Energy and its Relation to Complexity of the Economy

Granada Seminar 2015

Physics Meets the Social Sciences

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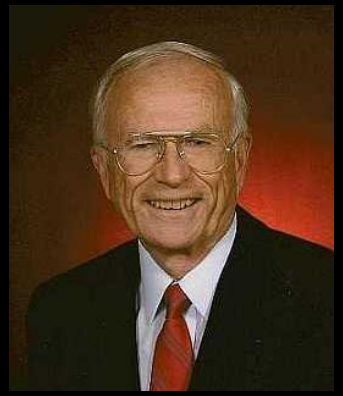
This presentation is a combination of ideas applied to the human economy

Howard T. Odum
(systems ecology)

Charles Hall
(net energy analysis)

Joseph A. Tainter
(anthropology)



Robert E. Ulanowicz
(systems ecology, information theory)

Me today
(engineer, systems)

Tainter: energy-complexity spiral

- Increased complexity needs resources
  - "… most of the time complexity increases to solve problems."
  - Societies "… subsequently must produce more energy and other resources to pay for the increased complexity."

    Tainter and Patzek (2012), *Drilling down : The Gulf Oil Debacle and Our Energy Dilemma.*

- <u>Theory:</u> High gross & net energy resources facilitate increased complexity
- <u>Research need:</u> quantitatively test theory for modern society

C. Hall: EROI = energy return on energy invested (measure of net energy)

- How much energy to needed to obtain energy
- Concept is simple

$$\text{EROI} = \frac{\int (\text{Power Output})dt}{\int (\text{Power input})dt}$$

- I use an interpretation with annual economic data (net power ratio):

$$\text{NPR}_{\text{econ}} = \frac{\text{GDP}}{\$/\text{yr spent by energy and food sectors}}$$

Ulanowicz: Information theory metrics to quantify distribution of network *flows*

- X, Mutual Constraint
  - Increases with concentration of flows, "efficiency"
  - "number of roles" = n = e^X
- Ψ, Conditional Entropy
  - Increases with more dispersed and uniform flows, "redundancy"
  - "connectivity" = m = $e^{(\Psi/2)}$
- H = X + Ψ, Information Entropy
  - C = T..×H = "capacity"
  - Systems with higher "capacity" can better adapt

$$X = \sum_{i,j} \frac{T_{ij}}{T_{..}} \ln\left(\frac{T_{ij}T_{..}}{T_{i.}T_{.j}}\right)$$

$$\Psi = -\sum_{i,j} \frac{T_{ij}}{T_{..}} \ln\left(\frac{T_{ij}^2}{T_{i.}T_{.j}}\right)$$

$$H = -\sum_{i,j} \frac{T_{ij}}{T_{..}} \ln\left(\frac{T_{ij}}{T_{..}}\right)$$

T.. = total flow in system

Ulanowicz (2009)

Understanding Ulanowicz's information theory interpretation for networks

1/4	1/4	1/4	1/4
1/4	1/4	1/4	1/4
1/4	1/4	1/4	1/4
1/4	1/4	1/4	1/4

- Uniform (fully connected)
  - X (Mutual Constraint) = 0
  - n (roles) = 1 (min)
  - m (connectivity) = 4 (max)
  - 'roles × connectivity' = 1 × 4 = 4
  - "redundant" undifferentiated organization

1			
	1		
		1	
			1

- Diagonal flows (one path)
  - Ψ (Conditional Entropy) = 0
  - n (roles) = 4 (max)
  - m (connectivity) = 1 (min)
  - 'roles × connectivity' = 4 × 1 = 4
  - "efficient" differentiated organization

There is a defined 'role-connectivity' space for networks

1/4	1/4	1/4	1/4
1/4	1/4	1/4	1/4
1/4	1/4	1/4	1/4
1/4	1/4	1/4	1/4

1			
	1		
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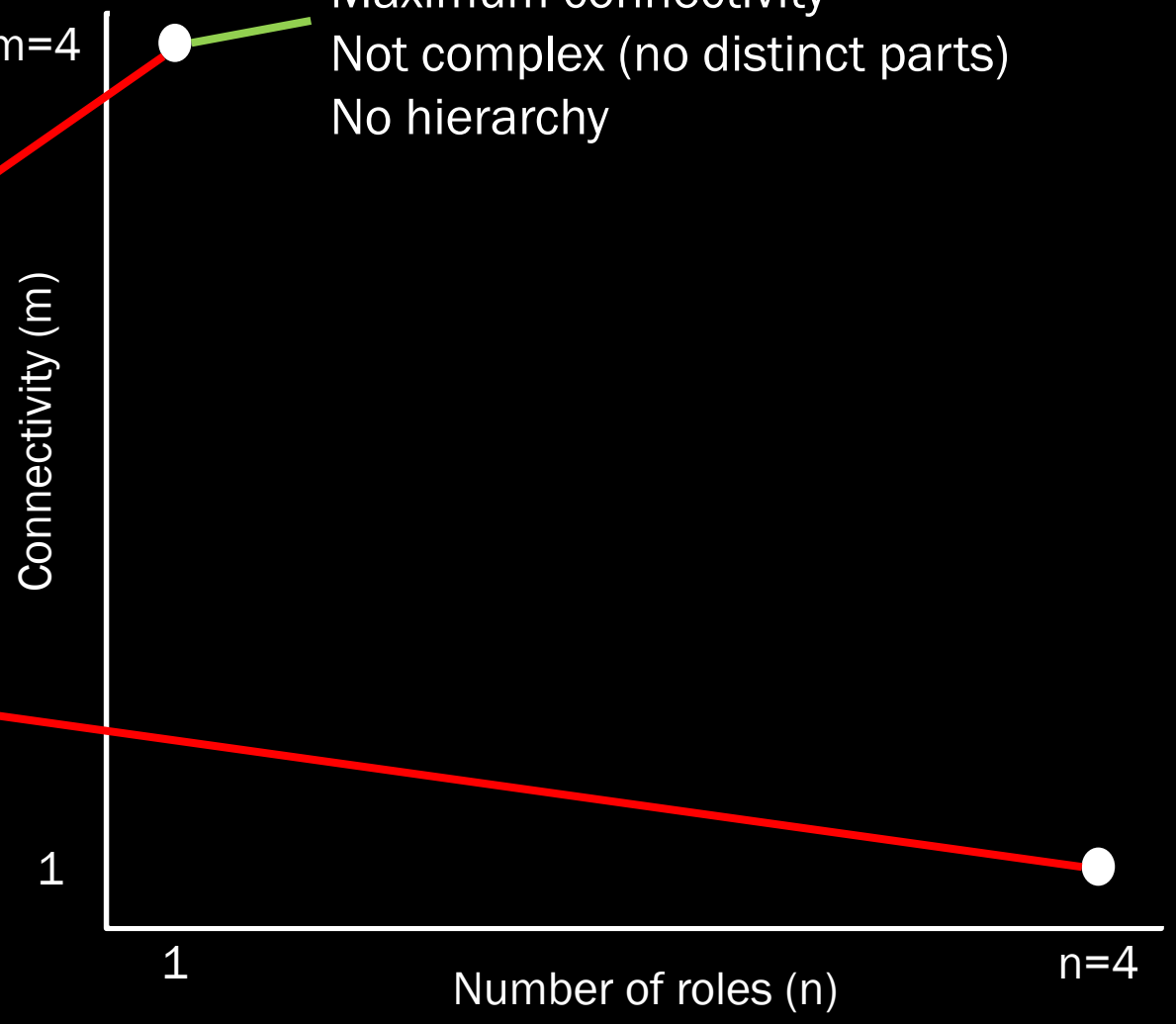
			1



