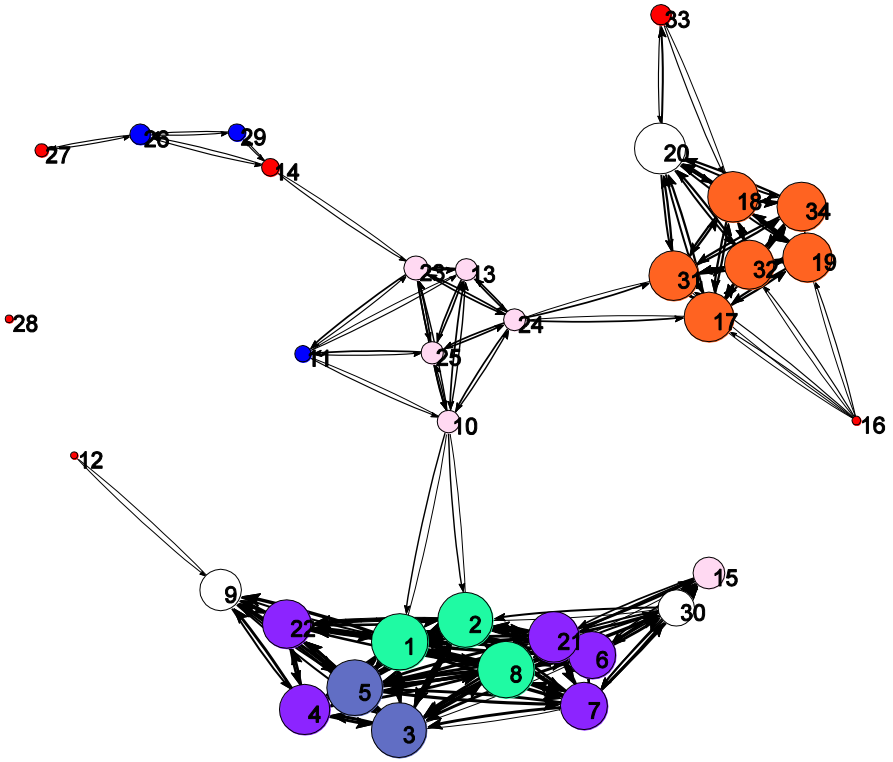
Imperial College London

Complexity & Networks

Complex Networks and Archaeology



Tim Evans
Theoretical Physics
and Complexity & Networks programme

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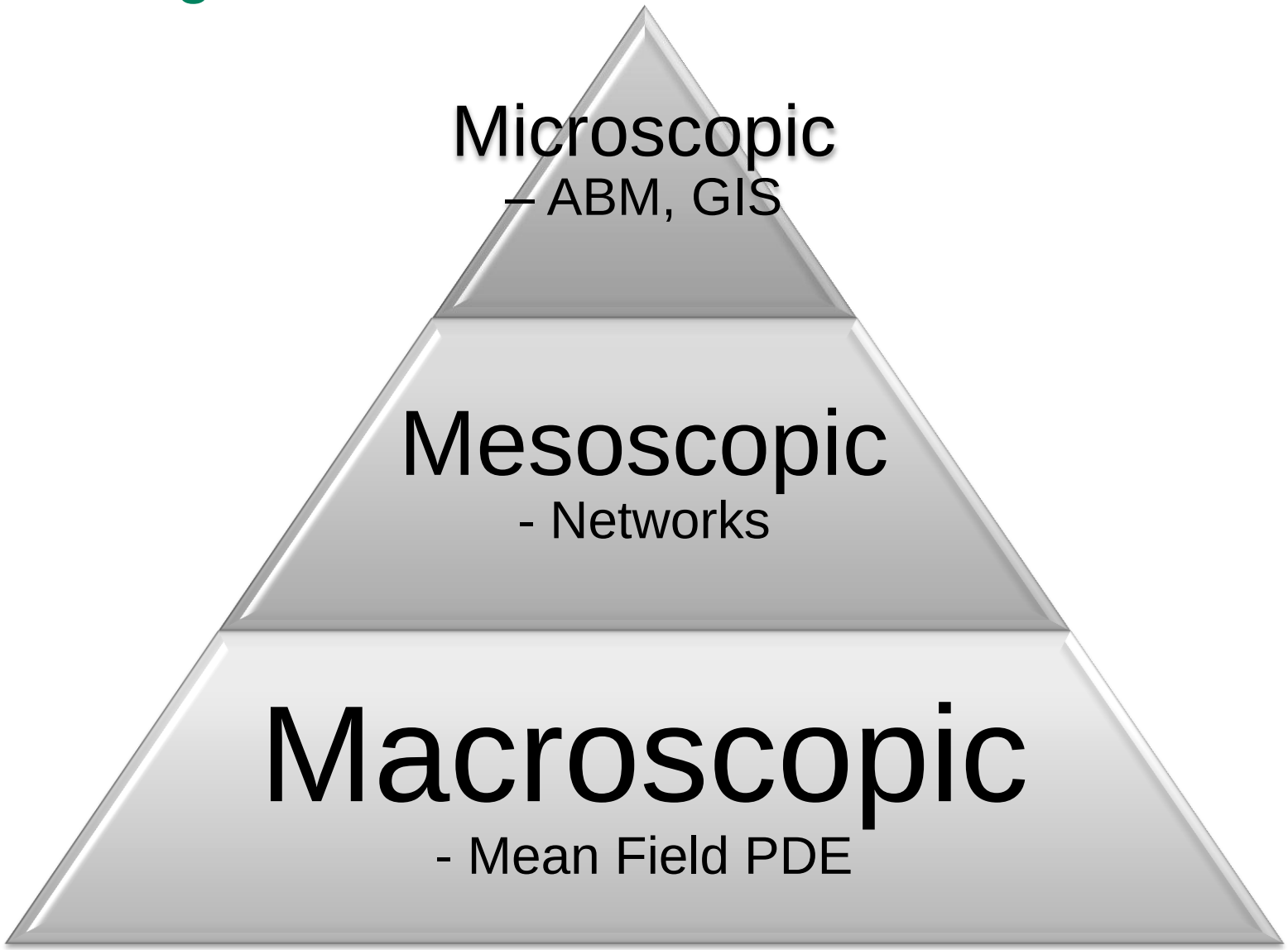
Maths Meets Myths Workshop, Coventry University, 25-26 July 2013

- General Approach to Modelling in Archaeology
- Geography and Zones of Control
- Geography and Interactions
- Our Model - **`ariadne`**
- Summary

