# Determinism and Total Explanation in the Biological and Behavioral Sciences

Advanced article

Article Contents




**Rasmus Grønfeldt Winther,** *University of California at Santa Cruz, Santa Cruz, California, USA*



**Online posting date: 15th July 2014**



**Should we think of our universe as law-governed and 'clockwork'-like or as disorderly and 'soup'-like? Alternatively, should we consciously and intentionally synthesise these two extreme pictures? More concretely, how deterministic are the postulated causes and how rigid are the modelled properties of the best statistical methodologies used in the biological and behavioural sciences? The charge of this entry is to explore thinking about causation in the temporal evolution of biological and behavioural systems. Regression analysis and path analysis are simply explicated with reference to a thought experiment of painting three universes (clockwork, soup and conscious) useful for imagining our actual universe. Attention to historical, structural and mechanistic explanatory perspectives broadens the palette of methodologies available for analysing determinism in, and explanation of, biological and behavioural systems. Each justified methodology provides a partial perspective on complex reality. Is a total explanation of any system ever possible and what would it require?**


## Introduction

The charge of this entry is to explore thinking about causation in the temporal evolution of biological and behavioural systems. Topics such as sexuality, intelligence, autism and 'criminality' provide windows into multifactorial biological, psychological and social causation. For instance, Foucault (1990, 1978), Butler (1990), Stein (1999), McManus (2012) and Longino (2013) examine the multi-faceted causes and complex nature of the biological and behavioural traits constituting sexuality. Such case studies shed important light on specific research programs, kinds and degrees of determinism between factors and outcomes and types of explanations adopted by specific researchers. In contrast, this article investigates general methodologies employed in the biological and behavioural sciences. **See also**: Autism; Sexual Orientation; Sexual Orientation: Genetics

Especially statistical methods shall be here considered. A quote from Hacking (1990, p. 4) illustrates the relevance of statistics and probability theory for contemporary research:

> Probability is… the philosophical success story of the first half of the twentieth century.
>
> …
>
> A quadruple success: metaphysical, epistemological, logical and ethical.
>
> Metaphysics is the science of the ultimate states of the universe. There, the probabilities of quantum mechanics have displaced universal Cartesian causation.
>
> Epistemology is the theory of knowledge and belief. Nowadays we use evidence, analyse data, design experiments and assess credibility in terms of probabilities.
>
> Logic is the theory of inference and argument. For this purpose we use the deductive and often tautological unravelling of axioms provided by pure mathematics, but also, and for most practical affairs, we now employ… the logic of statistical inference.
>
> Ethics is in part the study of what to do. Probability cannot dictate values, but it now lies at the basis of all reasonable choice made by officials. No public decision, no risk analysis, no environmental impact, no military strategy can be conducted without decision theory couched in terms of probabilities. By covering opinion with a veneer of objectivity, we replace judgement by computation.

This list could be generalised by calling probability a 'scientific success story'. We could also add a fifth item, methodology. Given the centrality of statistics and probability theory to the biological and behavioural sciences, philosophical questions about these methods are here


**eLS subject area:** Bioethics & Philosophy

**How to cite:**
Winther, Rasmus Grønfeldt (July 2014) Determinism and Total Explanation in the Biological and Behavioral Sciences. In: eLS. John Wiley & Sons, Ltd: Chichester.
DOI: 10.1002/9780470015902.a0024143

foregrounded. Which statistical assumptions and protocols permit the decomposition of a complex system into simpler causal factors, thereby allowing for explanation, understanding and intervention? What does 'determinism' mean (e.g. Hacking, 1983; Dupré, 1993), and how might deterministic processes ground statistical outcomes taken as causal claims? Which other explanatory perspectives complement statistical analyses in aiming towards 'total explanation'? Indeed, is a total explanation of any system ever possible, and what would it require?

To examine intuitions about determinism and total explanation, the first section presents two universes – a deterministic universe and an utterly disorderly universe – radically distinct from a third universe, a conscious universe, which many of us, though importantly not all, take our actual universe to be. Considering these three universes allows a deeper comprehension, in the second section, of standard statistical methodologies related to the General Linear Model (GLM) such as regression analysis, path analysis, and Structural Equation Modelling (SEM), as well as Analysis of Variance (ANOVA) and probabilistic causation. (Trail-blazing work on these methods include Wright (1921, 1931, 1934, 1968) Neyman (1990, 1923), Fisher (1925, 1935), Haavelmo (1943), Simon (1953), Blalock (1964), Duncan (1966), Holland (1986), Cartwright (1989, 2007), Spirtes *et al.* (1993), Pearl (2000). For introductions to GLM statistical methodology, see Hocking (1996), Kline (1998), Shipley (2000), Muller and Fetterman (2002). For critique of causal interpretations of statistical analyses, consult Freedman (1991, 2009) Lewontin (1974), Levins and Lewontin (1985). Diagnosis of assumptions in GLM-based methodologies can be found in Welsh *et al.* (1988), Wahlsten (1990) and Wade (1992).) Again, my focus is methodology, with occasional references to metaphysics and epistemology. (Alas, space constraints allow even less to be said about logic or ethics, as per Hacking's list.) Attention to historical, structural and mechanistic frameworks in the final, third section helps broaden the palette of methodologies available for analysing determinism in, and explanation of, biological and behavioural systems. We shall see that every methodological framework is partial, replete with particular and selective assumptions, questions and goals. Can distinct perspectives ever be successfully integrated?

## A Philosophical Prolegomenon: Three Universes

To motivate intuitions about determinism and total explanation, consider two extreme universes. We shall call the first the 'clockwork' universe, and the second the 'soup' universe. In the rigid clockwork universe, there are few laws, causal regularities or objects and properties of any kind. In particular, imagine that this universe consists solely of two identical spheres in empty space. These spheres are perfectly smooth. Only a single law operates in this make-believe universe – gravity. Thus, the spheres may be white and warm, but we do not know and it does not matter. (It might be irrelevant for one of two reasons. First, because there simply are no optical or thermal laws or properties – this is a bare universe indeed. Second, because any such 'laws' or 'properties' would be soup-like (see below).) The only causal regularity in this universe is perfect circular motion around a common centre of gravity, equidistant between the centres of mass of the two spheres. The clockwork universe is (1) deterministic, (2) orderly (across space and time), (3) simple and (4) (potentially) totally explainable.

Contrast this with the utterly disordered soup universe in which there are no reliable laws or regularities, and no stable kinds of objects or properties. Two interpretations of such a universe are possible. Under the first interpretation, all objects and regularities, if we can call them thus, are unstable spatially and temporally. For instance, what at first looks like a huge swirling mass of quicksand surrounded by empty space becomes a perfectly-shaped sphere of granite. After 40 days, this sphere irregularly and unpredictably morphs into thousands of fist-sized shaking cubes of sonic crystals of an unknown material. All sorts of shape-shifting occurs elsewhere in this universe. More radically, the soup universe can also be interpreted as a chaos broth with the complete absence of even relatively stable kinds or laws. All there 'is' is unstructured change. Under either interpretation, total disorder reigns. The soup universe is (1) stochastic and chancy, (2) disorderly, (3) utterly complex and (4) unexplainable.