Point of maximum information entropy
Maximum connectivity
Not complex (no distinct parts)
No hierarchy

There is a defined 'role-connectivity' space for networks

1/4	1/4	1/4	1/4
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1			
	1		
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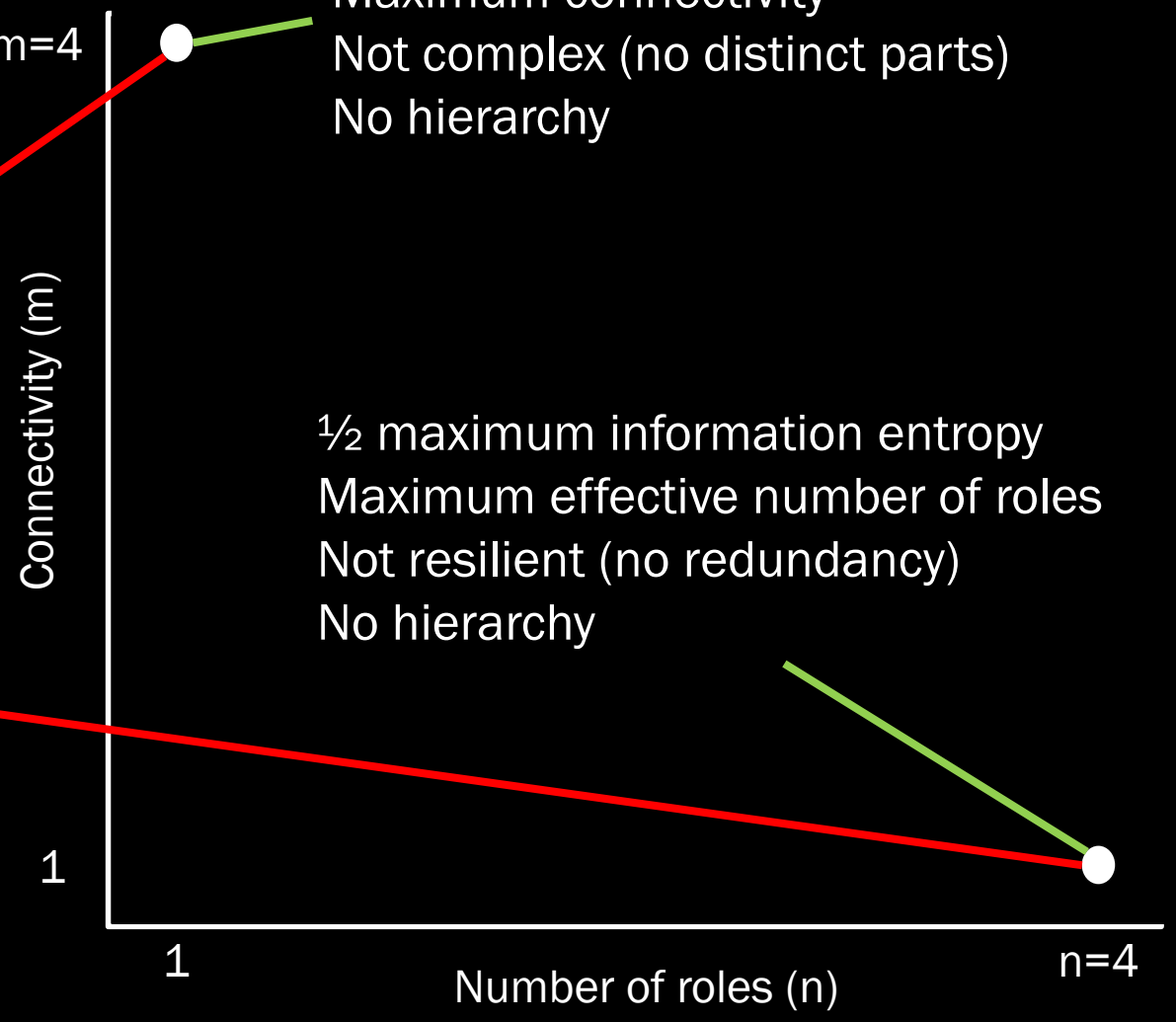
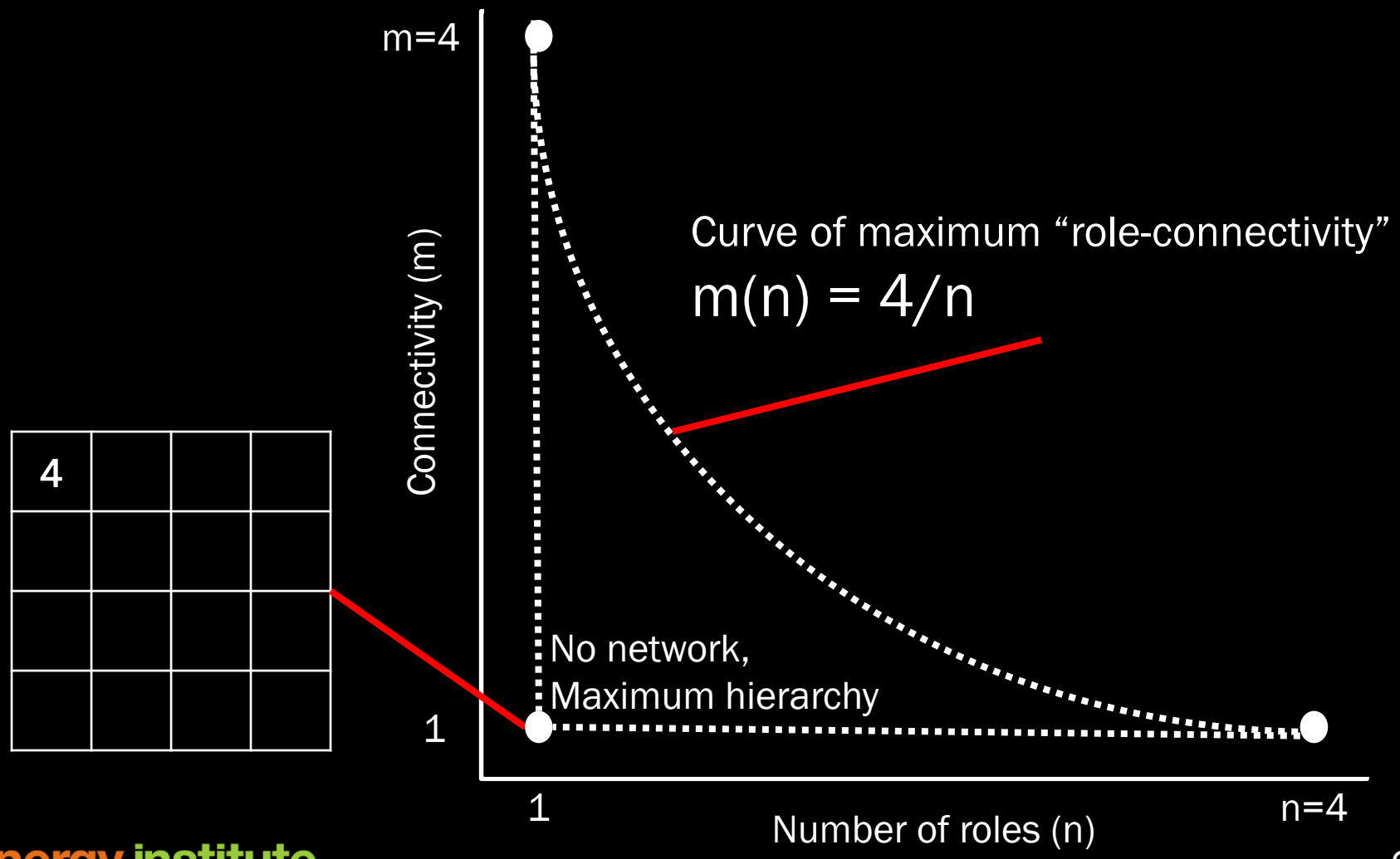


