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Fractional Calculus View of Intelligent Adaptive Systems

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Oct. 19, 2017. Thursday 1:30-2:30pm

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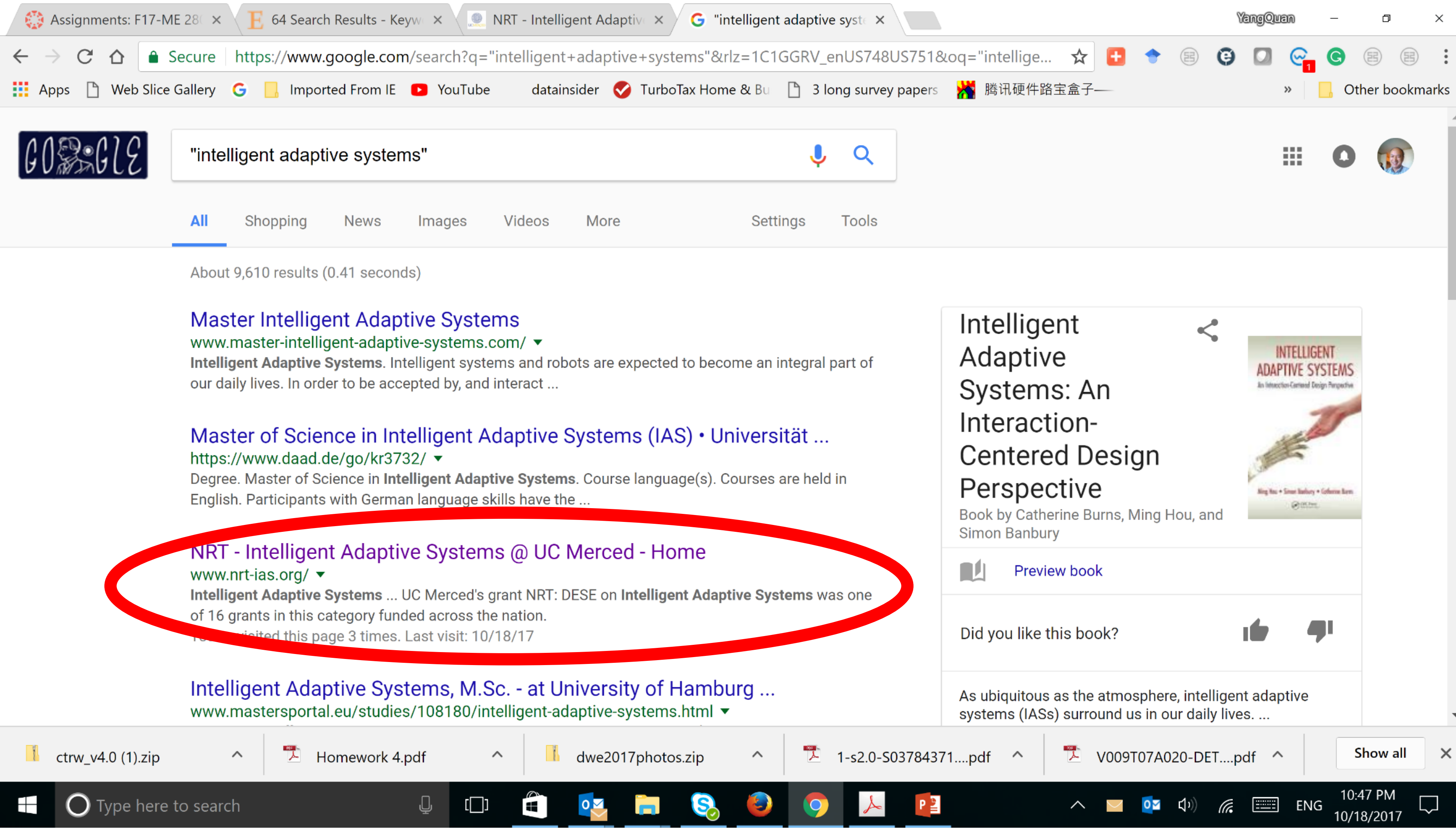
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Intelligent Adaptive Systems, M.Sc. - at University of Hamburg ...
www.mastersportal.eu/studies/108180/intelligent-adaptive-systems.html
Intelligent Adaptive Systems: An Interaction-Centered Design Perspective
Book by Catherine Burns, Ming Hou, and Simon Banbury
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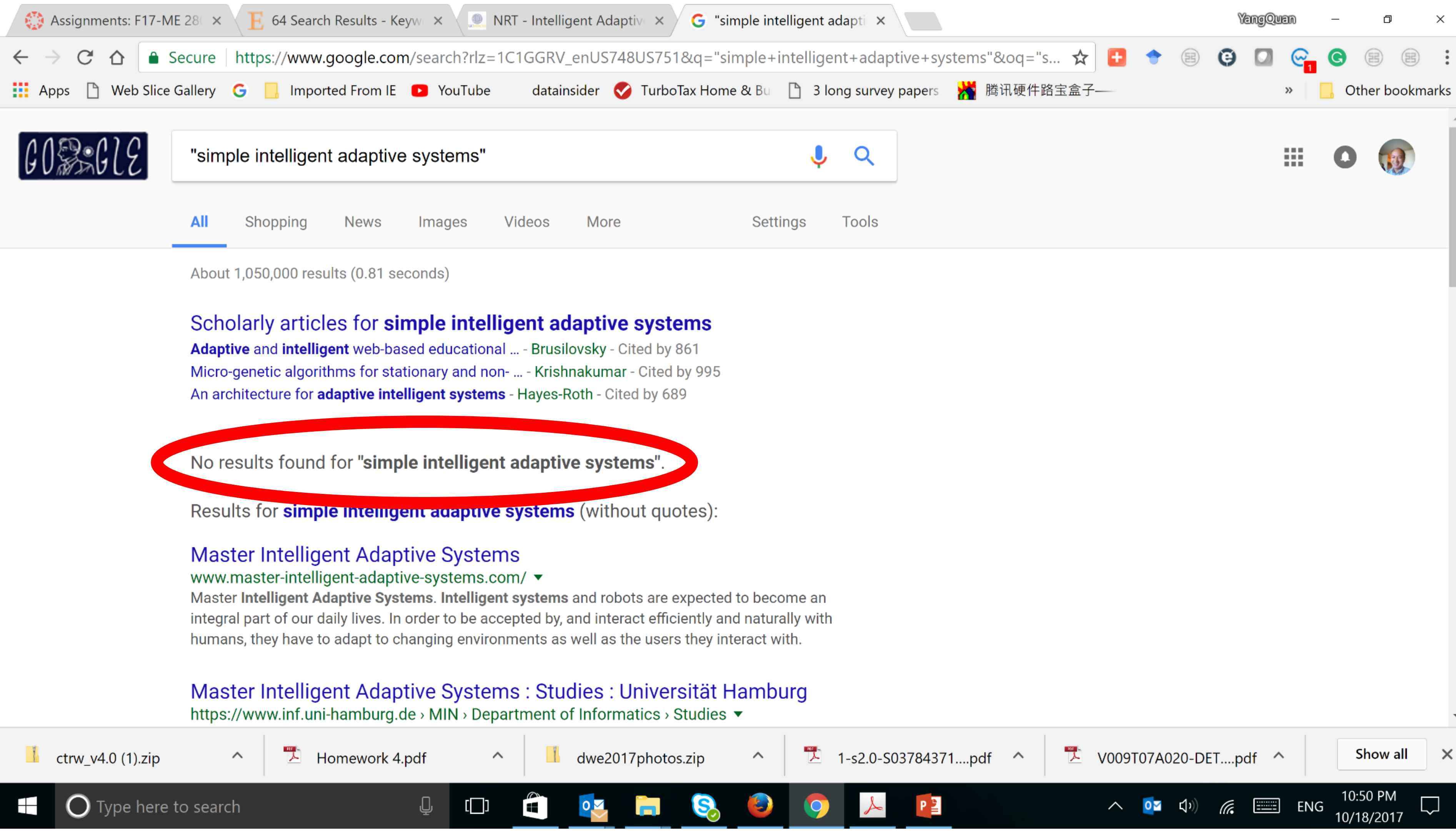
Assignments: F17-ME 28
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Results for simple intelligent adaptive systems (without quotes):
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Question

- Is "intelligent adaptive system" complex?
  - Yes
  - ME280 "Fractional Order Mechanics"

- Is adaptive control system always nonlinear?
  - Yes
  - ME211 "Nonlinear Control"

Fractional Calculus View of Complex Worlds

Outline

- What is fractional calculus
- What is considered as complex
- Fractional calculus view of complexity
- Conclusions
  - Big data hype and fractional calculus
  - A call for contributions

Outline

- **What is fractional calculus**
- What is considered as complex
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  - Big data hype and fractional calculus

What is “Fractional Calculus”?

- **Calculus**: integration and differentiation.
- **“Fractional Calculus”:** integration and differentiation of non-integer orders.
  - Orders can be real numbers (and even complex numbers!)
  - Orders are not constrained to be “integers” or even “fractionals”

How this is possible?

Why should I care?

Any (good) consequences (to me)?

Riemann–Liouville definition

$$ {}_aD_t^{\alpha} f(t) = \frac{1}{\Gamma(n-\alpha)} \left(\frac{d}{dt}\right)^n \int_a^t \frac{f(\tau)\, d\tau}{(t-\tau)^{\alpha-n+1}} $$

$$ (n-1 \le \alpha < n) $$

G.F.B. Riemann (1826–1866)

J. Liouville (1809–1882)

$$ I^{\alpha} f(t) = (\frac{1}{t^{1-\alpha}}) * f(t) / \Gamma(\alpha) $$

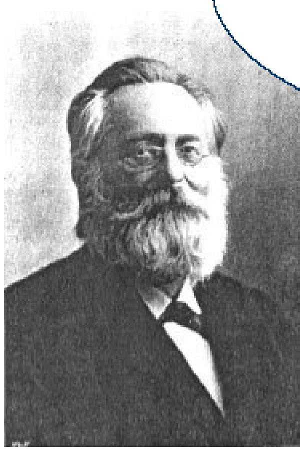
$$ D^{\alpha} f(t) = \frac{d}{dt}[I^{1-\alpha} f(t)] = \frac{d}{dt}[(\frac{1}{t^{\alpha}}) * f(t)] / \Gamma(1-\alpha) $$

Slide credit: Igor Podlubny

Grünwald–Letnikov definition

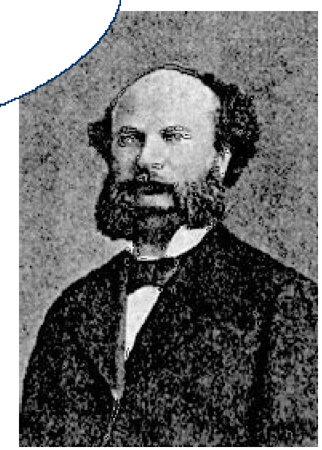
$$ {}_aD_t^{\alpha} f(t) = \lim_{h \to 0} h^{-\alpha} \sum_{j=0}^{\left[\frac{t-a}{h}\right]} (-1)^j \binom{\alpha}{j} f(t - jh) $$

$[x]$ – integer part of x



A.K. Grünwald

A.V. Letnikov

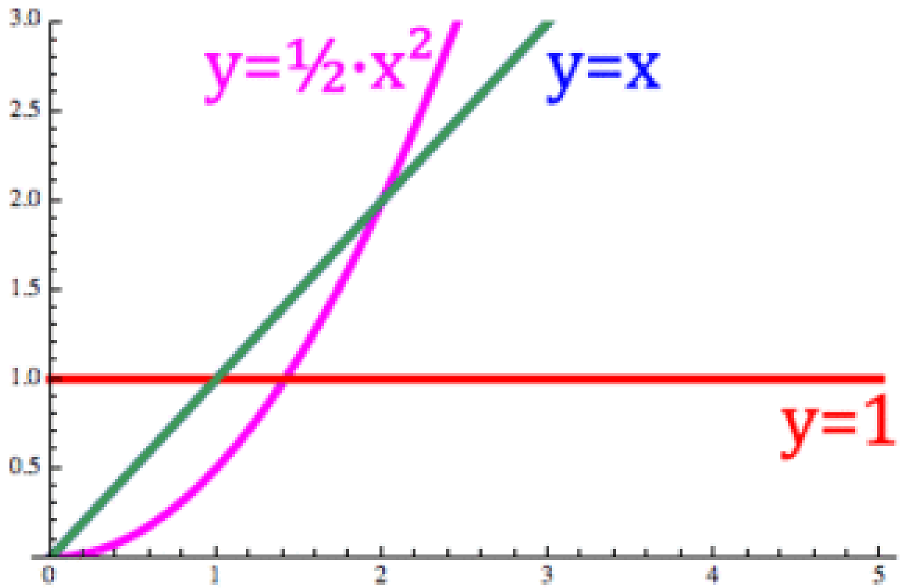


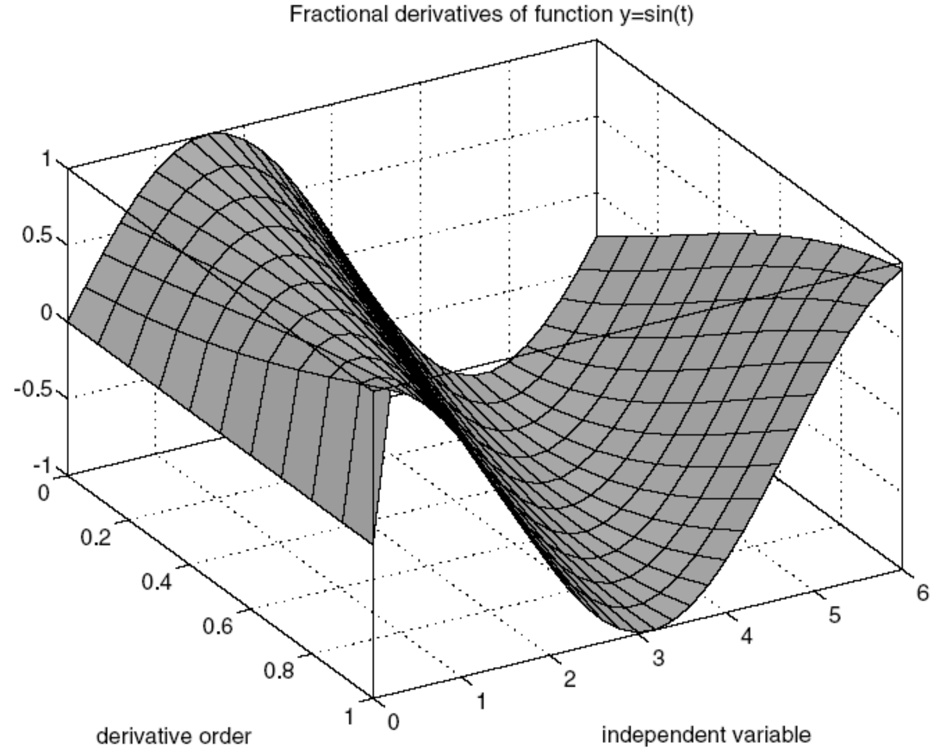
First Derivative:

$$ f'(a) = \lim_{h \to 0} \frac{f(a+h) - f(a)}{h}. $$

Slide credit: Igor Podlubny

Example: $\sin(t)$





The animation shows the derivative operator oscillating between the antiderivative (α=-1) and the derivative (α=1) of the simple power function y=x continuously.

