Pathway of technology innovation: from micro to macro

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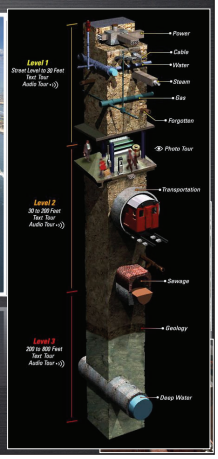
At macro scale…



INFRASTRUCTURE

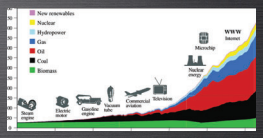
RECONFIGURING OUR ENVIRONMENT

Innovation Pathway:

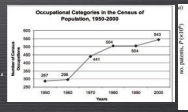
Indefinite circle of problem-solution-reconfiguration

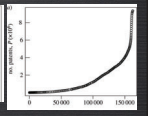
…unless we change the rules.

1. *Increasing* ***energy intensity***



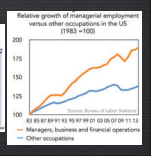
2. *Increasing* ***solution sets***
(tool kits, occupations, economic complexity, specialization…)





3. *Increasing* ***coordination costs***
(Laws, lawyers, managers, bureaucracy…)

…
It seems like to have its own purpose and mechanisms



Today's lecture includes…

Lecture 1: Modeling technological innovation & implications

Lecture 2: Complexity, Specialization and Coordination in the labor market

Using frameworks: *network science, scaling theory, collective intelligence, + management science, economics, urban science, statistical physics…and my personal experience*

Innovation

How have we been so successful?

Behind the scene of scientific and technological achievements are **individual unique/non-repeatable** geniuses

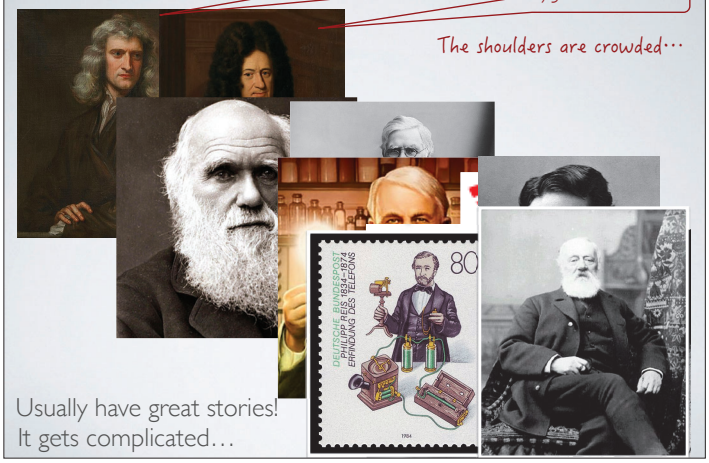
Usually have great stories!

Crowded Behind the scene

I'm Standing on the shoulders of giants

Well, you are not alone···

The shoulders are crowded···



Usually have great stories!
It gets complicated…

What about today's science and technology?

Theory in Biosciences
https://doi.org/10.1007/s12064-020-00333-3

ORIGINAL ARTICLE

Quantifying simultaneous innovations in evolutionary medicine

Deryc T. Painter[1] · Frank van der Wouden[2] · Manfred D. Laubichler[1,3] · Hyejin Youn[4,5,6]

Received: 6 October 2020 / Accepted: 13 November 2020

We wanted to identify **multiple innovators** who came up with the same concepts within **a narrow topic 'evolutionary medicine' within only four years.**

Excluding those with common references, shared affiliations, previous co-authorship
We found 13 authors
Many Type I errors because systematic quantification is challenging.

If innovation is attributed to just a collection of unique, individual processes, why are there so many inventors and thinkers who came up with the same ideas at the same time independently?

As if the discovery (new idea) was waiting for whoever to pick up.
The time must be ripe (Kuhn, 1959);
Ideas were in the air (Lamb &Easton 1984).

Where to begin?

Search space

Searching space theory perhaps explain abundant multiple inventors in a comprehensive, systematic way. It represents generating new ideas as individuals either **exploit or explore the search space**, if not do both, to find a better-yet-exist solution

Individuals searching space are **not alone, and not independent,** but **interactive** through **the underlying search space**.

