

The PoCSverse
Power-Law
Mechanisms, Pt. 3
1 of 51

Rich-Get-Richer Mechanism

Everywhereness

What Came Before

Simon's Model

Analysis

Words

Catchphrases

References

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Principles of Complex Systems,
Vols. 1, 2, 3D, 4 Fourever, V for Vendetta

Deliverator: Calla Beauregard

Showrunner: Prof. Peter Sheridan Dodds

Computational Story Lab | Vermont Complex Systems Institute
University of Vermont | Santa Fe Institute



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The PoCverse
Power-Law
Mechanisms, Pt. 2
2 of 51

Rich-Get-Richer
Mechanism

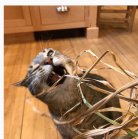
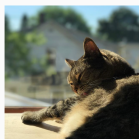
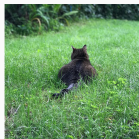
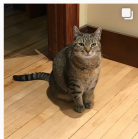
Everywhereness
What Came Before
Simon's Model
Analysis
Words
Catchphrases

References



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The PoCSverse
Power-Law
Mechanisms, Pt. 3
3 of 51

Rich-Get-Richer Mechanism

Everywhereness

What Came Before

Simon's Model

Analysis

Words

Catchphrases

References



Outline

The PoCSverse
Power-Law
Mechanisms, Pt. 3
4 of 51

Rich-Get-Richer Mechanism

Everywhereness

What Came Before

Simon's Model

Analysis

Words

Catchphrases

References

Rich-Get-Richer Mechanism

Everywhereness

What Came Before

Simon's Model

Analysis

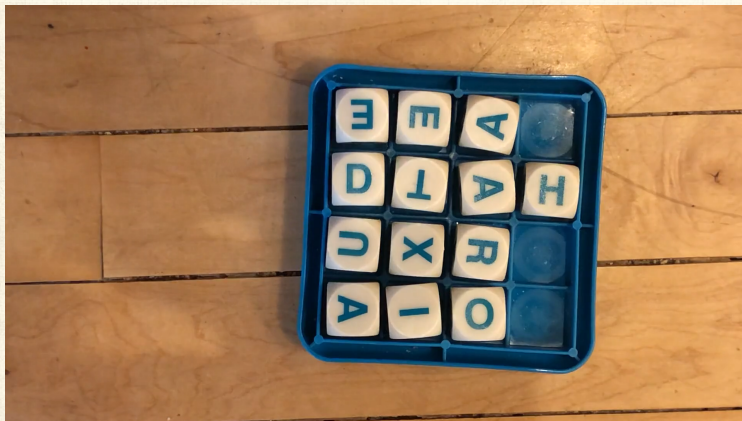
Words

Catchphrases

References



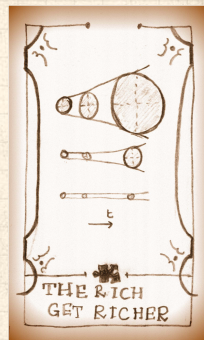
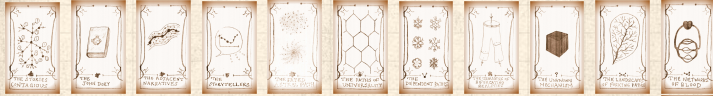
The Boggoracle Speaks:



Rich-Get-Richer Mechanism

Everywhereness
What Came Before
Simon's Model
Analysis
Words
Catchphrases
References





Aggregation:

The PoCverse
Power-Law
Mechanisms, Pt. 3
8 of 51

Rich-Get-Richer
Mechanism

Everywhereness

What Came Before

Simon's Model

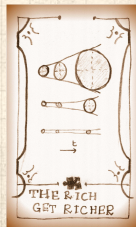
Analysis

Words

Catchphrases

References

-  Random walks represent **additive aggregation**
-  Mechanism: Random addition and subtraction
-  Compare across realizations, no competition.
-  Next: **Random Additive/Copying Processes** involving Competition.
-  **Widespread:** Words, Cities, the Web, Wealth, Productivity (Lotka), Popularity (Books, People, ...)
-  Competing mechanisms (trickiness)



Pre-Zipf's law observations of Zipf's law

The PoCSeve
Power-Law
Mechanisms, Pt. 3
10 of 51

Rich-Get-Richer
Mechanism

Everywhereness

What Came Before

Simon's Model

Analysis

Words

Catchphrases

References

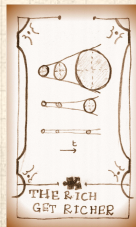
 1910s: Word frequency examined re Stenography  (or shorthand or brachygraphy or tachygraphy), Jean-Baptiste Estoup  ^[5].