http://en.wikipedia.org/wiki/Fractional_calculus

Slide credit: Igor Podlubny

Integer-Order Calculus

Fractional-Order Calculus

Slide credit: Richard L. Magin, ICCC12


NEURO FUZZY
Made in Japan
KEEP WARM
EXTENDED KEEP WARM
NS-ZCC10
WHITE RICE
REG/SUSHI
SOFTER
HARDER
QUICK COOKING
18:34
MIXED
PORRIDGE
SWEET
SEMIBROWN
BROWN
COOKING REHEAT
RESET
MENU
TIMER
PRE-WASHED
TIME SETTING
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"Fractional Order Thinking" or, "In Between Thinking"

- For example
  - Between integers there are non-integers;
  - Between logic 0 and logic 1, there is the "**fuzzy logic**";
  - Between integer order splines, there are "**fractional order splines**"
  - Between integer high order moments, there are **noninteger order moments (e.g. FLOS)**
  - Between "integer dimensions", there are **fractal dimensions**
  - Fractional Fourier transform (FrFT) – in-between time-n-freq.
  - Non-Integer order calculus (fractional order calculus – abuse of terminology.) (FOC)

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Rule of thumb for "Fractional Order Thinking"

- Self-similar
- Scale-free/Scale-invariant
- Power law
- Long range dependence (LRD)
- $1/f^{a}$ noise
- Porous media
- Particulate
- Granular
- Lossy
- Anomaly
- Disorder
- Soil, tissue, electrodes, bio, nano, network, transport, diffusion, soft matters (**bio**x) …

Outline

- What is fractional calculus
- **What is considered as complex**
- Fractional calculus view of complexity
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  - Big data hype and fractional calculus
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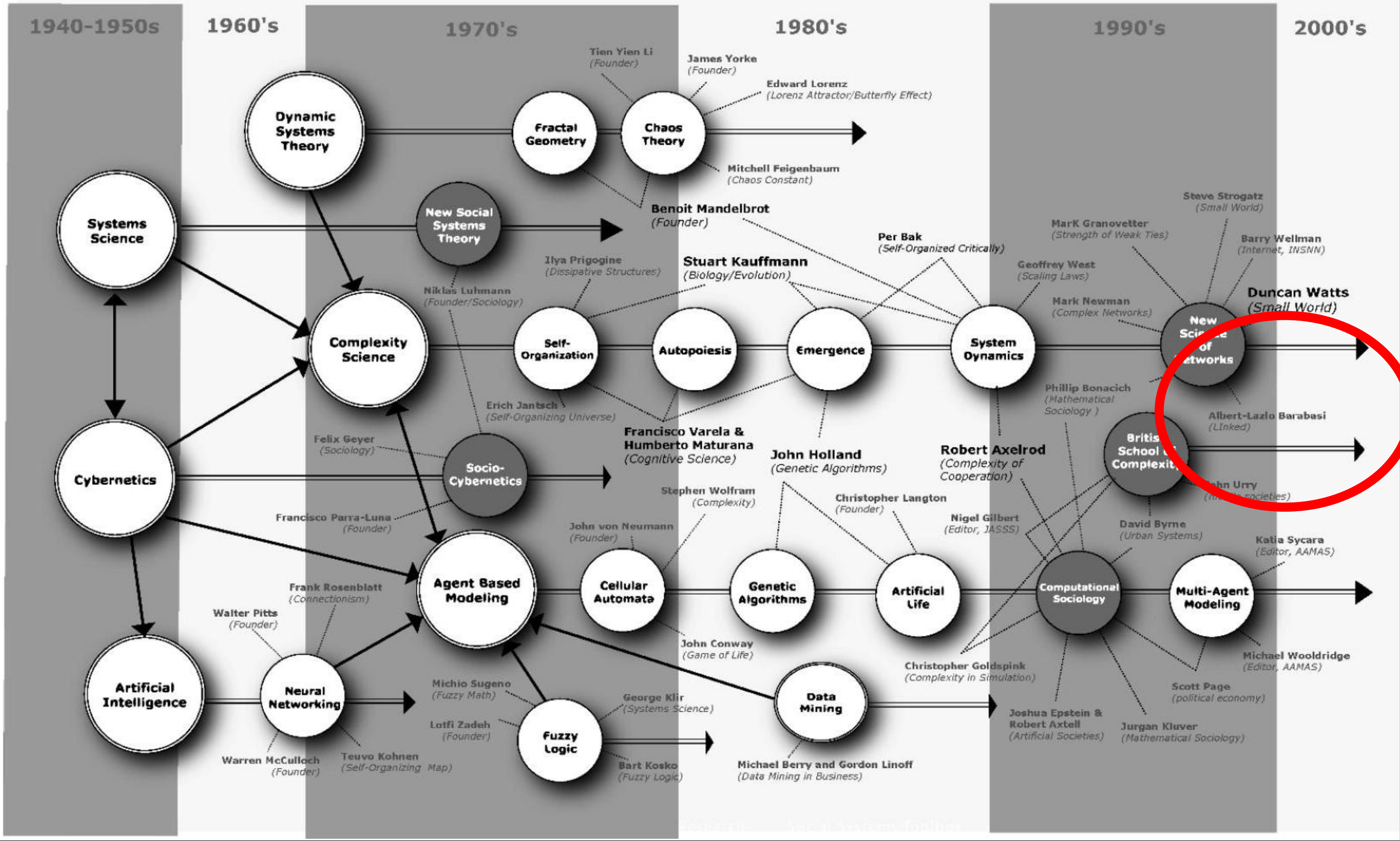
What's beyond?

Map 1: The New Science of Complexity



From Brian Castellani & Frederic William Hafferty (Eds.). "Sociology & Complexity Science -A New Field of Inquiry." Springer 2009.

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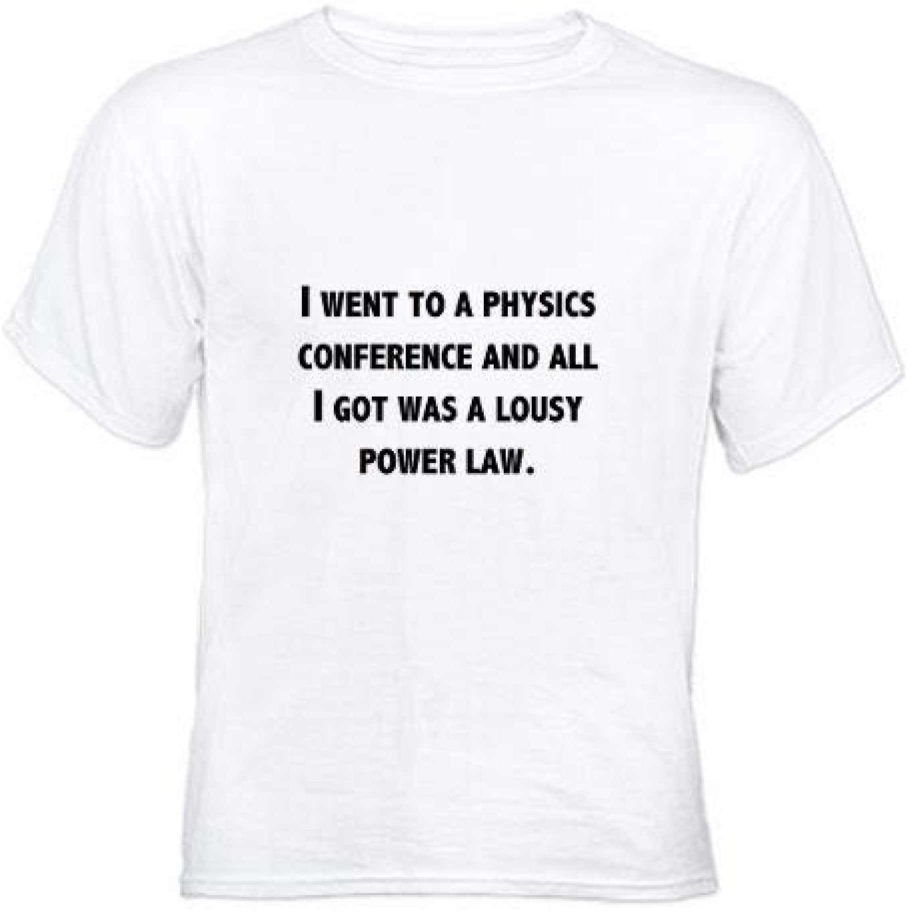


Empirical Power Laws

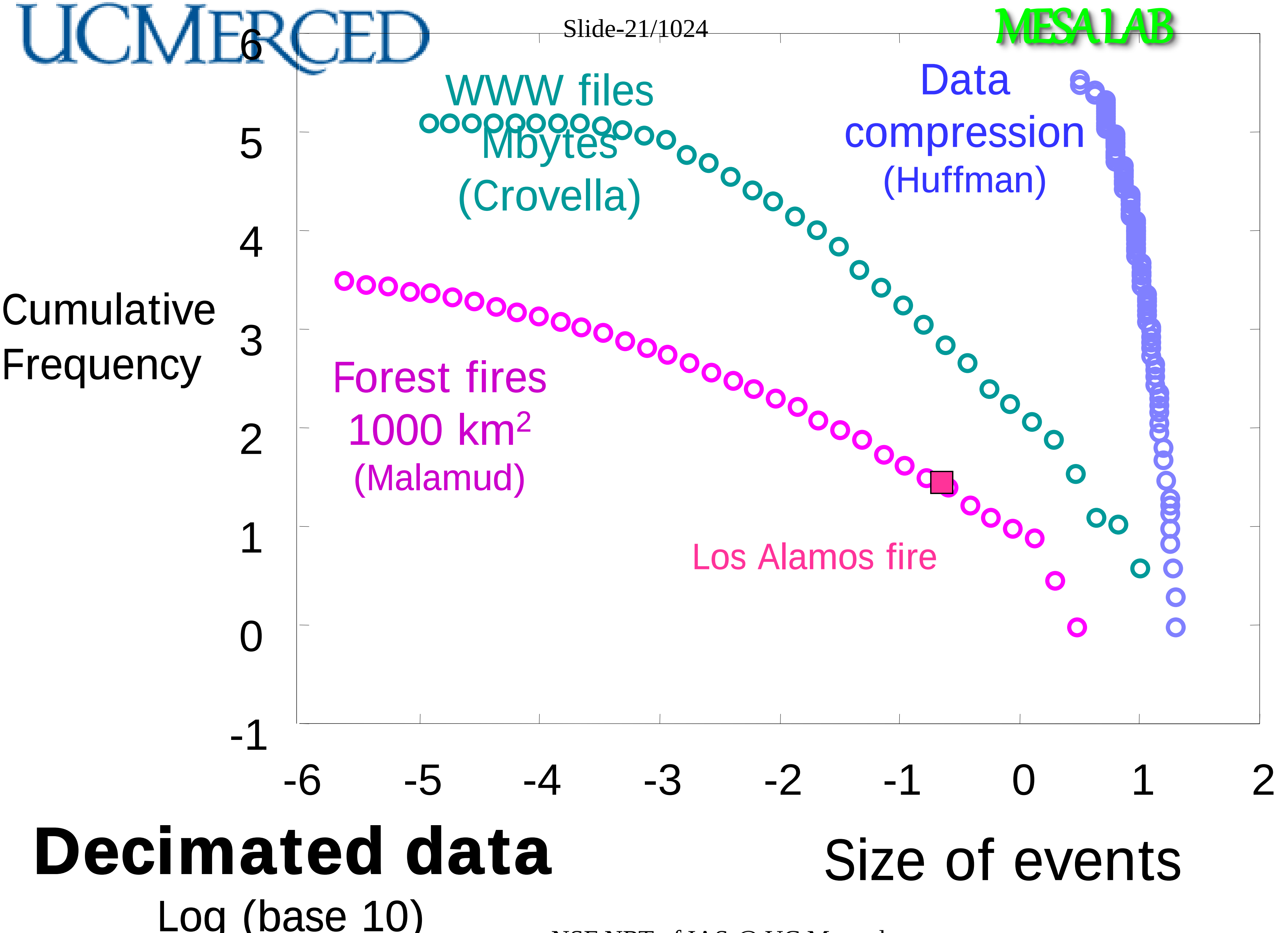
Discipline	Law's name	Form of law
Anthropology		
1913 [4]	Auerbach	Pr(city size rank r) $\propto 1/r$
1998 [65]	War	Pr(intensity $> I$) $\propto 1/I^{\alpha}$
1978 [86]	$1/f$ Music	Spectrum(f) $\propto 1/f$
Biology		
1992 [87]	DNA sequence	Symbol spectrum(frequency f) $\propto 1/f^{\alpha}$
2000 [49]	Ecological web	Pr(k species connections) $\propto 1/k^{1.1}$
2001 [35]	Protein	Pr(k connections) $\propto 1/k^{2.4}$
2000 [34]	Metabolism	Pr(k connections) $\propto 1/k^{2.2}$
2001 [40]	Sexual relations	Pr(k relations) $\propto 1/k^{\alpha}$
Botany		
1883 [64]	da Vinci	Branching; $d_0^{\alpha} = d_1^{\alpha} + d_2^{\alpha}$
1922 [101]	Willis	No. of genera(No. of species N) $\propto 1/N^{\alpha}$
1927 [51]	Murray	$d_0^{2.5} = d_1^{2.5} + d_2^{2.5}$
Economics		
1897 [56]	Pareto	Pr(income x) $\propto 1/x^{1.5}$
1998 [24]	Price variations	Pr(stock price variations x) $\propto 1/x^3$
Geophysics		
1894 [55]	Omori	Pr(aftershocks in time t) $\propto 1/t$
1933 [67]	Rosen–Rammler	Pr(No. of ore fragments $<$ size r) $\propto r^{\alpha}$
1938 [44]	Korčak	Pr(island area $A > a$) $\propto 1/a^{\alpha}$
1945 [31]	Horton	No. of segments at n/No. of segments at $n+1$ constant
1954 [26]	Gutenberg–Richter	Pr(earthquake magnitude $< x$) $\propto 1/x^{\alpha}$
1957 [27]	Hack	River length $\propto$ (basin area)$^{\alpha}$
1977 [44]	Richardson	Length of coastline $\propto$ 1/(ruler size)$^{\alpha}$
2004 [84]	Forest fires	Frequency density(burned area A) $\propto 1/A^{1.38}$
Information theory		
1999 [32]	World Wide Web	Pr(k connections) $\propto 1/k^{1.94}$
1999 [19]	Internet	Pr(k connections) $\propto 1/k^{\alpha}$