Point of maximum information entropy
Maximum connectivity
Not complex (no distinct parts)
No hierarchy

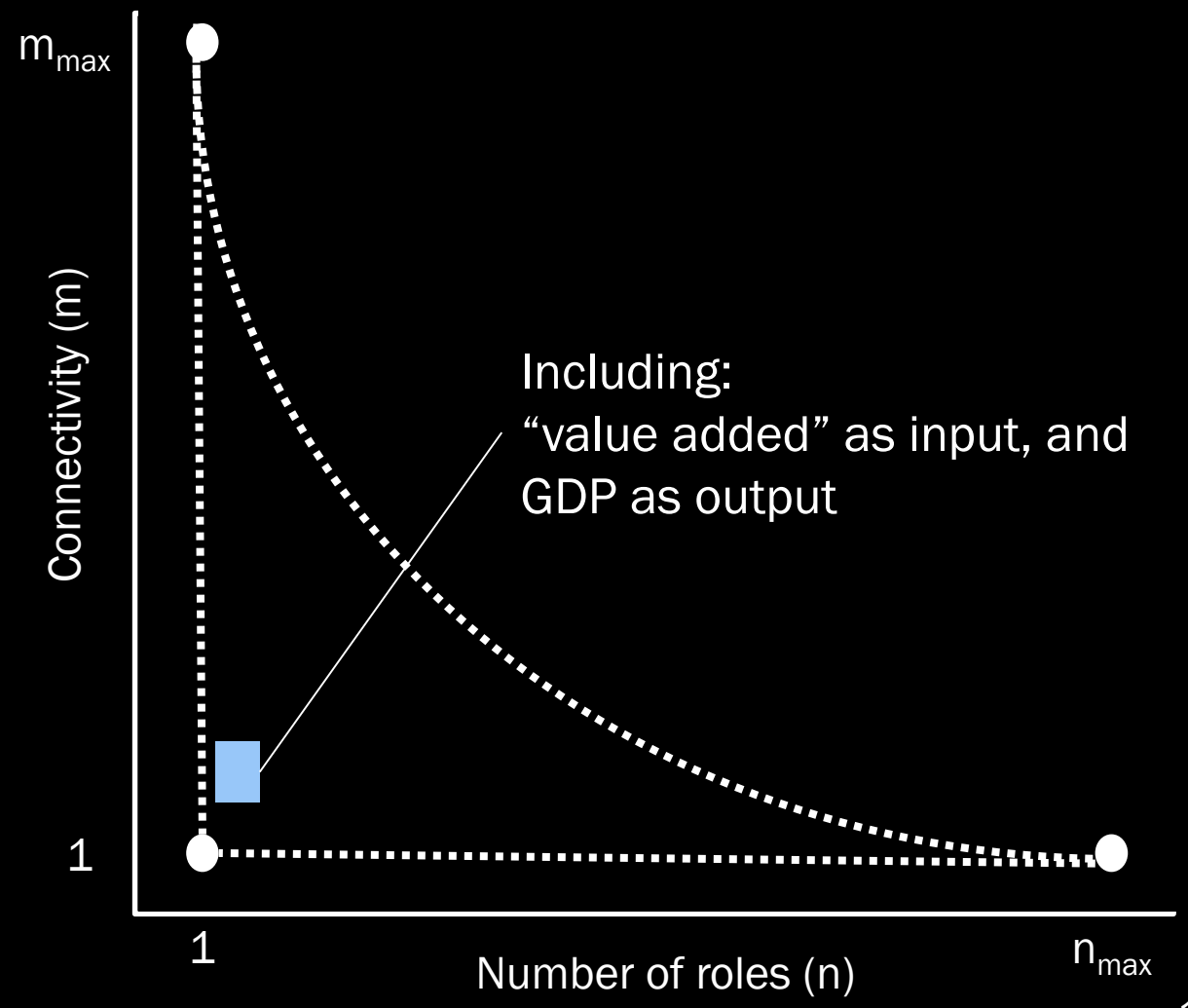
½ maximum information entropy
Maximum effective number of roles
Not resilient (no redundancy)
No hierarchy

There is a defined 'role-connectivity' space for networks

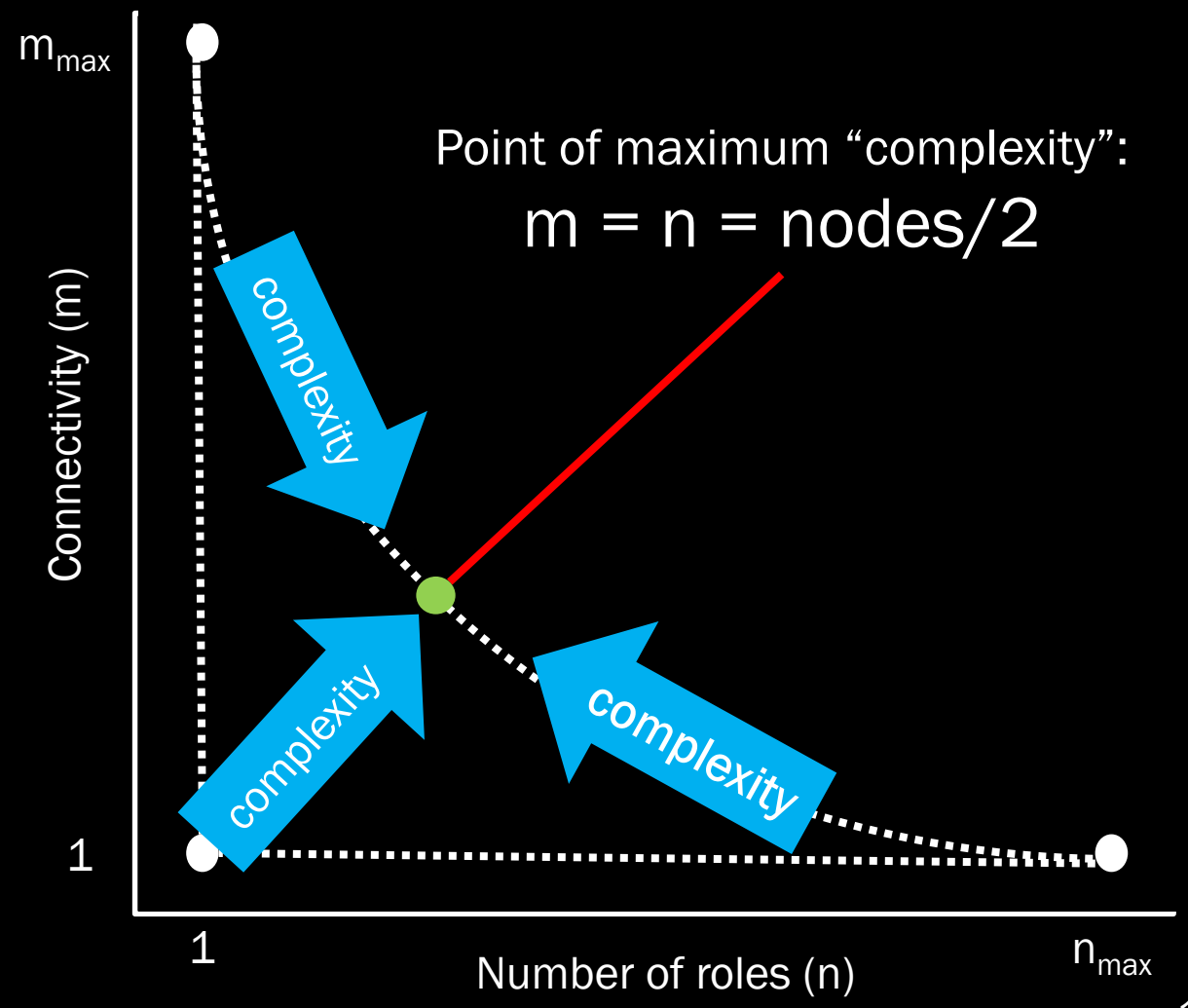


Data: U.S. Use tables reside at low connectivity and very low number of roles

- I-O tables from 1947 to 2012
  - Bureau of Economic Analysis
  - ~ every 5 years
  - Harmonized to 37 sectors each year to maintain consistency over time

