another field, that of causal analysis. Both these bodies of knowledge are vitally important to science.
4. Also important is that traditional methods of statistical analysis are reductionist and aim to isolate associations. SEM takes a system perspective. This turns out to be essential to representing causal hypotheses fully.

2. SEM is based on the fundamental notion that abstracting systems as causal, probabilistic networks is an efficient and effective way to understand the interrelations among their properties.

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3

Abstracting systems as networks of cause-effect relations among variables is a fundamental tenent of SEM. This was Sewell Wright's key realization in the development of path analysis and the roots of modern SEM. It is also the fundamental tenent of Judea Pearl in his modern redescription of SEM.

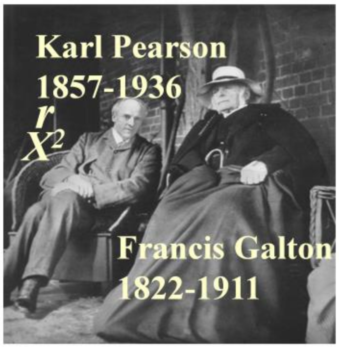
This point is further illustrated in a recent paper of ours in Functional Ecology:

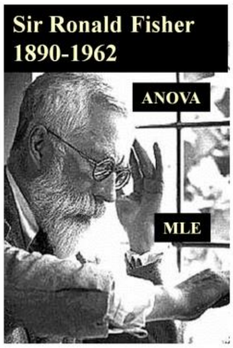
Grace, J.B., P.B. Adler, W.S. Harpole, E.T. Borer, and E.W. Seabloom. 2014. Causal networks clarify productivity-richness interrelations, bivariate plots do not. Functional Ecology, 28:787-798.

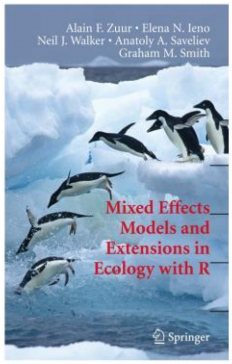
Accessible at:

http://onlinelibrary.wiley.com/doi/10.1111/1365-2435.12269/abstract

3. It is not generally appreciated that classical statistical analysis is not designed for the study of causal relations in systems.







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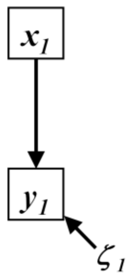
Part of our emphasis on SEM comes from a realization of what traditional statistical analysis does not provide. Typically, traditional methods do not strive to examine complex scientific hypotheses about systems, but are reductionist and attempt to isolate effects. Also, statistical analysis typically focuses on parameter estimation, description of associations, and statistical hypothesis testing. This basic point, which is often surprising to scientists, is the reason SEM can be seen as an alternative paradigm in quantitative analysis.

4. SEM is a form of graphical modeling.

equational form

$$y_1 = f(x_1)$$

graphical form



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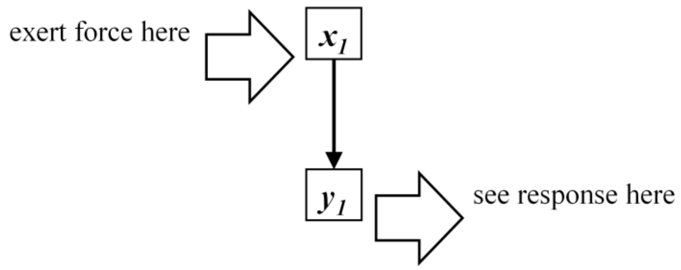
SEM is a graphical modeling methodology. At one level, this just means relationships are represented in both graphical and equational form, as shown here. The graph is not considered by SEM practitioners to be optional, however. Rather, graphical representation and analysis is seen to be essential for defining and reasoning about causal assumptions, network implications, and requirements for successful modeling.

5. A <u>structural</u> equation is one that attempts to estimate a <u>causal effect</u>.

Our concept of causation is that *A* is a cause of *B* if manipulation of *A* leads to a response in *B*.