Discipline	Law's name	Form of law
Physics		
1918 [70]	$1/f$ noise	Spectrum(f) $\propto 1/f$
2002 [25]	Solar flares	Pr(time between flares t) $\propto 1/t^{2.14}$
2003 [69]	Temperature anomalies	Pr(time between events t) $\propto 1/t^{2.14}$
Physiology		
1959 [61]	Rall	Neurons; $d_0^{1.5} = d_1^{1.5} + d_2^{1.5}$
1963 [76]	Mammalian vascular network	Veins and arteries; $d_0^{2.7} = d_1^{2.7} + d_2^{2.7}$
1963 [90]	Bronchial tree	$d_0^3 = d_1^3 + d_2^3$
1973 [48]	McMahon	Metabolic rate(body mass M) $\propto M^{0.75}$
1976 [103]	Radioactive clearance	Pr(isotope expelled in time t) $\propto 1/t^{\alpha}$
1987 [93]	West–Goldberger	Airway diameter(generation n) $\propto 1/n^{1.25}$
1991 [30]	Mammalian brain	Surface area $\propto$ volume$^{0.90}$
1992 [77]	Interbreath variability	No. of breaths(interbreath time t) $\propto 1/t^{2.16}$
1993 [58]	Heartbeat variability	Power spectrum(frequency f) $\propto f$
2007 [23]	EEG	Pr(time between EEG events) $\propto 1/t^{1.61}$
2007 [13]	Motivation and addiction	Pr(k behavior connections) $\propto 1/k^{\alpha}$
Psychology		
1957 [75]	Psychophysics	Perceived response(stimulus intensity x) $\propto x^{\alpha}$
1963 [71]	Trial and error	Reaction time(trial N) $\propto 1/N^{0.91}$
1961 [29]	Decision making	utility(delay time t) $\propto 1/t^{\alpha}$
1991 [3]	Forgetting	Percentage correct recall(time t) $\propto 1/t^{\alpha}$
2001 [20]	Cognition	Response spectrum(frequency f) $\propto 1/f^{\alpha}$
2009 [37]	Neurophysiology	Pr(phase-locked interval $< \tau$) $\propto 1/\tau^{\alpha}$
Sociology		
1926 [41]	Lotka	Pr(No. of papers published rank r) $\propto 1/r^2$
1949 [104]	Zipf	Pr(word has rank r) $\propto 1/r$
1963 [16]	Price	Pr(citation rank r) $\propto 1/r^3$
1994 [8]	Urban growth	Population density(radius R) $\propto 1/R^{\alpha}$
1998 [88]	Actors	Pr(k connections) $\propto 1/k^{2.3}$

Complex Webs: Anticipating the Improbable, B.J. West and P. Grigolini, Cambridge (2011).

Other connectedness to FC? (hidden)

- Fractal, irregular, anomalous, rough, Hurst
  - Multifractal, multi-scale, scale-rich
- Renormalization (?), Universality
- Extreme events– spikiness, bursty, intermittence
- Fluctuation in fluctuations; Variability,
- Emergence, Surprise, **Black swan**
- Nonlocality, Long term memory
- Complex (behavior, processes, network, fluid, dynamics, systems …)
- When the forest is big, there are all types of birds ("It takes all kinds" 林子大了什么鸟都有), 20/80 rule(二八定律)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Cumulative Frequency
WWW files Mbytes (Crovella)
Data compression (Huffman)
Forest fires 1000 km2 (Malamud)
Los Alamos fire
-6
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-3
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Size of events
Decimated data
Log (base 10)

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Science MAGAZINE 18 Sep 1998

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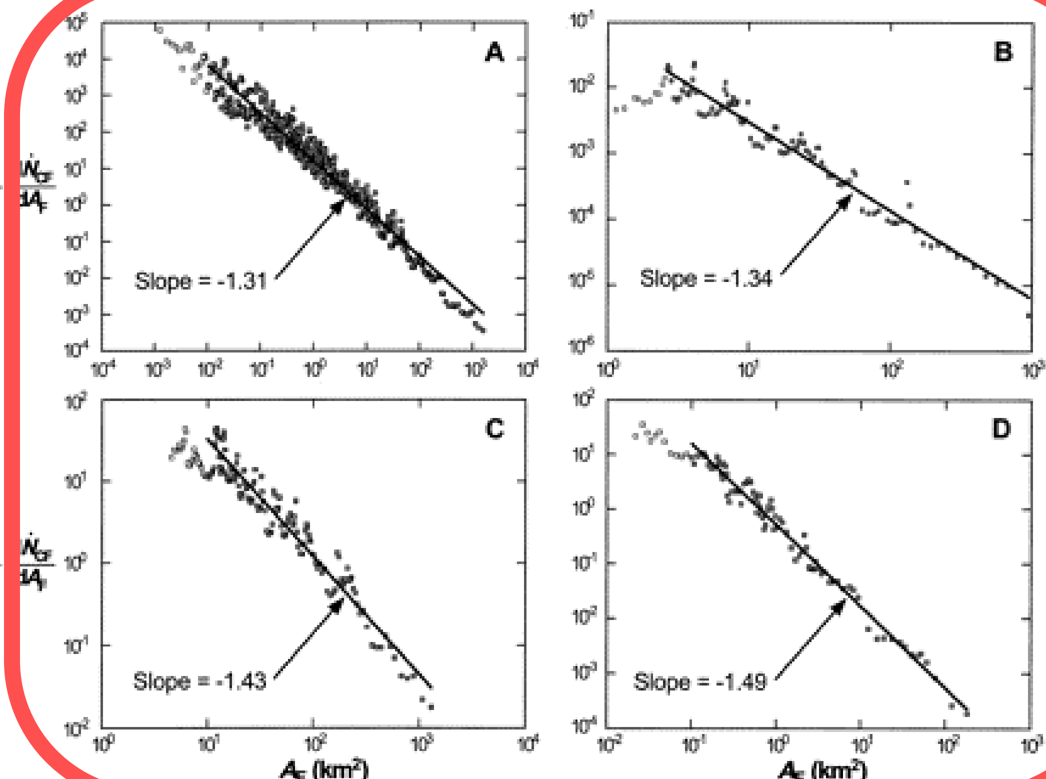
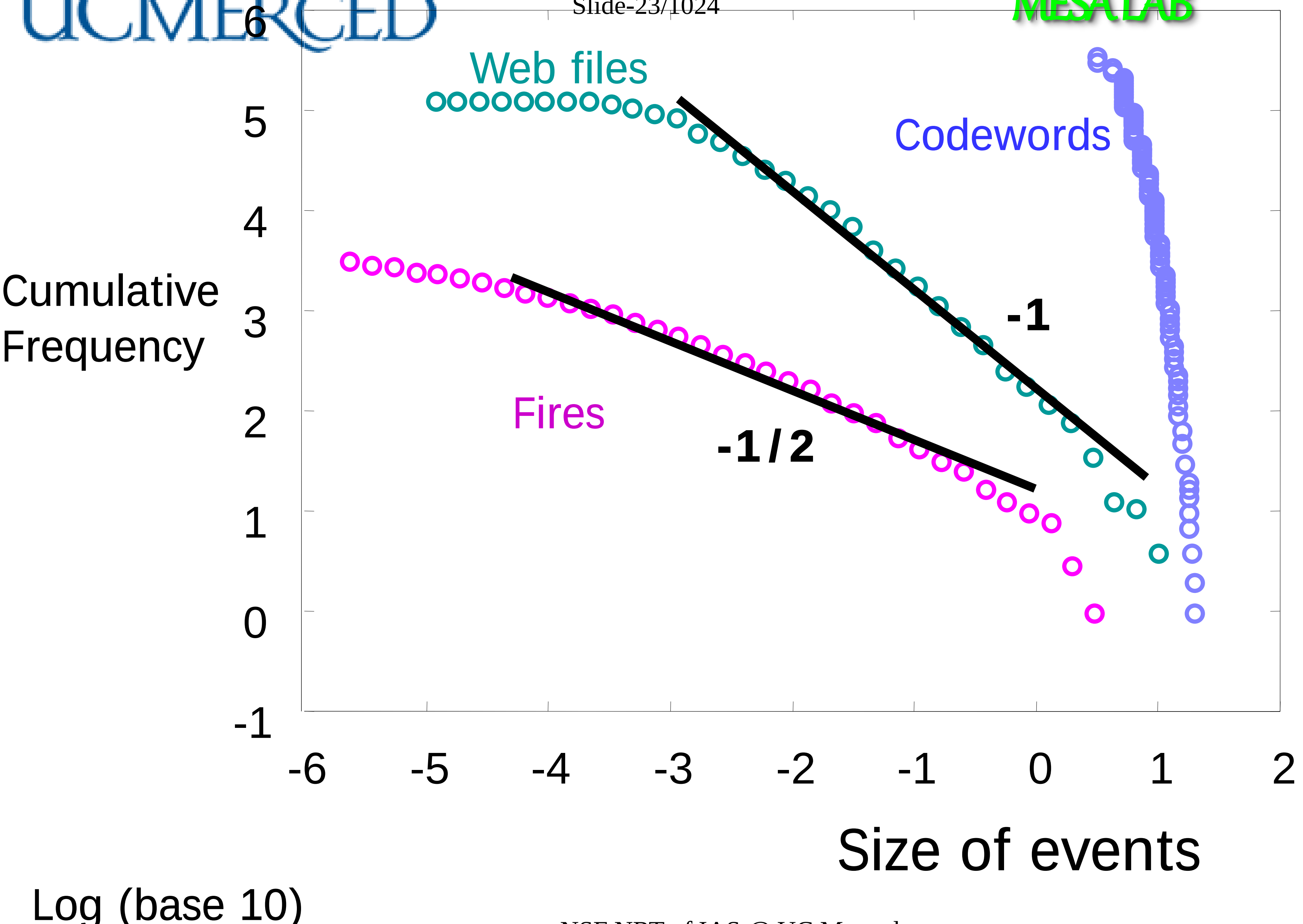
Forest Fires: An Example of Self-Organized Critical Behavior