Imagine we have a map of the space.
We can locate ourselves not only to plan where to go, but also to identify which route is the easiest and fastest. We can also prepare for rough roads ahead *(Hidalgo & Hausmann 2007; Abhishek & Stern 2020).*

Even when our map is incomplete, we can still know which strategy is best for my firm given the landscape we are embedded in.

We can also predict which terrain will be most likely crowded.

Therefore, innovation and economic development strategies require a good understanding of how to navigate the complex landscape

This is the goal

But it remains unclear where the underlying structure comes from.

Today's goal:

Can we make
a **computational bottom-up model**
at micro scale to explain
the underlying space
at macro scale?

Spoiler alert:
Innovation is a collective behavior of messy network

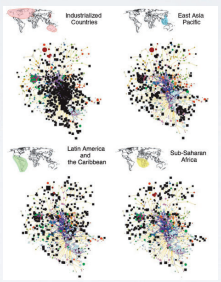
Three decisions to make before constructing a computational model

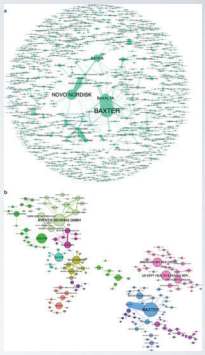
1. Representation of the space
2. Representation of inventive actions
3. **Interaction mechanism**
   between individuals and the underlying space. It's not only *individuals constrained by the space structure, but also structures are shaped by individuals.*

1. Network representation

- **Network** is a good mathematical representation for combinations
- Structural properties (roughness & modularity) are well known because there have been many studies, and hence easy to verify the theory and model.

Product Space by Hidalgo & Hausmann Science 2007





Patent network by C. G. Pereira et al. Nature BioTech 2018

2. Representation of inventive actions
Combination & Recombination

- A new idea is combination of new or pre-existing capabilities.
- Accumulation of combinations (recipe) reveals interdependencies of technologies

Schumpeter, Arthuer, Fleming, Uzzi, Youn

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2. Representation of inventive actions

Combination is a fundamental process from animals to humans.

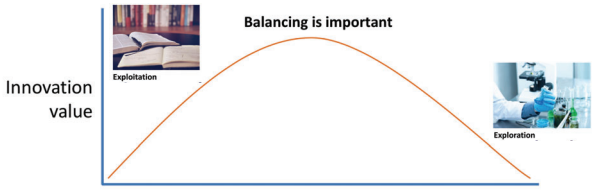
An adult male capuchin uses a stone to open a palm nut placed on a wooden anvil.
Valentina Truppa et al. 2018
Tomos Proffitt et al., Nature 2016

In addition, **Combination** is the most efficient process that **maximally (exponentially) generate the solutions given the limited tool kits**

Brain is a computational machine that automatically associate/ combine different things: e.g. Languages

3. Interaction mechanism:
How the structure of the space is shaped by & shaping pedestrians

Balance between exploitation and exploration



Sole exploitation
Eventually marginalizes the originality.
e.g. Doing similar researches over and over.
-> Reinforcing (building convention)

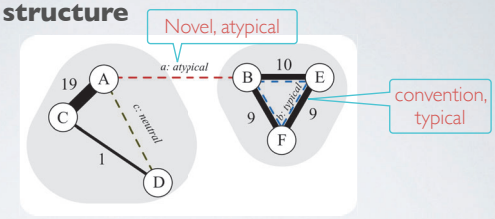
Sole exploration
Fails to grasp the full potentials of existing knowledge & High risk
e.g. 'Reinventing the wheel'
-> New path

***Invariant ratio** between **exploration** and **exploitation** in invention activities*

$$\Delta C = 0.6\,\Delta P$$

Youn et al. 2015
With Hyunuk Kim

Mathematical framework to quantify exploitation (convention) and exploration (novelty) on network structure



$$\text{Novelty } \mathbf{z} = \frac{\text{observation} - \text{expected weight}}{\text{standard dev.}}$$

Convention: large z (observation > expectation)

Novelty: negative z (observation < expectation)

Expected link weight comes from your null model

In case that a choice of null model is a **random connection**:

expected link weight between $\mu = \frac{n_\alpha n_\beta}{|P|}$, and std. dev $= \mu_{\alpha\beta}\left(1-\frac{n_\alpha}{|P|}\right)\left(\frac{|P|-n_\beta}{|P|-1}\right)$