 1910s: Felix Auerbach  pointed out the Zipfitude of city sizes in

“Das Gesetz der Bevölkerungskonzentration”
 (“The Law of Population Concentration”) ^[1].

 1924: **G. Udny Yule** ^[11]:
Species per Genus (offers first theoretical mechanism)

 1926: **Lotka** ^[7]:
Scientific papers per author (Lotka's law)



Theoretical Work of Yore:

The PoCVerse
Power-Law
Mechanisms, Pt. 3
11 of 51

Rich-Get-Richer
Mechanism

Everywhereness

What Came Before

Simon's Model

Analysis

Words

Catchphrases

References



1949: Zipf's "Human Behaviour and the Principle of Least-Effort" is published. ^[12]



1953: **Mandelbrot** ^[8]:

Optimality argument for Zipf's law; focus on language.



1955: **Herbert Simon** ^[10, 12]:

Zipf's law for word frequency, city size, income, publications, and species per genus.



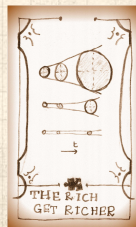
1965/1976: **Derek de Solla Price** ^[3, 9]:

Network of Scientific Citations.



1999: **Barabasi and Albert** ^[2]:

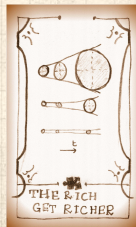
The World Wide Web, networks-at-large.





Herbert Simon (1916–2001):

-  Political scientist (and much more)
-  Involved in Cognitive Psychology, Computer Science, Public Administration, Economics, Management, Sociology
-  Coined ‘bounded rationality’ and ‘satisficing’
-  Nearly 1000 publications (see [Google Scholar](#) 
-  An early leader in Artificial Intelligence, Information Processing, Decision-Making, Problem-Solving, Attention Economics, Organization Theory, Complex Systems, And Computer Simulation Of Scientific Discovery.
-  1978 Nobel Laureate in Economics (his Nobel bio is [here](#) 



Essential Extract of a Growth Model:

The PoCVerse
Power-Law
Mechanisms, Pt. 3
14 of 51

Rich-Get-Richer
Mechanism

Everywhereness

What Came Before

Simon's Model

Analysis

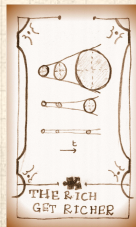
Words

Catchphrases

References

Random Competitive Replication (RCR):

1. Start with 1 Moo Deng (or element) of a particular flavor at $t = 1$
2. At time $t = 2, 3, 4, \dots$, add a new elephant in one of two ways:
 - With probability ρ , create a new elephant with a new flavor
= Mutation/Innovation
 - With probability $1 - \rho$, randomly choose from all existing elephants, and make a copy.
= Replication/Imitation
 - Elephants of the same flavor form a group



Random Competitive Replication—Simon's rich-get-richer model: ^[10]

The PoCverse
Power-Law
Mechanisms, Pt. 3
15 of 51

Rich-Get-Richer
Mechanism

Everywhereness

What Came Before

Simon's Model

Analysis

Words

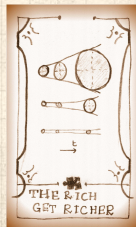
Catchphrases

References

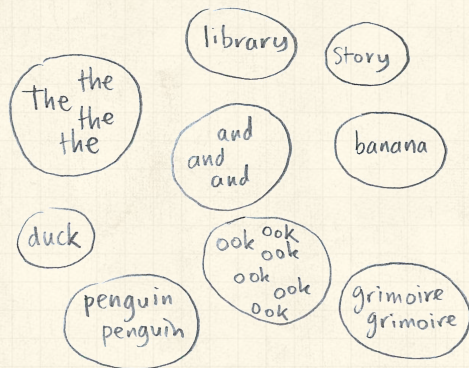
Example: Words appearing in a language

- Consider words as they appear sequentially.
- With probability ρ , the next word has not previously appeared
= **Mutation/Innovation**
- With probability $1 - \rho$, randomly choose one word from all words that have come before, and reuse this word
= **Replication/Imitation**

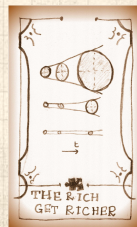
Note: This is a terrible way to write a novel.