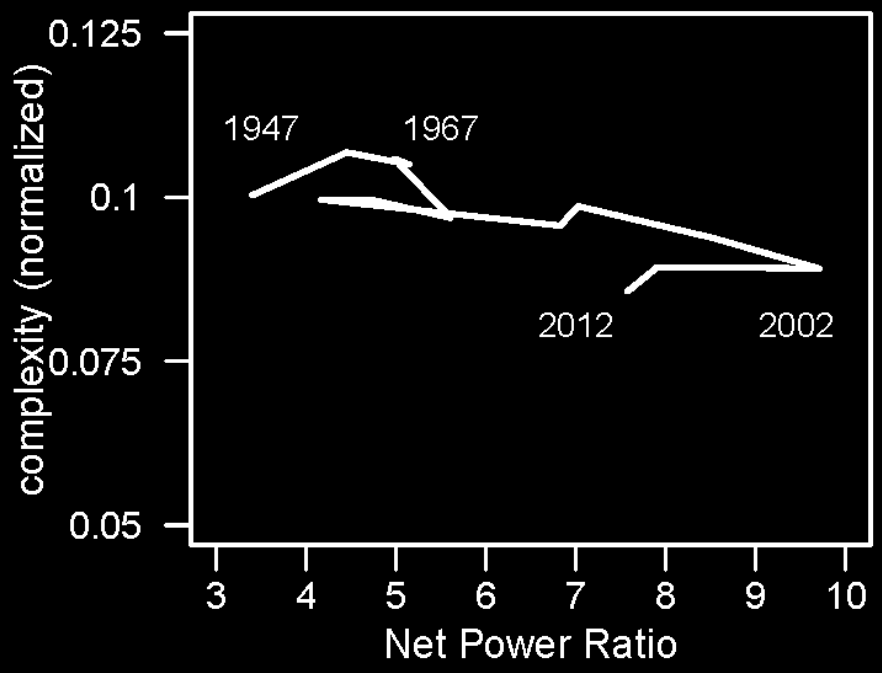


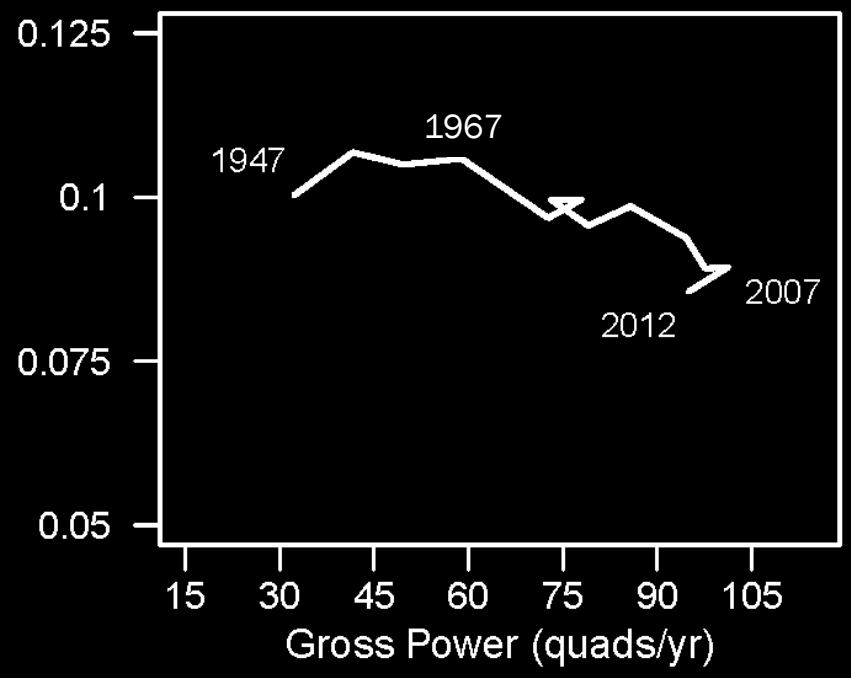
Here complexity is the nearness to the point of 'perfect balance' @ maximum 'role-connectivity' where *n = m = nodes/2*



U.S. Use Table complexity versus gross power and net power ratio (NPR),

NPR = GDP/Intermediate food and energy sector transactions





Including value added (input) and GDP (output)