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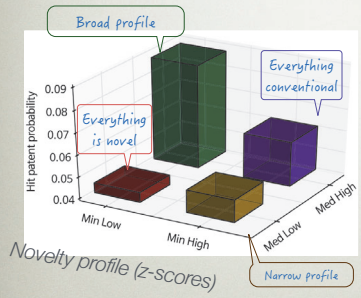
Uzzi et al. (2013), D. Kim et al. (2016)

Empirical Results: Science paper & Patent data

conventionality *with* **novelty** *for the highest Impact*



Novelty profile (z-scores)

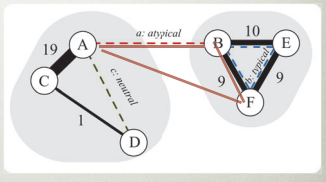
Sweet Spot for Impact

Sweet spot in exploitation & exploration

Uzzi et.al (2013), D. Kim et.al (2016)

Possible explanation 1:

Maturity & Infrastructure support
Network externality

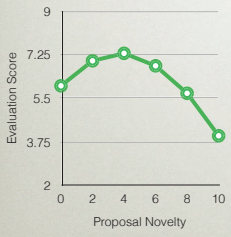


motor vehicle data processing

Technological ecosystems

Possible explanation 2:

We don't know, then we don't like, but we don't want to be boring.
We love **familiar surprise, achievable challenge**



Boudreau et al. l 2012

acquired taste

all set…

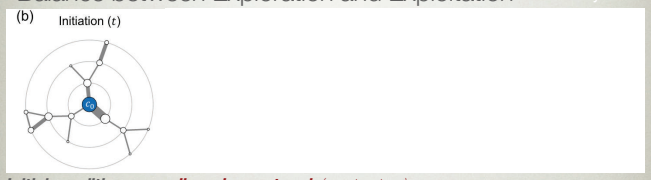
let's make a bottom-up toy model

all set… let's make a bottom-up toy model

Micro-strategic decisions

Balance between Exploration and Exploitation

With Hyunuk Kim



1. ***Initial condition***: ***a small random network*** *(no structure)*
   (~100 nodes growing by 10,000 times up to ~1,000,000 nodes)
2. ***Discovery***: *occasional discovery of concept (new to everyone) decreasing with time* $\sim t^{-\delta}$.
3. ***Search***: *randomly select a* ***focal concept*** c_0 *(domain knowledge) with* ***decreases w/ distance,*** e^{-d/d_s} *where* d_s *is the characteristic search range and* d *is distance from* c_0
4. ***Once searched,***

   Combine them and the searched paths are ***reinforced to be further exploited*** *-> increasing* ***conventionality, nucleation of a module. Coevolution mechanisms***

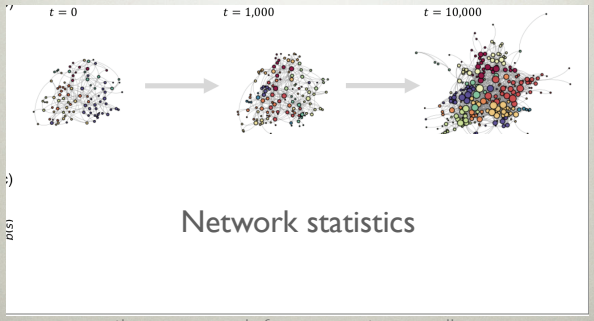
Two parameters: exploration (δ) & exploitation parameter (d_s)

- *new node enters with* $\sim t^{-\delta}$.
- *new connection is made but not far away from my domain knowledge* e^{-d/d_s}

Toy model: result

Micro-strategic decisions

Balance between Exploration and Exploitation



conventions reinforcement cliques

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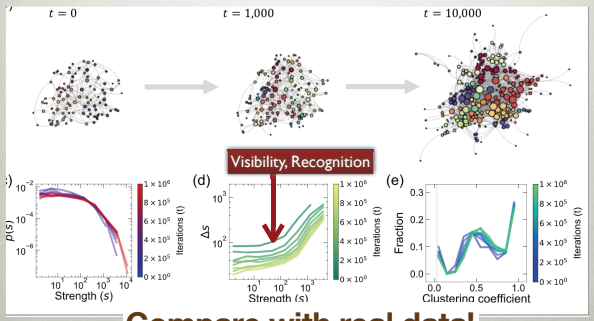
Toy model: result