For example:



- 21 words used
 - next word is new with prob p
 - next word is a copy with prob $1-p$
- | prob: | next word: |
|----------|------------|
| $6/21$ | ook |
| $4/21$ | the |
| $3/21$ | and |
| $2/21$ | penguin |
| $\vdots$ | |
| $1/21$ | library |

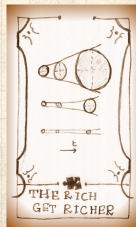


Some observations:

-  Fundamental **Rich-get-Richer** story;
-  Competition for replication between individual elephants is random;
-  Competition for growth between groups of matching elephants is not random;
-  Selection on groups is biased by size;
-  Random selection sounds **easy**;
-  Possible that no great knowledge of system needed (but more later ...).

Your free set of tofu knives:

-  Related to Pólya's Urn Model , a special case of problems involving urns and colored balls .
-  Sampling with super-duper replacement and sneaky sneaking in of new colors.



The long tail of religious studies?

August 5, 2010 @ 10:33 am · Filed by [Mark Liberman](#) under [Computational linguistics](#)

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Google Books isn't the only outfit that sometimes has [trouble](#) with [metadata](#). I happened to notice this morning that Oxford University Press has classified [Herbert A. Simon's "On a class of skew distribution functions"](#) (*Biometrika* 43:425-440, 1955) as "Religious Studies..Death":

BIOMETRIKA

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[Oxford Journals](#) > [Mathematics & Physical Sciences](#) > [Biometrika](#) > [Volume 42, Numb](#)

Biometrika 1955 42(3-4):425-440; doi:10.1093/biomet/42.3-4.425
© 1955 by [Biometrika Trust](#)

ON A CLASS OF SKEW DISTRIBUTION FUNCTIONS

HERBERT A. SIMON

You have reached the most complete version of this article accessible without further authentication.

More complete versions are available.

[Link to article](#)

Article topics:

- Religious Studies..Death

The PoCVerse
Power-Law
Mechanisms, Pt. 3
18 of 51

Rich-Get-Richer
Mechanism

Everywhereness

What Came Before

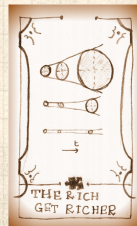
[Simon's Model](#)

Analysis

Words

Catchphrases

References



Carl Burke said,

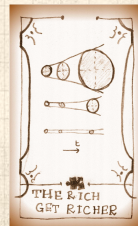
August 5, 2010 @ 12:14 pm

If I had to guess at features that suggest 'Religious Studies — Death', I'd have to go with the word 'urn' and the suffix 'xion', almost never seen except on 'crucifixion'. Granted that Biometrika is published by Oxford University Press, and 'connexion' is a perfectly good British word, the classification algorithm might be more familiar with the American form 'connection'.

[(myl) Looking a bit further into the paper, one finds things like

it is well known that the negative binomial and the log series distributions can be obtained as the stationary solutions of certain stochastic processes. For example, J.H. Darwin (1953) derives these from birth and death processes, with appropriate assumptions as to the birth- and death-rates and the initial conditions.

]



Random Competitive Replication:

The PoCverse
Power-Law
Mechanisms, Pt. 3
20 of 51

Rich-Get-Richer
Mechanism

Everywhereness

What Came Before

Simon's Model

Analysis

Words

Catchphrases

References

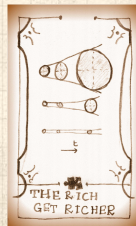
Some observations:

 Steady growth of system: +1 elephant per unit time.

 Steady growth of distinct flavors at rate ρ

 We can incorporate

1. Elephant elimination
2. Elephants moving between groups
3. Variable innovation rate ρ
4. Different selection based on group size
(But mechanism for selection is not as simple...)

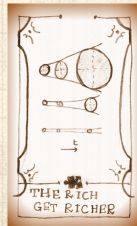




“The Self-Organizing Economy” [a](#) [↗](#)
by Paul Krugman (1996). ^[6]

Ch. 3: An Urban Mystery, p. 46

“...Simon showed—in a completely impenetrable exposition!—that the exponent of the power law distribution should be ...”^{1, 2}



¹Krugman’s book was handed to the Deliverator by a certain [Álvaro Cartea](#) [↗](#)
many years ago at the Santa Fe Institute Summer School.

²Let’s use π for probability because π ’s not special, right guys?

