

predictability and global disease dynamics

dirk brockmann northwestern institute on complex systems

### predictability



### predictability





### predictability = knowing initial conditions

### predictability



### predictability = knowing parametric conditions

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### the millennium bridge, London



### traveling waves in measles epidemic



Grenfell, B., et al., Nature 414, 716–723 (2001).

### predictability in global disease dynamics

### 1760



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### MATHEMATICS IN EPIDEMIOLOGY



DANIEL BERNOULLI (1700-1782) model for smallpox inoculation

- use of differential equations
- published in 1766
- the use of calculus, in particular differential equations was novel

I simply wish that, in a matter which so closely concerns

the wellbeing of the human race, no decision shall be made

without all the knowledge which a little analysis and

calculation can provide'

Mem Math Phy Acad Roy Sci Paris 1766

Daniel Bernoulli 1760.



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### inoculation debate





Charles Maríe de la Condamíne (1701–1774)





Pierre Louis Moreau de Maupertuis (1698-1759) D'ALEMBERT WAS A MEMBER OF THE ROYAL SOCIETY

KNEW OF BERNOULLI'S WORK SINCE 1760 PRESENTATION BY CONDAMINE

GENERALIZED BERNOULLI'S MODEL AND PUBLISHED IT BEFORE HIM IN 1765 D'ALEMBERT DID NOT LIKE LEONARD EULER, EULER WAS A GOOD FRIEND OF BERNOULLI HOWEVER.

BERNOULLI WAS VERY ANGRY ABOUT D'ALEMBERT'S BEHAVIOUR

What do you say about the enormous platitudes of the great d'Alembert about the probabilities; as I find myself too frequently unjustly treated in his publications, I have decided already some time ago to read nothing anymore which comes from his pen; I have taken this decision on the occasion of a manuscript about inoculation which I sent to the Academy in Paris eight years ago and which was greatly appreciated because of the novelty of the analysis; it was, I dare say, like incorporating a new province into the body of mathematics; it seems that the success of this new analysis caused him pains of the heart;

he has criticized it in a thousand ways all equally ridiculous, and after having it well criticized, he pretends to be the first author of a theory which he did not only hear mentioned. He, however, knew that my manuscript could only appear after some seven or eight years, and he could only have knowledge about it in his capacity as member of the Academy, and in this respect my manuscript should have stayed sacred until it was made public. Dolus an virtus quis in hoste requirat!

### 2013



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### global mobility and dense populations



- > 50 % urban population
- population > 7 billion
- 3 billion passengers / yr
- 5 trillion km / yr



### HINI (swine flue) 2009



The boundaries and names shown and the designations used on this map do not imply the expression of any opinion whatsoever on the part of the World Health Organization concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. Dotted lines on maps represent approximate border lines for which there may not yet be full agreement. Data Source: World Health Organization Map Production: Public Health Information and Geographic Information Systems (GIS) World Health Organization



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Map produced: 01 July 2009 11:38 GMT



### EHEC 2011



Intected: Cases of enteronaemorrhagic E. coll without haemolytic uraemic syndrome (HUS). HUS: Cases with HUS. Numbers in brackets show recorded deaths

- foodborn disease
- E. Coli
- May June 2011
- 4000 affected, 60 died



### Frank, et al., New England Journal of Medicine (2011).

### finding outbreaks



Ackland, G. J., Signitzer, M., Stratford, K. & Cohen, M. H. P PNAS (2007). Pinhasi, R., Fort, J. & Ammerman, A., Plos Biol (2005) Hamilton, M. J. & Buchanan, B., PNAS, (2007).

### questions



Noble, Nature (1974) vol. 250 (5469) pp. 726-728 Fort, J. & Méndez, V.,. Phys Rev Lett (1999).

### SIR DYNAMICS



mean field dynamics:  $\partial_t S = -R_0 I S$   $\partial_t I = R_0 I S - I$ R = 1 - S - I



The basic reproduction number

$$\alpha \times T = R_0 > 1$$



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### reaction diffusion models

$$\partial_t I = \alpha I S / N - \beta I + D \partial_x^2 I$$
  
$$\partial_t S = -\alpha I S / N + D \partial_x^2 S$$
  
$$v \propto \sqrt{(R_0 - 1)D}$$







$$\partial_t j_n = \alpha s_n j_n - \beta j_n + \gamma \sum_{\substack{m \neq n}} P_{nm} \left( j_m - j_n \right).$$
$$\partial_t s_n = -\alpha s_n j_n + \gamma \sum_{\substack{m \neq n}} P_{nm} \left( s_m - s_n \right).$$

### geographic distance and arrival times in a hypothetical pandemic





### quantitative computational models

### GLEaMviz



Hufnagel et al. Forecast and control of epidemics in a **globalized** world. PNAS (2004)

Ferguson et al. Strategies for containing an emerging influenza **pandemic** in Southeast Asia. Nature (2005)

Hollingsworth et al. Will **travel restrictions** control the **international spread** of pandemic influenza?. Nat Med (2006)

Colizza et al. The role of the **airline transportation** network in the prediction and predictability of global epidemics. PNAS (2006)

Ferguson et al. Strategies for mitigating an influenza **pandemic**. Nature (2006)

Colizza et al. Modeling the **worldwide spread** of pandemic influenza: Baseline case and containment interventions. Plos Med (2007)

Colizza et al. Reaction-diffusion processes and metapopulation models in heterogeneous networks. Nat Phys (2007)

Colizza et al. Invasion threshold in heterogeneous metapopulation networks. Phys Rev Lett (2007) vol. 99 (14)