Bruce D. Malamud, Gleb Morein, Donald L. Turcotte



4 data sets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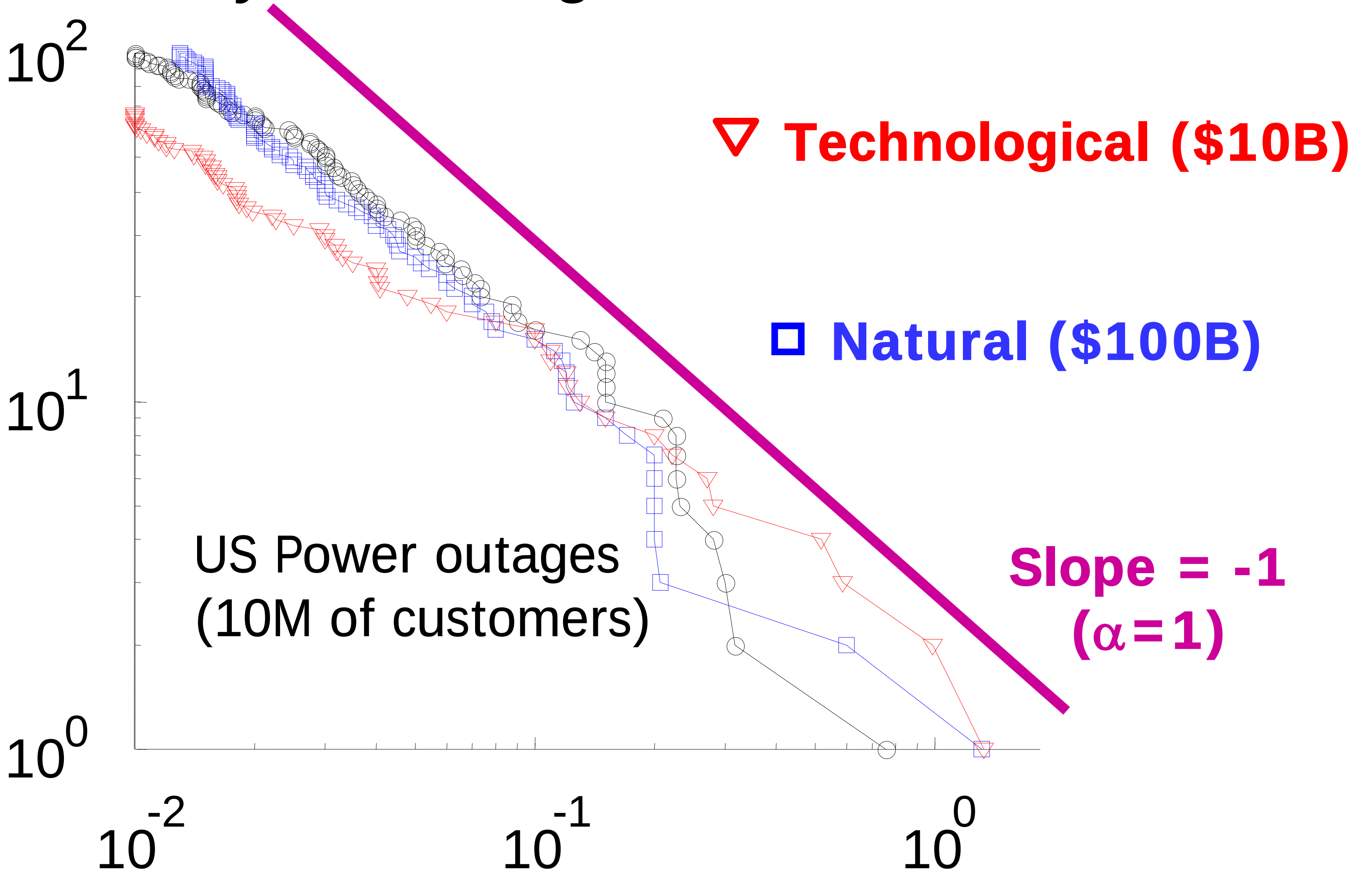
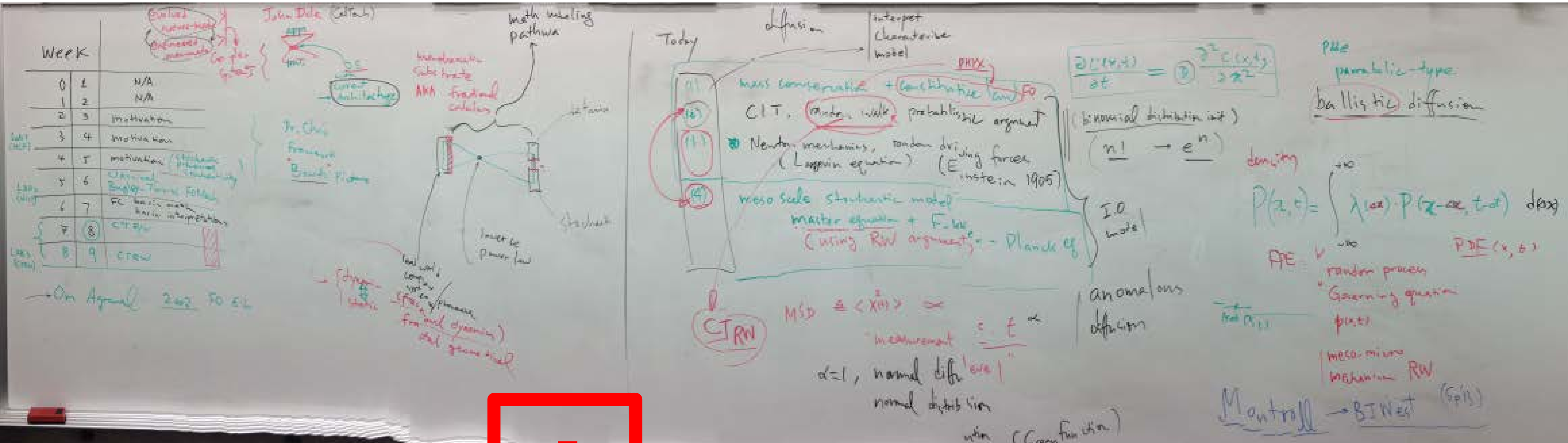
Size of events
Log (base 10)

20th Century's 100 largest disasters worldwide



Complexity “bow tie”



Complex systems. phenomena, behaviors, …

I P L

Scale-Free, Heavy-Tailedness, Long Range Dependence, Long Memory …

IPL in Different Contexts

- Scale-free networks (degree distributions)
- Pink noise (power spectrum)
- Probability density function (PDF)
- Autocorelation function (ACF)
- Allometry ($Y=a\,X^b$)
- Anomalous relaxation (evolving over time)
- Anomalous diffusion (MSD versus time)
- Self-similar

Outline

- What is fractional calculus
- What is considered as complex
- **Fractional calculus view of complexity**
- Conclusions
  - Big data hype and fractional calculus
  - A call for contributions

My submission:

Fractional dynamics point of view of complex systems for complexity characterization and regulation

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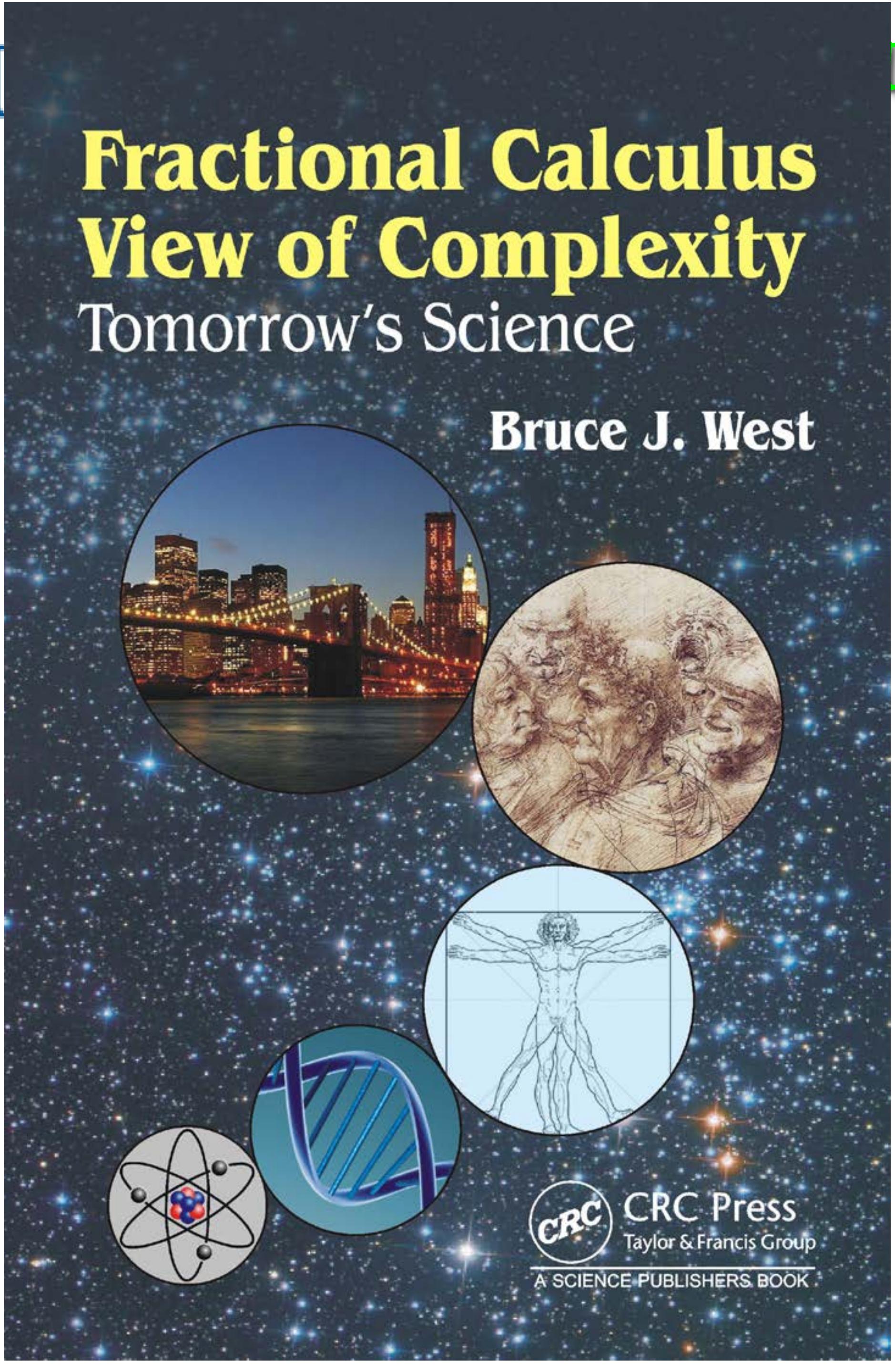

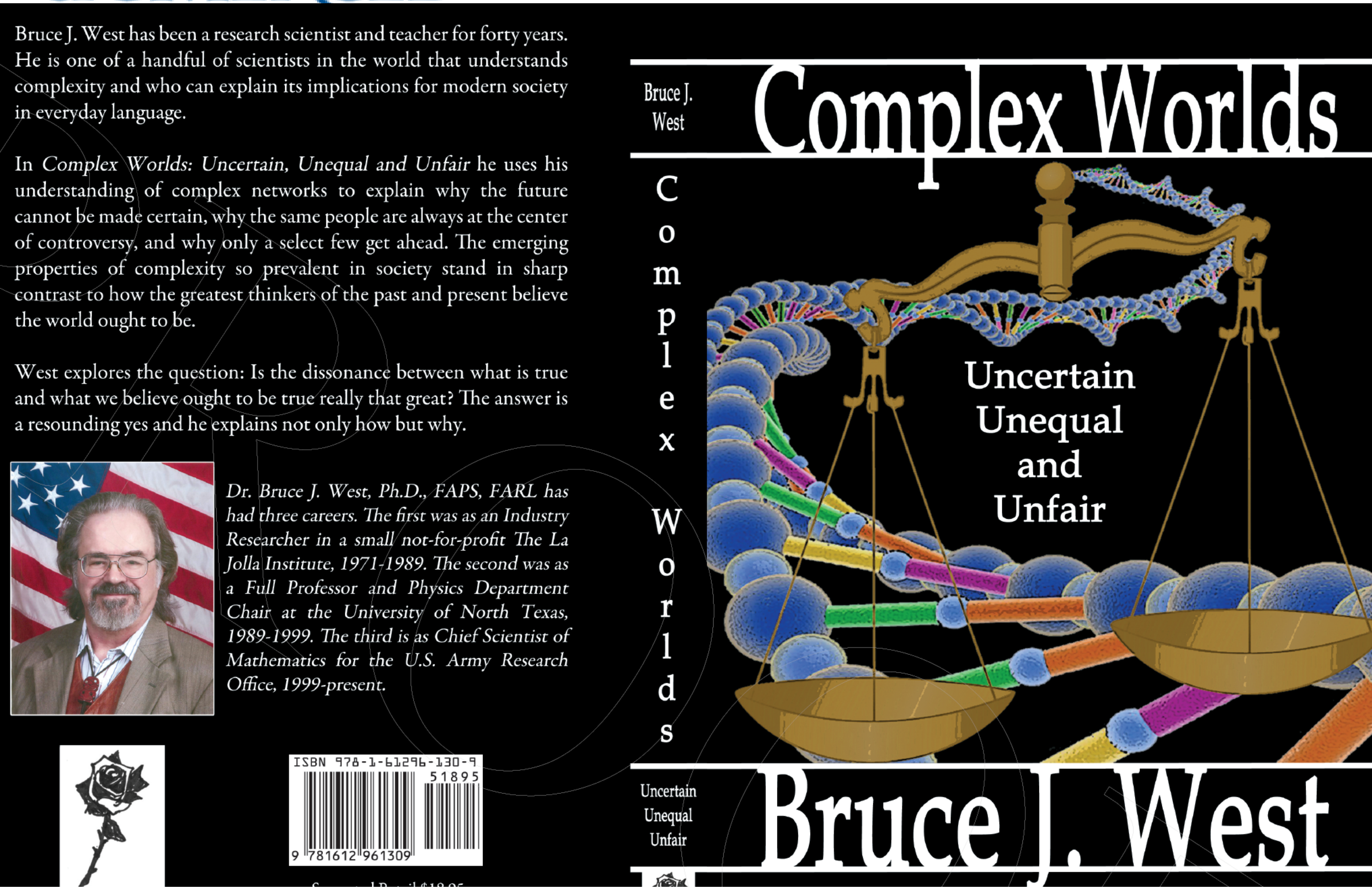

Bruce J. West has been a research scientist and teacher for forty years. He is one of a handful of scientists in the world that understands complexity and who can explain its implications for modern society in everyday language.

In *Complex Worlds: Uncertain, Unequal and Unfair* he uses his understanding of complex networks to explain why the future cannot be made certain, why the same people are always at the center of controversy, and why only a select few get ahead. The emerging properties of complexity so prevalent in society stand in sharp contrast to how the greatest thinkers of the past and present believe the world ought to be.

West explores the question: Is the dissonance between what is true and what we believe ought to be true really that great? The answer is a resounding yes and he explains not only how but why.

Dr. Bruce J. West, Ph.D., FAPS, FARL has had three careers. The first was as an Industry Researcher in a small not-for-profit The La Jolla Institute, 1971-1989. The second was as a Full Professor and Physics Department Chair at the University of North Texas, 1989-1999. The third is as Chief Scientist of Mathematics for the U.S. Army Research Office, 1999-present.