Because nothing exists upon which to build or organise, neither of these universes is hierarchical. Potential building blocks lack complexity in the clockwork universe, stability in the soup universe. Moreover, neither universe is particularly interesting. All the laws and kinds in the first can be written down on a small napkin (set aside the three-body or, more generally, the *n*-body problem; on this problem, consult Suppes, 1984, pp. 125–130). There are no predictive or stable laws or kinds in the second. The clockwork universe is boringly simple; the soup universe is wholly unknowable.

In contrast, consider another universe with numerous and varied laws and kinds. Such a universe is in a middle 'ground' or middle 'distance' between a clockwork universe and a soup universe. (See Cantwell Smith, 1996, 293ff. for an intriguing discussion of 'middle distance' for articulating 'the registering world, including all of ontology'.) Call this the 'conscious' universe. In it, both laws and chance operate, and structure all the way up to consciousness exists. Although difficult and controversial to define, consciousness is here understood as having self-awareness and intentionality, and exhibiting criticality and creativity. In all of this, keep in mind that the clockwork, soup, and conscious universes are thought experiments of how we can imagine our universe. The intention is to use these analogies (viz., a kind of model, see Hesse, 1966; Bartha, 2010; Winther, Under Contract) to illustrate statistical practice, rather than illuminate actual, basic properties of the universe, as described by physicists. Indeed, the interested reader may wish to learn about 'Boltzmann brain', 'quantum information,' or 'spacetime'.

A brief historical interlude indicates how we have come to think of our universe as a hierarchical universe, containing consciousness. A classic statement of laws and determinism is found in the first pages of de Laplace's *A Philosophical Essay on Probabilities* (1814):

> All events, even those which on account of their insignificance do not seem to follow the great laws of nature, are a result of it just as necessarily as the revolutions of the sun (de Laplace, 1902, 1814, p. 3).

With this metaphysical determinism, Laplace argues against 'final causes' and 'hazard', considering both 'imaginary causes'. Indeed, he also alludes to a superior intelligence, later baptised 'de Laplace's demon':

> …an intelligence which could comprehend all the forces by which nature is animated and the respective situation of the beings who compose it – an intelligence sufficiently vast to submit these data to analysis – it would embrace in the same formula the movements of the greatest bodies of the universe and those of the lightest atom; for it, nothing would be uncertain and the future, as the past, would be present to its eyes. (de Laplace, 1902, 1814, p. 4)

A contemporary statement referring to epistemological dimensions of laws of nature, but in a more psychologistic and personal light, can be found in Lightman (2013):

> The laws of nature help us create sanity in this strange cosmos we find ourselves in. The laws of nature protect us from the vagaries of the gods. The laws of nature satisfy a deep emotional need for order and reason and control (Lightman, 2013, p. 117).

Laws comfort. However, as Lightman acknowledges, chance also pervades our universe. C.S. Peirce eloquently articulates the power of chance thus:

> For a long time, I myself strove to make chance that diversity in the universe which laws leave room for, instead of a violation of law, or lawlessness (Peirce, 1893, p. 544).

Peirce eventually came to believe in 'absolute chance, a metaphysical thesis of irreducible chanciness and even of laws of nature as fundamentally dynamic. Hacking (1990) observes:

> [Peirce] opened his eyes, and chance poured in. …His working days of experimental routine, and his voyages of the mind, took place in a new kind of world that his century had been manufacturing: a world made of probabilities (Hacking, 1990, p. 201).

Complementing Peirce's metaphysical argument stands fellow pragmatist John Dewey's epistemological critique of necessity and determinism from the same journal volume:

> When we say something or other *must* be so and so, the 'must' does not indicate anything in the nature of the fact itself, but a trait in our *judgment* of that fact (Dewey, 1893, p. 363).

Dewey diagnosed a variety of fallacies associated with determinists imposing inappropriate parts and causal pathways (Winther, 2014). Such an 'epistemological anti-determinism' should be distinguished from 'epistemological indeterminism', which is rather the claim that we simply do not – and perhaps cannot – know whether statistical laws and regularities are fundamentally deterministic or absolutely chancy. Chance was riding a crest of influence towards the end of the ninteenth century, flooding into the twentieth century.

According to the conscious universe, then, law and chance are seen as interweaving. Here is Galton in *Natural Inheritance*:

> I know of scarcely anything so apt to impress the imagination as the wonderful form of cosmic order expressed by the 'Law of Frequency of Error.' The law would have been personified by the Greeks and deified, if they had known of it. It reigns with serenity and in complete self-effacement amidst the wildest confusion. The huger the mob, and the greater the apparent anarchy, the more perfect is its sway. It is the supreme law of Unreason. Whenever a large sample of chaotic elements are taken in hand and marshalled in the order of their magnitude, an unsuspected and most beautiful form of regularity proves to have been latent all along (Galton, 1889, p. 66).

In many areas of knowledge, especially in the biological and behavioural sciences, statistical distributions became regularities. Whether 'statistical laws' are fundamentally stochastic at some basement level (i.e. 'metaphysical indeterminism') or whether laws are statistical because of our ignorance (i.e. epistemological indeterminism; see Suppes, 1984; Dupré, 1993, chap. 8; Glennan, 1997) are less important in the conscious universe than the fact that statistical laws now have an 'autonomy' in that they can 'be used not only for the prediction of phenomena but also for their explanation' (Hacking, 1990, p. 182). In the imaginary of the conscious universe, as constructed towards the end of the ninteenth century, and as represented and applied today in our best statistical methodologies, determinism and chance no longer conflict.[1]

[1]The relationship remains complex. In a letter to Max Born dated 7 Sep 1944, Albert Einstein writes "We have become Antipodean in our scientific expectations. You believe in a God who plays with dice, and I in complete law and order in a world which objectively exists, and which I, in a wildly speculative way, am trying to capture" (Born, 1971, p. 149).

Returning to the analogies of our thought experiment after this historical interlude, because our universe is structured into molecules, planets, multicellular organisms and societies – and many take our universe to be most like the conscious universe – scientists can make predictions; effective explanations furthering understanding become possible; and interventions (e.g. economic and educational) can be recommended. For instance, because of the imperfectly nested hierarchy and statistical laws we take our universe to exhibit, even evolutionary theorists can make novel, surprising, and correct predictions of bacterial or symbiotic evolution (Williams, 1982; Winther, 2009). Moreover, conscious entities in our universe seek and produce explanations (Woodward, 2011). Finally, intervention is produced by goal-oriented action (Walsh, 2013), responds to social learning and organisation (Dewey, 1929), and is driven by community and institutional needs (Longino, 2002). Thus, in contrast to clockwork and soup universes, the conscious universe has (1) structured complexity, (2) emergent hierarchy, (3) consciousness and (4) the possibility of interesting – yet incomplete and multiple – explanations.