Micro-strategic decisions

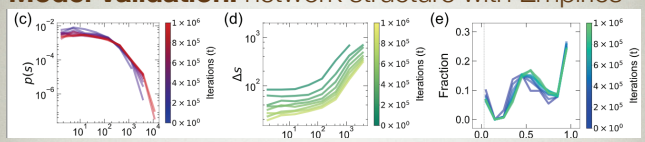
Balance between Exploration and Exploitation



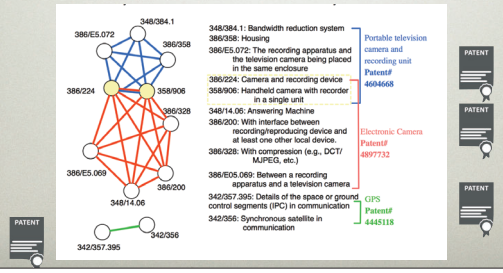
convent **Compare with real data!** ies

With Hyunuk Kim

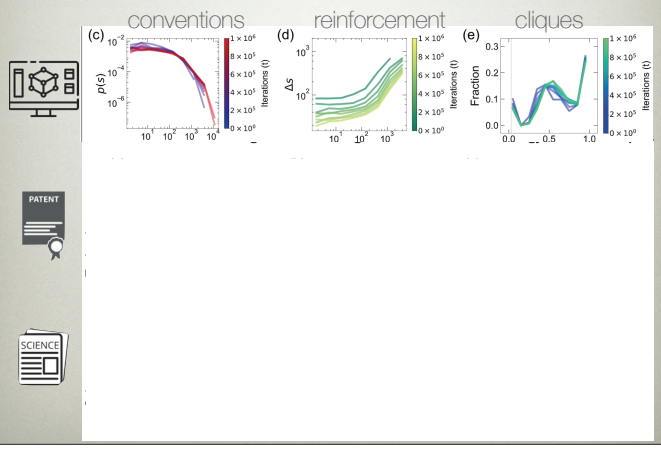
Model Validation: network structure with Empirics



Empirics: Academic papers & Patents data



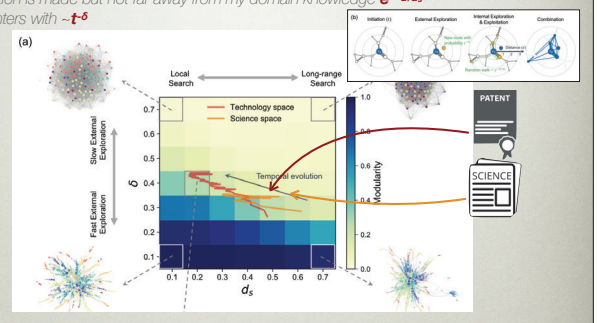
Model Validation: network structure of Empirics Academic papers & Patents data



Create counter factual worlds… (modularity)

(all possible parameter pairs: δ & d_s)

- *new connection is made but not far away from my domain knowledge* e^{-d/d_s}
- *new node enters with* $\sim t^{-\delta}$



Observed world path on modularity ridge (essential tension)

Academic papers (yellow) & Patents data (red)

With Hyunuk Kim

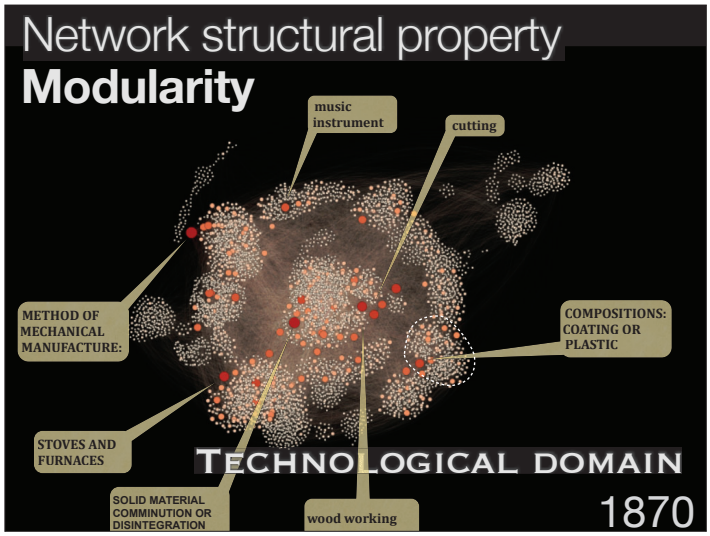
What is modular structure?