ISBN 978-1-61296-130-9
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Bruce J. West

Complex Worlds

Uncertain Unequal Unfair

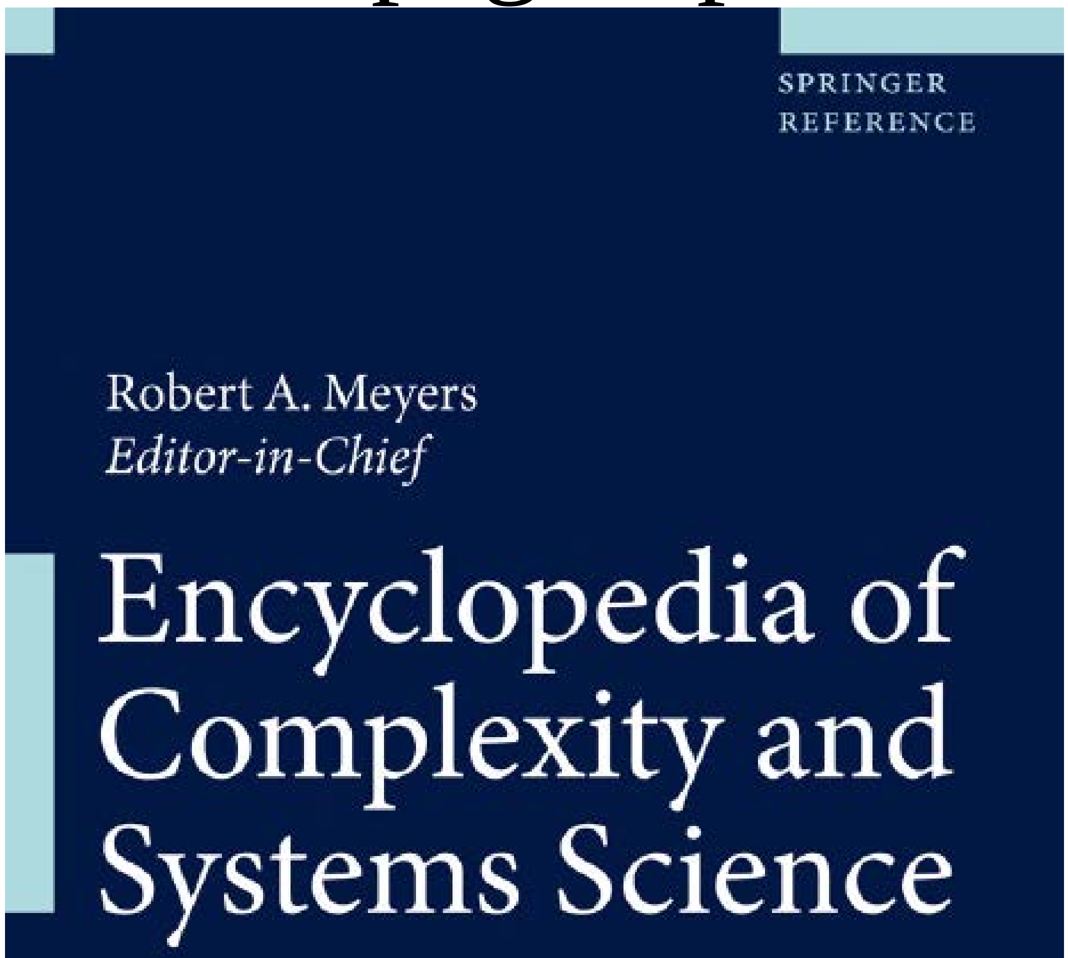
Complex Worlds

Uncertain
Unequal
and
Unfair

Bruce J. West

"fractional calculus" appeared once

10453 pages, p.1416



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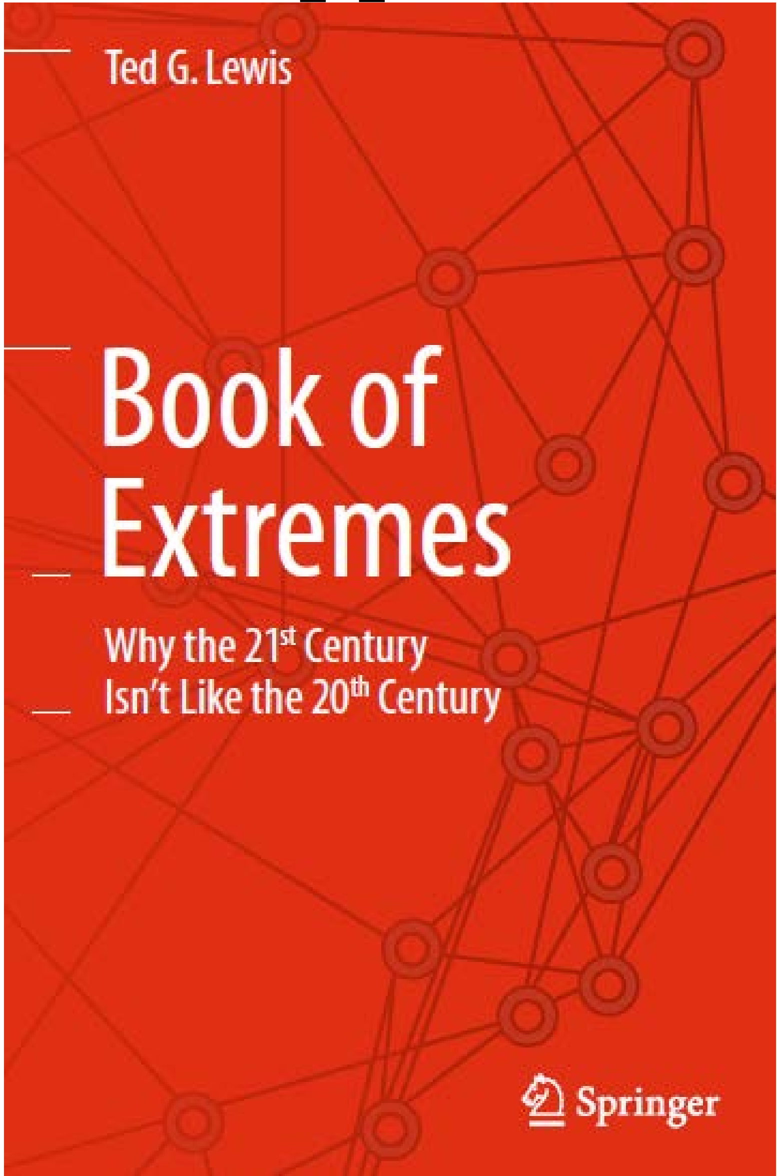
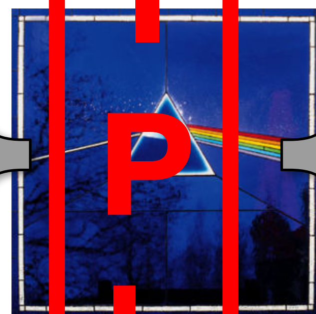


Complex systems. phenomena, behaviors, …



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Scale-Free,
Heavy-Tailedness,
Long Range Dependence,
Long Memory …

Fractional dynamic

Fractional calculus based models

Mittag-Leffler Law

Power Law

$$f(x) = ax^k$$

When k is negative: Inverse power law

Scale-free

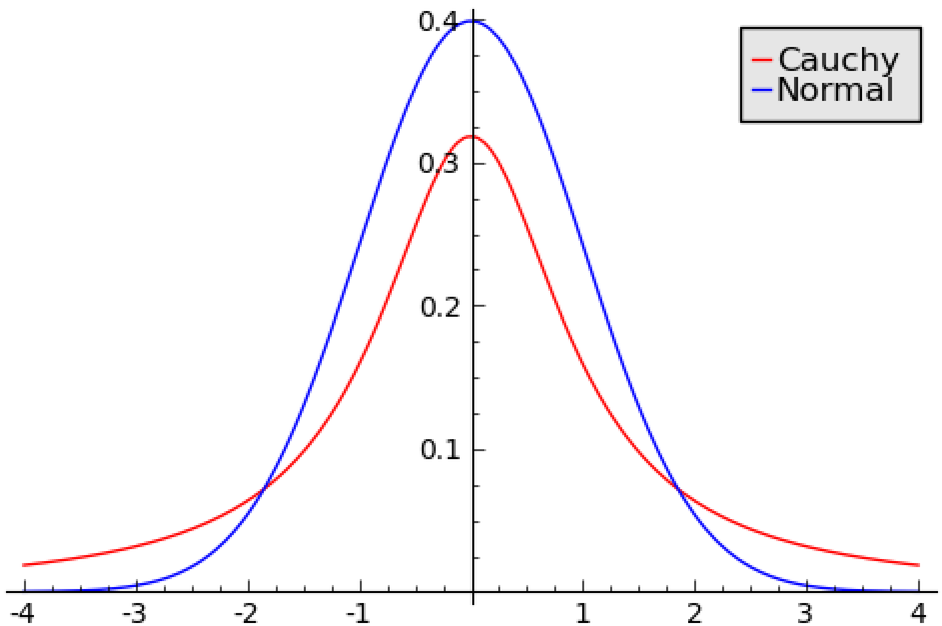
Scale invariance

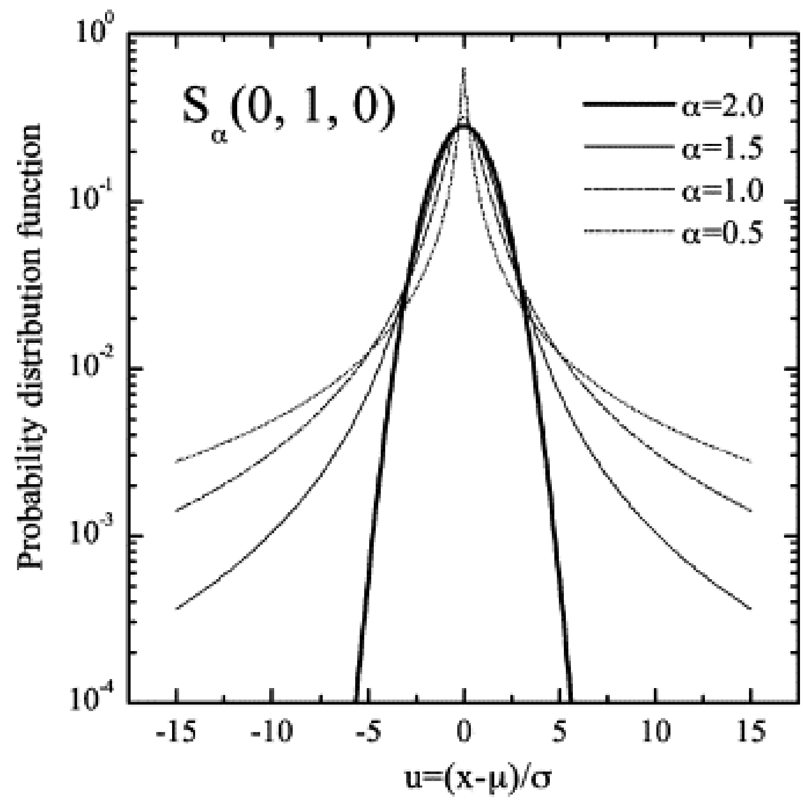
$$f(cx) = a(cx)^k = c^k f(x) \propto f(x).$$

- "Scaling laws in cognitive sciences" by CT Kello, GDA Brown, R Ferrer-i-Cancho, JG Holden, K Linkenkaer-Hansen, T. Trends in Cognitive Sciences 14 (5), 223-232, 2010

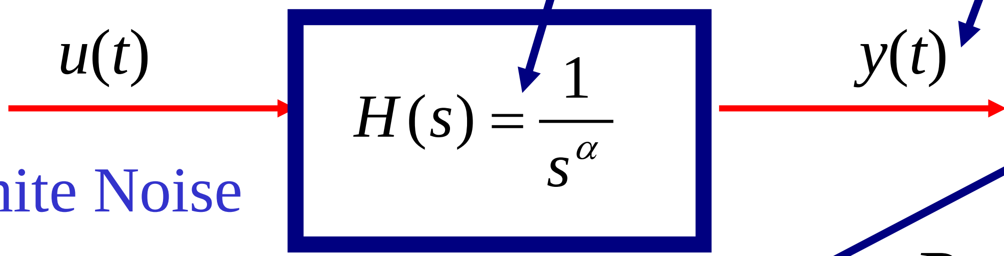
Heavy tail, fat tail

$$P[X > x] \sim x^{-\alpha}$$





Fractional Calculus, LRD, Power Law,



$$H(s)=\frac{1}{s^{\alpha}}$$

$$h(t)=\frac{t^{\alpha-1}}{\Gamma(\alpha)}$$

$$Ryy(\tau)=\sigma^{2}\frac{|\tau|^{2\alpha-1}}{2\Gamma(2\alpha)\cos\alpha\pi}$$

y(t) is a Brownian motion when α=1, i.e., $1/f^{2}$ process.