From an archaeological email dig:

% cat ~/Mail/2018-04-13pine-uvn/past/archive-
2009-09-25/PaulKrugman

● ● ● Duck-Billed-Platypus-2024.local:/Users/dodds/pocverse/lectures — more ~...

id AA06867; Thu, 19 Feb 98 08:53:53 EST
Received: from KRUGMAN.MIT.EDU by MIT.MIT.EDU (5.61/4.7) id AA15443; Thu, 19 Feb 98 08:53:32 EST
Message-Id: <2.2.32.19980219135345.00989f60@po10.mit.edu>
X-Sender: krugman@po10.mit.edu
X-Mailer: Windows Eudora Pro Version 2.2 (32)
Mime-Version: 1.0
Content-Type: text/plain; charset="us-ascii"
Date: Thu, 19 Feb 1998 08:53:45 -0500
To: Peter Sheridan Dodds <dodds@math.mit.edu>
From: "Paul R. Krugman" <krugman@MIT.EDU>
Subject: Re: a reference please (very quick!)

Status: RO
X-Status:
X-Keywords:

At 06:47 PM 2/18/98 -0500, you wrote:
>prof krugman,
>
>i was hoping that you might have a second to pass
>on the reference for Herbert Simon's paper
>'on a class of skew distribution functions'...
>
It's in Biometrika, of all places. But also in Simon's collected papers (I think titled Models of Mind); and the basics are repeated in a book by him and Ijiri, "skew distributions and the sizes of firms" (I think)

For all this, and a MUCH simpler derivation of Simon's rule, check out my own book The self-organizing economy

Paul Krugman
Department of Economics, MIT
50 Memorial Drive
Cambridge, MA 02139
617-253-1551/fax 617-253-4096
email: krugman@mit.edu
home page: <http://web.mit.edu/krugman/www/>

(END)

The PoCVerse
Power-Law
Mechanisms, Pt. 3
22 of 51

Rich-Get-Richer
Mechanism

Everywhereness

What Came Before

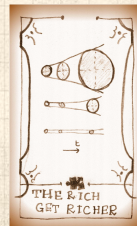
Simon's Model

Analysis

Words

Catchphrases

References



Random Competitive Replication:

The PoCverse
Power-Law
Mechanisms, Pt. 3
24 of 51

Rich-Get-Richer
Mechanism

Everywhereness

What Came Before

Simon's Model

Analysis

Words

Catchphrases

References

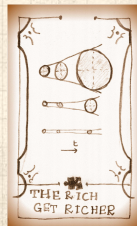
Definitions:

 k_i = size of a group i

 $N_{k,t}$ = # groups containing k elephants at time t .

Basic question: How does $N_{k,t}$ evolve with time?

First: $\sum_k k N_{k,t} = t$ = number of elephants at time t



Random Competitive Replication:

The PoCVerse
Power-Law
Mechanisms, Pt. 3
25 of 51

Rich-Get-Richer
Mechanism

Everywhereness

What Came Before

Simon's Model

Analysis

Words

Catchphrases

References

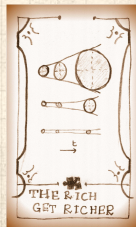
$P_k(t)$ = Probability of choosing an elephant that belongs to a group of size k :

 $N_{k,t}$ size k groups

 $\Rightarrow kN_{k,t}$ elephants in size k groups

 t elephants overall

$$P_k(t) = \frac{kN_{k,t}}{t}.$$



Random Competitive Replication:

The PoCVerse
Power-Law
Mechanisms, Pt. 3
26 of 51

Rich-Get-Richer
Mechanism

Everywhereness

What Came Before

Simon's Model

Analysis

Words

Catchphrases

References

$N_{k,t}$, the number of groups with k elephants, changes at time t if

1. An elephant belonging to a group with k elephants is replicated:

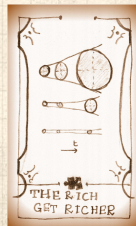
$$N_{k,t+1} = N_{k,t} - 1$$

Happens with probability $(1 - \rho)kN_{k,t}/t$

2. An elephant belonging to a group with $k - 1$ elephants is replicated:

$$N_{k,t+1} = N_{k,t} + 1$$

Happens with probability $(1 - \rho)(k - 1)N_{k-1,t}/t$



Random Competitive Replication:

The PoCVerse
Power-Law
Mechanisms, Pt. 3
27 of 51

Rich-Get-Richer
Mechanism

Everywhereness

What Came Before

Simon's Model

Analysis

Words

Catchphrases

References

Special case for $N_{1,t}$:

1. The new elephant is a new flavor:

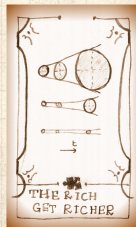
$$N_{1,t+1} = N_{1,t} + 1$$

Happens with probability ρ

2. A unique elephant is replicated:

$$N_{1,t+1} = N_{1,t} - 1$$

Happens with probability $(1 - \rho)N_{1,t}/t$



Random Competitive Replication:

The PoCverse
Power-Law
Mechanisms, Pt. 3
28 of 51

Rich-Get-Richer
Mechanism

Everywhereness

What Came Before

Simon's Model

Analysis

Words

Catchphrases

References

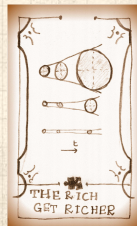
Putting everything together:

For $k > 1$:

$$\langle N_{k,t+1} - N_{k,t} \rangle = (1-\rho) \left((+1)(k-1) \frac{N_{k-1,t}}{t} + (-1)k \frac{N_{k,t}}{t} \right)$$

For $k = 1$:

$$\langle N_{1,t+1} - N_{1,t} \rangle = (+1)\rho + (-1)(1-\rho)1 \cdot \frac{N_{1,t}}{t}$$



Random Competitive Replication:

Assume distribution stabilizes: $N_{k,t} = n_k t$
(Reasonable for t large)



Drop expectations



Numbers of elephants now fractional



Okay over large time scales



For later: the fraction of groups that have size k is n_k/ρ since

$$\frac{N_{k,t}}{\rho t} = \frac{n_k t}{\rho t} = \frac{n_k}{\rho}.$$

The PoCVerse
Power-Law
Mechanisms, Pt. 3
29 of 51

Rich-Get-Richer
Mechanism

Everywhereness

What Came Before

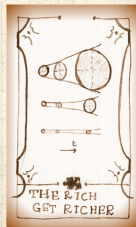
Simon's Model

Analysis

Words

Catchphrases

References



Random Competitive Replication:

Stochastic difference equation:

$$\langle N_{k,t+1} - N_{k,t} \rangle = (1 - \rho) \left((k-1) \frac{N_{k-1,t}}{t} - k \frac{N_{k,t}}{t} \right)$$

becomes

$$n_k(t+1) - n_k t = (1 - \rho) \left((k-1) \frac{n_{k-1} t}{t} - k \frac{n_k t}{t} \right)$$

$$n_k(\cancel{t} + 1 - \cancel{t}) = (1 - \rho) \left((k-1) \frac{n_{k-1} \cancel{t}}{\cancel{t}} - k \frac{n_k \cancel{t}}{\cancel{t}} \right)$$

$$\Rightarrow n_k = (1 - \rho) ((k-1)n_{k-1} - kn_k)$$

$$\Rightarrow n_k (1 + (1 - \rho)k) = (1 - \rho)(k-1)n_{k-1}$$

The PoCverse
Power-Law
Mechanisms, Pt. 3
30 of 51

Rich-Get-Richer
Mechanism

Everywhereness

What Came Before

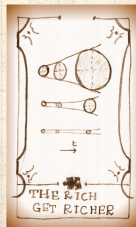
Simon's Model

Analysis

Words

Catchphrases

References



Random Competitive Replication:

We have a simple recursion:

$$\frac{n_k}{n_{k-1}} = \frac{(k-1)(1-\rho)}{1+(1-\rho)k}$$

 Interested in k large (the tail of the distribution)

 Can be solved exactly.

Insert assignment question 

 For just the tail: Expand as a series of powers of $1/k$

Insert assignment question 

We (okay, you) find

$$n_k \propto k^{-\frac{(2-\rho)}{(1-\rho)}} = k^{-\gamma}$$

$$\gamma = \frac{(2-\rho)}{(1-\rho)} = 1 + \frac{1}{(1-\rho)}$$

The PoCverse
Power-Law
Mechanisms, Pt. 3
31 of 51

Rich-Get-Richer
Mechanism

Everywhereness

What Came Before

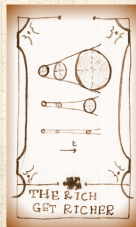
Simon's Model

Analysis

Words

Catchphrases

References





Micro-to-Macro story with ρ and γ measurable.

$$\gamma = \frac{(2 - \rho)}{(1 - \rho)} = 1 + \frac{1}{(1 - \rho)}$$



Observe $2 < \gamma < \infty$ for $0 < \rho < 1$.



For $\rho \simeq 0$ (low innovation rate):

$$\gamma \simeq 2$$



‘Wild’ power-law size distribution of group sizes, bordering on ‘infinite’ mean.



For $\rho \simeq 1$ (high innovation rate):

$$\gamma \simeq \infty$$



All elephants have different flavors.



Upshot: Tunable mechanism producing a family of universality classes.