Which sorts of explanation – partial or total – do these universes support? And recalling Hacking's distinctions above, which epistemology follows from the metaphysics of each universe? In a clockwork universe, scientific maps can easily be provided. However, in this universe, not only is there no one to care, but the simple and nonprobabilistic theories that explain and predict this universe totally, unambiguously, and without remainder, do not seem to be particularly analogous to the theories required to explain, even partially, our actual universe. Second, coherent theoretical maps of the soup universe are impossible to produce. Such a universe changes too unreliably. What about the conscious universe? Many questions about the unity and applicability of laws of nature and causal regularities, and about the uniqueness of kinds and classifications of kinds, require attention for a total account, as it were, of total explanation. Some interlocutors disparage the possibility of universal laws, unique classifications, and total explanations (e.g. Cartwright, 1983; Dupré, 1993; Hacking, 2007b; Wimsatt, 2007), while others argue that the universe is a simulation, a complex mathematical structure, or both, in which total explanation is not only possible but necessary (e.g. Wolfram, 2002; Bostrom, 2003; Tegmark, 2014; but see Frenkel, 2014; Hacking, 2014). Perhaps most interestingly, and extending Hacking's 'looping effect' (Hacking, 2007a), if consciousness itself affects explanation, then 'closed' total explanations even of purely material processes such as chemical reactions and embryonic development bracketing the explainer, and the needs, history, and assumptions of the community of explainers, would not be forthcoming (Longino, 2002). Put differently, pragmatic factors will always enter explanations and different factors will alter the explanation itself. Unsurprisingly, controversies about the possibility and nature of total explanations in a conscious universe remain strong. What is clear is that explanation is interesting, and intervention important, in a conscious universe with emergence, hierarchy, and agency, such as we commonly – but importantly not always – take ours to be.

A passage taken from work in probabilistic causation[2] provides yet another view on the difference between a deterministic clockwork universe and a disorderly soup universe:

> …we shall express preference toward de Laplace's quasi-deterministic conception of causality and will use it, often contrasted with the stochastic conception, to define and analyse most of the causal entities that we study. This preference is based on three considerations. First, the Laplacian conception is more general. Every stochastic model can be emulated by many functional relationships (with stochastic inputs), but not the other way around… Second, the Laplacian conception is more in tune with human intuition. The few esoteric quantum mechanical experiments that conflict with the predictions of the Laplacian conception evoke surprise and disbelief, and they demand that physicists give up deeply entrenched intuitions about locality and causality. Our objective is to preserve, explicate, and satisfy – not destroy – those intuitions.
>
> Finally, certain concepts that are ubiquitous in human discourse can be defined only in the Laplacian framework. We shall see, for example, that such simple concepts as "the probability that event *B* occurred *because* of event *A*" and "the probability that event *B* would have been *different* if it were not for event *A*" cannot be defined in terms of purely stochastic models. These so-called *counterfactual* concepts will require a synthesis of the deterministic and probabilistic components embodied in the Laplacian model (2000, pp. 26–27).

Adopting a purely soup universe metaphysically consisting of 'absolute chance' (Peirce), or endorsing epistemological indeterminism, as even so-called hidden variable theories in quantum mechanics sometimes do, will simply not do justice to our intuitions about causality or our ways of using words such as 'because'. This is Pearl's Laplacian, deterministic streak. Even so, we must also respect causal complexity, measurement error, and inevitable ignorance. This is Pearl's acceptance of metaphysical, epistemological and methodological disorder and indeterminism in the world. Thus, a 'synthesis' of a clockwork and a soup universe is required. I too desire Laplacian chance guided by consciousness.

[2]See Pearl (2000), Cartwright (2007), Hitchcock (2012), Woodward (2013). The basic idea is that probabilities of co-occurrence can be assigned to the relations between any two factors in a complex system. If a flow chart ('directed acyclic graph') can be drawn, and probability distributions written that indicate that the probability of a certain factor occurring depends only on the probability of a certain set of other factors – 'the parents' – but not on any other factors, then those parents can be considered the causes of the given factor (this is the 'Markov Causal Condition'; consult Cartwright, 2007; Hitchcock, 2012). But how should these probabilities to be interpreted and conceptualised? That is what Pearl is addressing in the passage below.

How can we ontologise or make real each of these three universes? Consider a passage from van Fraassen's *Laws and Symmetry*:

> A model is called a model of a theory exactly if the theory is entirely true if considered with respect to this model alone. (Figuratively: the theory would be true if this model was the whole world) (1989, p. 218).

Extending van Fraassen's apt distinction between model and theory, three analogies have been explored: the clockwork universe, the soup universe, and the conscious universe. The clockwork universe is the well-known metaphor of the Laplacian clockwork universe pared down to its bare essentials (alternatively: imagine "this [rigid] model [as] the whole world"). In other words, *conceiving and reifying the rigid clockwork universe as being the entire universe, and imagining our universe as being exactly like such a clockwork universe, will make our universe a clockwork universe*. The soup universe and the conscious universe analogies themselves refract distinct pictures and metaphors of the kind of universe we inhabit, which processes it contains, and, thereby, which explanations, interventions and understandings a given universe justifies.

## Scientific Methodology: Statistics and Probability Theory

Diagnosing causation in a complex system requires abstracting out individual factors and identifying their relative effects and combined interactions. The most straightforward way to study causation, and thereby produce explanations, is to use randomised experiments together with relatively simple statistical analysis. In many cases, though, randomised experiments are impractical (e.g. comparing the macroeconomies of different countries), unethical (e.g. heritability studies in humans), or both. In some cases in which randomised experimentation is impossible, a 'natural experiment' might be available, such as in John Snow's well-known study of cholera in ninteenth century London. When a natural experiment is not available, many researchers use observational data (i.e. data that do not result from randomised experiments) and more complex statistical procedures to study the relationships among factors that might be considered causally fundamental (Blalock, 1964; Lieberson, 1987). Under certain assumptions of the GLM, and within particular research programs (e.g. path analysis and SEM), causation can be inferred from correlational data. However, it is not clear whether and when these assumptions hold, and many causal inferences from observational data are controversial.

GLM-based methods start with a mathematical model that relates a set of independent variables to a set of dependent variables. For instance, we could imagine hanging up a spring and attaching serially heavier weights, measuring the extension of the spring associated with each weight. Our model for the experiment might propose that the extension we measure is a combination of (1) a deterministic function of the weight we apply and (2) a random 'error' term that stochastically generates deviations from the deterministic prediction. If we represent spring length by $Y$, applied weight by $X_1$, and random error by $e_1$, we could write:

$$Y = B_0 + B_1 X_1 + e_1 \quad (1)$$

This is a linear regression model for the spring. Researchers are often interested in terms like $B_1$. $B_1$ is called a 'regression coefficient', and it measures the strength of the relationship between the independent and dependent variable – in this case, the weight applied to the spring and the length of the spring. Furthermore, and thinking visually, recall from your high school days that the equation of a line is $y = mx + b$. Equation (1) essentially specifies a family of lines, where the $y$-intercept (i.e. $b$) of a given line is $B_0$ and the slope (i.e. $m$) is $B_1$. In the particular case here considered, applied weight is the $x$-axis and spring length is the $y$-axis. According to this simplest model of functional relations between independent and dependent variables, actual data measured for particular springs do not fit perfectly on a straight line – indeed, the plotted points deviate above and below the line according to the chancy 'random variable' error term, $e_1$. So far, the authors have merely written down a mathematical model. At this stage, the researcher can impose the model on real data and ask questions such as, "If one assumes that the model I have written is a true description of the spring, what is the best possible guess for the value of $B_1$?"