Modelling Scales

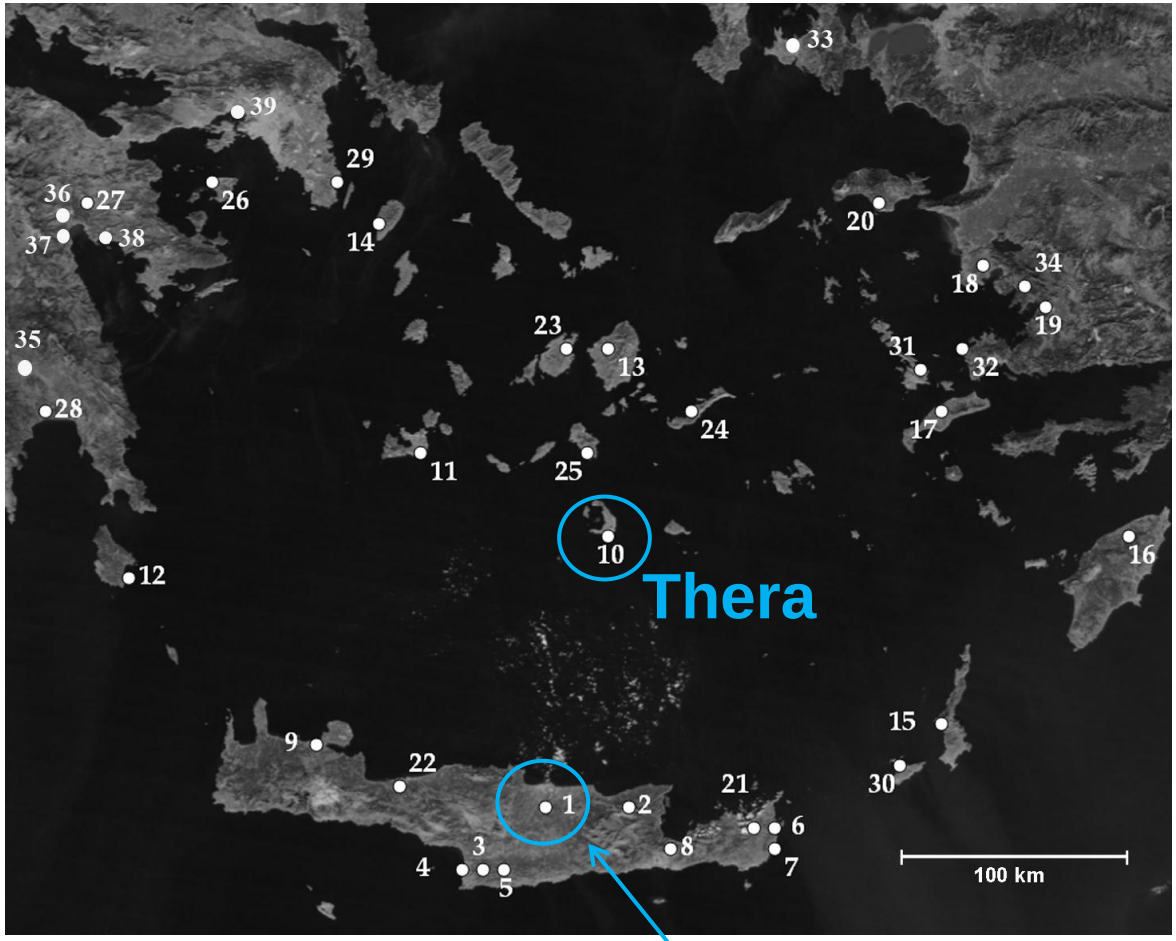


Site-Site Interactions

- Archaeology can be "Site Centric"
  - Regional and global interactions hard to consider
- Networks emphasise interactions

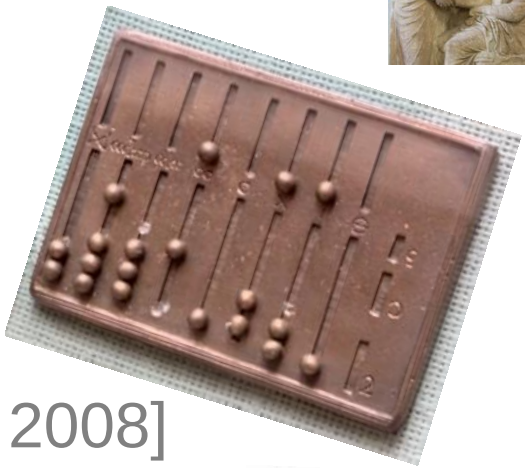
The Problem

Given the locations of sites, what were their interactions?

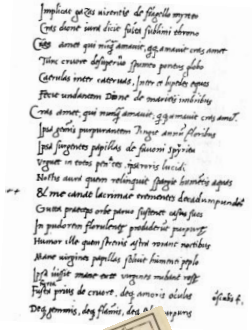


Major sites of the Minoan Aegean

Deducing Interactions



- Texts
  - Appearance of sites in text [Isaksen 2006; “Anskar’s Vita” Sindbæk 2008]
- Artefact counts
  - Measure similarity of sites through counts [Terrell 2010; Sindbæk 2007]
- Geography
  - Direct from geography [Terrell 1977; Irwin 1983; Hage & Harary 1991; Broodbank 2000; Knappett et al. 2006+; Collar 2007; Bevan 2010]



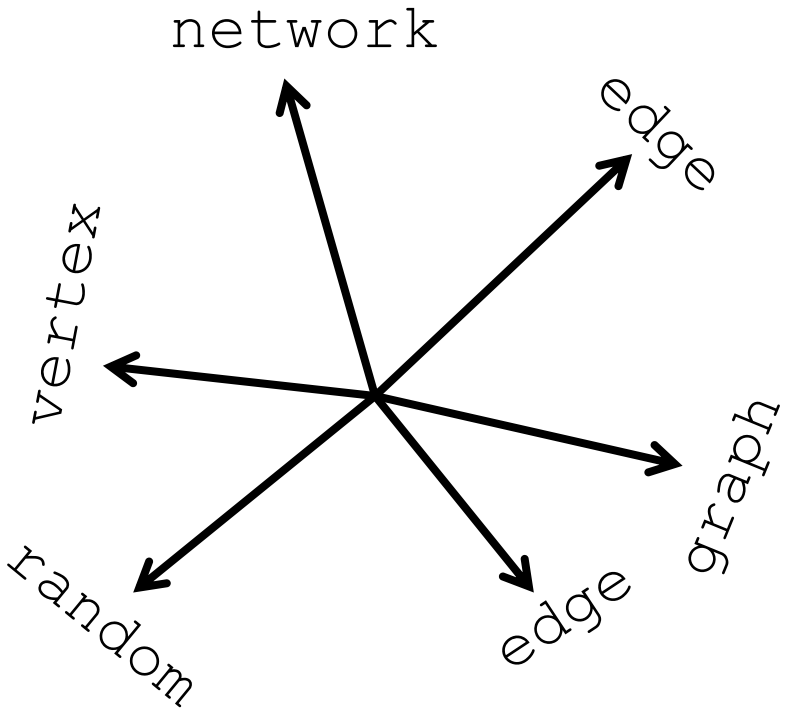
Deducing Interactions

- Texts
- Artefact counts
- Interactions here deduced from geography

Different Spaces

- We work with two-dimensional geographical space

- All ideas can be applied to artefact spaces
  e.g. word frequency space for text similarities



Different Distances

- Physical Distances
  - As the crow lies
  - Shortest route in km
  - Quickest time
  - Lowest costs
  - ...