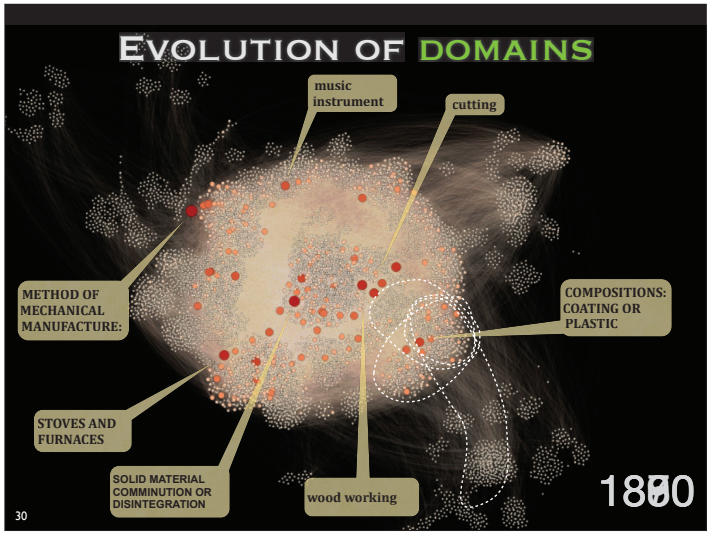
A system's components are relatively well separated (clusters, groups, communities)
Encapsulate reducible information package (homogeneous within the group) such that they become a thing (frequent-usage of phrases, idioms… *Coase' why do firms exist?!?*)

Modular landscape makes innovation predictable or less predictable?

First, is the evolution of knowledge creation predictable?!?

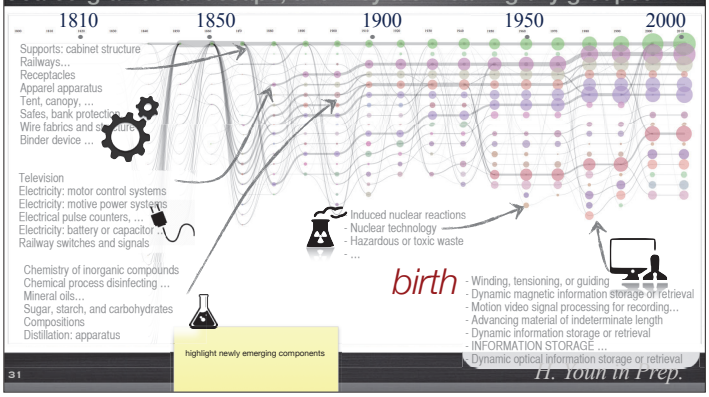
Before that, how the modular structure looks like?





Emergence of technological domains

Coarse-grained landscape, and they are meaningfully grouped



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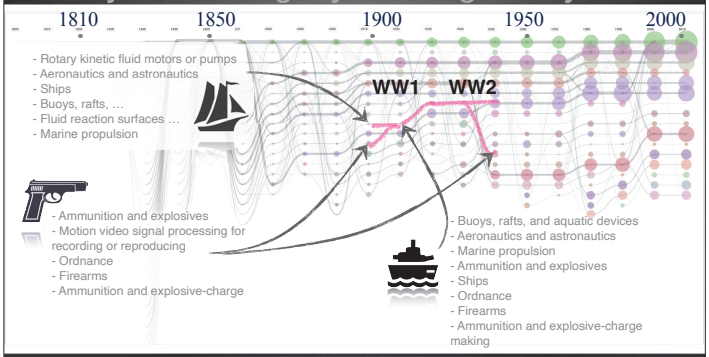
H. Youn in Prep.

Emergence of technological domains

And they are meaningfully reflecting society



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H. Youn in Prep.

If technological change is a **structural change** (the way things are put together),

Modularity =? Paradigm

Modules: encapsulated knowledge & consensus technology domain & status quo

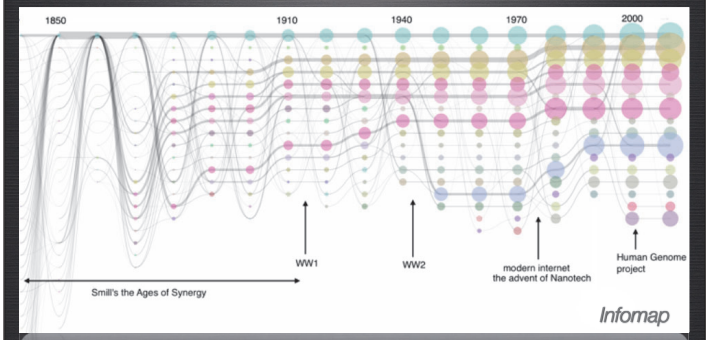
Modular landscape makes innovation predictable.