Riley. **Large-scale spatial-transmission** models of infectious disease. Science (2007)

Colizza et al. Epidemic modeling in metapopulation systems with heterogeneous coupling pattern: Theory and simulations. J Theor Biol (2008)

### measuring human mobility



### THE FLUX OF DOLLARS





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### A MODEL FOR THE SPREAD OF HINI IN THE US



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### HINI PROJECTIONS US





500 or wore

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### HINI PANDEMIC 2009





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### QUANTITATIVE MODELS



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Uses and Abuses of Mathematics in Biology

the particulate nature of inheritance were contemporary with Darwin, and his published work accessible to Darwin. Fisher and others have suggested that Fleeming Jenkin's fundamental and intractable objections to The Origin of Species could have been resolved by Darwin or one of his colleagues, if only they had grasped the mathematical significance of Mendel's results (1). But half a century elapsed before Hardy and Weinberg (H-W) resolved the difficulties by proving that particulate inheritance preserved variation have solved one of Darwin's major problems. In his day, it was thought that in-Today, the H-W Law stands as a kind of heritance "blended" maternal and paternal within populations (2). Newton's First Law (bodies remain in their characteristics. However, as pointed out to state of rest or uniform motion in a straight Darwin by the engineer Fleeming Jenkin line, except insofar as acted upon by external and others, with blending inheritance it is forces) for evolution: Gene frequencies in a virtually impossible to preserve the natural variation within populations that is both observed and essential to his theory of how

evolution works. Mendel's observations on 6 FEBRUARY 2004 VOL 303 SCIENCE www.sciencemag.org

Zoology Department, Oxford University, Oxford OX1 3PS, UK.

NICO

VIEWPOINT

Dirk Brockmann

Darwin once wrote "I have deeply regretted

that I did not proceed far enough at least to

understand something of the great leading

principles of mathematics; for men thus

endowed seem to have an extra sense."

With the benefit of hindsight, we can see

how much an "extra sense" could indeed

In the physical sciences, mathematical theory and experimental investigation

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Increasingly in recent decades, however, mathematics has become pervasive in

biology, taking many different forms: statistics in experimental design; pattern

much else. I offer an opinionated overview of such uses—and abuses.

seeking in bioinformatics; models in evolution, ecology, and epidemiology; and

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Uses and Abuses of Mathematics in Biology the particulate nature of inheritance contemporary with Darwin, and his p lished work accessible to Darwin, Fis and others have suggested that Fleeni fundamental and intractable jections to The Origin of Species cou have been resolved by Darwin or one of h if only they had grasped th significance of Mendel But half a century elapse colleagues, mathematical Hardy and Weinberg (H-W) solved the difficulties by proving that par results (1).

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The increasing speed and sophistication and ease of use of computers enables an increasingly large number of life scientists who have no substantial background in mathematics to explore "mathematical models" and draw conclusions about them.



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Uses and Abuses of Mathematics in Biology the particulate nature of inheritance contemporary with Darwin, and his p lished work accessible to Darwin, Fis and others have suggested that Fleemi fundamental and intractable The Origin of Species con lections to the origin of species out have been resolved by Darwin or one of h Jenkin's if only they had grasped t significance of Mendel But half a century elapse colleagues, mathematical

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> Such activity usually consists of representing sensible and evidence-based assumptions as the starting point for a complicated and usually nonlinear dynamical system, assigning particular parameters (often in an arbitrary way), and then letting this complicated system rip.



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# Uses and Abuses of Mathematics in Biology

In the physical sciences, mathematical theory and experimental investigation In the physical sciences, mathematical theory and experimental investigation have always marched together. Mathematics has been less intrusive in the life sciences, possibly because they have until recently been largely description have always marched together. Mathematics has been less intrusive in the life sciences, possibly because they have until recently been largely descriptive, leaving the invariance principles and fundamental natural constants of physics sciences, possibly because they have until recently been largely descriptive, lacking the invariance principles and fundamental natural constants of physics. lacking the invariance principles and fundamental natural constants of physics. Increasingly in recent decades, however, mathematics has become pervasive in history, taking many different former statistics in province to decide and the second seco increasingly in recent decades, however, mathematics has become pervasive in biology, taking many different forms: statistics in experimental design; pattern whim in bioinformatics models in evolution ecology and endowinterm Y, taking many different forms: statistics in experimental design; pattern 3 in bioinformatics; models in evolution, ecology, and epidemiology; and the Loffer an oninionated overview of each account abuse have solved one of Darwin's major prob-

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we arguably are seeing an increasingly large body of work in which sweeping conclusions - "emergent phenomena" - are drawn from the alleged working of a mathematical model, without clear understanding of what is actually going on. I think this can be worrying.



vorks. Mendel's observations on



### is something more fundamental going on?

### redefining the notion of distance

# simple idea: effective distance LHR, New York P(i|j): fraction of traffic: $j \rightarrow i$ PIT, Pittsburgh, PA FRA, Frankfurt JFK, New York RDU, Raleigh Durham, NC

## a different notion of distance



# shortest path trees $d(i|j) = 1 - \log P(i|j) \qquad \lambda(\Gamma) = L - \sum_{i=1}^{L-1} \log P(i|j)$

### $D(m|n) = \min_{\Gamma} \lambda(\Gamma)$

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Grady, Thiemann, Brockmann., Nat. Comm. (2012).





### propagating waves









### the spread in effective distance





### reconstructing an outbreak origin

### outbreak origin reconstruction



### outbreak origin reconstruction





### outbreak origin reconstruction



### a key component of predictability



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### ARTICLE



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### ongoing projects

### HUS/EHEC 2011

### neolithic spread of farming