- Ranked distances
  - Nearest neighbour, second nearest neighbour, etc

Ranked distances

- Used in **PPA** (Proximal Point Analysis)
  - a more sophisticated version in the **Intervening Opportunities model** [Stouffer 1940]
- Connect to potential targets in the order of proximity irrespective of physical distance
  - closest first,
    next closest second,
    etc

e.g. Will prefer to visit nearest hospital in an emergency

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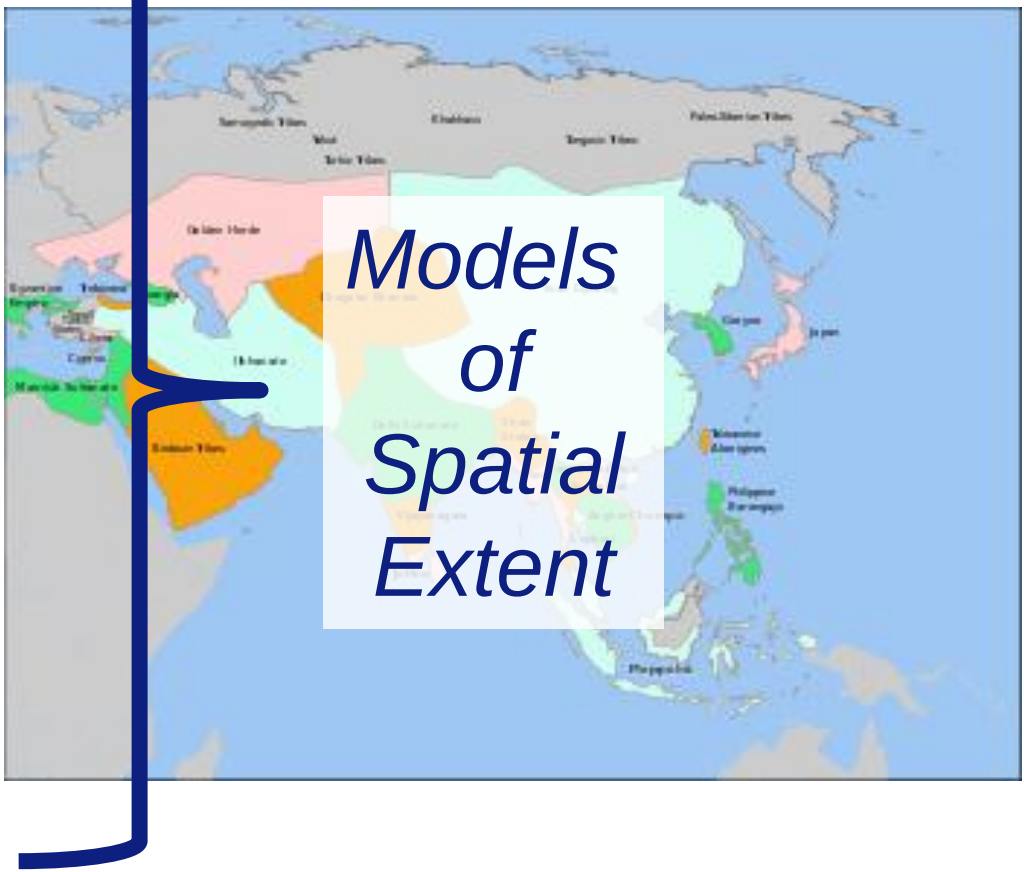
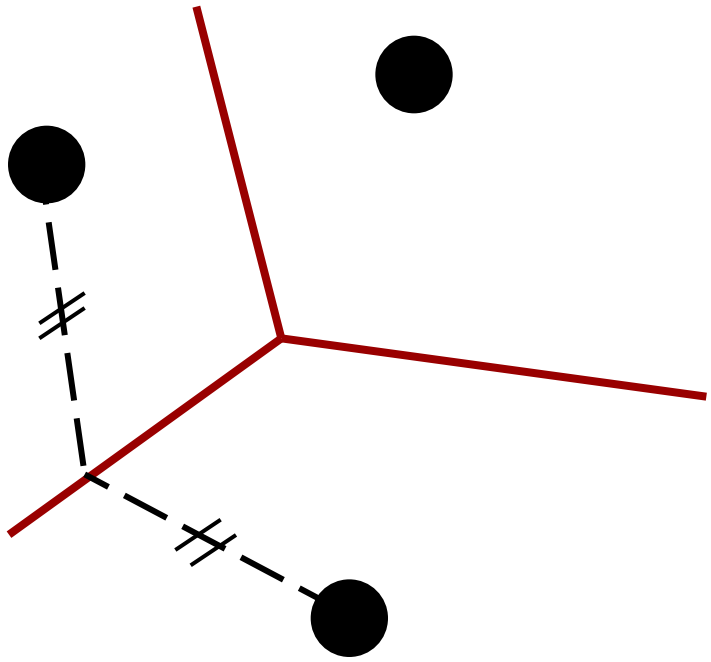
Geography and Zones of Control

- Thiessen Polygons (Voronoi Diagrams)
  - equal site sizes
- XTent model [Renfrew and Level 1979]
  - Theissen with variable site sizes
- Rihll & Wilson model [1987,1991]



Theissen Polygons (Voronoi Tesselation)

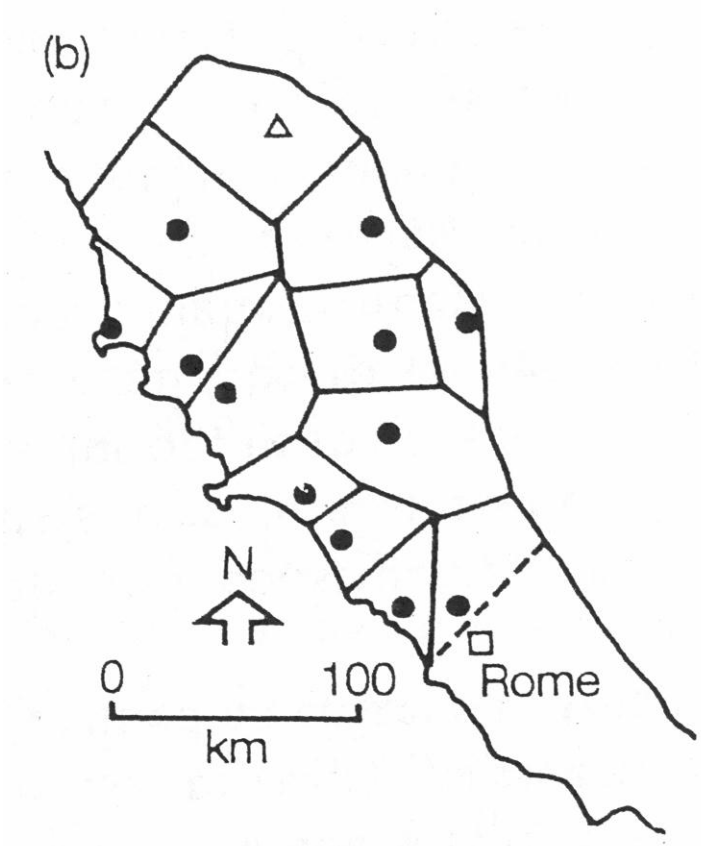
- Boundaries = Midpoint between nearest sites
- All sites equal