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Our definition of “causal” is simple and operational. If variations in one entity/variable produce subsequent variations in another, it is seen as a cause.

We often use thought experiments when designing causal hypotheses (if we were to induce changes in *x*, could we expect that there might be responses in *y*?)

Our concept of causation is as defined by Pearl 2009. Causality. Cambridge Univ. Press.

A more advanced subject is the question as to whether a causal effect is <u>transportable</u>. It is quite possible for an historical influence to not be something that can be projected into the future. This happens when processes are not reversable.

6. In practice, we describe SEM as a method for studying causal hypotheses.

SEM results should not be taken as proof of causal claims, but instead as evaluations or tests of models representing causal hypotheses.

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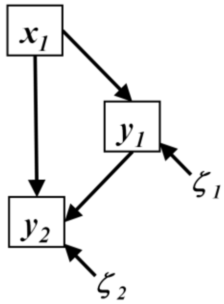
7

It is important for our credibility that we <u>not</u> imply that the results are automatically causal effects. Failure to state this distinction clearly has been one of the major impediments to the acceptance and use of SEM. Always keep in mind that some of the causal assumptions upon which your conclusions are based are not tested in the present analysis.

7. Structural equation models typically involve multiple equations and represent network hypotheses.



Network models require that *y*s can depend on *y*s.

$$y = f(x, y).$$

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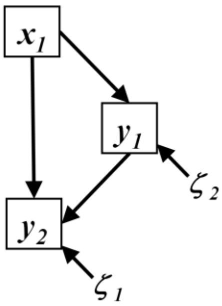
8

Here we see an hypothesized set of relations involving three different variables. The x variable is exogenous, in that it only serves as a predictor. Note that the y variables have arrows pointing at them and are response variables in at least one equation. We think of this as a network hypothesis. To represent networks we need equations in which ys can be functions of other ys.

Network relations are required for causal investigations. Hypothetically, a non-network model might be causal, and therefore “structural”. However, we cannot investigate causes further or develop a system-level understanding without networks.

8. There is at least one underlying equation for each dependent variable in the network.



Corresponding Equations:

$$y_1 = f(x_1)$$
$$y_2 = f(x_1, y_1)$$

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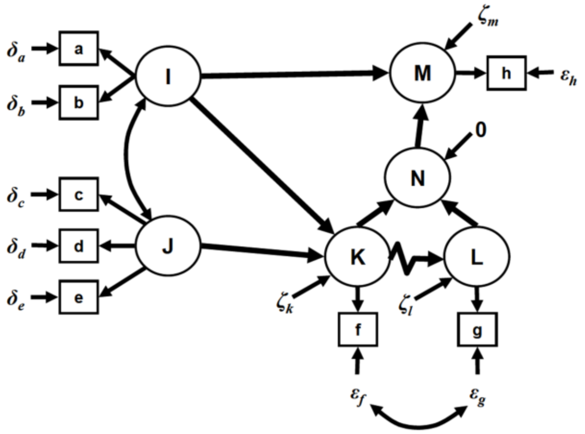
To understand the equations that go along with the graph, one equation (at least) is required for each response variable (but none for the exogenous/root variables).

9. SEM is meant to be very flexible and capable of allowing the specification of complex hypotheses.



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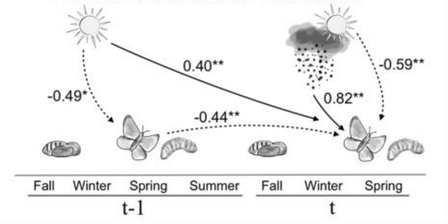
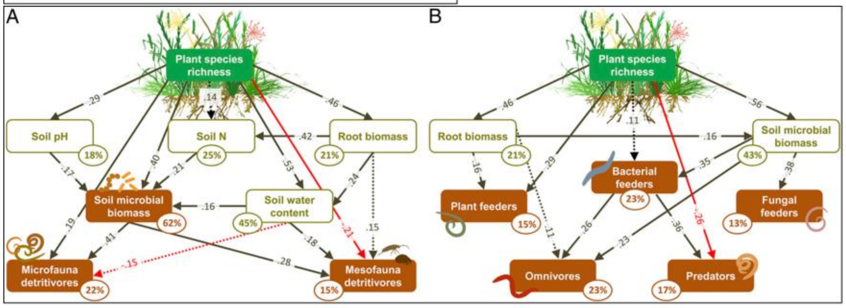
10