In this example, we can take one spring and manipulate it, adding different weights, exposing the spring to different temperatures, and so forth. In many situations in the biological and behavioural sciences, our situation is more analogous to that of a researcher who can never actually change the mass on any one spring, or even place many springs in sufficiently randomised environments. A researcher who cannot experiment can only gather information from various springs, hoping that the springs are similar in important respects, that the weights used represent the relevant range of possible weights, and that we have measured any other variables that might matter.

The three universes are useful for understanding statistical analysis under the GLM more generally. The GLM imposes a clockwork-like universe – the deterministic part of the GLM is simple, orderly, and separable into distinct influences of different independent variables ($X_1$, $X_2$, … $X_n$). Even the corresponding error terms for each factor ($e_1$, $e_2$, …$e_n$), the disordered and chancy part of the regression, are rigidified.[3] How so? When a model with single or multiple explanatory factors is fit to real data using

[3]Typically, we employ models with various explanatory variables and corresponding error terms. Such multiple regression models might look like this: $Y = B_0 + (B_1X_1 + B_2X_2 + B_3X_3 \ldots B_nX_n) + (e_1 + e_2 + e_3 \ldots + e_n)$. The lines would thus be drawn through multidimensional space. More technically, such an equation can be written with the Greek letter, Sigma, $\Sigma$.

procedures such as 'least squares estimation' (e.g. Kline, 1998; Freedman, 2009), conclusions about the regression coefficients are typically based on a standard set of assumptions about the errors. The stochastic errors are assumed to have these properties:

1. independence across subjects measured (i.e. error independence)
2. a mean or 'expectation' of 0 as well as the same finite, constant variance (Let us set aside so-called 'generalised linear models' which permit different variances across error terms (e.g. Nelder and Wedderburn, 1972). While these models are more 'general' and certainly interesting, it is difficult to prove exact results for them, and considering them would not change any of the basic arguments in this entry.) (i.e. error homogeneity, which goes by the fancy term 'homoscedasticity')
3. no correlation to the measurements of any of the explanatory variables of X (i.e. exogeneity) (Muller and Fetterman, 2002, pp. 10–11; Kline, 1998, pp. 24–25; Freedman, 2009, p. 98).

The addition of a stochastic error term does not amount to an anti-Laplacian assumption that the universe is even partly fundamentally stochastic. That is, the errors are modelled as random, but the randomness could be attributable to measurement error or to our ignorance about un-measured causal factors, both of which are consistent with (but do not presuppose) metaphysical determinism. Indeed, 'methodological determinism' might be a better description and concept of how the clockwork universe tames error terms in the GLM-based statistical models of actual scientific practice.

Experimental protocol is also required to force a clockwork universe. First of all, experiments involving procedures such as randomising, replicating, blocking and blinding are sufficient for GLM error term assumptions to hold. Experiment permits the domestication of disorder. Carefully designed experiments help us avoid 'confounding', viz., spurious or obscure external factors being co-associated with the factors studied. Experiment thus also permits diagnosing, and controlling for, single factors.

In all of this, the conscious universe comes to the fore, though this might sometimes be forgotten. Consciousness is actually the force behind intelligent and deliberate statistical and experimental analysis. After all, the scientists' statistical training and analytical goals are enforced when disorder is domesticated, explanation and understanding produced and informed intervention suggested. Indeed, given that we are notoriously biased observers as well as systematically unreliable statistical thinkers (e.g. Kahneman, 2011), scientists attempt, via proper experimental protocol (e.g. blinding and controlling), to eliminate their own consciousness' pernicious footprints. For instance, double-blind procedures in medical 'Randomised control trials' help eliminate various kinds of mutual expectations and behaviour adaptations between medical professionals and patients (e.g. Solomon *et al.*, 2009). With respect to intervention, consciousness must decide how seriously it wishes to take statistical results. Who gets to use statistically inferred causal claims and for what? Is the causal story told by scientists and used by the powers-that-be objectively true or is it more like a beautiful fairy tale? We cannot escape the political and ethical implications of the results of intentional statistical analyses in the biological and behavioural sciences. In general, consciousness makes the universe more clock-like, with clear knobs and switches that we can set, and, thereby, peer through increasingly transparent panels to see the machinery ticking away inside. A motto emerges: *via careful experiment and rigorous statistical assumptions and methods, consciousness helps make a disordered soup universe more like a rigid clockwork universe*.

Let us explore path analysis and SEM more concretely, to see this motto in action. Wright (1921) starts thus:

> The ideal method of science is the study of the direct influence of one condition on another in experiments in which all other possible causes of variation are eliminated. Unfortunately, causes of variation often seem to be beyond control. In the biological sciences, especially, one often has to deal with a group of characteristics or conditions which are correlated because of a complex of interacting, uncontrollable, and often obscure causes. The degree of correlation between two variables can be calculated by well-known methods, but when it is found it gives merely the resultant of all connecting paths of influence (Wright, 1921, p. 557).

This article inaugurated the method of path analysis. The basic idea of this procedure is to identify a series of factors, and write a set of simultaneous regression equations indicating all the (assumed) direct and indirect causal influences among the factors. Here is the full, original diagram from Wright (1921, p. 560) (**Figure 1**).

One regression equation among several captures rate of growth as a linear function of heredity, size of litter, and condition of dam, with each variable having an estimated path coefficient. In articulating all the correlational dependencies, Wright assumes that:

> A cause has a linear relation to the effect and is combined additively with the other factors (Wright, 1921, p. 563).

Wright ultimately appealed to a kind of causal total explanation. That is, he wished to quantitatively map the correlation between any two variables as "the sum of the products of the chains of path coefficients along all of the paths by which they are connected." (1921, p. 568) For any pairwise correlation between factors X and Y, the diagram together with regression analysis allowed him to separate various scenarios, including: (1) X causes, or, strongly specifies, Y (or vice-versa); (2) X and Y are caused (specified) by a third factor Z; (3) X directly influences Y as well as indirectly through Z, viz., there are multiple rather than single causal pathways (see also Wright, 1931, 1934;

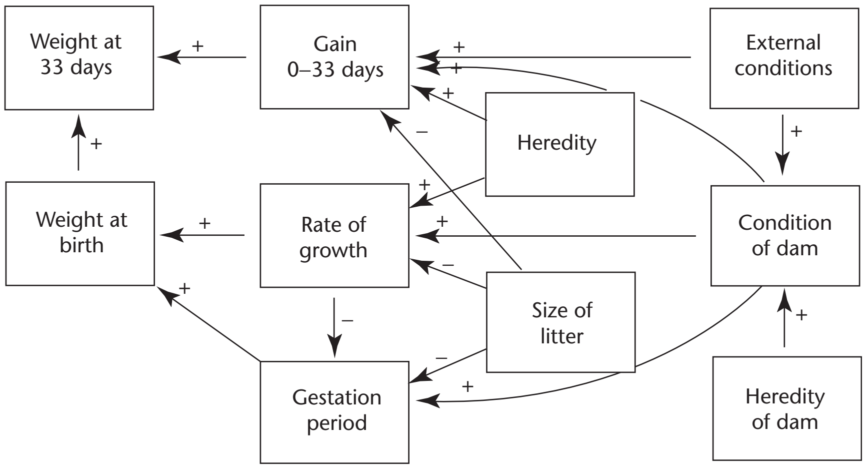


**Figure 1** Diagram illustrating the interrelations among the factors which determine the weight of guinea pigs at birth and at weaning (33 days).