The PoCverse
Power-Law
Mechanisms, Pt. 3
32 of 51

Rich-Get-Richer
Mechanism

Everywhereness

What Came Before

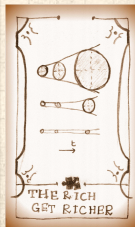
Simon's Model

Analysis

Words

Catchphrases

References



 Recall size-ranking law: $s_r \sim r^{-\alpha}$
(s_r = size of the r th largest group of elephants)

 We found $\alpha = 1/(\gamma - 1)$ so:

$$\alpha = \frac{1}{\gamma - 1} = \frac{1}{\cancel{\gamma} + \frac{1}{(1-\rho)} - \cancel{\gamma}} = 1 - \rho.$$

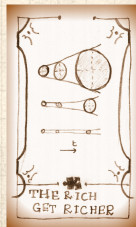
 $\gamma = 2$ corresponds to $\alpha = 1$

 We (roughly) see Zipfian exponent^[12] of $\alpha = 1$ for many real systems: city sizes, word distributions, ...

 Corresponds to $\rho \rightarrow 0$, low innovation.

 Still, **other quite different** mechanisms are possible...

 Must look at the details to see if mechanism makes sense...
more later.



What about small k ?:

We had one other equation:



$$\langle N_{1,t+1} - N_{1,t} \rangle = \rho - (1 - \rho)1 \cdot \frac{N_{1,t}}{t}$$



As before, set $N_{1,t} = n_1 t$ and drop expectations



$$n_1(t+1) - n_1 t = \rho - (1 - \rho)1 \cdot \frac{n_1 t}{t}$$



$$n_1 = \rho - (1 - \rho)n_1$$

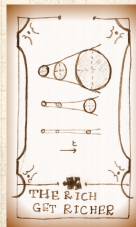


Rearrange:

$$n_1 + (1 - \rho)n_1 = \rho$$



$$n_1 = \frac{\rho}{2 - \rho}$$



So...
$$N_{1,t} = n_1 t = \frac{\rho t}{2 - \rho}$$



Recall number of distinct elephants = ρt .



Fraction of distinct elephants that are unique (belong to groups of size 1):

$$\frac{1}{\rho t} N_{1,t} = \frac{1}{\cancel{\rho t}} \frac{\cancel{\rho t}}{2 - \rho} = \frac{1}{2 - \rho}$$

(also = fraction of groups of size 1)



For ρ small, fraction of unique elephants $\sim 1/2$



Roughly observed for real distributions



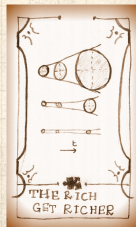
ρ increases, fraction increases



Can show fraction of groups with two elephants $\sim 1/6$



Model works well for large and small k #awesome



Rich-Get-Richer
Mechanism

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What Came Before

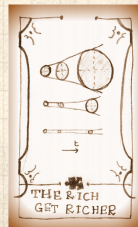
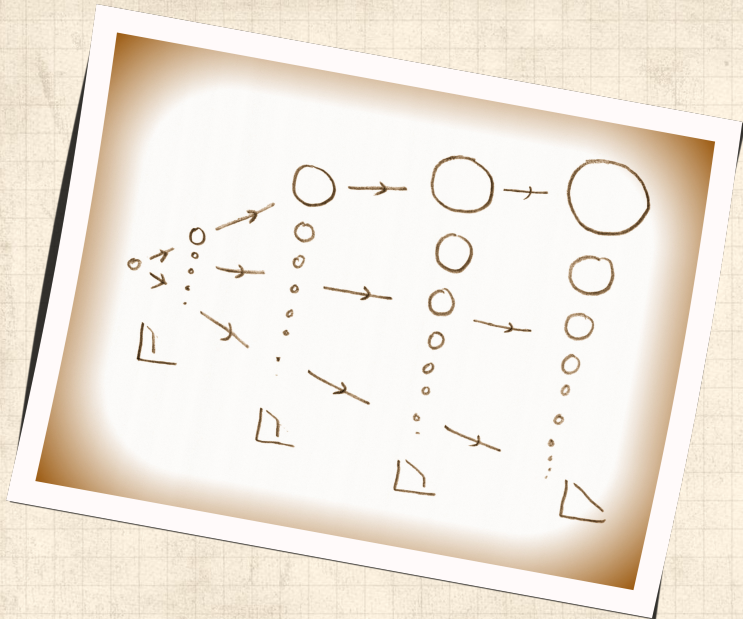
Simon's Model

Analysis

Words

Catchphrases

References



Words:

The PoCverse
Power-Law
Mechanisms, Pt. 3
38 of 51

Rich-Get-Richer
Mechanism

Everywhereness

What Came Before

Simon's Model

Analysis

Words

Catchphrases

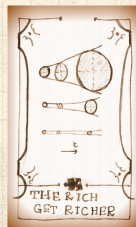
References

From Simon ^[10]:

Estimate $\rho_{\text{est}} = \# \text{ unique words} / \# \text{ all words}$

For Joyce's **Ulysses**: $\rho_{\text{est}} \simeq 0.115$

N_1 (real)	N_1 (est)	N_2 (real)	N_2 (est)
16,432	15,850	4,776	4,870



Evolution of catch phrases:



Yule's paper (1924) ^[11]:

"A mathematical theory of evolution, based on the conclusions of Dr J. C. Willis, F.R.S."