This model contains observed variables, unobserved/latent variables, derived variables, composites, and error covariances (which describe implied latent variables). Another possible relation is the non-recursive element of causal loops or feedbacks. Source of this figure is Grace (2006) Structural Equation Modeling and Natural Systems. Cambridge University Press.

10. SEM presentations can also be flexible.

Forister et al. 2011. J. Insect Sci.





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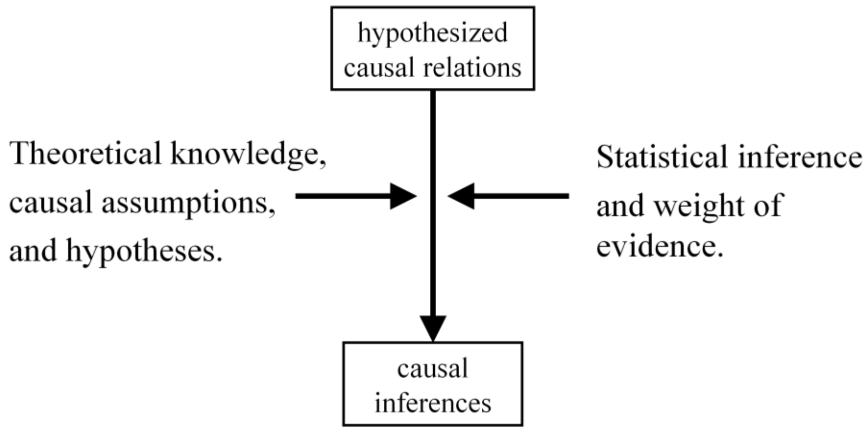
Eisenhauer et al. 2013. Proc. Nat. Acad. Sci.

There is actually tremendous flexibility in presentations as well. These illustrations just hint at the creative license granted to the investigator in conveying their results to the reader.

As an additional note, annotated SEM diagrams are not meant to be the sole summary of the results and often there are tables included that provide additional details such as raw parameter values, standard errors, fit statistics, and more.

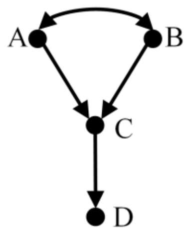
11. Investigation of causal relations requires theoretical knowledge.



USGS ***No causes in, no causal estimates out."*** 12

When it comes to drawing conclusions from models, just like in everyday life, we combine new data with our ideas and look for consistency when doing causal modeling. One axiom worth knowing is, "No causal assumptions in, no causal estimates out."

12. SE models include some causal assumptions, but usually also imply some testable implications.



All correlations must be considered for their causal implications.

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While our models include assumptions that are not tested with the data in hand, there are often some testable implications that are evaluated. These testable implications include omitted linkages that allow the model to be inconsistent with the data, as well as the evaluation of whether links are supported by the evidence.

13. SEM seeks to progress knowledge through <u>sequential learning</u>.

structural equation modeling

exploratory/ model-building applications → **confirmatory/ hypothesis-testing/ model-comparison applications**

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14

Our intent with SEM is to build our knowledge as we go. Multiple, overlapping investigations are required to build confidence in causal interpretations. Our initial investigations are often exploratory or "model-building" in that we use the data to build the model, thereby not permitting an independent test of the model with the same data. We have some ways of constraining just how exploratory our efforts are, which will be introduced later. It may take several subsequent studies before one graduates to true model-comparing or confirmatory studies.

14. SEM is one of the few applications of statistical inference where the results of estimation are frequently "you have the wrong model!"