Griesemer, 1991 and Shipley, 2000 elucidate path analysis; Cartwright, 2007, pp. 72–78 discusses 'from probabilistic dependence to causality'). In short, by identifying appropriately distinct factors, diagramming their presumed causal relations, randomising and controlling for exogenous factors (at least in guinea pig breeding), and taming error terms appropriately, Wright attempted to impose a clockwork universe via conscious statistics and experiment.

Path analysis, and related causal models including SEM emerged in the social sciences, especially economics and sociology. Freedman (2009) presents a clear analysis of one example, the work of Blau and Duncan (1978), which investigated factors in status attainment in American society. Citing Blau and Duncan (1978), Freedman observes that these sociologists wanted to answer questions such as "how and to what degree do the circumstances of birth condition subsequent status"? (Freedman, 2009, p. 81). The path analysis and SEM developed from 1962 census data isolated five factors: father's occupation ($F_O$), father's education ($F_E$), son's occupation ($S_O$), son's education ($S_E$), and son's first job ($S_J$). The dependent variable was taken to be son's occupation, and a complex path diagram involving the five other explanatory variables (not all independent) was articulated. Here is one of Blau and Duncan's three simultaneous equations:

$$S_O = B_1 S_E + B_2 F_O + B_3 S_J + e \qquad (2)$$

The $B$ path coefficients (standardised correlation coefficients, $r$) were, respectively, .394, .115 and .281, which implies that son's occupation is more sensitive to his education than to his father's occupation. Slightly more technically, $S_E$ explains more of the total variance of $S_O$ than $F_O$ – it explains 15.5% of the variance, whereas $F_O$ only explains 1.3% of the variance. Overall, Blau and Duncan's SEM model did not exhibit a particularly good fit – it left 58% of the variation in the son's occupation (and status) unexplained. This could perhaps be remedied by including more causal variables, and thereby formulating a more subtle causal model. Freedman humorously identifies methodological concerns with Blau and Duncan's study:

> As social physics… [Blau and Duncan's path model] leaves something to be desired. Why linearity? Why the same [path] coefficients for everybody? What about variables like intelligence or motivation? And where are the mothers?? (Freedman, 2009, p. 86)

Indeed, Blau and Duncan did not and could not have done a randomised experiment. GLM assumptions are here imposed without proper (because unethical and impractical) experimental procedures. But does this alone remove the validity of causal inference? Is rigorous experimentation the only way to make GLM error term assumptions hold? Freedman would answer these questions with a resounding 'yes!'. In contrast, because they believe in the power of careful statistical analysis on non-experimental data – i.e. because they hold that experiment is sufficient but not necessary for GLM assumptions to hold – Blau and Duncan, and Lieberson (1987), would insist on answering 'no!'.[4] In this noninterventionist statistical study, Duncan and Blau consciously forced as much of a rigid universe as they could through path analysis and SEM.

The extent to which the clockwork universe – imposed by consciousness – can be taken to grant causal information is controversial. In fields such as econometrics, behavioural psychology, and quantitative sociology, many hold that causation can be inferred from correlational data given appropriate statistical rigidifying strategies, even without randomised experiments. Even so, others argue,

[4]Interestingly, Pearl, 2000; Hitchcock, 2012; Woodward, 2013 'abstract' randomised, controlled experiment, advocating for 'ideal interventions' in which experiments are done computationally, through formal probability theory and directed graphs. Thus, they might reply 'yes and no' to the above questions.

our most carefully executed statistical and experimental strategies are not sufficient for grounding causal – and thereby explanatory – claims. For instance, Fisher (1925, 1935) was more focused on testing hypothetical causal claims and insisted (analogously to Popper, and resonating with an empiricist and anticausal attitude of the times, trail-blazed by philosophers and scientists such as Ernst Mach, Karl Pearson and Bertrand Russell) that causal hypotheses could be disproved but never definitively proved (Box, 1976). A different line of attack on causal inference in statistics can be found in Freedman (1991):

> To derive a regression model, we need an elaborate theory that specifies the variables in the system, their causal interconnections, the functional form of the relationships, and the statistical properties of the error terms – independence, exogeneity, etc (Freedman, 1991, pp. 292–293).

Causation can only be claimed if a causal model is already assumed (e.g. Holland, 1986; chap. 2, ‘‘No Causes In, No Causes Out’’, Cartwright, 1989). The justificatory and inferential relations between even the most elegantly implemented rigid and ordered correlation data and causal claims are highly controversial. **See also**: Path Analysis in Genetic Epidemiology

ANOVA, which is essentially a special case of regression analysis, and other GLM related statistical research protocols and programs such as probabilistic causation, also pertain to determinism and explanation in the biological and behavioural sciences. For instance, in the ‘IQ wars’ the causal meaning, or not, of the so-called heritable component of genetic variance in IQ, as well as the stability of IQ heritability across race, gender or other putatively biological relevant grouping of *Homo sapiens*, results in incendiary disputes with strong ramifications for possible socio-political intervention.[5] In all of this, the delicate and complex interplay among imposing clockwork, soup and conscious universes must also be considered. In the case of ANOVA, the same strategies of conscious rigidification discussed above vis-à-vis regression models emerge. Probabilistic causation and other more complex statistical procedures associated with, for instance, so-called big data (e.g. model selection, network analysis, graph theory, visualisation, e.g. Newman, 2010) also require intentionally instituting a clockwork universe, with new sorts of statistical regularities emerging (e.g. scale-free networks and modular networks). Questions to be left unanalysed here include: what kind of universe(s) can we assume – or must we assume – our world to be in order to produce explanations, understanding and intervention consonant with these other statistical and probabilistic methodologies in the biological and behavioural sciences? How and why did we get so lucky to live in a universe, perhaps most like the conscious universe, in which intentional agents have a magical key for causal inference – randomised and controlled experiments? **See also**: Eugenics: Contemporary Echoes; Heritability Wars; Nature/Nurture – A Philosophical Analysis; Twin Methodology

## Other Methodologies on Determinism and Total Explanation

Let us return to our spring example. There are other questions we might ask about these springs, even if we are interested only in the linear regression consistent with Hooke’s law. We could ask about the history, the composition and the organisation of the springs. The composition and organisation of the springs might affect the regression coefficient. If we lack direct information about the materials the springs are made of and the way in which they are coiled, then knowledge about the factory in Germany that constructed the spring or about which mines the iron and chromium (or copper) ore originated from might be useful. So, other sorts of information and methodologies for acquiring it, are pertinent to our statistical explanation of the behaviour of springs. Moreover, such information is important in and of itself if we are, instead, mainly interested in explaining the aetiology or chemical make-up of a particular spring.