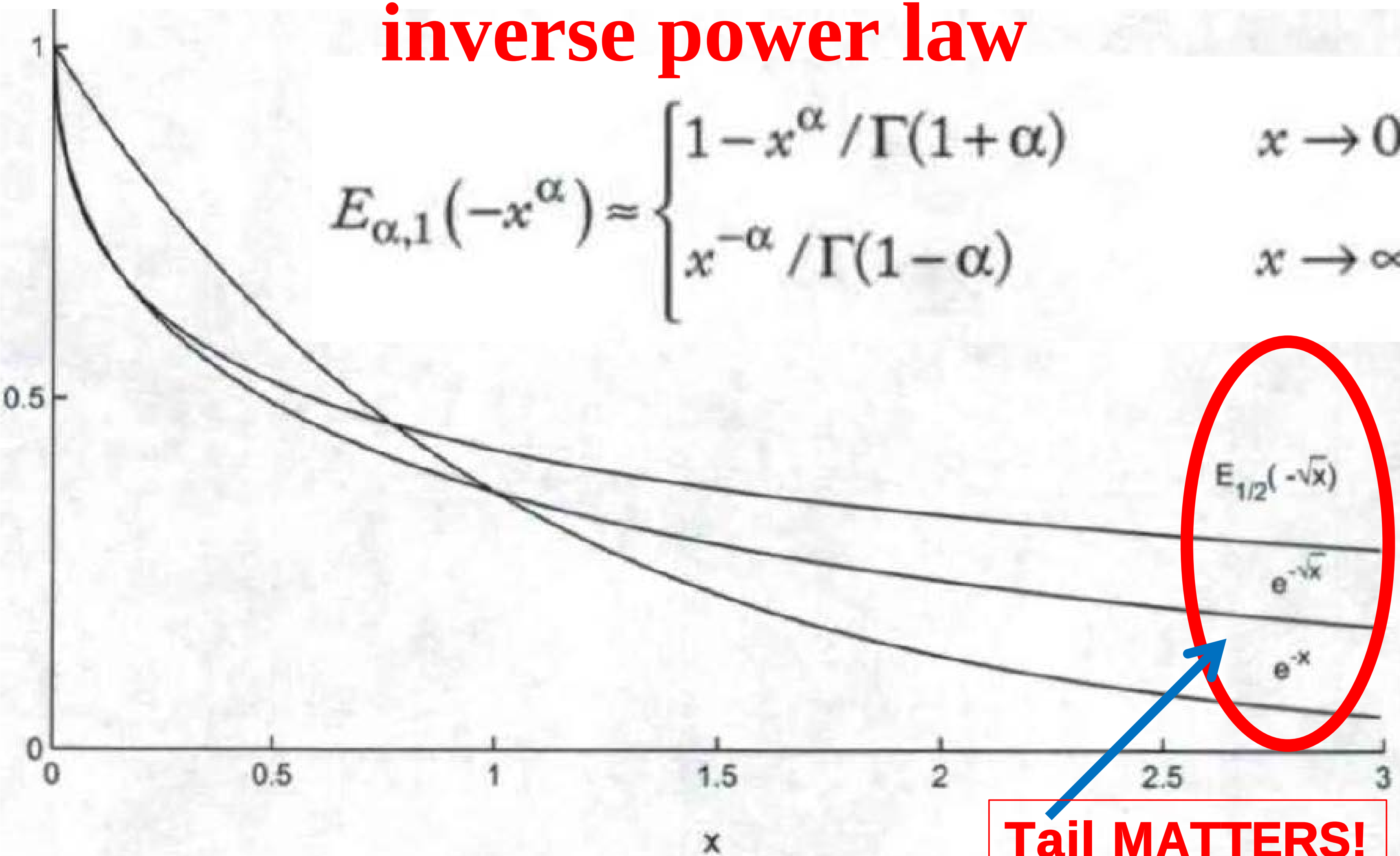
$1/f^{2\alpha}$ noise (signal) generation via fractional dynamic system

Power laws in

- Signal/Systems
- Probability distribution
- Random processes (correlation functions)

Root of long (algebraic) tail, or inverse power law

$$E_{\alpha,1}(-x^{\alpha}) \approx \begin{cases} 1 - x^{\alpha}/\Gamma(1+\alpha) & x \to 0^{+} \\ x^{-\alpha}/\Gamma(1-\alpha) & x \to \infty \end{cases}$$



Connection to FC via PDF

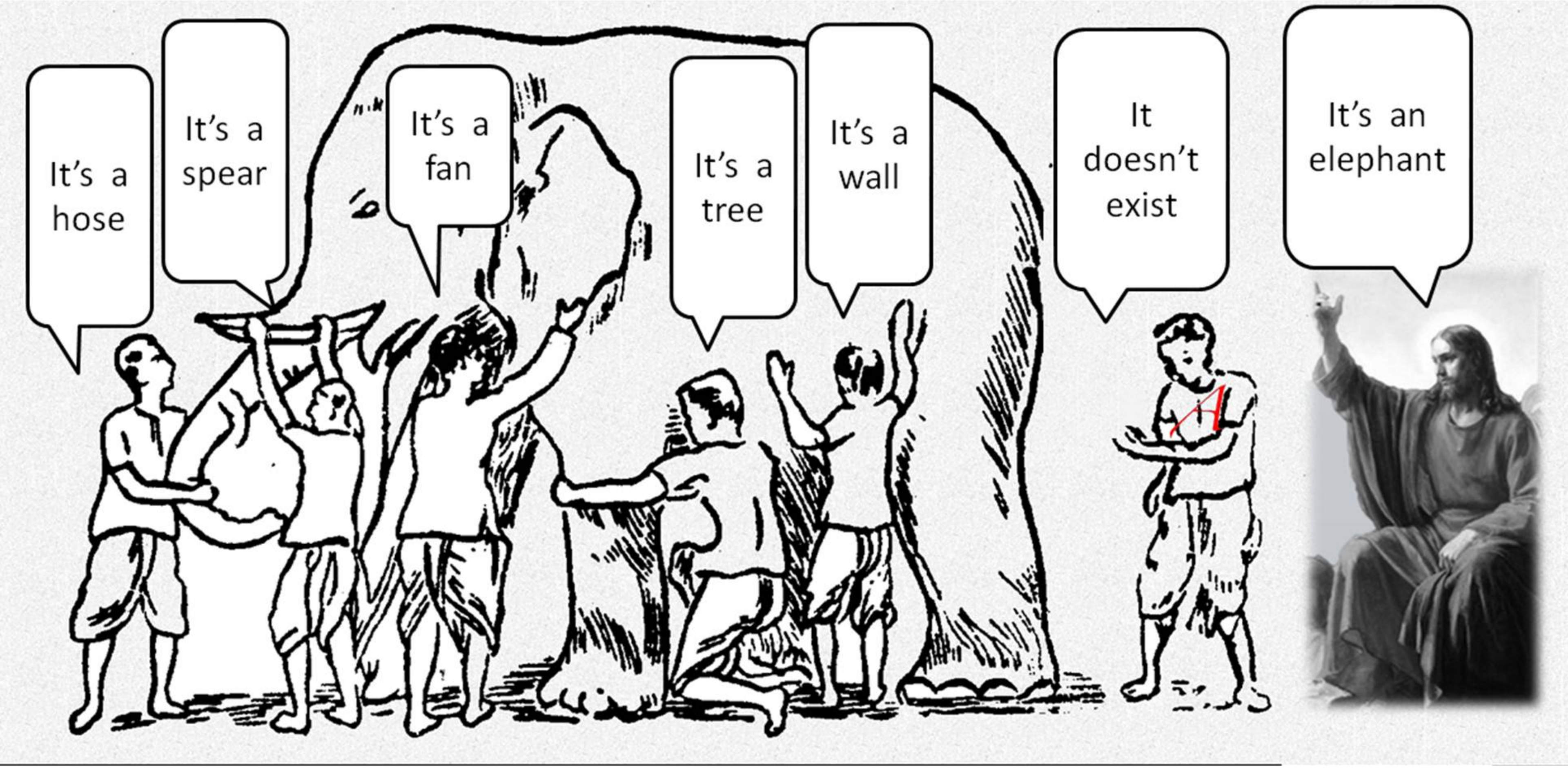
- "*Fractional Calculus and Stable Probability Distributions*" (1998) by Rudolf Gorenflo , Francesco Mainardi http://arxiv.org/pdf/0704.0320.pdf

$$\frac{\partial u}{\partial t} = D(\alpha)\,\frac{\partial^\alpha u}{\partial |x|^\alpha}\,, \quad -\infty < x < +\infty\,, \quad t \ge 0\,,$$

$$\text{with} \quad u(x,0) = \delta(x) \quad 0 < \alpha \le 2$$

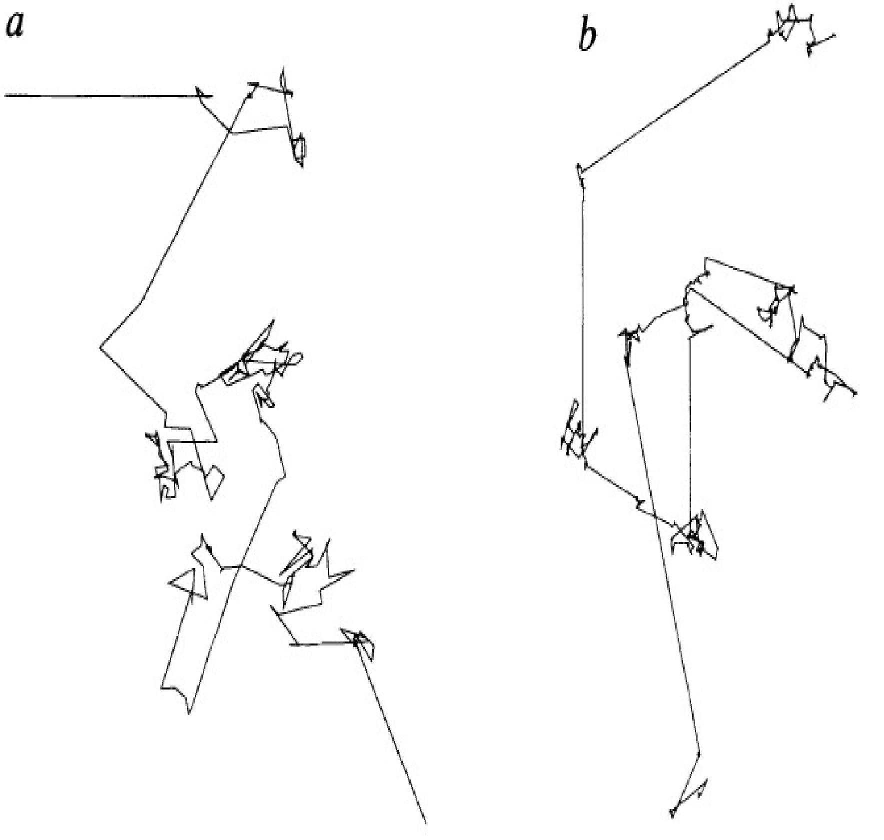
$$\frac{\partial^{2\beta} u}{\partial t^{2\beta}} = D(\beta)\,\frac{\partial^2 u}{\partial x^2}\,, \quad x \ge 0\,, \quad t \ge 0\,,$$

$$\text{with} \quad u(0,t) = \delta(t) \quad 0 < \beta < 1$$



Source:
https://www.flickr.com/photos/atheism_christian_apologetics/11078762214/in/photostream/

Wandering albatrosses



flight search patterns

G.M. Viswanathan, et al. *Nature* 381 (1996) 413–415.

Outline

- What is fractional calculus
- What is considered as complex
- Fractional calculus view of complexity
- **Conclusions**
  - **Big data hype and fractional calculus**
  - **A call for contributions**

Big Data

- **V**olume
- **V**ariety
- **V**elocity
- **V**eracity
- **V**alue

- So, to be complex to have big data??

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Fractional Order Data Analytics:

connecting dots of Drones, Big Data, and Fractional Calculus

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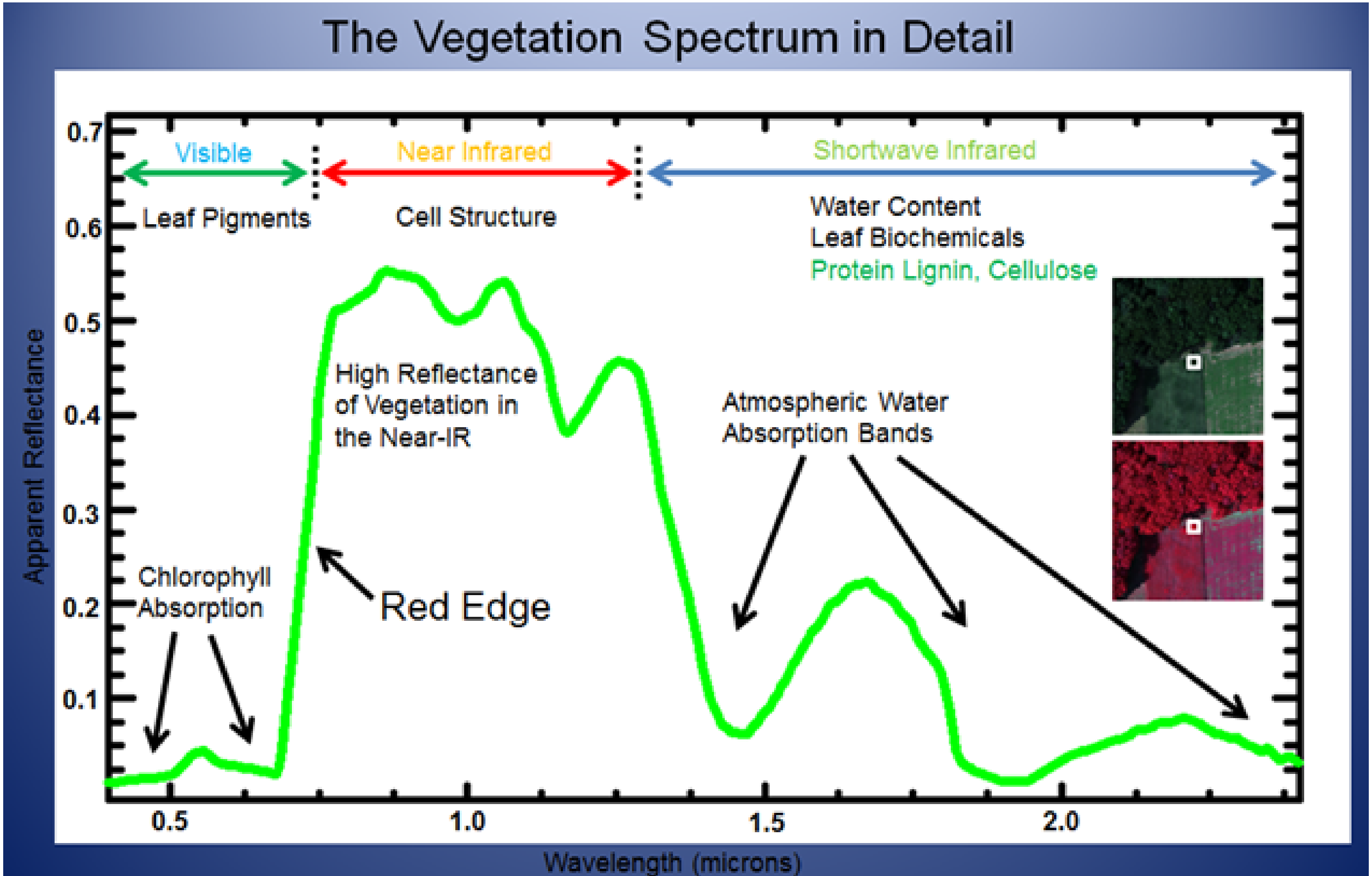
T: (209)228-4672; **O**: SE1-254; **Lab**: CAS Eng 820 (**T**: 228-4398)