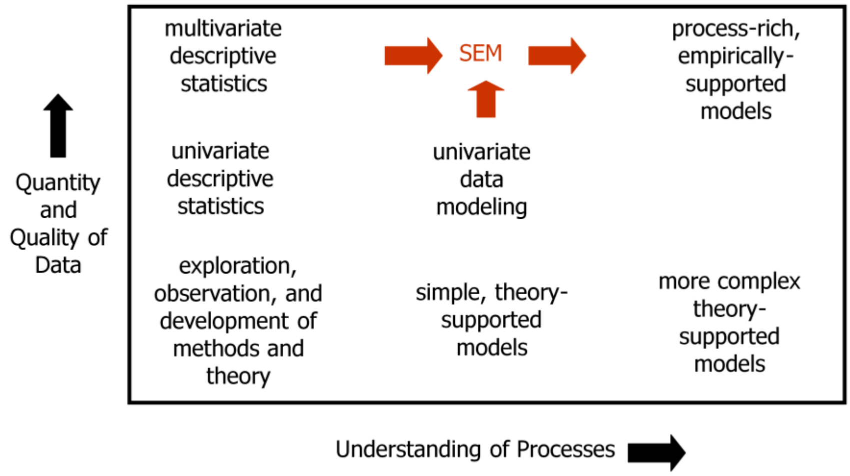
= discovery!

This feedback comes from the unique feature that in SEM we compare patterns in the data to those implied by the model

15

In SEM, model failure often leads to a search for alternatives that represents a new discovery of some missing component or need for an alternative theory. There are now many examples of discovery through SEM.

15. SEM fills a particular role in the scientific enterprise.



modified from Grace et al. 2009. Chapter 12, In: Real World Ecology. Springer Verlag

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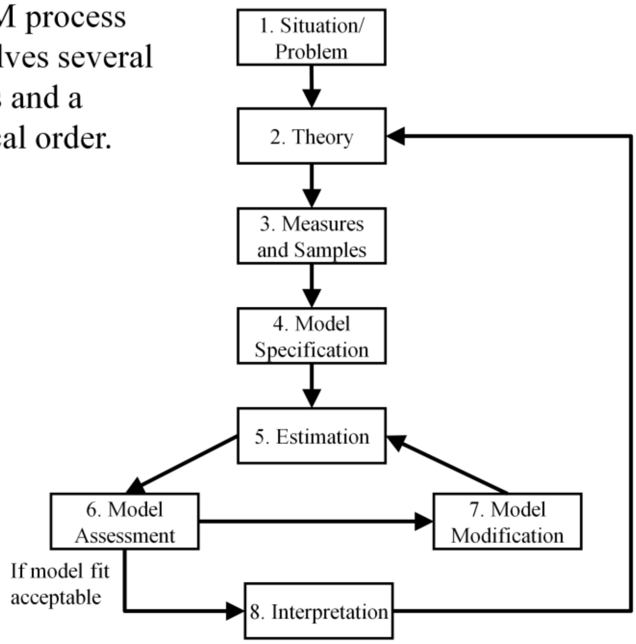
It is important to realize that SEM plays a particular role in the scientific process. In the lower left-hand corner of this diagram, we see that with new topics, where we do not have much understanding of processes or much hard data, work tends to be descriptive. We often aspire to reach the upper right corner of this box where we have strong theoretical knowledge and well-described relations. SEM can help us move across the page, but again, only plays a particular role in the whole process.