Simon's paper (1955) ^[10]:

"On a class of skew distribution functions" (snore)

From Simon's introduction:

It is the purpose of this paper to analyse a class of distribution functions that appear in a wide range of empirical data—particularly data describing sociological, biological and economic phenomena.

Its appearance is so frequent, and the phenomena so diverse, that one is led to conjecture that if these phenomena have any property in common it can only be a similarity in the structure of the underlying probability mechanisms.

The PoCVerse
Power-Law
Mechanisms, Pt. 3
40 of 51

Rich-Get-Richer
Mechanism

Everywhereness

What Came Before

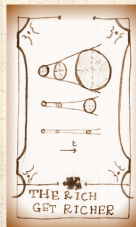
Simon's Model

Analysis

Words

Catchphrases

References



Evolution of catch phrases:

The PoCVerse
Power-Law
Mechanisms, Pt. 3
41 of 51

Rich-Get-Richer
Mechanism

Everywhereness

What Came Before

Simon's Model

Analysis

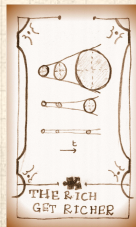
Words

Catchphrases

References

Derek de Solla Price:

-  First to study network evolution with these kinds of models.
-  Citation network of scientific papers
-  Price's term: **Cumulative Advantage**
-  Idea: papers receive new citations with probability proportional to their existing # of citations
-  Directed network
-  Two (surmountable) problems:
 1. New papers have no citations
 2. Selection mechanism is more complicated



Evolution of catch phrases:

The PoCVerse
Power-Law
Mechanisms, Pt. 3
42 of 51

Rich-Get-Richer
Mechanism

Everywhereness

What Came Before

Simon's Model

Analysis

Words

Catchphrases

References

Robert K. Merton: the Matthew Effect 



Studied careers of scientists and found credit flowed disproportionately to the already famous

From the Gospel of Matthew:

“For to every one that hath shall be given...

(Wait! There's more....)

but from him that hath not, that also which he seemeth to have shall be taken away.

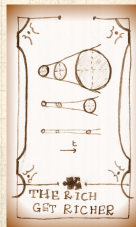
And cast the worthless servant into the outer darkness; there men will weep and gnash their teeth.”



(**Hath** = suggested unit of purchasing power.)



Matilda effect:  women's scientific achievements are often overlooked



Evolution of catch phrases:

The PoCVerse
Power-Law
Mechanisms, Pt. 3
43 of 51

Rich-Get-Richer
Mechanism

Everywhereness

What Came Before

Simon's Model

Analysis

Words

Catchphrases

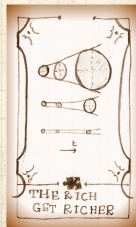
References

Merton was a catchphrase machine:

1. Self-fulfilling prophecy
2. Role model
3. Unintended (or unanticipated) consequences
4. Focused interview → focus group
5. Obliteration by incorporation ↗ (includes above examples from Merton himself)

And just to be clear...

Merton's son, Robert C. Merton, won the Nobel Prize for Economics in 1997.



Evolution of catch phrases:

The PoCVerse
Power-Law
Mechanisms, Pt. 3
44 of 51

Rich-Get-Richer
Mechanism

Everywhereness

What Came Before

Simon's Model

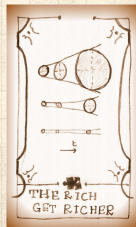
Analysis

Words

Catchphrases

References

- Barabasi and Albert ^[2]—thinking about the Web
- Independent reinvention of a version of Simon and Price's theory for networks
- Another term: “Preferential Attachment”
- Considered undirected networks (not realistic but avoids 0 citation problem)
- Still have selection problem based on size (non-random)
- Solution: Randomly connect to a node (easy) ...
- ...and then randomly connect to the node's friends (also easy)
- “Scale-free networks” = food on the table for physicists



More mattering:

Rich-get-richness in social contagion:

