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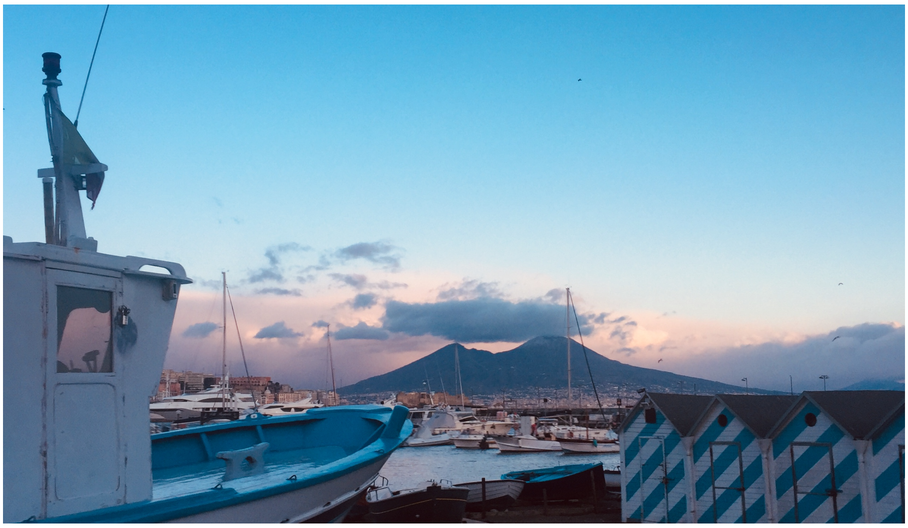

The 'Why' of Methodology in Scale Modeling / SUSAN G. STERRETT

Scale models are special among all models in science, in that they are so intimately connected with what they model. They are both models in the (physical) world, and models of the (physical) world. Those who use scale models in their research know that the design of the scale model experiment, as well as the interpretation of its results, are informed by physical theory. Though practical experiential knowledge is often also involved, physical theory is fundamental to the use of scale models, even if only implicit in the methods used. There are different approaches to applying physical theory in the design of scale model experiments.

An intriguing question is whether the fundamental reasons that these different approaches are effective (when they are) are the same.

In this talk, I take a philosophical look at the methodology of scale models, especially the question: Why does the methodology work? I center my investigation on the approach of similar systems. To emphasize that the kind of similarity that is meant here is similarity with respect to the behaviour studied in the physical sciences, the term physically similar systems has been used. Though proportions, and even dimensionless ratios, had been used as a basis for scale model experiments long before the formalization of the method in terms of sets of dimensionless parameters (pi groups), the articulation of the concept in terms of physically similar systems by Buckingham in 1914 was distinctive.

It is also notable that Buckingham presented the method as an application of something called dimensional equations. The paper was titled "On Physically Similar Systems: Illustrations of the use of Dimensional Equations." Some discussions of dimensional analysis use dimensions and units interchangeably but they are not the same. In some contexts, it may not matter, but in others the difference is telling. I will explain the significance of dimensions in metrology (the science of measurement). Understanding their role in metrology provides insight into why dimensions and similarity really are related, when a system of measurement is designed to be a coherent system of measurement. A system of measurement is coherent (as the term is used here) when the relations between its units are the same as the relations between quantities.

I will explain that the notion of system also plays a crucial role in explaining why the methodology works when it does. If time permits, I will also raise the question of what insights from this inquiry into methodology of scale modeling in terms of dimensions might be useful in the new suggestions to use data-driven methods in scale modeling.

Keywords: Physically Similar Systems; Buckingham; Dimensions; Models.

Susan G Sterrett is the Curtis D Gridley Distinguished Professor of History and Philosophy of Science in the Department of Philosophy at Wichita State University in Wichita, Kansas, USA. She has a B.S. in Engineering Science from CornellUniversity, an M.A. in Mathematics and a M.A. and Ph.D. in Philosophy from the University of Pittsburgh. She taught at Duke University and Carnegie-Mellon University before taking up her current position. Much of her work involves the use of analogy and models in science and the logic of science. She has written on the use of analogy in history of science, including the use of analogy in the works of Darwin, Einstein, Wittgenstein, and Turing. Her extensive work on philosophy of models in physics and engineering include "Similarity and Dimensional Analysis", "Experimentation on Analogue Models", "Physically Similar Systems: a history of the concept"; "Relations Between Units and Relations Between Quantities", "Scale Modeling", and "Dimensions."

The Theory of Scaled Experimentation / KEITH DAVEY

Scaled experimentation provides the means to investigate complex behaviours at a fraction of the time and cost of full-sized investigations. Experiments at scale are often performed under controlled laboratory conditions to ensure high levels of accuracy and provide opportunities for multiple investigative trials. An unfortunate drawback with scaling, however, is scale effects, which are those changes in behaviour that manifest at scale and can be so pronounced to severely limit the benefits of any scaled experiment. In quite general terms, scale effects have invariably had the effect of limiting the reach and benefits of scaled experimentation.