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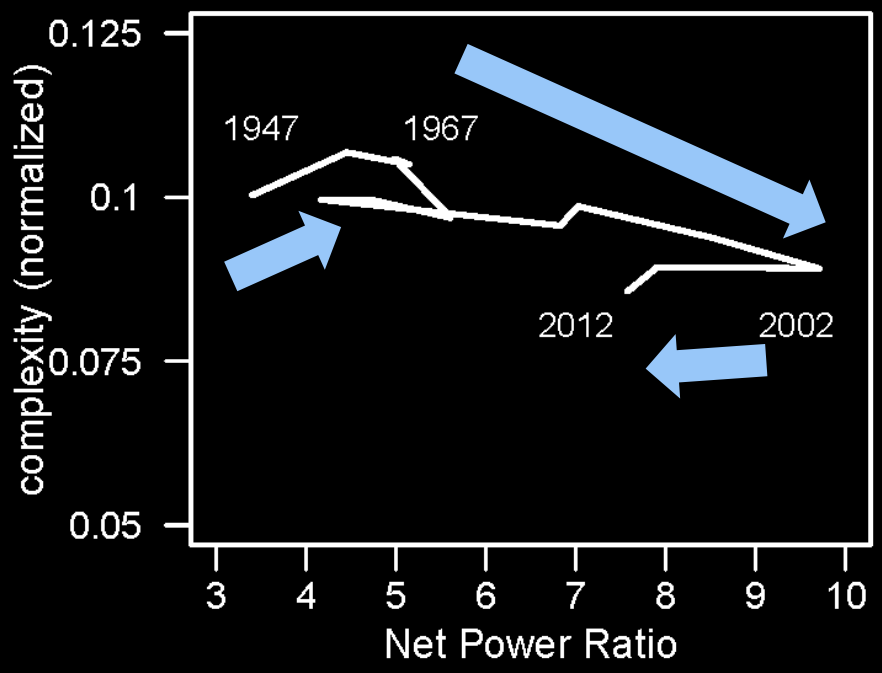
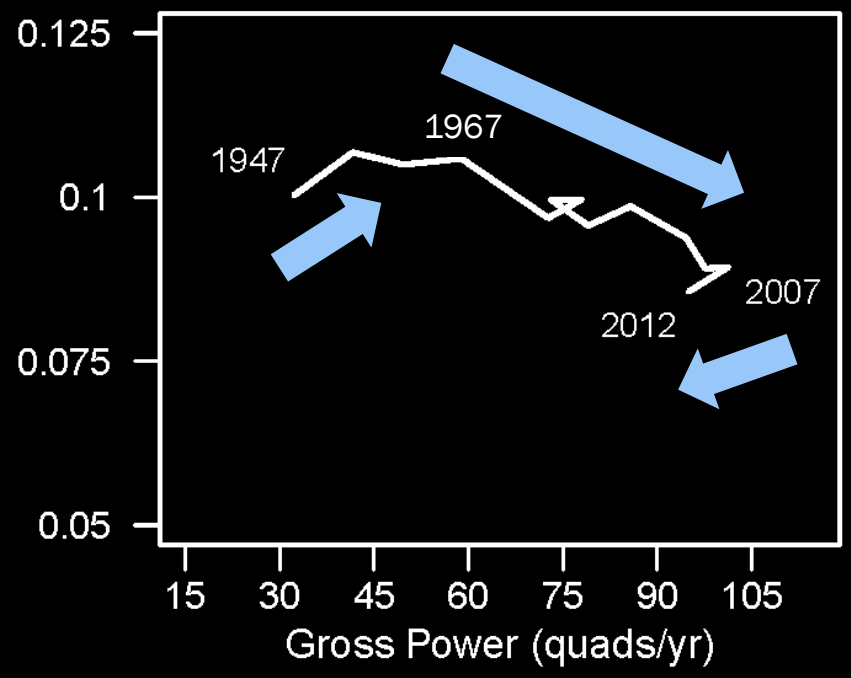
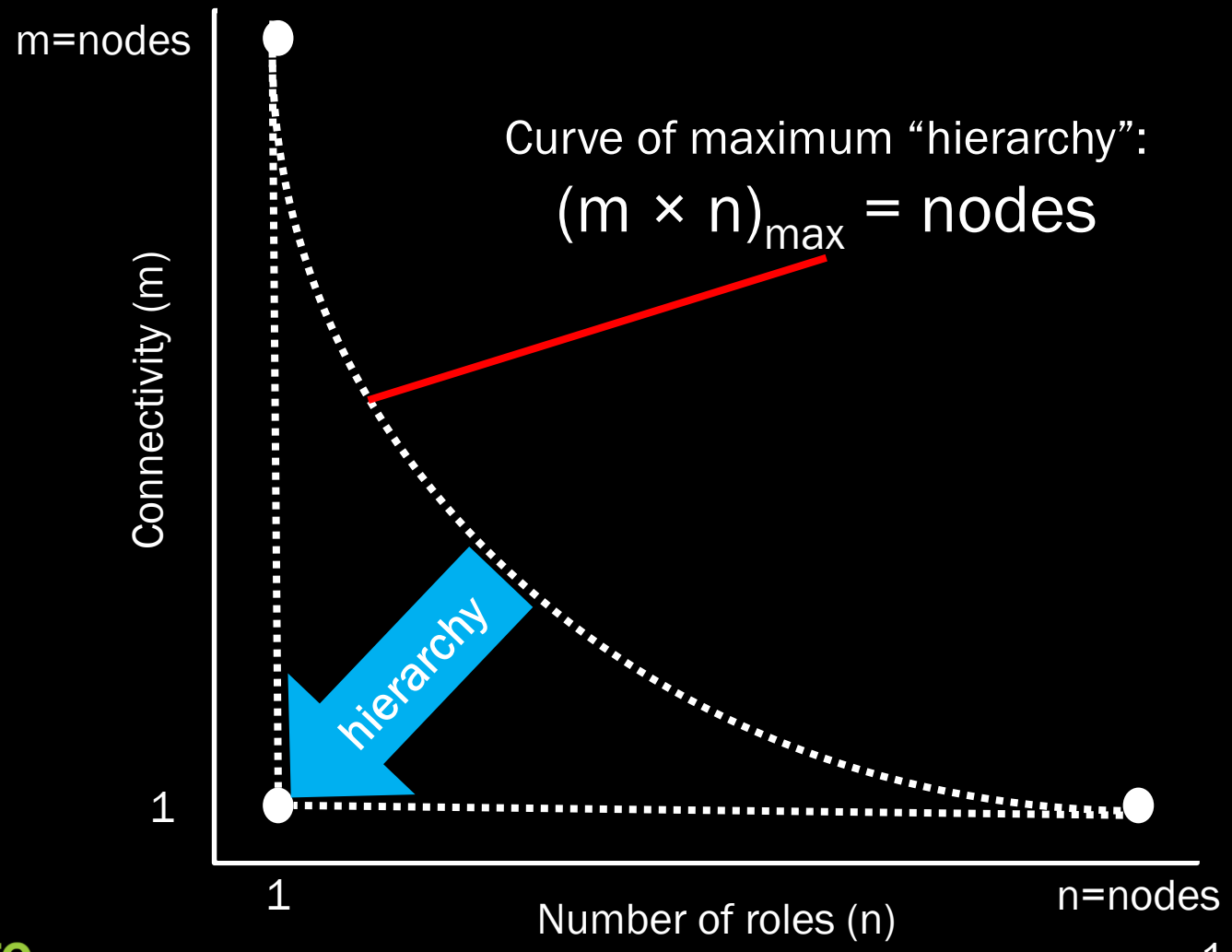




Including value added (input) and GDP (output)

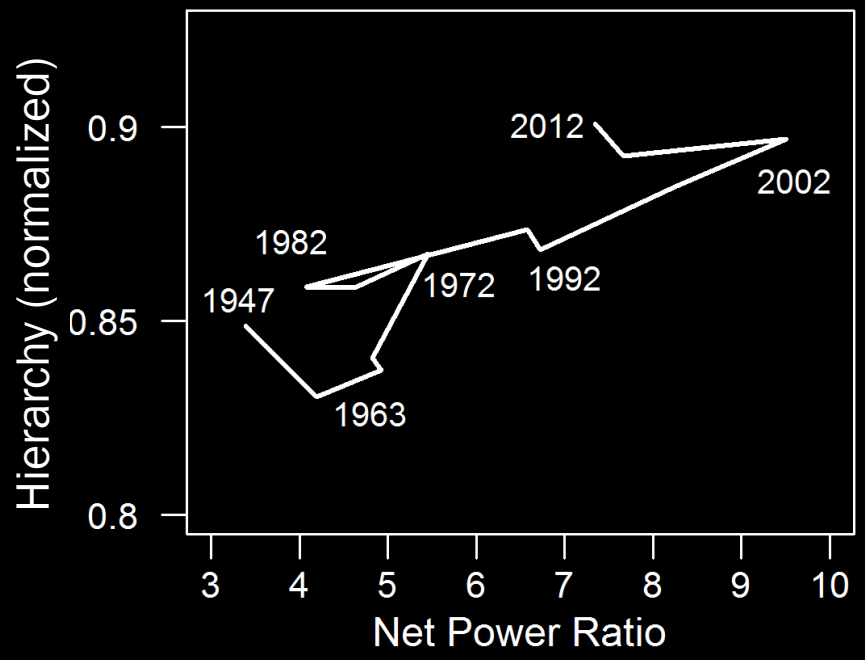
Here hierarchy is the distance from the curve of maximum 'role-connectivity' $= (n \times m)_{max} = nodes$