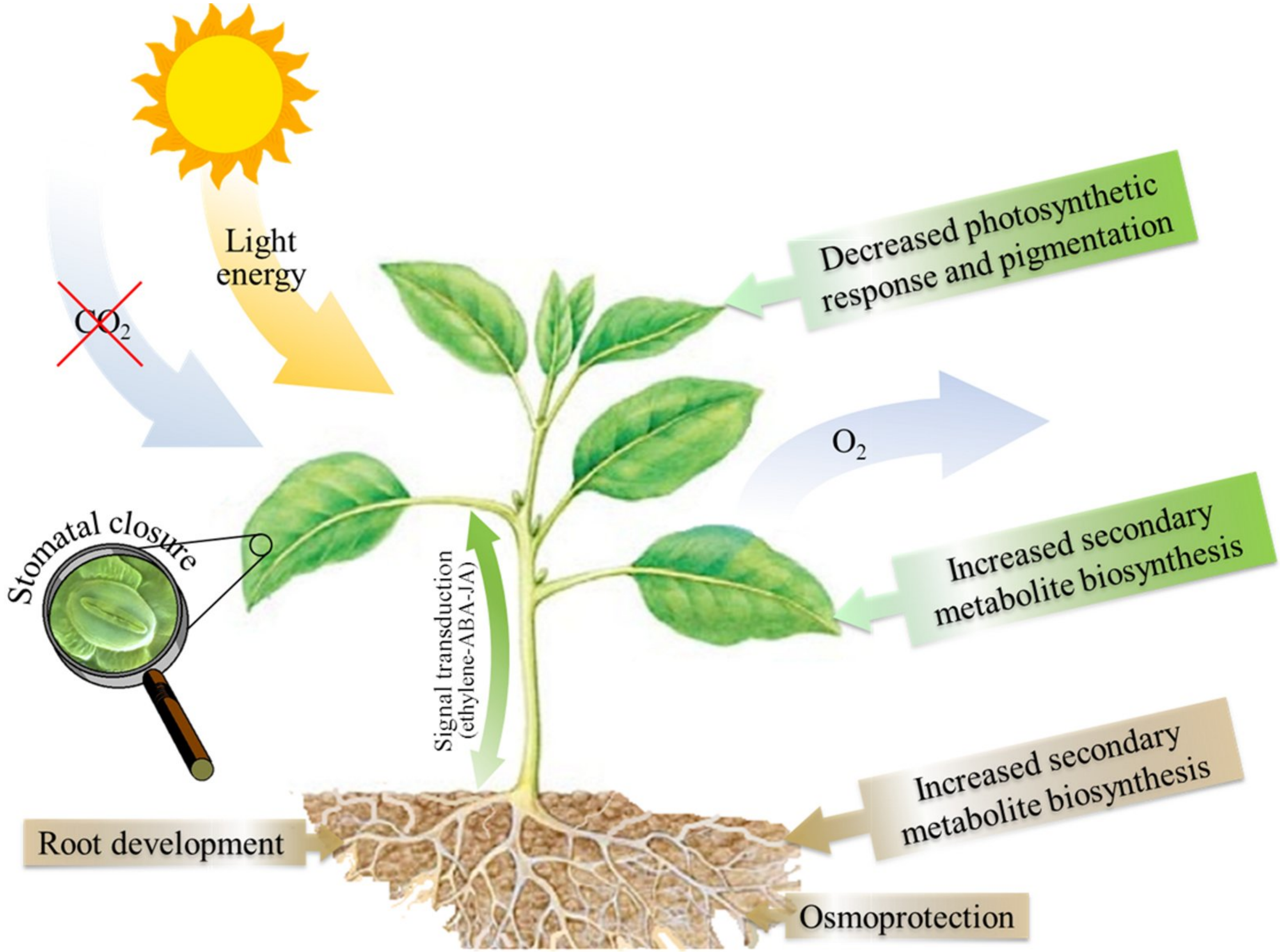
March 21, 2015. Saturday 2:00-2:15 PM
Robots & Ribs Day @ MESA LAB Symposium @ UC Merced

FODA: Fractional Order Data Analytics

- First proposed by Prof. YangQuan Chen last weeks.
- *Metrics based on using fractional order signal processing techniques for quantifying the generating dynamics of observed or perceived variabilities.*
  - Hurst parameter, fGn, fBm, …
  - Fractional order integral, differentiation
  - FLOM/FLOS (fractional order lower order moments/statistics)
  - Alpha stable processes, Levy flights
  - ARFIMA, GARMA (Gegenbauer), CTRW …

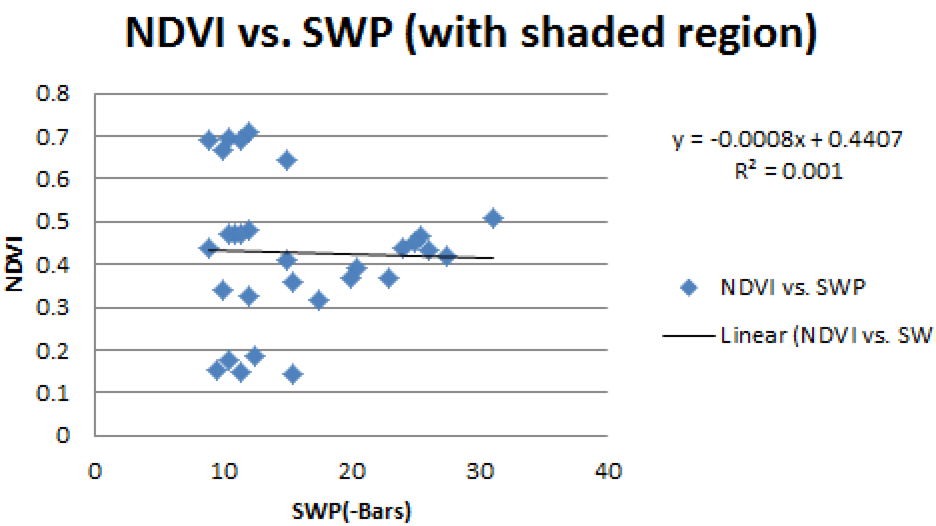


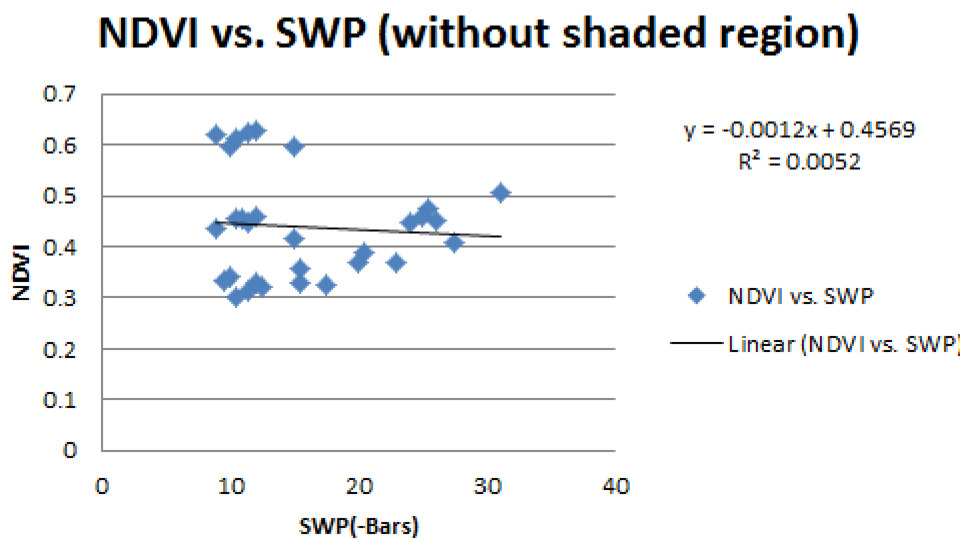
https://www.exelisvis.com/Learn/WhitepapersDetail/TabId/802/ArtMID/2627/ArticleID/13742/Vegetation-Analysis-Using-Vegetation-Indices-in-ENVI.aspx

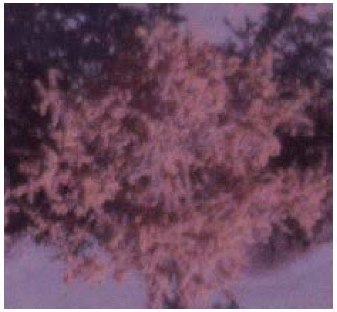


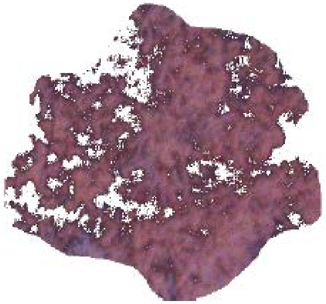
http://www.intechopen.com/books/responses-of-organisms-to-water-stress/water-stress-and-agriculture

NDVI vs. water stress??



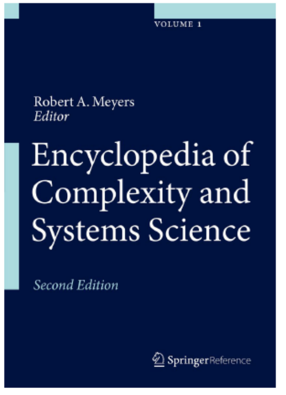






Drones as “Tractor 2.0” for Farmers

- RRR or SSM of water, fertilizers, pesticides etc.
- Fractional Calculus may save the world one day.
- Drones create big data and demand FODA due to “complexity” thus variability, inherent in life process.



2nd ed. 2020, 16000 p. 5600 illus., 3000 illus. in color. In 15 volumes, not available separately.

SPRINGER REFERENCE

R.A. **Meyers** (Ed.)

Encyclopedia of Complexity and Systems Science

- Substantially updated from the groundbreaking first edition
- Assembles for the first time the concepts and tools for analyzing complex systems in a wide range of fields
- Reflects the real world by integrating complexity with the deterministic equations and concepts that define matter, energy, and the four forces identified in nature
- Benefits a broad audience: undergraduates, researchers and practitioners in mathematics and many related fields

This reference work provides an authoritative single source for understanding and applying the concepts of complexity theory together with the tools and measures for analyzing complex systems in all fields of science and engineering. The science and tools of complexity and systems science include theories of self-organization, complex systems, synergetics, dynamical systems, turbulence, catastrophes, instabilities, nonlinearity, stochastic processes, chaos, neural networks, cellular automata, adaptive systems, and genetic algorithms. Examples of near-term problems and major unknowns that can be approached through complexity and systems science include: The structure, history and future of the universe; the biological basis of consciousness; the integration of genomics, proteomics and bioinformatics as systems biology; human longevity limits; the limits of computing; sustainability of life on earth; predictability, dynamics and extent of earthquakes, hurricanes, tsunamis, and other natural disasters; the dynamics of turbulent flows; lasers or fluids in physics, microprocessor design; macromolecular assembly in chemistry and biophysics; brain functions in cognitive neuroscience; climate change; ecosystem management; traffic management; and business cycles. All these seemingly quite different kinds of structure formation have a number of important features and underlying structures in common. These deep structural similarities can be exploited to transfer analytical methods and understanding from one field to another. This unique work will extend the influence of complexity and system science to a much wider audience than has been possible to date.

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UCMEI

Call for chapters for a new volume

"**Fractional Calculus for Complex Systems**" in Encyclopedia of Complexity and Systems Science, Second Edition

MESA LAB

This volume in the "Encyclopedia of Complexity and Systems Science, Second Edition," offers a detailed account of fractional calculus tools, signatures of complex systems, hidden connections to fractional calculus, and applications and case studies involving fractional calculus in complex signal analysis and complex system modelling, analysis and control (MAD). The authors document both the foundational concepts of fractional calculus in complexity science as well as their applications to, and role in the optimization of, complex engineered systems. Fractional calculus is about differentiation and integration of non-integer orders. Convenience has driven the use of integer-order models and controllers for complex natural or man-made systems, but these traditional models and tools for the control of dynamic systems may result in suboptimum performance and even "anomalous" phenomena. In contrast, the growing literature documents "more optimal" performance when fractional order calculus tools are applied. From an engineering point of view, new and beneficial uses of this versatile mathematical tool are both possible and important, and may become an enabler of new science discoveries.

- Presents the first comprehensive coverage of the fractional calculus role in complex systems.
- Discusses major existing signatures such as power law of complex systems with emphasis on the connections to the fractional calculus
- Includes a wide variety of real world case studies in signal analysis and complex system modeling and control

Topic Areas (Table of Contents in preparation):

- Fractional calculus:
    - definitions, history, basic properties
    - Fractional order dynamic systems
    - Fractional noises
- Signatures of complex systems and its fractional calculus connection
    - Power law
    - Long range dependence
    - Long memory
    - Long range interaction
    - Heavytailedness
    - etc.
- Complex signal analysis using fractional calculus
- Complex system modeling using fractional calculus
- Complex system control using fractional calculus

Key parameters: Minimum number of chapters 30 to 50 (no upper limit); 9,000–12,000 words (plus figures and references) per chapter (or 10-12 published pages); delivery date 12/31/2018; submission via online system only at https://meteor.springer.com

If you are interested in contributing a chapter in this new volume "**Fractional Calculus for Complex Systems**", please visit http://mechatronics.ucmerced.edu/fccs for Guidelines and background information. Send me a chapter proposal (one page) with title/authors/affiliations/contact info/synopsis/keywords to email: yqchen@ieee.org with FCCS on email subject title for easy search. Thank you! 6/24/2017

Backup slides

- https://www.youtube.com/watch?v=QWvDPe6GaSA&feature=youtu.be
- Kecai Cao, YangQuan Chen, Daniel Stuart. A Fractional Micro-Macro Model for Crowds of Pedestrians Based on Fractional Mean Field Games. *IEEE/CAA Journal of Automatica Sinica*, 2016, 3(3), 261-270

https://www.youtube.com/watch?v=o8XoMMFdLyE&feature=youtu.be

- Jiacai Huang, YangQuan Chen, Haibin Li, Xinxin Shi. Fractional Order Modeling of Human Operator Behavior with Second Order Controlled Plant and Experiment Research. *IEEE/CAA Journal of Automatica Sinica*, 2016, 3(3), 271-280

- https://www.youtube.com/watch?v=iNuyigyidR8
- Cheng et al. "Study on Four Disturbance Observers for FO-LTI Systems." IEEE/CAA Journal of Automatica Sinica (2016).