The principal issue and problem facing scaled experimentation is the absence of a theory that accounts for scale effects. For over a century, dimensional analysis has been the sole ubiquitous similitude theory available to scaling but unfortunately scale effects are not accommodated by this theory. Dimensional analysis, in scaling terms, is founded on an invariance principle that dimensionless equations do not change with scale, which can at best be used to detect scale effects by the breaking of similitude rules. This was the situation until very recently prior to the appearance of a new theory in the open literature, which is the focus of this presentation. The new theory is called finite similitude, which provides a countable infinite number of similitude rules, and each rule can be shown to be unique. It can also be shown that the theory of dimensional analysis is captured completely by just one of these rules.

The new theory can be applied to all classical physics including mechanics, electromagnetism and thermodynamics and is able to link an unlimited number of experiments across the scales. It approaches scaling in a new and somewhat unusual manner being founded on a metaphysical concept called space scaling. Although space scaling cannot be achieved practically it nevertheless can be defined precisely mathematically and its effect on governing equations in transport form can be quantified. The approach accounts for all possible scale effects that can occur in physical experiments.

In this presentation the foundations for the theory are introduced and the transport forms for mechanics, electromagnetism and thermodynamics are considered. A critical feature of the theory is the projection of physics, taking place at scale, onto the full-size physical space. It is shown how this projection captures all possible scale effects and consequently rather than simply ignoring these, as in the case of dimensional analysis, their representation is central to the new approach.

The overall focus therefore is the revealing and representation of scale effects, which is achieved by introducing a calculus for scaling in the form of differential equations whose order is linked to the number of scaled experiments required for a particular study.

The solution to these equations provides the rules for linking scaled experiments, which are applied here to problems in earthquake mechanics, nonlinear dynamics, and fracture mechanics.

Keywords: scaling; High-Order Finite Similitude; Continuum Mechanics, Electromagnetism, Thermodynamics.

Keith Davey has degrees in engineering and mathematics, obtained his doctorate in 1989, and joined the University of Manchester (UMIST) as a lecturer in 1990 after lecturing for one year at the University of Sheffield. He has over ten years of industrial experience and prior to becoming an academic, he worked in metal processing and heavy construction industries. He has published some 200 papers, mainly in international conferences and journals. His main areas of research relate to the mathematical modelling of physical phenomena with particular focus on models for advanced processes in areas closely related to solid mechanics. In recognition of his research record of accomplishment and work with industry he is was appointed Editor-in-Chief for the International Journal of Mechanical Sciences and was invited to become: a Visiting Professor at the University of Wolverhampton, a Technical Panel Member of the UK Die Casting Centre, and a member of numerous editorial and scientific conference committees. His industrial-research interests looking into scaled experimentation have recently been supported through the auspices of an EPSRC HVM Fellowship to facilitate collaborative work at the AFRC Catapult in Scotland. Dr. K. Davey has re-focused his research interests in recent years to explore applications, where transport equations play a significant role in solid mechanics. This includes research on shocks, fracture and moving boundary problems but most notably is his work on scaled experimentation and the discovery of finite similitude. This new concept has led to publications on scaled experimentation in biomechanics, metal forming, powder processing, impact, damage and fracture mechanics, earthquake engineering, structural dynamics, and presently work is ongoing in the areas of fatigue, electromagnetism, electro-mechanical systems, and the application of 3-D printed scaled models in biomechanics.

Similitude in Hydraulic Modeming / VALENTIN HELLER

Hydraulics is the branch of science and technology concerned with the conveyance of liquids through pipes and channels. Hydraulics has a wide range of applications in open channel flows, renewable energy, pipe flows and natural hazards. It typically concerns the quantification of the discharge, water depth, fluid forces and sometimes the entrainment and/or transport of air, floating bodies, and sediment. An important method to investigate complex hydraulic phenomena are physical hydraulic scale models in the laboratory environment. This keynote lecture addresses different strategies to achieve similitude between hydraulic models and the corresponding phenomena in nature, i.e., in the prototype.

The Froude scaling laws (FSL) have been used to model a wide range of hydraulic flows at reduced size for almost a century. These laws were derived by assuming that the Froude number F = (inertial force/gravity force) 1/2 is identical in the model and its prototype. Other force ratios, e.g. the Reynolds number R = (inertial force/viscous force) and Weber number W = (inertial force/surface tension force), are incorrectly represented if the fluid properties are the same in the model and its prototype. A precise application of the FSL (mechanical similarity) has not been achieved in the laboratory as the options to alter the fluid properties are limited, i.e. viscous and surface tension forces are incorrectly scaled. These incorrectly scaled forces can result in significant scale effects, i.e., deviations between the up-scaled model and prototype observations. Scale effects are particularly significant for air-water flows, sediment transport and for fluids interacting with flexible structures.

Strategies to deal with significant scale effects in Froude models are presented, including avoidance (e.g., respecting limiting values for R and/or W), compensation (e.g., model geometry distortion) and correction (e.g., removal in the upscaling process). For phenomena affected by both F and R, the first strategy to exclude R scale effects is closely related to self-similarity and R invariance. This is illustrated with a range of examples such as wakes, jets, tidal energy converters and gravity currents.