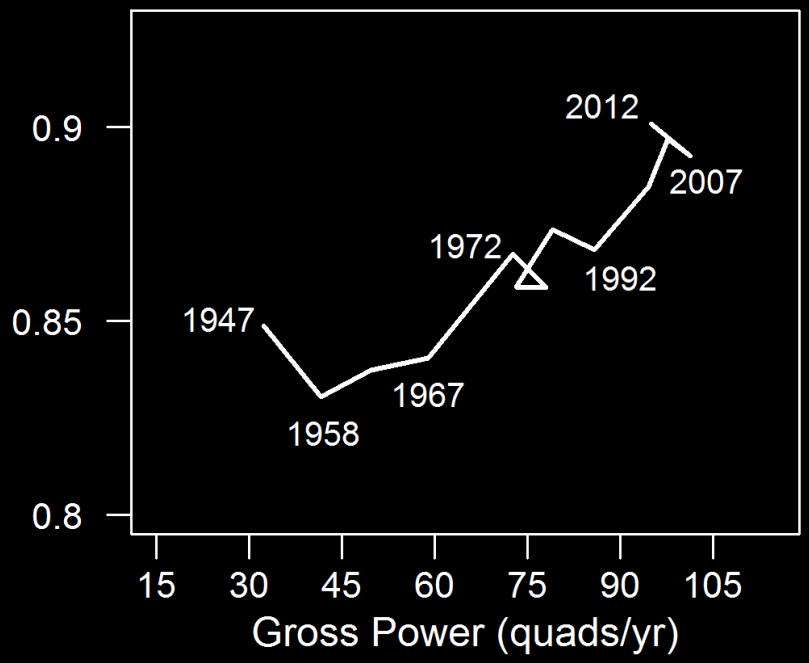


Hierarchy of U.S. Use I-O transactions has been increasing

(shown: intermediate I-O table w/ value added (input) and GDP (output))

NPR = GDP/Intermediate food and energy sector transactions





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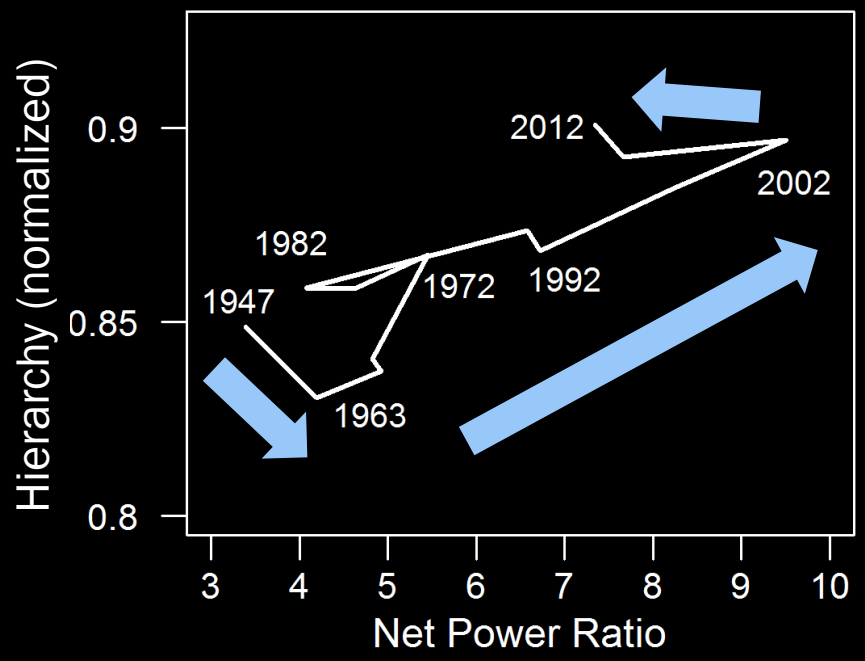

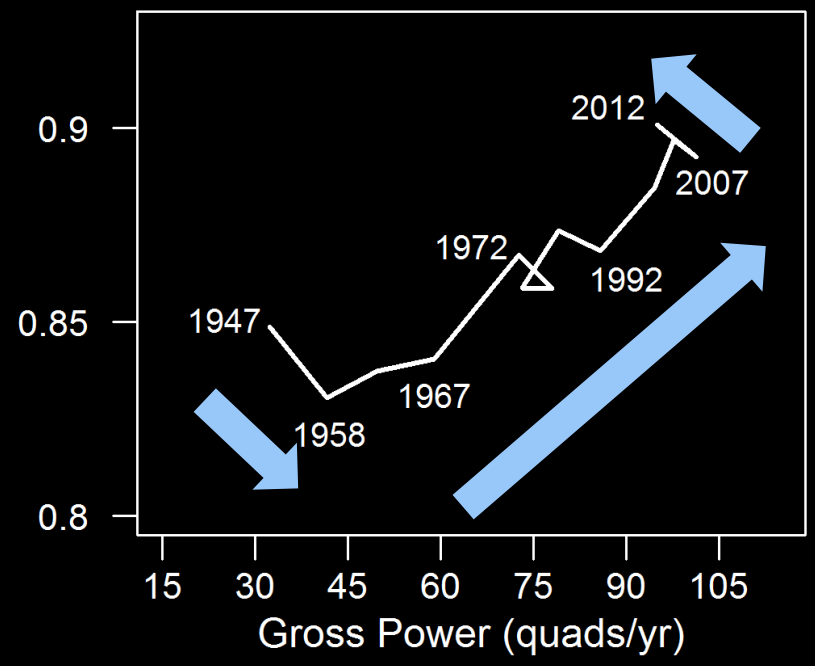

Conclusions: Generally support that less energy (and energy/capita) → less 'complexity,' more 'hierarchy'

- 'Complexity' of U.S. Use matrix decreasing since 1950s
- 'Hierarchy' is increasing overall since 1960s
- After 1960s energy/person was no longer increasing exponentially

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Extra

Here complexity (C) is the nearness to the point of 'perfect balance' @ maximum 'role-connectivity' where *n* = *m* = *nodes/2*

$$C = \text{nodes} - \left(\left| \text{nodes}/2 - n \right| + \left| \text{nodes}/2 - m \right| \right)$$

Complexity normalized to [0,1]

$$C_{norm} = \frac{C}{C_{\max}} = \frac{\text{nodes} - \left(\left| \text{nodes}/2 - n \right| + \left| \text{nodes}/2 - m \right| \right)}{\text{nodes}}$$