Malgorzata Turalska, Bruce J. West, US Army Research Office

- 2016 Conference on Complex Systems titled "Fractional calculus: new language of complexity". The satellite session is scheduled to be held on September 21st, 2016 in Amsterdam, Netherlands.
- https://fractionalcalculus2016.wordpress.com/

"Individuality, Imitation and Influence"

- **Bruce J. West 2013 @ UC Merced**
- https://vimeo.com/75511143
-
- http://mechatronics.ucmerced.edu/events/bruce-j-wests-invited-seminar-individuality-imitation-and-influence

Of what use is fractional calculus?

Fractional calculus can help physical, life and social scientists to understand problems that are otherwise too;

- Big (the bio- and social-spheres)
- Small (molecular structure, individuals)
- Slow (macroevolution of species, societies..)
- Fast (photosynthesis, phase transitions)
- Remote in time (early extinctions, genetics, memory)
- Remote in space (life at extremes, heterogeneity)
- Complex (human brain, IoBT)
- Dangerous or unethical (infectious agents, cyber fog)

Credit: Bruce West

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Credit: Bruce West

- **Complexity-induced barriers to understanding**
  - Heterogeneity in space
  - Non-locality in time
  - No characteristic time scales (fractals, scaling)
    - Geometrical, statistical, dynamical
  - Dynamics
    - Strange attractors
    - Non-integrable Hamiltonians
    - Fractional differential equations
  - Trajectories are chaotic
    - Ensembles of chaotic trajectories
    - Scaling ensemble probability distribution functions
    - Fractional probability calculus
  - How do we begin to build a coherent picture?

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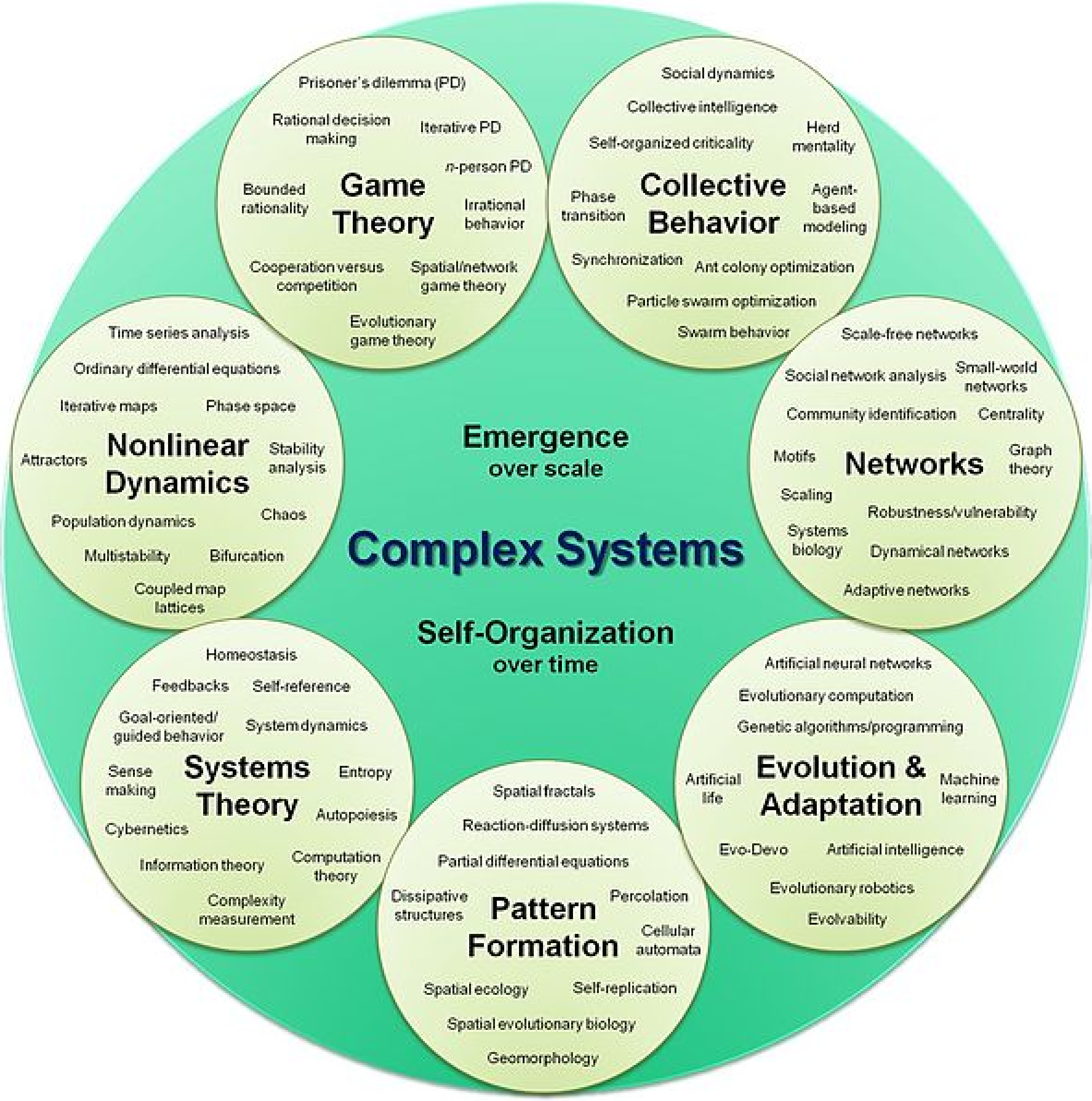
Credit: Bruce West

- Can these be synthesized?
- Is the fractional calculus entailed by complexity?



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Regional Sensing & Actuation of Fractional Order Distributed Parameter Systems

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University of California, Merced
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October 21, 2016. Friday. 11am-12noon

A Workshop on Future Directions in Fractional Calculus Research and Applications, MSU, East Lansing, MI.

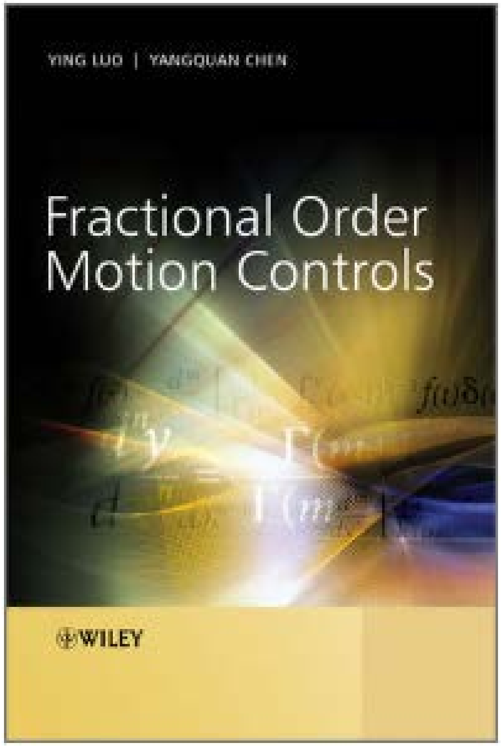
Two questions

- So what? / Why bother?
- What else I/you/we can do?

So what? / Why bother?

- Three answers
  - Complexity
  - Better than the best
  - xxx

Better than the best, “more optimal”



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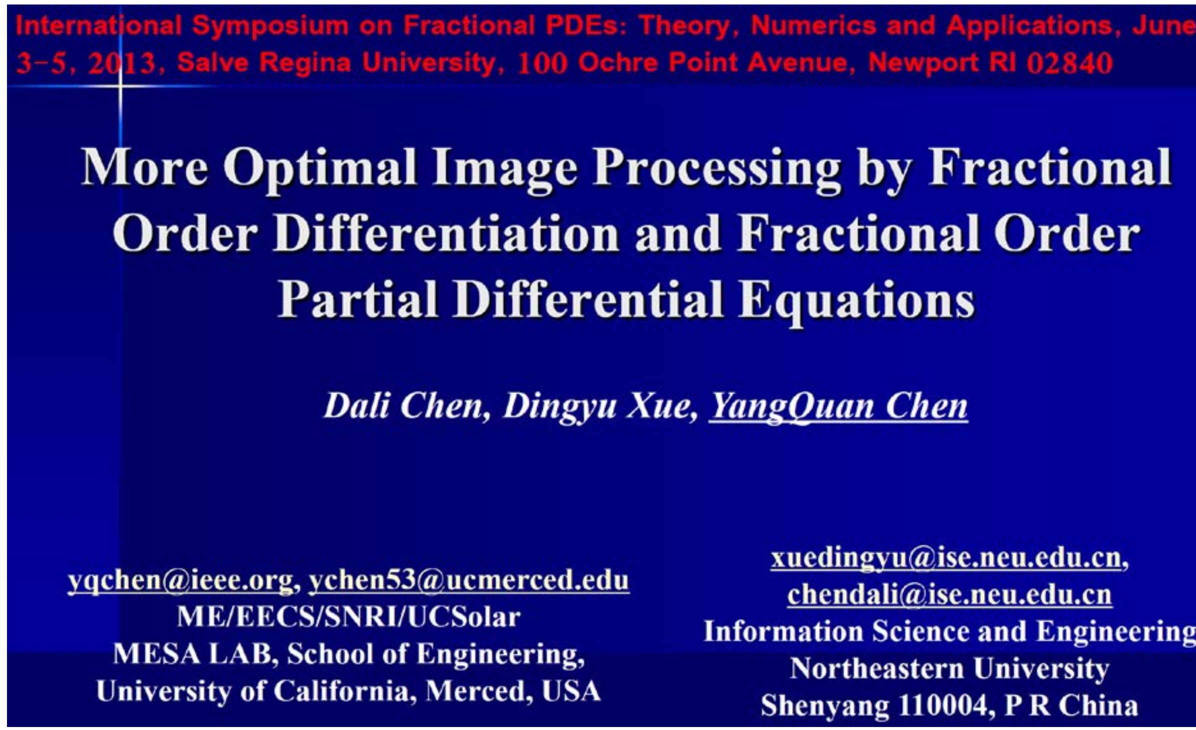
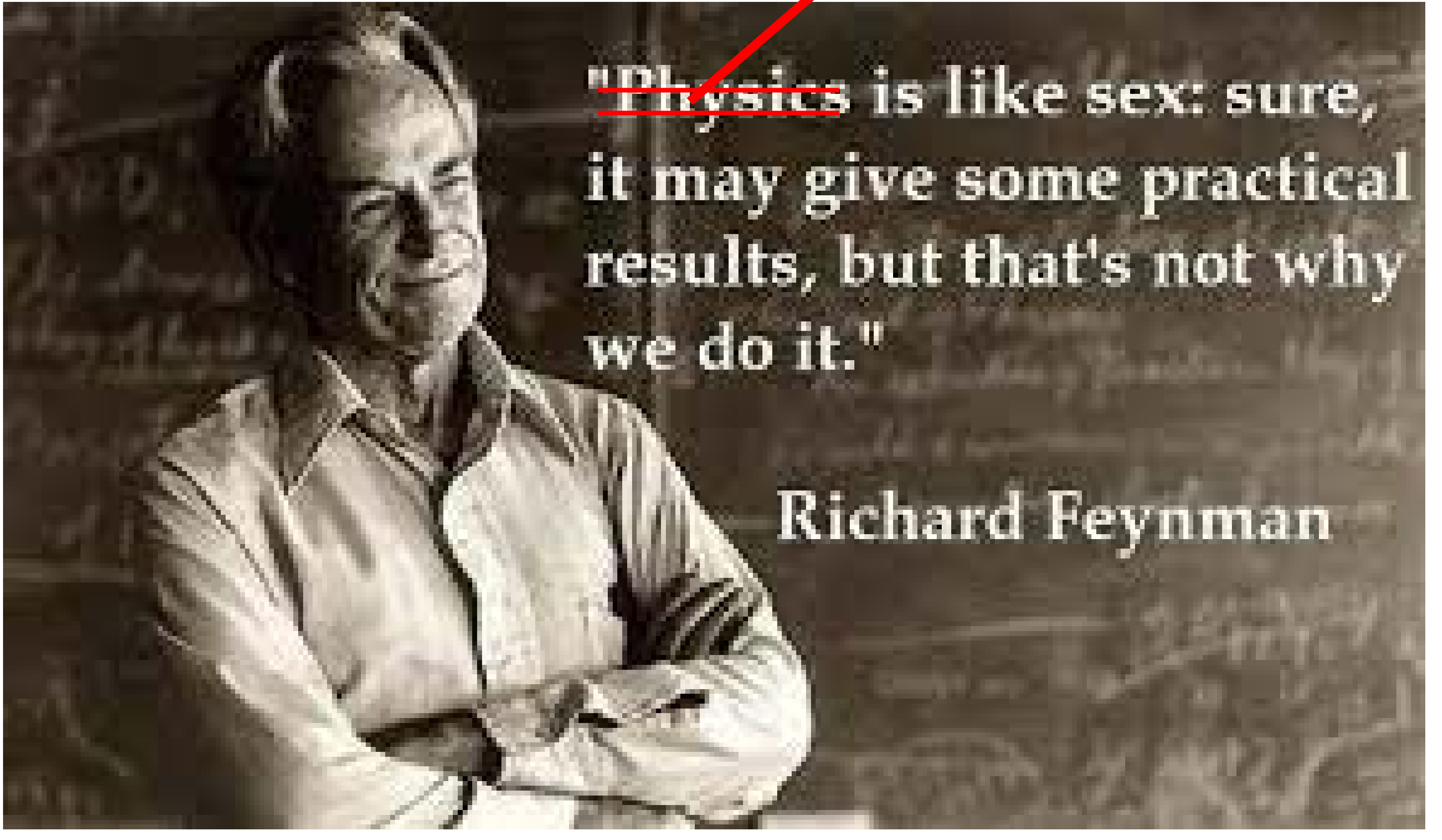


So what? / Why bother?

- Three answers
  - Complexity
  - Better than the best
  - **xxx**


"Physics is like sex: sure,
it may give some practical
results, but that's not why
we do it."
Richard Feynman