To make the analogy with the biological and behavioural sciences explicit: if, as above, we are interested in statistically-inferred causal operations of a system, then historical, structural and mechanistic information can be relevant. Knowing about the origins and organisation of a system helps to rein in the statistical model. , a regression or path analysis model is not just imposed from a vacuum. The variables and relationships that appear in the regression model must be reasonable in the context of the theoretical background the researcher brings to the problem under study. That is, statistical practice must be embedded into a larger theoretical framework, where it may not always fit comfortably (e.g. Meehl, 1978). As Plato and other philosophers have suggested, theory must cut nature at its joints, and statistical models should reflect and apply that carving. Consider again the Blau and Duncan study discussed earlier. Independently and previously to the mathematics, knowledge about social and psychological history, structure and mechanism provides ways to justify and measure the factors included in our model (e.g. father’s

[5]For causal interpretations of heritability, and of heritability of IQ in particular, see for example Wright (1931) (especially ‘chart 4’, p. 161), Jensen (1969), Herrnstein and Murray (1995), Sesardić (2005), Visscher *et al.* (2008). For anticausal, critical interpretations of the heritability of IQ, refer, for example Lewontin, 1970, 1974; Layzer, 1972; Block, 1995; Sarkar, 1998. For alternative ‘complex systems’ frameworks in which (1) cause cannot be uniquely decomposed, (2) ‘nature’ and ‘nurture’ interact and the distinction itself is questioned and (3) various forms of Laplacian chance in a conscious universe are adopted, consult, for example Levins and Lewontin, 1985; Oyama, 2000a, b; Wimsatt, 2007; Winther, 2008; Walsh, 2012. Recent reviews of the relation between IQ heritability and race include Downes, 2014; Kaplan and Winther, 2014.

 

**Box 1** Historical explanation

In a historical explanation, we attempt to diagnose the factors interacting in the origin and development of, for instance, an organism, a firm or a culture. In keeping with the emphasis on actual method in this entry, the interested reader may wish to consult Felsenstein (2004) and Gaddis (2004) for discussion of a rich variety of methodologies of the reconstruction of history, and for analysis of historical explanation, in the fields of biology and history, respectively. Investigations into how historical explanation might be a distinct style of scientific inference, pertinent especially to the biological and behavioural sciences can be found in Ragin and Zaret (1983), Ragin (1987), Crombie (1994), Frodeman (1995), Hacking (2002) and Winther (2012). As a topic in historical explanation particularly relevant for determinism and explanation consider path dependence (Page, 2006). Is the current state of historically situated systems contingent and accidental (Gould, 1989), or is it necessary and inevitable (Conway Morris, 2003)? That is, would convergence to the same organisms be rampant if we were to replay the tape of life (see Oyama, 2000b Chapter 6; Beatty, 2006)? A clockwork universe would suggest historical inevitability, whereas a soup universe would resonate with historical contingency. A conscious universe would articulate a synthesis of these two scientific assumptions about historical outcomes, and even, self-reflectively, about its own history. (As an example of a visualisation pertinent to historical explanation, see **Figure 1** of the eLS article Cladistics.) **See also**: Phylogeny Reconstruction; Philosophy of Biological Classification

**Box 2** Mechanistic explanation

A mechanistic explanation involves disarticulating the actual machinery of a system, independently of statistical inference. For instance, the structure and mechanisms of hierarchical components of biological systems can be identified and modelled via material experimental protocols and computer simulations, as elucidated by Webster and Goodwin (1996), Craver (2007), Wimsatt (2007) and Winther (2011). In the behavioural sciences more generally, Lévi-Strauss (1966, 1962) and Steel (2008) show, respectively, that appeals to structure and mechanism are pervasive and deep. As a topic in mechanistic explanation particularly relevant for determinism and explanation consider reductionism. Is a whole 'nothing but' the sum of its parts or are there emergent and autonomous – and, thereby, non-reducible – properties and causes at higher levels? Deep conceptualizations of the mind and society are at stake. Nagel (1961), Andersen *et al*. (2001), Wimsatt (2007) and Jones (2013) are excellent sources on this topic. Returning to our universes, important questions about whether determinism, utter chance or something more akin to Laplacian chance operates at various levels of organisation. For instance, it is well-known that deterministic relations between pressure, volume and temperature are actually grounded in statistical, thermodynamic properties as described by the kinetic theory of gases (e.g. Nagel, 1961; Glennan, 1997; Callender, 1999). Glennan (1997) discusses various combinations of higher-level deterministic or stochastic behaviours being grounded by deterministic or stochastic behaviour of lower-level parts. His examples stem from the physical sciences, and we would do well to consider analogous combinations in the biological and behavioural sciences. Again, in imposing the conscious universe in research design, as part of scientific explanatory projects, scientists and philosophers might also wish to explore the possibility of the emergence and the irreducibility of consciousness itself. (As an example of a visualisation pertinent to mechanistic explanation, see **Figure 5** of the eLS article Metabolic Turnover.) **See also**: Genetics, Reductionism and Autopoiesis; Philosophy of Molecular Biology; Reductionism in Biology

occupation and son's education) as well as their relationships. Contextual knowledge beyond statistics remains critical in statistical model construction, model application and model validation.

These other forms of knowledge, explanation and questions are also important in another very simple way. Because reality is complex, we need to approach it from multiple perspectives. That is, if we wish to understand the full range of causes and outcomes in the temporal evolution of complex systems, and to intervene intelligently in reality in order to change it for the better, scientists need to investigate broad biological, psychological and social aspects of reality. Statistical models give us only one window into explaining complex reality. Historical (**Box 1**) as well as structural and mechanistic (**Box 2**) methodologies are as important as statistical methodology if we desire a full picture of the phenomena studied by the biological and behavioural sciences.

Open questions remain. Our three universes provide insight into how determinism and chance interact, in scientific methodologies. More concretely, what exactly is determinism in historical and mechanistic explanation? And how do intentional researchers – under the model of a conscious universe – integrate the various forms of knowledge produced by distinct general methodologies? As Longino (2013) suggests, perhaps distinct methodologies carve up their respective "causal space" in a manner incommensurable – and thus potentially non-integratable – to that of other methodological paradigms (Kuhn, 1970). If so, the plurality of explanatory projects and scientific methodologies could be at an 'explanatory impasse' (McManus, 2012). But might general research strategies instead not produce knowledge that is explanatorily 'miscible' (Walsh, 2013). That is, with sufficient interdisciplinary knowledge might we not be able to replace spotlight visions of reality with an overarching floodlight vision (Winther, 2011). **See also**: Complex Genetic Systems and Diseases; Personal Identity: Genetics and Determinism

## Acknowledgements

Doc Edge, Ryan Giordano, Jonathan Kaplan, Katie Kendig, Cory Knudson, Sergio Martínez, Lia Salaverry, Mette Smølz Skau, and an anonymous reviewer provided useful feedback on earlier drafts.

## References

Andersen EA, Christiansen PV, Emmeche C and Finnemann NO (2001) *Downward Causation. Minds, Bodies, and Matter*. Aarhus, Denmark: Aarhus University Press.

Bartha PFA (2010) *By Parallel Reasoning: The Construction and Evaluation of Analogical Arguments*. New York, NY: Oxford University Press.

Beatty J (2006) Replaying life's tape. *Journal of Philosophy* **103**: 336–362.

Blalock HM Jr (1964) *Causal Inferences in Nonexperimental Research*. Chapel Hill, NC: University of North Carolina Press.