Theissen Polygon Example

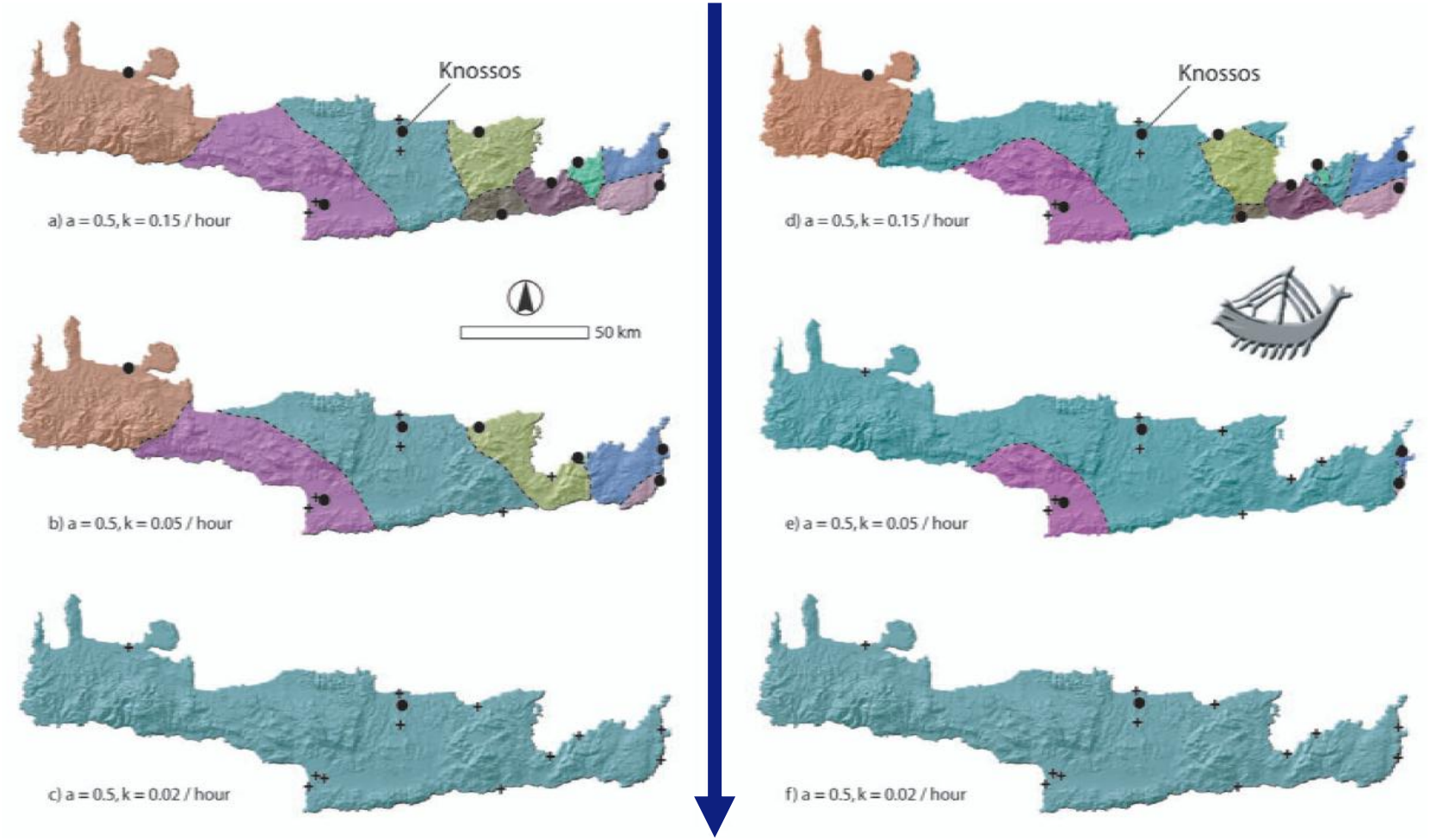
12 Etrurian Cities

[Renfrew 1975]



Xtent Model Neopalatial Crete
(~1750BC - ~1500BC)

[Bevan 2010]



On foot

By sea or land

Increasing distance

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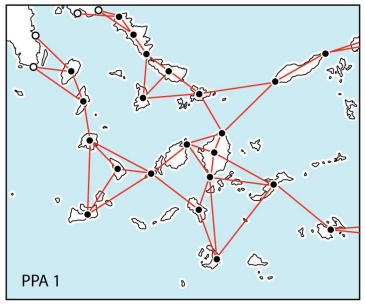
PPA - Proximal Point Analysis

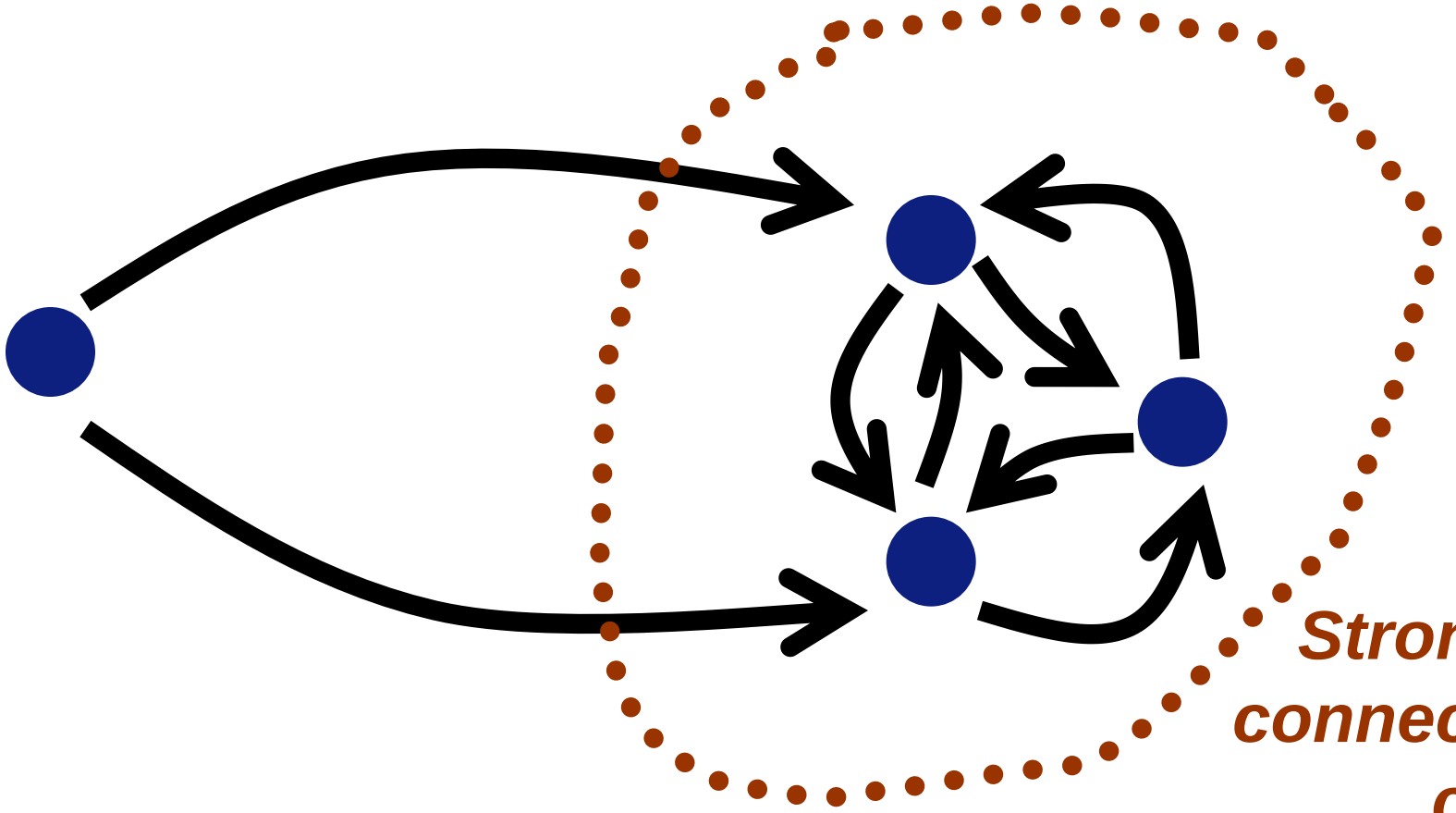


- Equal sized sites or size ignored
- Sites connect to ***k*** nearest neighbours
- Analyse graph
  - Often without directions on edges
  - Sometimes only local measures used *e.g. Degree*
  - Sometimes global measures used
    e.g. ranking, centrality, betweenness