Properties:

1. **Technological recursive** (a module becomes a thing)
2. **Evolution of modules**: paradigm shift *(Thomas Kuhn)* *resulting* **discontinuous** transition or multi-scale dynamics

Episodic Change

Technological change (structural change) not continuous but **discontinuous**

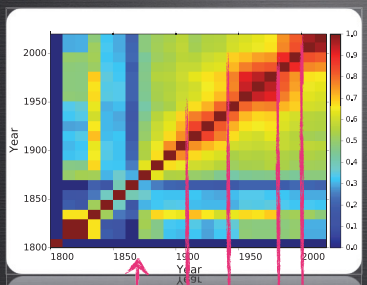


Mention circle size

H. Youn in Prep.

Demarcation of Eras

Normalized Mutual Information (NMI)



$$I_{norm}(X,Y) = \frac{I(X,Y)}{[H(X)+H(Y)]/2}$$

$$I(X,Y) = -\sum_{y\in Y}\sum_{x\in X} p(x,y) log \frac{p(x,y)}{p(x)p(y)}$$

$$H(X) = -\sum_{x\in X} p_x log p_x$$

Interpretation:
How much information *year x* has on *year y*?
Or how well I can predict *year y* given *year x* information?

shannon entropy
let me giv you what intuition for

normalise based on the size of

prediction blocks

H. Youn in Prep.

Why does innovation exhibit **discontinuous** dynamics?

Possible mechanisms to make paradigm shift… *(work-in-progress)*

Mechanism for phase-1 (normal science):

- Reinforcing consensus/conventions (behavioral reason)
- Preferential attachment (Mathew effect)
- Visibility response, Familiarity
- Reducing information processing (finite brain-size, burden of knowledge)

Mechanism for phase-2 (revolutionary science):

- External/Exogenous shocks
- Age (people die with theories)
- New entrance (no burden of knowledge)
- Aspiration of novelty and differentiation
- Core-periphery network

Obsolescence or Exhaustion ?

Counter-balance

Modular landscape makes innovation predictable: then can we predict future technology?

This is why our toy model successfully reproduced the empirics.
There is another way to construct a prediction model (machine-learning)

1. Toy model: emergence of network structures
2. **Link prediction: Forecasting machine (trained from the past)**

Given G[t0, t0'] a graph on edges up to time t'0, output a ranked list L of links (not in G [t0, t0']) that are predicted to appear in G[t1, t1']

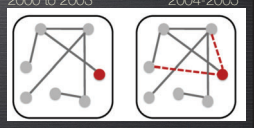
Evaluation:

n = [Enew]: # new edges that appear during the test period [t1, t1']
Take top n elements of L and count correct edges

Input

Network measures (shortest paths, shared neighbors, degree…)

Training [t0, t0'] 2000 to 2003 | Testing G[t1, t1'] 2004-2005



Is there a model for innovation?

What does a model usually do?
Explanation and Prediction

Explanation & Understanding

According to Stephen Hawking's model-dependent realism, our sense organs provide input, and we build a model or models of the world, and thus reality should be interpreted based upon these models

Prediction

Model has to predict the future state at high accuracy and precision.

Categorizing predicable innovation

Surprise

Suspense

Conclusion (long version)

1. *provides an operationalized explanation of knowledge structure through* ***individually decentralized decisions****.*
2. *These somewhat philosophical hypotheses are addressed by not only theoretical computation model, but also empirical validation, promising future expansion to many new directions model to demonstrate that* ***knowledge domains can indeed emerge from collective behaviors*** *with a* ***simple set of rules****:* ***reinforcement of conventionality while seeking novelty****.*
3. *The structural change seems to* ***operate as its own.***
5. *suggests that scientists, or whoever engaging in scientific enterprise, often perceived as individual and independent actors of knowledge production, could potentially be in fact* ***heavily influenced by historical paths****.*
   -> ***predictable innovation***

Conclusion: Short version

network model of collective brain *to demonstrate that knowledge domains (or even cultural elements) can indeed emerge from* ***collective behaviors*** *with* ***a simple set of rules****:* ***reinforcement of conventionality while seeking novelty.***

Innovation is
a collective behavior of messy network

Thank you

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