Novel scaling laws (NSL) for air-water flows, as an alternative to FSL, are then introduced. They are based on the self-similarity of the Reynolds-averaged Navier-Stokes equations, including surface tension effects. All physical processes considered by these equations are similar between different scales such that no scale effects are observed. These NSL were validated in numerical simulations for (i) a dam break flow interacting with an obstacle and (ii) a vertical plunging water jet. The results demonstrate self-similarity at different scales, i.e., they collapse in dimensionless form, in contrast to those obtained with the FSL showing significant scale effects.

A validation of these NSL in the laboratory is still pending, however, this is less challenging than achieving mechanical similarity for the FSL as the NSL are more universal and flexible. Further, similar scaling laws may be derived for sediment transport and fluids interacting with flexible structures, to complement the NSL for air-water flows and to overcome some significant limitations of FSL in achieving similitude in hydraulic modelling.

Keywords: Froude Scaling Laws; Hydraulic Modelling; Scale Effects; Self-similarity.

Valentin Heller is currently an Assistant Professor in Hydraulics in the Department of Civil Engineering at the University of Nottingham and a member of the Environmental Fluid Mechanics and Geoprocesses research group (www.nottingham.ac.uk/Engineering/People/valentin.heller).
Previously, he held one of the prestigious Imperial College London Research Fellowships (2011-2014), worked as a Research Fellow at the University of Southampton (2008-2011) and as a postdoctoral researcher at ETH Zurich (2008). ETH Zurich is also the place where he was awarded his PhD degree for the experimental investigation of landslide-tsunamis. Valentin is mainly active in Experimental and Computational Fluid Dynamics with applications into a wide range of fluid-structure interactions from small to very large scale (www.drvalentinheller.com). He has a keen interest in scale modelling and scale effects and investigated them for a range of applications including landslide-tsunamis, air-water flows, granular slides, wave impact on flexible structures and shallow-water vortices. He published the review articles “Scale effects in physical hydraulic engineering models” (2011) and “Self-similarity and Reynolds number invariance in Froude modelling” (2017) in the Journal of Hydraulic Research (JHR). The former article is currently the most cited article of the JHR with over 400 citations on Google Scholar and received the Harold Jan Schoemaker Award in 2013 as the most outstanding paper published in the JHR in 2011-2012. He currently supervises a Research Fellow and 5 PhD students and was the project leader of an EU funded HYDRALAB+ project. He was the PI of a NERC funded project and worked as a researcher on a range of further research projects. He is an Editor of Landslide (Springer) and an Editorial Board Member of the Journal of Marine Science and Engineering (MDPI) where he run two special issues. He has been a technical reviewer for 40 academic journals and for four research councils.

Measuring scaling relationships: error, discretization and chance / MITCHELL NEWBERRY

Power-law scaling relationships of the form Y = c X $^{\alpha}$ underlie scale modeling through the principles of similitude and renormalization. Often, the exponent alpha is known theoretically. When the exponent is not known, as often occurs in biology, estimating it from empirical data has been notoriously challenging.

Mapping out the relationship by collecting data over many orders of magnitude in X, for example, poses unique experimental challenges of making measurements of vastly different sizes with different kinds of experimental error. Furthermore, whereas linear regression provides a reliable statistical method for estimating the parameters of linear relationships, the corresponding statistical methods for estimating the exponent of a power law are less developed and less reliable. Historical methods such as visual inspection, regression on log-log plots and maximum likelihood each suffer unique drawbacks. When Y counts the number of occurrences of magnitude X, the scaling relationship Y = c X $^{\alpha}$ can be interpreted as a probability distribution.

Probability offers a rich set of mathematical results including a method for estimating parameters by maximizing the likelihood of the data. Estimating alpha from a probability distribution offers a powerful technique: for example, if we ask how many blood vessels exist of a certain size, we recover a value alpha that describes a physical constraint on blood vessels due to fluid mechanics. Yet maximum likelihood too exhibits unique pitfalls when applied to power-law distributions. One example is that the assumption that Y scales continuously with X fails in practice for blood vessels and earthquakes.

I show that accounting for discrete scaling fixes errors in estimation, and furthermore makes estimates more robust by eliminating a key problem with maximum likelihood. The idea then applies more generally to other methods of measuring scaling relationships. Along the way, we will encounter examples from lungs, mammals, fractals, vortices in turbulence, earthquakes, and dinosaur bones.

Keywords: Power-law Distribution; Inference; Discrete-Scale Invariance; Self-similarity.
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Mitchell Newberry develops mathematical and computational theory to understand biological and cultural evolution as Assistant Professor of Complex Systems at University of Michigan and the Michigan Society of Fellows. He has measured self-similarity and scaling relationships in circulatory morphology as well as biological and cultural diversity. He specializes in probability theory and statistical inference and has developed new methods for inferring power law scaling exponents. He has practiced as a professional software engineer and contributed to open-source software. He completed a B.S. in Physics at University of Washington, M.S. in Biomathematics at UCLA, and PhD in theoretical population genetics at University of Pennsylvania. His research has appeared in Physical Review Letters, PLoS Computational Biology and Nature as well as popular press venues such as The Conversation, Buzzfeed and The Atlantic.