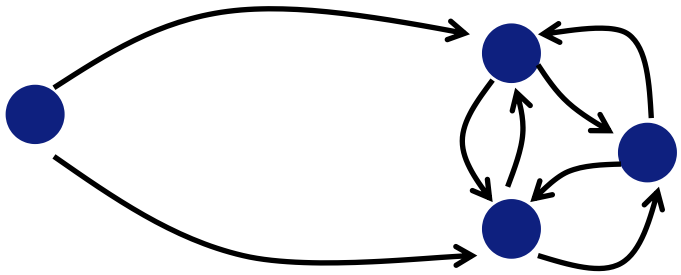
Examples: Terrell 1977; Irwin 1983; Hage & Harary 1991; Broodbank 2000; Collar 2007

PPA Example

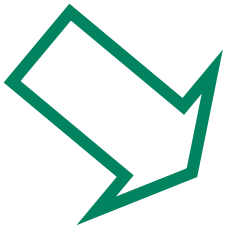
Connect each site to its ***k=2*** nearest neighbours

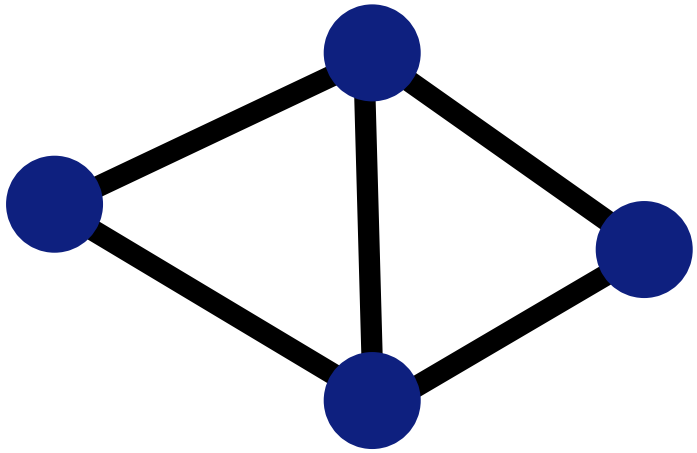


PPA Example



Ignore direction





- All edges equal
- Network now simply connected

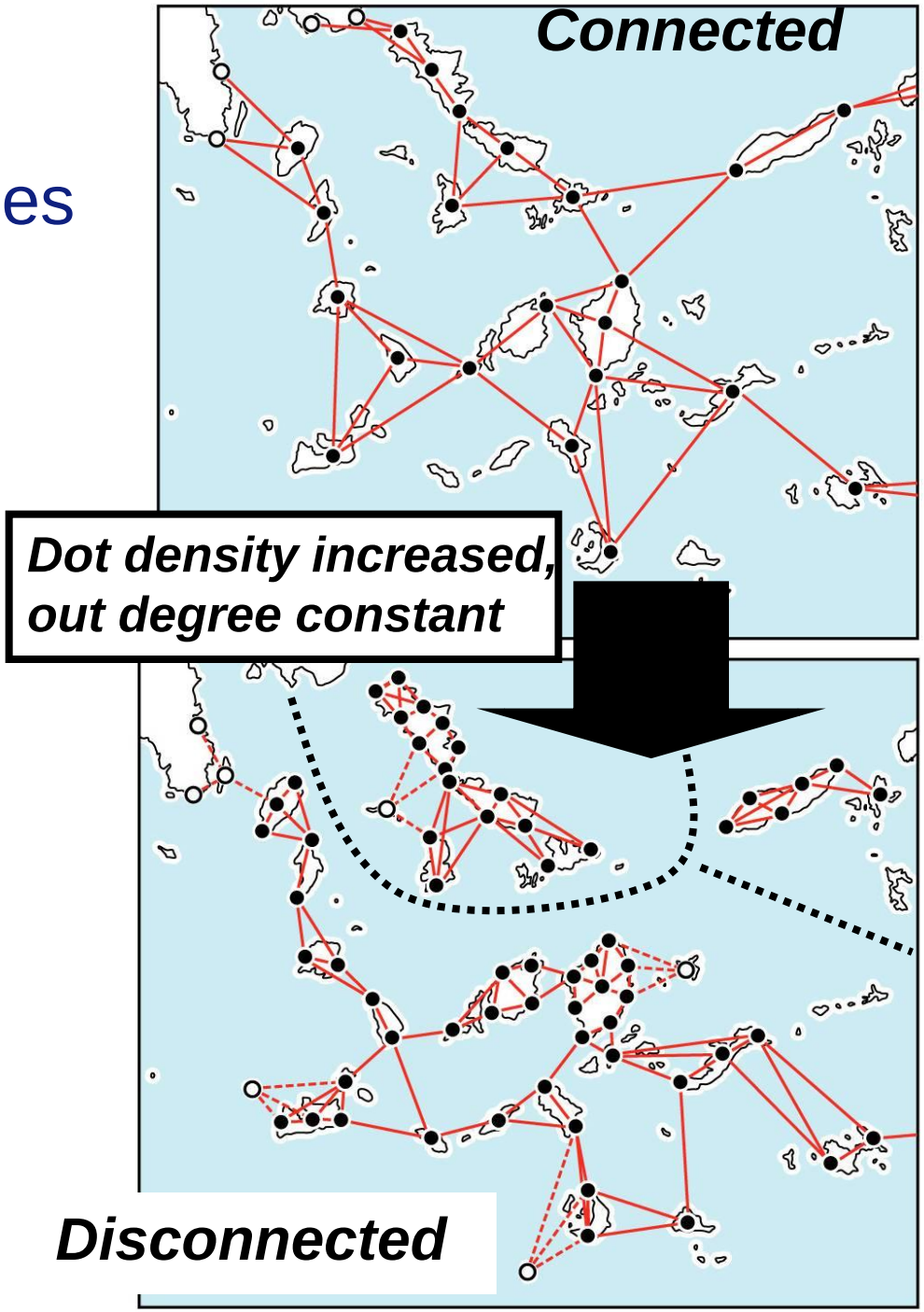
Broodbank PPA

- Early Bronze Age Cyclades
- Population = # vertices

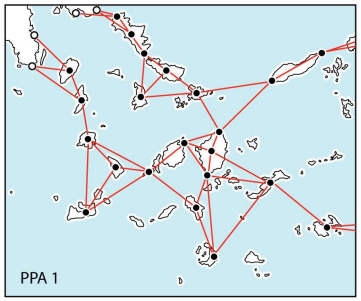
⇒Low density = connected graph

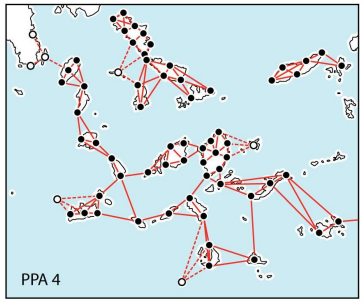
⇒High density = disconnected graph, clusters on large islands