-  We love to rank everyone, everything: Top n lists.
-  People, wealth, sports, music, movies, books, schools, cities, countries, dogs (13/10) , ...
-  Gameable: payola , astroturfing , sockpuppetry , John Barron  (the sockpuppet hype man ) , ...
-  Black-box ranking algorithms make ranking opaque.
-  Black boxes are gameable but takes money and commensurate skill.
-  Black box algorithms can make things spread rampantly.¹
-  No “regramming” is a positive feature of Instagram (also: Pratchett the Cat )
-  What if a healthier Facebook is just ... Instagram? 
(hahahhaaha)

The PoCVerse
Power-Law
Mechanisms, Pt. 3
45 of 51

Rich-Get-Richer
Mechanism

Everywhereness

What Came Before

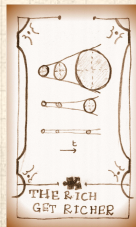
Simon's Model

Analysis

Words

Catchphrases

References



¹“With great power comes great responsibility.” –S. Man.

Rich-get-richness is everywhere in reality

The PoCVerse
Power-Law
Mechanisms, Pt. 3
46 of 51

Rich-Get-Richer
Mechanism

Everywhereness

What Came Before

Simon's Model

Analysis

Words

Catchphrases

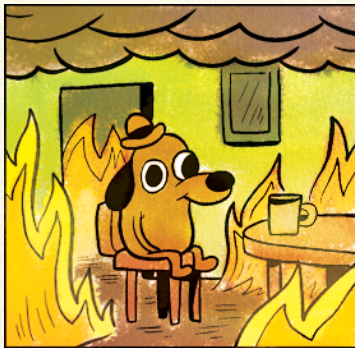
References

But:

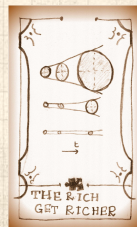
Simon's Model

Is

WRONG.



To be continued ...



Burn it all down.



“Simon’s fundamental rich-get-richer model entails a dominant first-mover advantage” ↗

Dodds et al.,

Physical Review E, **95**, 052301, 2017. [4]

The PoCVerse
Power-Law
Mechanisms, Pt. 3
47 of 51

Rich-Get-Richer
Mechanism

Everywhereness

What Came Before

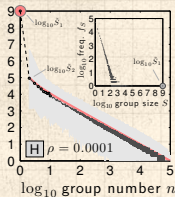
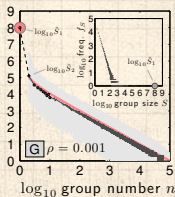
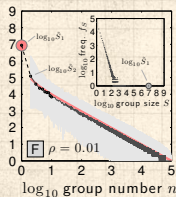
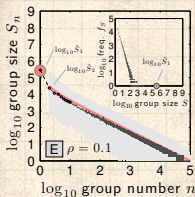
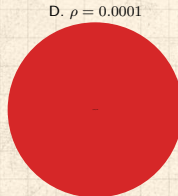
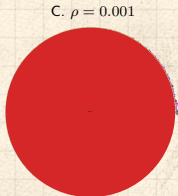
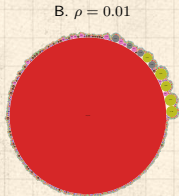
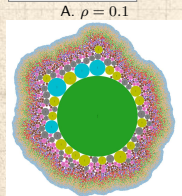
Simon’s Model

Analysis

Words

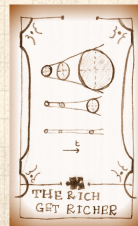
Catchphrases

References



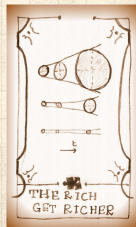
See Fletcher Hazlehurst’s visualization at paper’s [online](#)

[app-endices](#) ↗



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The PoCverse
Power-Law
Mechanisms, Pt. 3
49 of 51

Rich-Get-Richer
Mechanism

Everywhereness

What Came Before

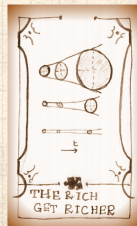
Simon's Model

Analysis

Words

Catchphrases

References



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The PoCverse
Power-Law
Mechanisms, Pt. 3
50 of 51

Rich-Get-Richer
Mechanism

Everywhereness

What Came Before

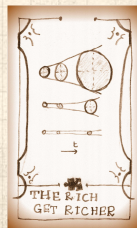
Simon's Model

Analysis

Words

Catchphrases

References



References IV

The PoCverse
Power-Law
Mechanisms, Pt. 3
51 of 51

Rich-Get-Richer
Mechanism

Everywhereness

What Came Before

Simon's Model

Analysis

Words

Catchphrases

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