Blau PM and Duncan OD (1978) *The American Occupational Structure*. New York, NY: Free Press.

Block N (1995) How heritability misleads about race. *Cognition* **56**: 99–128.

Born M (ed.) (1971) *The Born-Einstein Letters. The Correspondence Between Max & Hedwig Born and Albert Einstein, 1916–1955* (transl.), Irene Born, commentary Max Born, London: Macmillan.

Bostrom N (2003) Are you living in a computer simulation? *Philosophical Quarterly* **53**(211): 243–255.

Box GEP (1976) Science and statistics. *Journal of the American Statistical Association* **71**(356): 791–799.

Butler J (1990) *Gender Trouble: Feminism and the Subversion of Identity*. New York, NY: Routledge.

Callender C (1999) Reducing thermodynamics to statistical mechanics: the case of entropy. *Journal of Philosophy* **96**: 348–373.

Cantwell Smith B (1996) *On the Origin of Objects*. Cambridge, MA: MIT Press.

Cartwright N (1983) *How the Laws of Physics Lie*. New York, NY: Oxford University Press.

Cartwright N (1989) *Nature's Capacities and Their Measurement*. New York, NY: Oxford University Press.

Cartwright N (2007) *Hunting Causes and Using Them: Approaches in Philosophy and Economics*. New York, NY: Cambridge University Press.

Conway Morris S (2003) *Life's Solution: Inevitable Humans in a Lonely Universe*. New York, NY: Cambridge University Press.

Craver CF (2007) *Explaining the Brain: Mechanisms and the Mosaic Unity of Neuroscience*. New York, NY: Oxford University Press.

Crombie AC (1994) *Styles of Scientific Thinking in the European Tradition*, (vols. 1–3), London: Duckworth.

Dewey J (1893) The superstition of necessity. *Monist* **3**(3): 362–379.

Dewey J (1929) The quest for certainty. In: Boydston A (ed.) *The Later Works of John Dewey*, vol. 4, pp. 1–250. Carbondale, IL: University of Southern Illinois Press.

Downes SM (2014) Heritability. In: Zalta EN (ed.) *The Stanford Encyclopedia of Philosophy* (Spring 2014 Edition). http://plato.stanford.edu/archives/spr2014/entries/heredity/

Duncan OD (1966) Path analysis: sociological examples. *American Journal of Sociology* **72**(1): 1–16.

Dupré J (1993) *The Disorder of Things: Metaphysical Foundations of the Disunity of Science*. Cambridge, MA: Harvard University Press.

Felsenstein J (2004) *Inferring Phylogenies*. Sunderland, MA: Sinauer Associates.

Fisher RA (1925) *Statistical Methods for Research Workers*. Edinburgh: Oliver and Boyd.

Fisher RA (1935) *The Design of Experiments*. Edinburgh: Oliver and Boyd.

Foucault M (1990, 1978) *The History of Sexuality, volume 1: An Introduction*, (transl. Robert Hurley). New York, NY: Vintage Books.

Freedman DA (1991) Statistical models and shoe leather. *Sociological Methodology* **21**: 291–313.

Freedman DA (2009) *Statistical Models: Theory and Practice*. New York, NY: Cambridge University Press.

Frenkel E (2014) Ad Infinitum: A Review of Our Mathematical Universe by Max Tegmark. *The New York Times Sunday Book Review*. http://www.nytimes.com/2014/02/16/books/review/our-mathematical-universe-by-max-tegmark.html?_r=1

Frodeman R (1995) Geological reasoning: geology as an interpretative and historical science. *GSA Bulletin* **107**(8): 960–968.

Gaddis JL (2004) *The Landscape of History. How Historians Map the Past*. New York, NY: Oxford University Press.

Galton F Sir (1889) *Natural Inheritance*. New York, NY: Macmillan and Co.

Glennan SS (1997) Probable causes and the distinction between subjective and objective chance. *Noûs* **31**(4): 496–519.

Gould SJ (1989) *Wonderful Life: The Burgess Shale and the Nature of History*. New York, NY: W.W. Norton and Co.

Griesemer JR (1991) Must scientific diagrams be eliminable? The case of path analysis. *Biology and Philosophy* **6**: 155–180.

Haavelmo T (1943) The statistical implications of a system of simultaneous equations. *Econometrica* **11**(1): 1–12.

Hacking I (1983) Nineteenth century cracks in the concept of determinism. *Journal of the History of Ideas* **44**(3): 455–475.

Hacking I (1990) *The Taming of Chance*. New York, NY: Cambridge University Press.

Hacking I (2002) *Historical Ontology*. Cambridge, MA: Harvard University Press.

Hacking I (2007a) Kinds of people: moving targets. *Proceedings of the British Academy* **151**: 285–318.

Hacking I (2007b) Natural kinds: Rosy Dawn, scholastic twilight. *Royal Institute of Philosophy Supplements* **61**: 203–240.

Hacking I (2014) *Why Is There Philosophy of Mathematics at All?* New York, NY: Cambridge University Press.

Herrnstein RJ and Murray C (1995) *The Bell Curve. Intelligence and Class Structure in American Life*. New York, NY: The Free Press.

Hesse M (1966) *Models and Analogies in Science*. Notre Dame, IN: University of Notre Dame Press.

Hitchcock C (2012) Probabilistic causation. In: Zalta EN (ed.) *The Stanford Encyclopedia of Philosophy* (Winter 2012 Edition). http://plato.stanford.edu/archives/win2012/entries/causation-probabilistic/

Hocking RR (1996) Methods and applications of linear models. *Regression and the Analysis of Variance*. New York, NY: John Wiley & Sons, Ltd.

Holland PW (1986) Statistics and causal inference. *Journal of the American Statistical Association* **81**(396): 945–960.

Jensen A (1969) How much can we boost IQ and scholastic achievement? *Harvard Educational Review* **39**: 1–123.

Jones RH (2013) *Analysis & the Fullness of Reality: An Introduction to Reductionism & Emergence*. Amazon: CreateSpace Independent Publishing Platform.

Kahneman D (2011) *Thinking, Fast and Slow*. New York, NY: Farrar, Straus, and Giroux.

Kaplan JM and Winther RG (2014) Realism, antirealism, and conventionalism about race. *Philosophy of Science*. http://philpapers.org/rec/KAPRAA

Kline RB (1998) *Principles and Practice of Structural Equation Modeling*. New York, NY: Guilford Press.

Kuhn TS (1970) *The Structure of Scientific Revolutions*, 2nd ed. Chicago, IL: University of Chicago Press.

de Laplace PS (1902, 1814) *A Philosophical Essay on Probabilities*, (transl. F.W. Truscott and F.L. Emory). New York, NY: John Wiley & Sons.

Layzer D (1972) Science or superstition? (A physical scientist looks at the IQ controversy). *Cognition* **1**(2–3): 265–299.

Levins R and Lewontin RC (1985) *The Dialectical Biologist*. Cambridge, MA: Harvard University Press.

Lewontin RC (1970) Race and intelligence. *Bulletin of the Atomic Scientists* **26**: 2–8.

Lewontin RC (1974) Annotation: the analysis of variance and the analysis of causes. *American Journal of Human Genetics* **26**: 400–411.