[Broodbank 2000]



Broodbank PPA (2)





- EBA Cyclades (Early Bronze Age)
  - Settlements similar size
  - rowing ~ 10km daily

⇒ PPA appropriate

- More analysis is possible
  but perhaps not useful for such a `simple' era?
  e.g. use inherent directionality of edges

Gravity Models

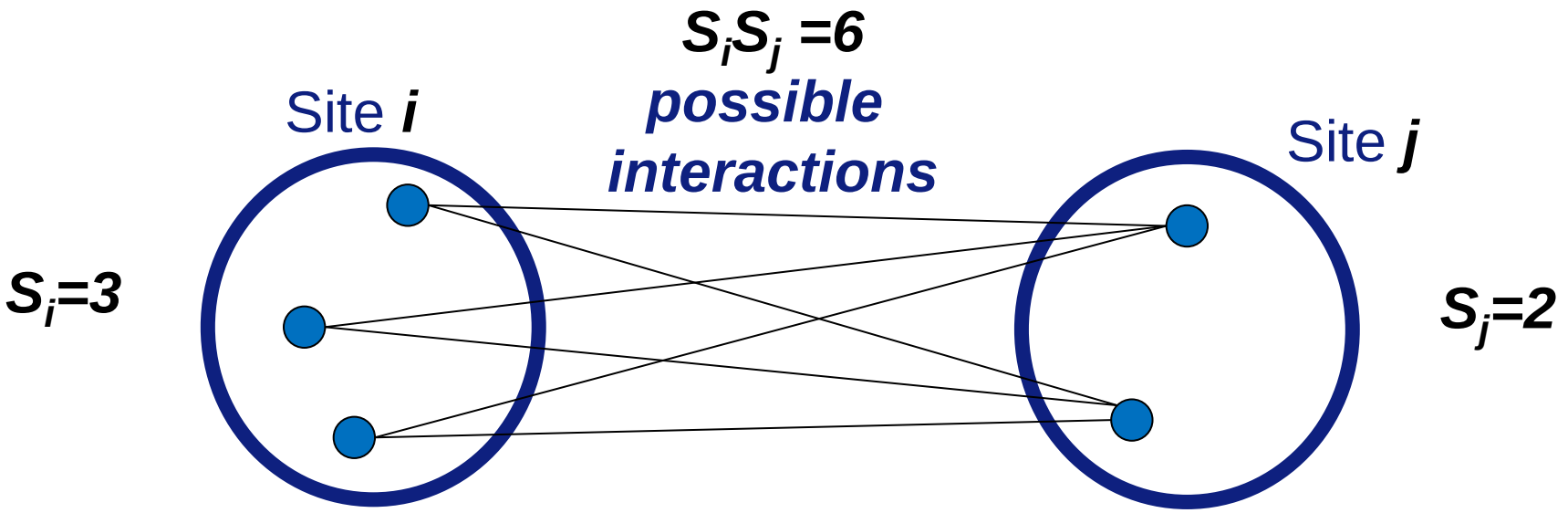
- Models of modern transport systems
  - "Applications to traffic engineering of the law of retail gravitation" [Casey 1955]

- Cost-Benefit viewpoint
  - All trips equally likely subject to constraint on total ***"cost"***
  - Maximum Entropy [Wilson, 1967]
  - Almost **all models** fit into this framework

Gravity Models & Number of Interactions

With no constraints, all trips equally easy, expect the flow F_{ij} from site i size S_i to site j size S_j to be

$$F_{ij} = S_i S_j$$



Cost constraint – Simple Gravity Models

Flow F_{ij} from site i size S_i to site j size S_j is

- Cost $c_{ij} = d_{ij}$
  $\Rightarrow$ exponential fall off

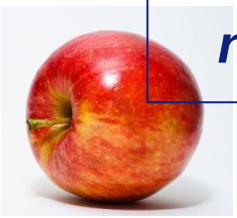
$$F_{ij} = S_i S_j \exp\left(-\gamma d_{ij}\right)$$

- Cost $c_{ij} = \ln(d_{ij})$
  $\Rightarrow$ power law fall off

$$F_{ij} = \frac{S_i S_j}{\left(d_{ij}\right)^{\gamma}}$$

- Total travel costs $\leftrightarrow \gamma$

Similar to Newton's law of gravity hence model's name



Beyond these archaeological models

- Models deterministic – one answer
- Site sizes and interactions never both *variable* and *interlinked*
  - *Not all sites are equal*
  - *Not all edges are equal*
- Surely the regional network influences the sizes of sites *and* the site sizes determine the nature of the network?

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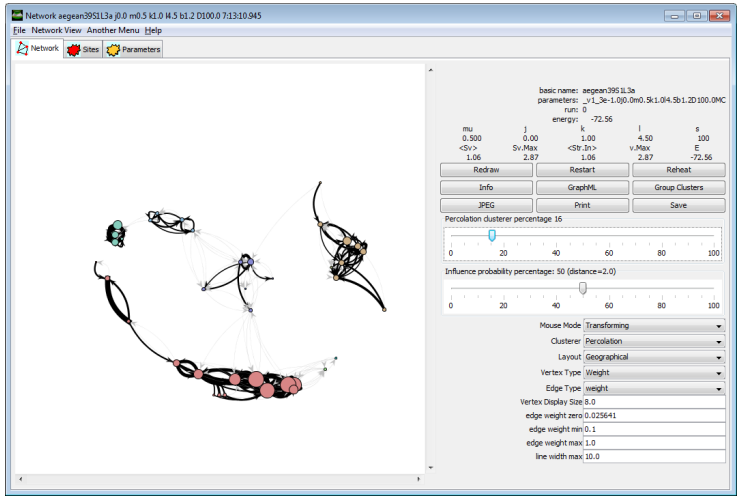
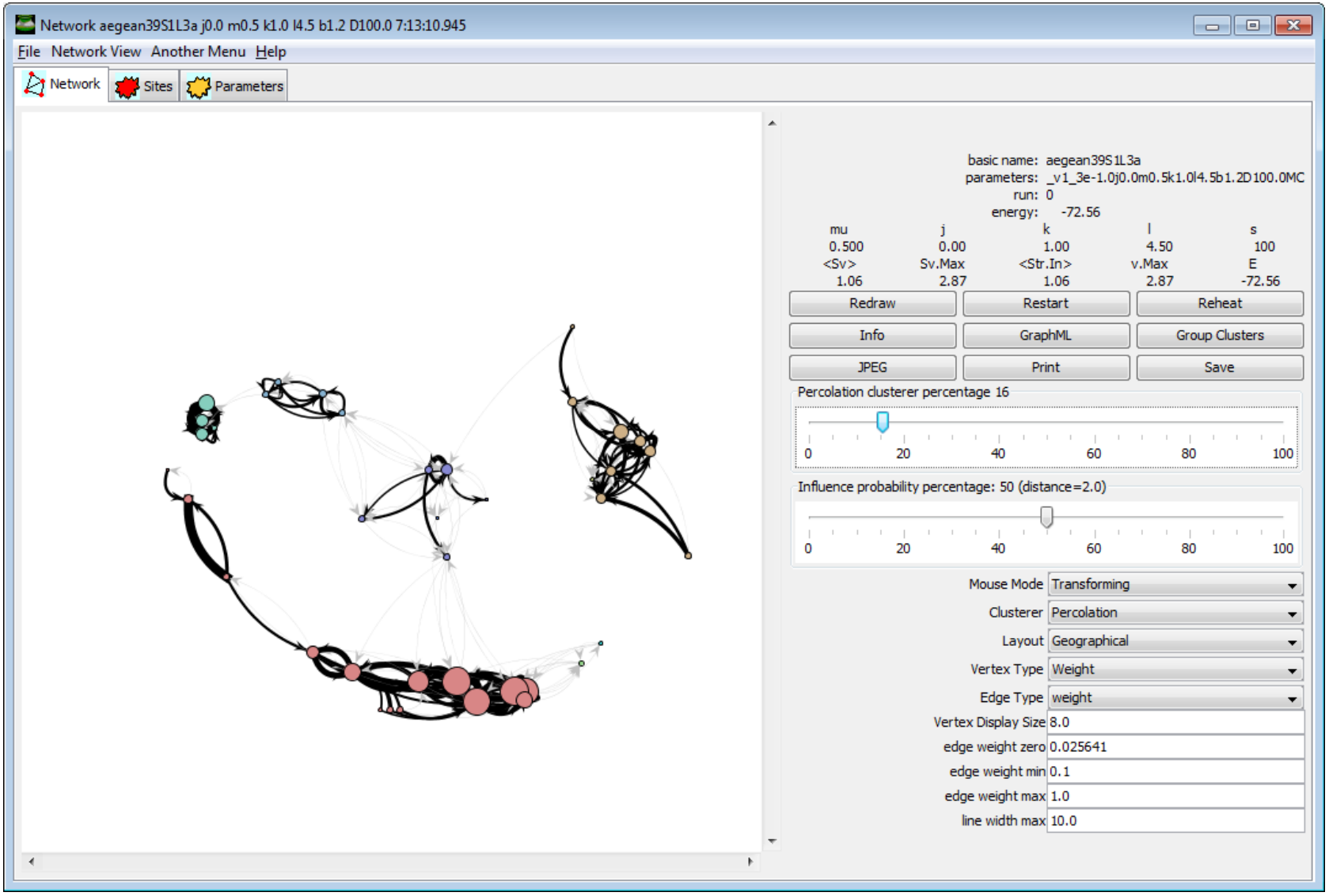