16. SEM process involves several steps and a logical order.



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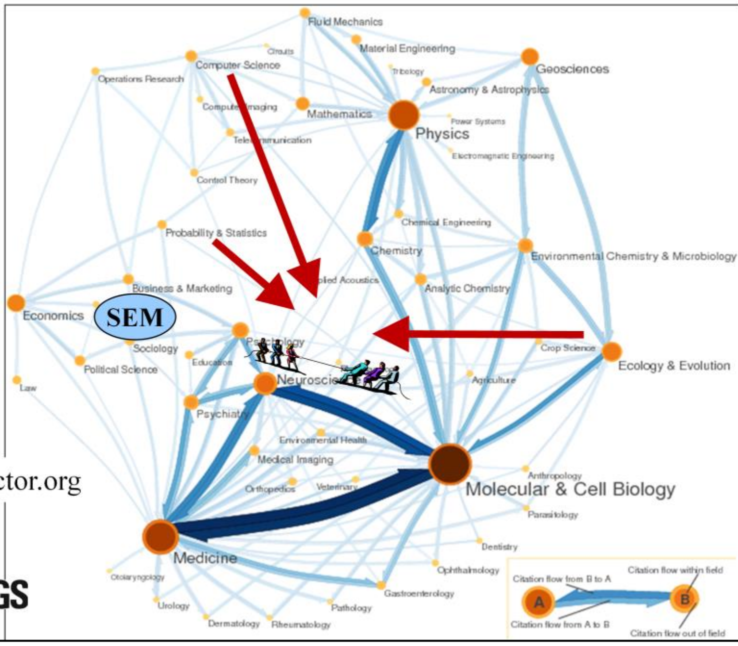
17

SEM is also a work-flow process. This can be described in various degrees of detail, but essentially we start with our objectives, ideas and assumptions, add in data, and then proceed to develop and evaluate specific models that give us both results and shed light on our theoretical ideas and assumptions.

One implication of this diagram is that our ultimate test is nearly always found in the next sample or the next study.

Where is the Methodology from and Where is it Headed?



eigenfactor.org

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History has played a role in shaping the literature on SEM.

This diagram represents a citation map (http://www.eigenfactor.org/map/maps.htm) showing the historical flow of knowledge among disciplines.

It is important to realize how the flow of information, and especially the lack of flow of information, shapes peoples' perceptions of quantitative methods.

Understanding the influence of history helps us to realize how many important bodies of knowledge, such as that related to SEM, are relevant to our science even if not currently part of the common body of practice.

As the animation of this slide conveys, we have been working to bring SEM into a more central position regarding the natural sciences and also to bring in the latest advances in statistics and causal analysis (from the field of artificial intelligence). Further, we have tried to illustrate how SEM can be adapted to the needs of ecology and evolutionary biology. This is described in our 2012 paper in *Ecosphere*.

Textbooks dealing with SEM

Grace (2006) Structural Equation Modeling and Natural Systems. Cambridge Univ. Press.

Shipley (2000) Cause and Correlation in Biology. Cambridge Univ. Press.

Kline (2014) Principles and Practice of Structural Equation Modeling. (3rd Edition) Guilford Press. (forthcoming)

Bollen (1989) Structural Equations with Latent Variables. John Wiley & Sons.

Lee (2007) Structural Equation Modeling: A Bayesian Approach. John Wiley & Sons.

Hoyle (2012) Handbook of Structural Equation Modeling. Guilford Press.

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19

There are now a large number of resources related to SEM. Here are just a few sources, the first two being books related to biological systems. Kline's books are a nice non-mathematical entry to the subject. Bollen's is a classic description of the modern method. Lee illustrates the relation of Bayesian analysis to SEM. Hoyle has now edited a volume with an extensive series of chapters on various SEM topics.

Key Papers Relevant to Ecological Applications

Grace, J.B., Anderson, T.M., Olff, H., and Scheiner, S.M. 2010. On the specification of structural equation models for ecological systems. Ecological Monographs 80:67-87. (http://www.esajournals.org/doi/abs/10.1890/09-0464.1)

Grace, J.B., Schoolmaster, D.R. Jr., Guntenspergen, G.R., Little, A.M., Mitchell, B.R., Miller, K.M., and Schweiger, E.W. 2012. Guidelines for a graph-theoretic implementation of structural equation modeling. Ecosphere 3(8): article 73 (http://www.esajournals.org/doi/abs/10.1890/ES12-00048.1)

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20

Two of our recent papers that cover broad fundamental treatments are given here. The first of these discusses some fundamental principles about the specification of models and how data are related to theoretical ideas. The second of these represents our outlining of the next (third) generation of SEM practice, in the form of guidelines.