Lieberson S (1987) *Making It Count. The Improvement of Social Research and Theory*. Berkeley, CA: University of California Press.

Lightman A (2013) *The Accidental Universe*. New York, NY: Pantheon Books.

Longino HE (2002) *The Fate of Knowledge*. Princeton, NJ: Princeton University Press.

Longino HE (2013) *Studying Human Behavior. How Scientists Investigate Aggression and Sexuality*. Chicago, IL: University of Chicago Press.

Lévi-Strauss C (1966, 1962) *The Savage Mind*. Chicago, IL: University of Chicago Press.

McManus F (2012) The structure of explanations and counter-explanations of homosexuality. *Open Journal of Philosophy* **2**(4): 235–243.

Meehl PE (1978) Theoretical risks and tabular asterisks: Sir Karl, Sir Ronald, and the slow progress of soft psychology. *Journal of Consulting and Clinical Psychology* **46**: 806–834.

Muller KE and Fetterman BA (2002) *Regression and ANOVA: An Integrated Approach Using SAS Software*. Cary, NC: SAS Institute.

Nagel E (1961) *The Structure of Science. Problems in the Logic of Scientific Explanation*. New York, NY: Harcourt, Brace & World.

Nelder JA and Wedderburn RWM (1972) Generalized linear models. *Journal of the Royal Statistical Society Series A (General)* **135**(3): 370–384.

Newman MEJ (2010) *Networks. An Introduction*. Oxford: Oxford University Press.

Neyman J (1990, 1923) On the application of probability theory to agricultural experiments. Essay on principles. Section 9. (transl. D.M. Dabrowska and T.P. Speed). *Statistical Science* **5**(4): 465–472.

Oyama S (2000a) *The Ontogeny of Information: Developmental Systems and Evolution*, 2nd ed. Durham, NC: Duke University Press.

Oyama S (2000b) *Evolution's Eye: A Systems View of the Biology-Culture Divide*. Durham NC: Duke University Press.

Page SE (2006) Path dependence. *Quarterly Journal of Political Science* **1**(1): 87–115.

Pearl J (2000) *Causality: Models, Reasoning, and Inference*. New York, NY: Cambridge University Press.

Peirce CS (1893) Reply to the necessitarians: rejoinder to Dr Carus. *Monist* **3**(4): 526–570.

Ragin CC (1987) *The Comparative Method. Moving Beyond Qualitative and Quantitative Strategies*. Berkeley, CA: University of California Press.

Ragin CC and Zaret D (1983) Theory and method in comparative research: two strategies. *Social Forces* **61**(3): 731–754.

Sarkar S (1998) *Genetics and Reductionism*. Cambridge: Cambridge University Press.

Sesardić N (2005) *Making Sense of Heritability*. Cambridge: Cambridge University Press.

Shipley B (2000) *Cause and Correlation in Biology. A User's Guide to Path Analysis, Structural Equations and Causal Inference*. Cambridge: Cambridge University Press.

Simon HA (1953) Causal ordering and identifiability. In: Hood WC and Koopmans JC (eds) *Studies in Econometric Method*, pp. 49–74. New York, NY: Wiley.

Solomon P, Cavanaugh MM and Draine J (2009) *Randomized Controlled Trials: Design and Implementation for Community-Based Psychosocial Interventions*. New York, NY: Oxford University Press.

Spirtes P, Glymour C and Scheines R (1993) *Causation, Prediction, and Search*. Dordrecht, NL: Springer.

Steel D (2008) *Across the Boundaries: Extrapolation in Biology and Social Science*. Oxford: Oxford University Press.

Stein E (1999) *The Mismeasure of Desire. The Science, Theory, and Ethics of Sexual Orientation*. New York, NY: Oxford.

Suppes P (1984) *Probabilistic Metaphysics*. Oxford: Blackwell.

Tegmark M (2014) *Our Mathematical Universe: My Quest for the Ultimate Nature of Reality*. New York, NY: Knopf.

Visscher PM, Hill WG and Wray NR (2008) Heritability in the genomics era – concepts and misconceptions. *Nature Reviews Genetics* **9**: 255–266.

Wade MJ (1992) Sewall Wright: gene interaction and the shifting balance theory. In: Antonovics J and Futyuma D (eds) *Oxford Surveys of Evolutionary Biology VI*, pp. 35–62. New York, NY: Oxford University Press.

Wahlsten D (1990) Insensitivity of the analysis of variance to heredity-environment interaction. *Behavioral and Brain Sciences* **13**: 109–161.

Walsh D (2012) Mechanism and purpose: a case for natural teleology. *Studies in History and Philosophy of Science Part C: Studies in History and Philosophy of Biological and Biomedical Sciences* **43**(1): 173–181.

Walsh D (2013) Mechanism, emergence, and miscibility: the autonomy of Evo-Devo. In: Huneman P (ed.) *Functions:*

*Selection and Mechanisms*, pp. 43–65. Dordrecht, NL: Springer.

Webster G and Goodwin B (1996) *Form and Transformation. Generative and Relational Principles in Biology*. Cambridge: Cambridge University Press.

Welsh AH, Peterson AT and Altmann SA (1988) The fallacy of averages. *American Naturalist* **132**(2): 277–288.

Williams M (1982) The importance of prediction testing in evolutionary biology. *Erkenntnis* **17**: 291–306.

Wimsatt WC (2007) *Re-Engineering Philosophy for Limited Beings: Piecewise Approximations to Reality*. Cambridge, MA: Harvard University Press.

Winther RG (2008) Systemic darwinism. *Proceedings of the National Academy of Sciences of the USA* **105**(33): 11833–11838.

Winther RG (2009) Prediction in selectionist evolutionary theory. *Philosophy of Science* **76**: 889–901.

Winther RG (2011) Part-whole science. *Synthese* **178**: 397–427.

Winther RG (2012) Interweaving categories: styles, paradigms, and models. *Studies in History and Philosophy of Science, Part A* **43**(4): 628–639.

Winther RG (2014) James and Dewey on Abstraction. *The Pluralist* **9**(2): 1–28.

Winther RG (Under Contract) *When Maps Become the World. Abstraction and Analogy in Philosophy of Science*. University of Chicago Press. http://ihr.ucsc.edu/when-maps-become-the-world/

Wolfram S (2002) *A New Kind of Science*. Champaign, IL: Wolfram Media.

Woodward J (2011) Scientific explanation. In: Zalta EN (ed.) *The Stanford Encyclopedia of Philosophy* (Winter 2011 Edition). http://plato.stanford.edu/archives/win2011/entries/scientific-explanation/

Woodward J (2013) Causation and manipulability. In: Zalta EN (ed.) *The Stanford Encyclopedia of Philosophy* (Winter 2013 Edition). http://plato.stanford.edu/entries/causation-mani/

Wright S (1921) Correlation and causation. *Journal of Agricultural Research* **20**(7): 557–585.

Wright S (1931) Statistical methods in biology. *Journal of the American Statistical Association* **26**(173): 155–163.

Wright S (1934) The method of path coefficients. *Annals of Mathematical Statistics* **5**(3): 161–215.

Wright S (1968) *Evolution and the Genetics of Population*, vol. 1, Chicago, IL: University of Chicago Press.