ariadne



Network Description – Variables

Relative values are found stochastically:-

- v_i Variable site occupation *fraction*
  $\Rightarrow$ Site **Weight** (S_i v_i) = Site `*population*'

- e_{ij} Fractional Edge values $0 \leq \Sigma_j e_{ij} \leq 1$
  $\Rightarrow$ Edge **Weights** (S_i v_i e_{ij})
  = Interaction ('trade')
  from site ***i*** to site ***j***

Optimisation of what? Cost/Benefit Analysis

`Energy', resources

Isolated sites have optimal size $v_i = 0.5$

Interactions (trade) bring benefits

Increasing 'population' has a cost

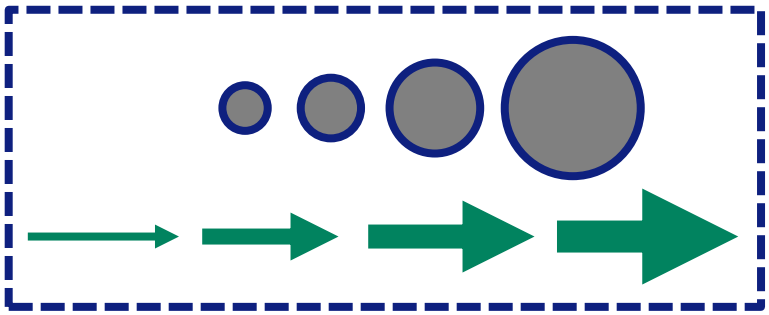
Each trade link has a cost

$$H = -\kappa \sum_i 4 S_i v_i (1 - v_i) - \lambda \sum_{i,j} (S_i v_i).e_{ij} V(d_{ij} / D).(S_j v_j) + j \sum_i S_i v_i + \mu \sum_{i,j} S_i v_i e_{ij}$$

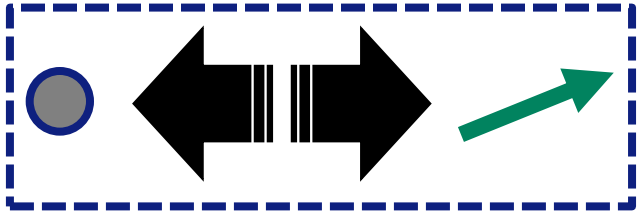
$$0 \le \sum_j e_{ij} \le 1 \qquad 0 \le v_i$$

Features of ariadne

- Both vertices and edges of variable size

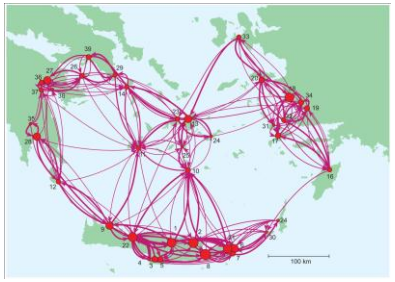


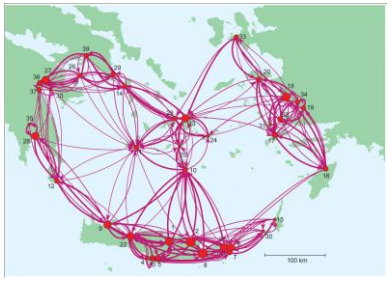
- Values of both are interlinked



- Cost/Benefit balance

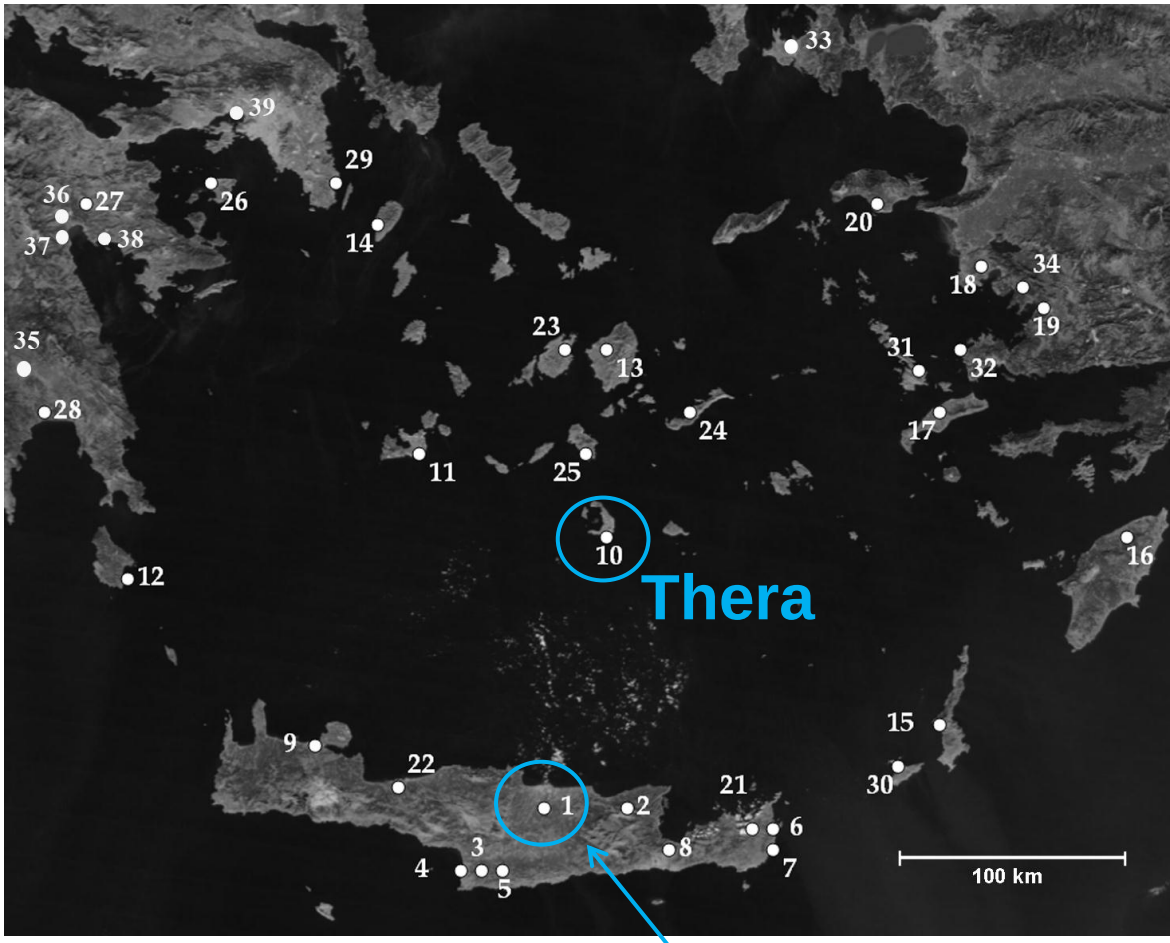
- Not a fixed single solution good but never perfect