I define hiearchy (Hi) as the distance from the line of maximum

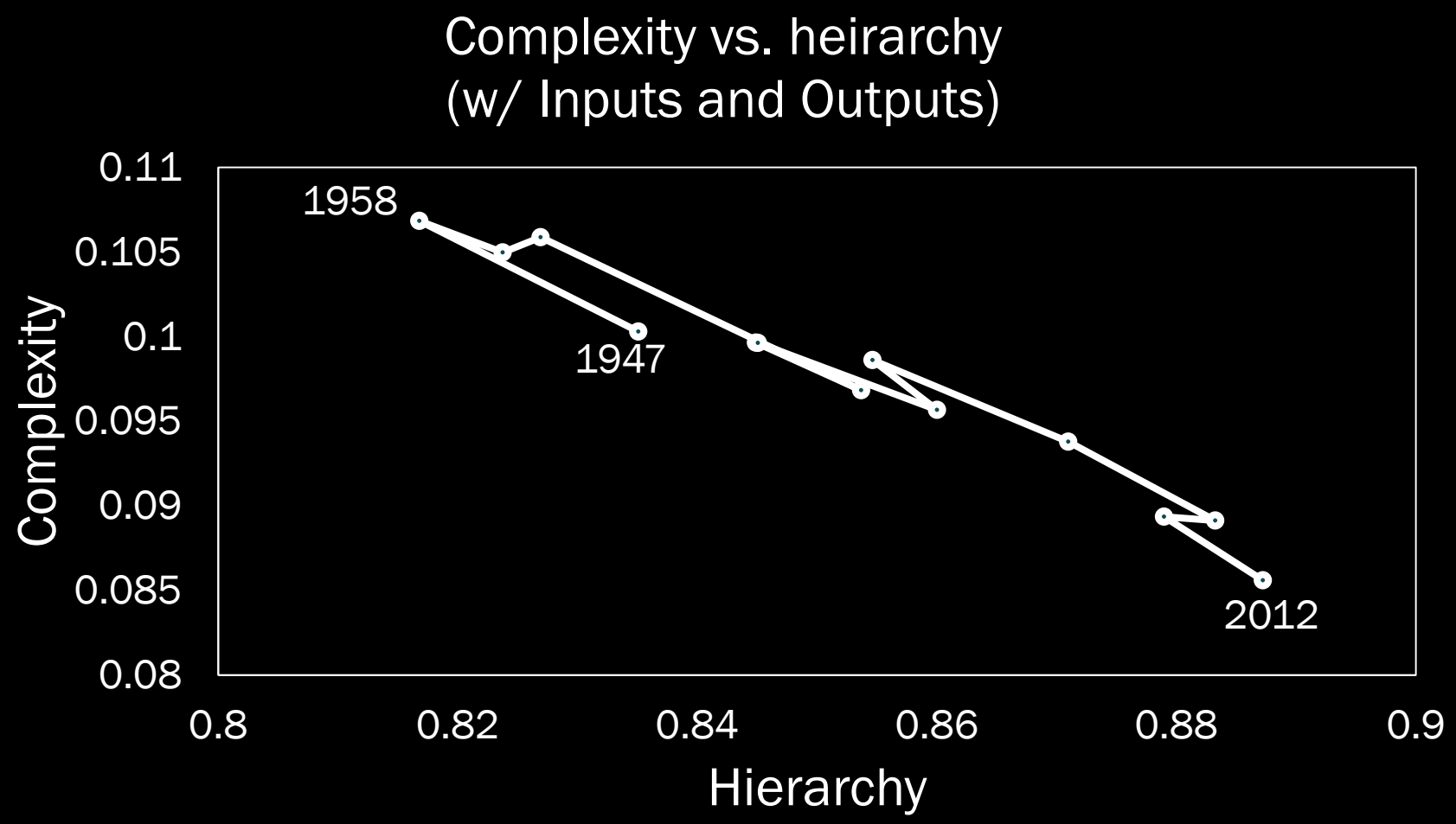
"role (n) × connectivity (m)" = *n*×*m*

$$Hi = 1 - \frac{n \times m}{(n \times m)_{\max}} = 1 - \frac{n \times m}{\text{number of nodes}}$$

Hierarchy normalized to [0,1]

$$Hi_{norm} = \frac{Hi}{Hi_{\max}} = \frac{1 - \frac{n \times m}{\text{nodes}}}{1 - \frac{1}{\text{nodes}}} = \frac{\text{nodes} - (n \times m)}{\text{nodes} - 1}$$

A tradeoff of complexity versus hierarchy



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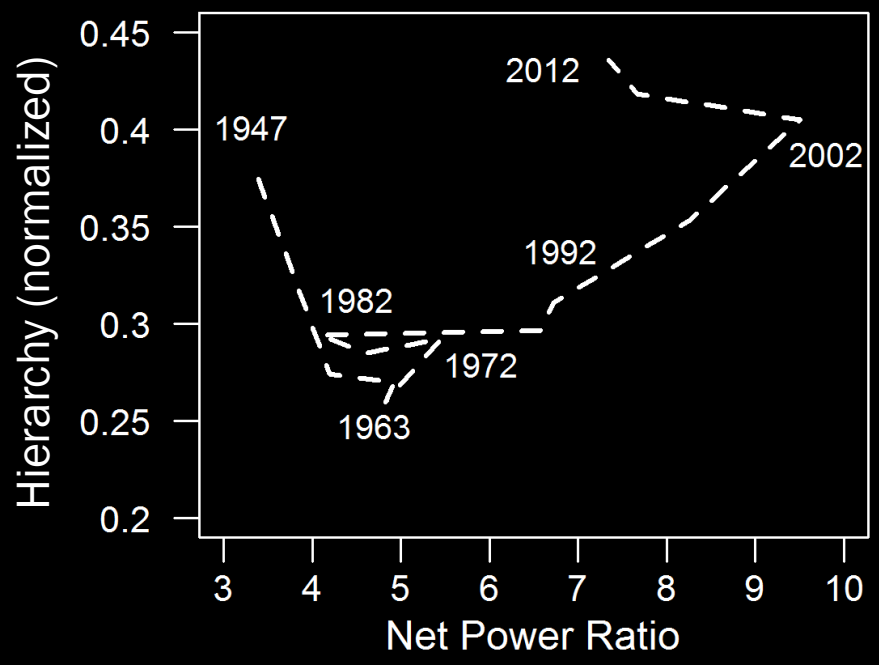
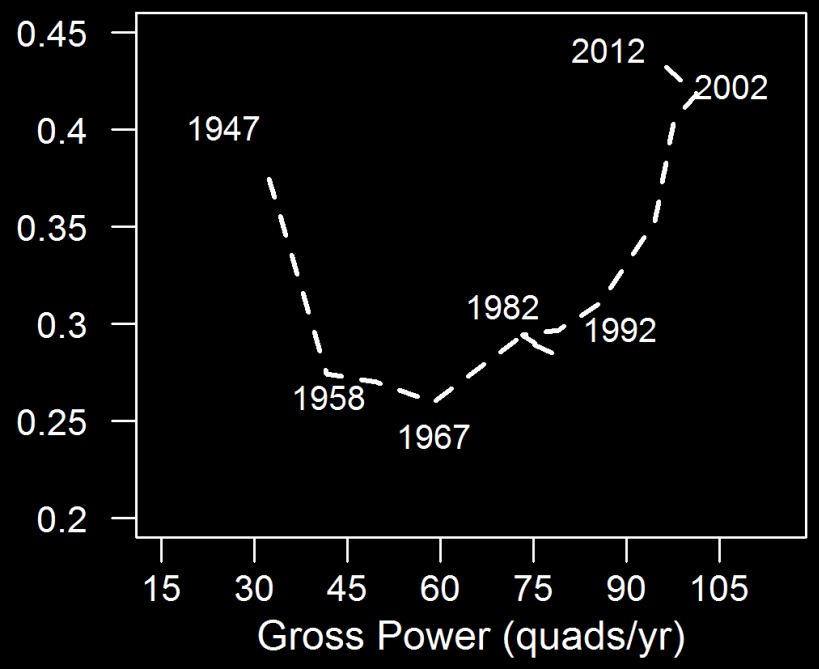