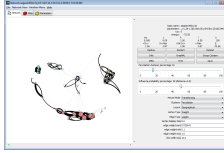




Focus: Minoan Aegean

- c.2000BC distinct Minoan culture starts
  (sail replaces oar)
- c.1500BC Minoan dominance ends (50yr after Thera)
- Physically largely self contained (Egypt?)





Some Possible Questions

- The Knossos Question [Knappett et al, 2008]
  - The palace at Knossos does not have the best local environment
- Eruption of Thera [Knappett et al, 2011]
  - Relation to Minoan collapse
- Minoanisation
  - Spread of Minoan influence

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Summary

- Use of networks is now increasing in archaeology
- Many models very simple
- Role of geography relatively easy to study
- Comparing against finds much harder
- **Many options remain to be explored**

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- All work done with
  - **Carl Knappett (Toronto)**
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- Publications
  netplexity.org
  search for “Tim Evans archaeology”

Bibliography

- Bevan, A., 2010. Political Geography and Palatial Crete , Journal of Mediterranean Archaeology 23.1 , 27-54.
- Broodbank, C., 2000. An Island Archaeology of the Early Cyclades, CUP.
- Collar, A, 2007. Network Theory and Religious Innovation *Mediterranean Historical Review, 22*, 149-162 .
- Evans, T.S., 2004. Complex Networks, *Contemporary Physics, 45*, 455-474.
- Evans, T.; Knappett, C. & Rivers, R., Physical and Relational Networks in the Aegean Bronze Age ,in *Proceedings of The European Conference on Complex Systems,* J. Jost, F. R.-T. & Schuster, P. *(Eds.), ECCS,* **2006**, 81. http://dx.doi.org/10.6084/m9.figshare.750447
- Evans, T., Knappett, C., & R. Rivers, 2009. Using statistical physics to understand relational space: a case study from Mediterranean prehistory, in D. Lane, S. van der Leeuw, D. Pumain & G. West (eds.), *Complexity perspectives in innovation and social change*: 451-79. Berlin: Springer Methodos Series. http://dx.doi.org/10.1007/978-1-4020-9663-1
- Evans, T.S., Knappett, C., & R.J. Rivers, 2012. Interactions in Space for Archaeological Models, *Advances in Complex Systems 15*, 1150009 (http://dx.doi.org/10.1142/S021952591100327X
- Evans, T., Knappett, C., Rivers, R., 2013. Thirty Nine Minoan Sites, Figshare http://dx.doi.org/10.6084/m9.figshare.97395
- Graham, S. 2006. Networks, Agent-Based Modeling, and the Antonine Itineraries. *The Journal of Mediterranean Archaeology, 19*, 45-64 http://www.equinoxjournals.com/JMA/article/viewArticle/2436
- Hage, P. & Harary, F. 1991. Exchange in Oceania: a graph theoretic analysis, *Clarendon Press.*
- Irwin 1983. Chieftainship, kula and trade in Massim prehistory in Leach, J. & Leach, E. *(Eds.) The Kula: New Perspectives on Massim Exchange, Cambridge: CUP,* 29-72 .
- Isaksen, L. 2006. Network Analysis of Transport Vectors in Roman Baetica, MSc Thesis, Univ. Southampton. http://eprints.soton.ac.uk/204535/
- Isaksen, L. 2008. The application of network analysis to ancient transport geography: A case study of Roman Baetica, *Digital Medievalist, 4 http://www.digitalmedievalist.org/journal/4/isaksen/*
- Knappett, C., Evans, T. & R. Rivers, 2008. Modelling maritime interaction in the Aegean Bronze Age, *Antiquity* 82: 1009-24. http://antiquity.ac.uk/ant/082/ant0821009.htm
- Knappett, C.; Evans, T. & Rivers, R., 2011. The Theran eruption and Minoan palatial collapse: new interpretations gained from modelling the maritime network, *Antiquity, 85*, 1008-1023. http://antiquity.ac.uk/ant/085/ant0851008.htm

Bibliography

- Ortúzar, J. d. D. & Willumsen, L. 1994. “Modelling Transport” Wiley.
- Rihll, T.E. & A.G. Wilson, 1987. Spatial interaction and structural models in historical analysis: some possibilities and an example, *Histoire & Mesure* 2: 5-32.
- Rihll, T.E. & A.G. Wilson, 1991. Modelling settlement structures in ancient Greece: new approaches to the polis, in J. Rich & A. Wallace-Hadrill (eds.), *City and country in the ancient world:* 59-95. London: Routledge.
- Rivers, R.; Knappett, C. & Evans, T., 2013. Network Models and Archaeological Spaces in *Computational Approaches to Archaeological Spaces,* A.Bevan & Lake, M. *(Eds.)*, *Left Coast Press.*
- Sindbæk, S. M. 2007. The Small World of the Vikings: Networks in Early Medieval Communication and Exchange *Norwegian Archaeological Review, 40*, 59-74.
- Sindbæk, S.M. 2007. Networks and nodal points: the emergence of towns in early Viking Age Scandinavia, Antiquity 81 , 119–132
- Renfrew & Level, 1979. Exploring dominance: predicting polities from centres, in Renfrew, A. & Cooke, K. *(Eds.)* Transformations: Mathematical Approaches to Culture Change, Academic Press, London, 145-67.
- Stouffer, S. A., 1940. Intervening Opportunities: A Theory Relating to Mobility and Distance, American Sociological Review 5, 845–867. doi:10.2307/2084520.
- Terrell, J. 1977. Human biogeography in the Solomon Islands, *Fieldiana, Anthropology, 68* .
- Wilson, A.G. 1967. A statistical theory of spatial distribution models, Transport Research 1, 253-269