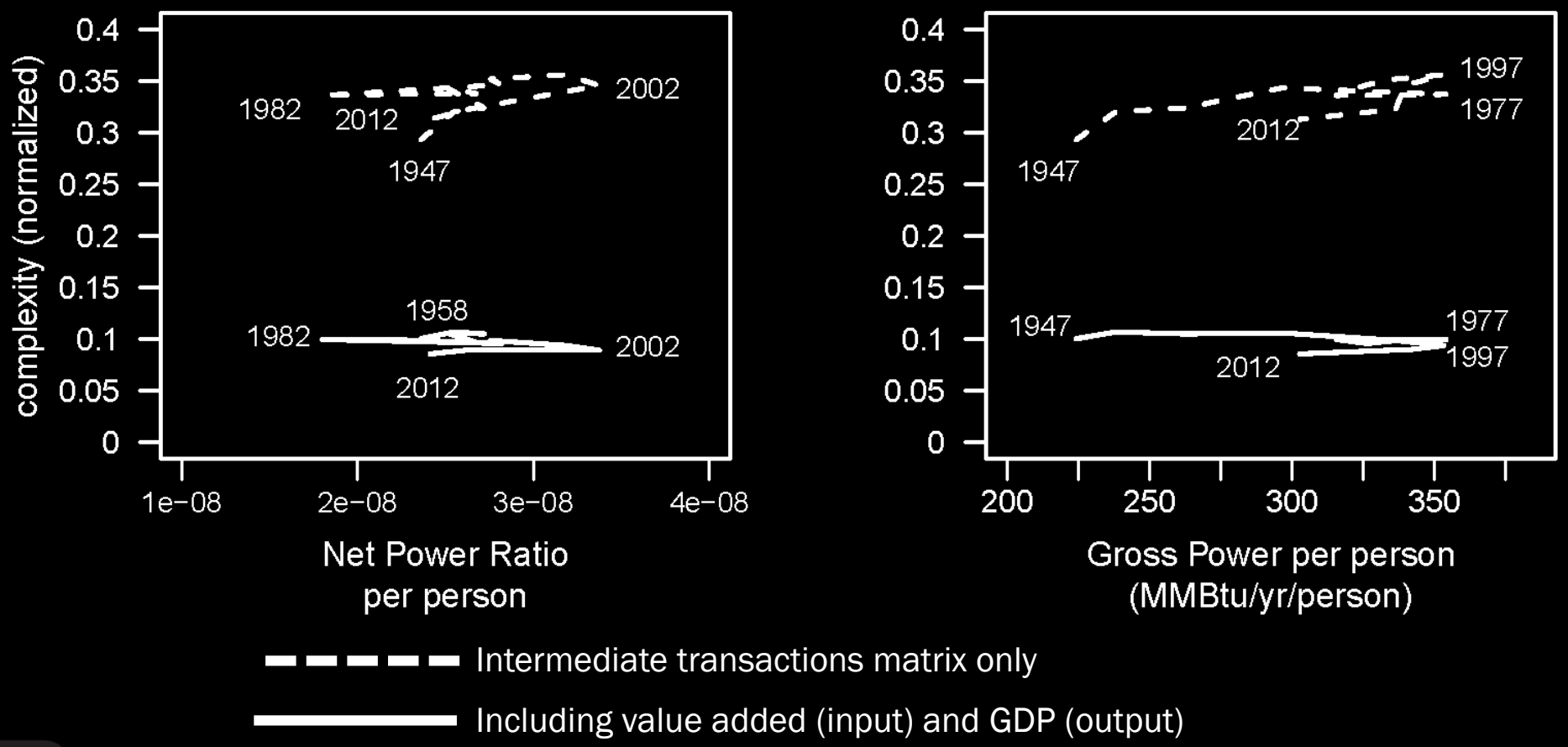


Conclusions: Generally support that less energy (and energy/capita) → less 'complexity,' more 'hierarchy'

- 'Complexity' trends for overall U.S. use matrix
  - Including inputs (wages, profits) and outputs (GDP)
    - Decreasing since 1950s
  - Intermediate matrix only
    - 1947-1997: increasing (food and energy getting cheaper)
    - 1997-2012: decreasing (food and energy getting more expensive)
- 'Hierarchy' is increasing overall since 1960s
  - After 1960s energy/person was no longer increasing exponentially

Per Person Graphics

U.S. Use Table complexity versus gross power and net power ratio (NPR) *per person*



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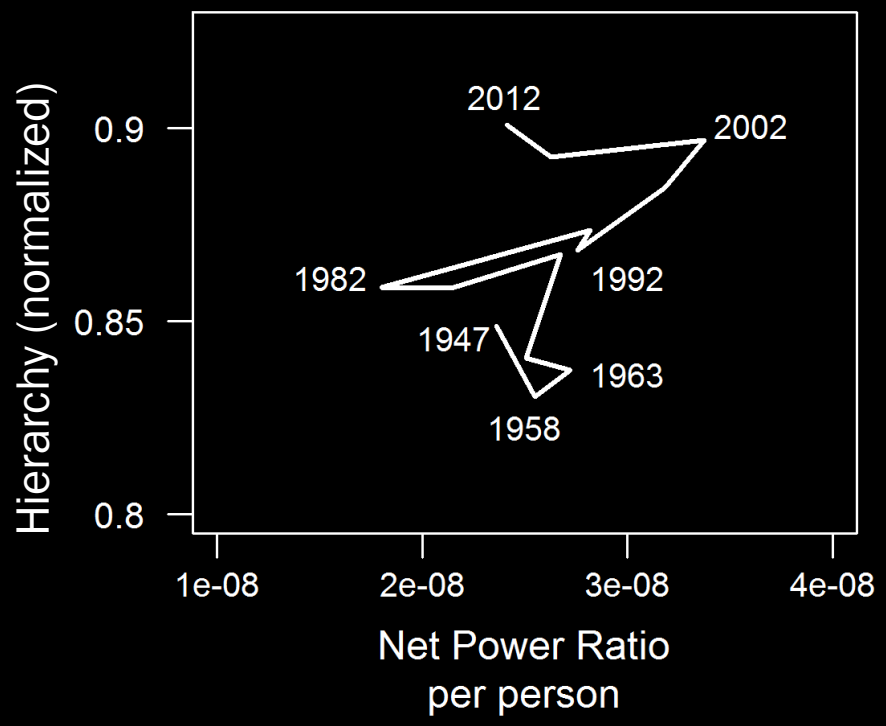

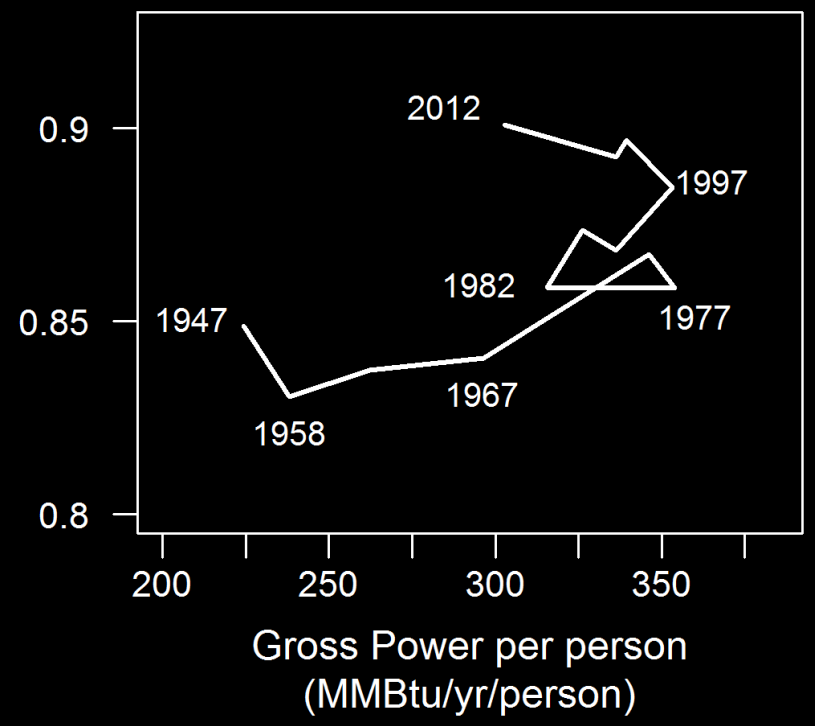

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