Network Analysis in Archaeology and History
U. of Aarhus

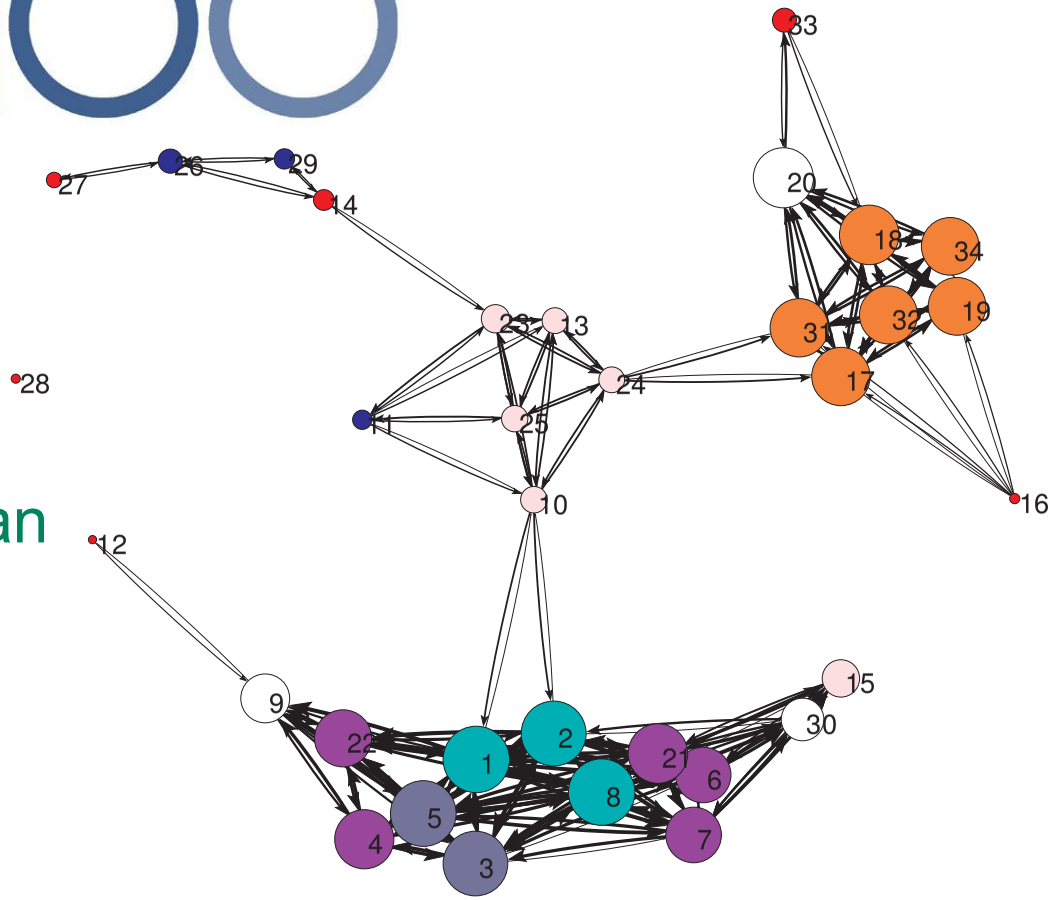
Imperial College London

100 years of living science

Ray Rivers
Theoretical Physics

Beyond Small World Networks:

A case study from the Aegean Bronze Age



Acknowledgements

- Work in collaboration with
  - Carl Knappett (Dept. of Archaeology, U. of Exeter)
  - Tim Evans (Physics, Imperial)
  - Edmund Hunt (Physics, Imperial)

- Initiated through the ISCOM project:

  Complexity Perspectives on Innovation and Social Change
  D.Lane, D.Pumain, S. van der Leeuw and G.West (eds) (Springer Methodos series, 2008)

Topics:

- Island networks and early models
- Problems with making models
- Our model for the Middle Bronze Age (MBA) Aegean

1. Island Archipelagos as a physical substrate for social Networks

- Sea isolates communities → Natural Vertices

- Interactions controlled by physical limitations of ancient sea travel → Simple Links

- Coastal Sites often isolated like islands due to geography and difficulty of ancient land travel

1. Island Archipelagos as a physical substrate for social Networks

- Vertices/Nodes = Population or Resource Sites

- Edges/Links = Exchange between sites
  - physical trade or exchange of goods
  - people, influence (e.g. exogamy)
  - ideas, techniques (culture?)

Several examples (particularly Oceania – e.g. Hage and Harary – 'Kula' ring):

We were motivated by Broodbank (2000) – EBA Cyclades (PPA)

Limitations of Early Network Models:

1. Deterministic

History only occurs once but with high levels of contingency e.g.

- luck (But for a nail…..)

- external conditions, weather, volcanoes,…

Archaeology closer to Astrophysics,

- requires statistical approach

- Bayesian?

Limitations of Early Network Models:

2. Not robust

Not like physics – no immutable laws

If your model or input changes slightly because of new knowledge about sites, for example, do your conclusions change slightly, or a lot?

If slightly, model is 'robust'

Relevance - Impossible to avoid unknown systematic bias

e.g. some sites under modern settlements,
some data survives better in some places than others

Robust models limit the effects of one's ignorance but whether relevant or not depends on social organisation, technology, etc.

'Robust' is not the same as 'resilient'

2. Our model:

Middle Bronze Age Aegean (2000 – 1500 BC)

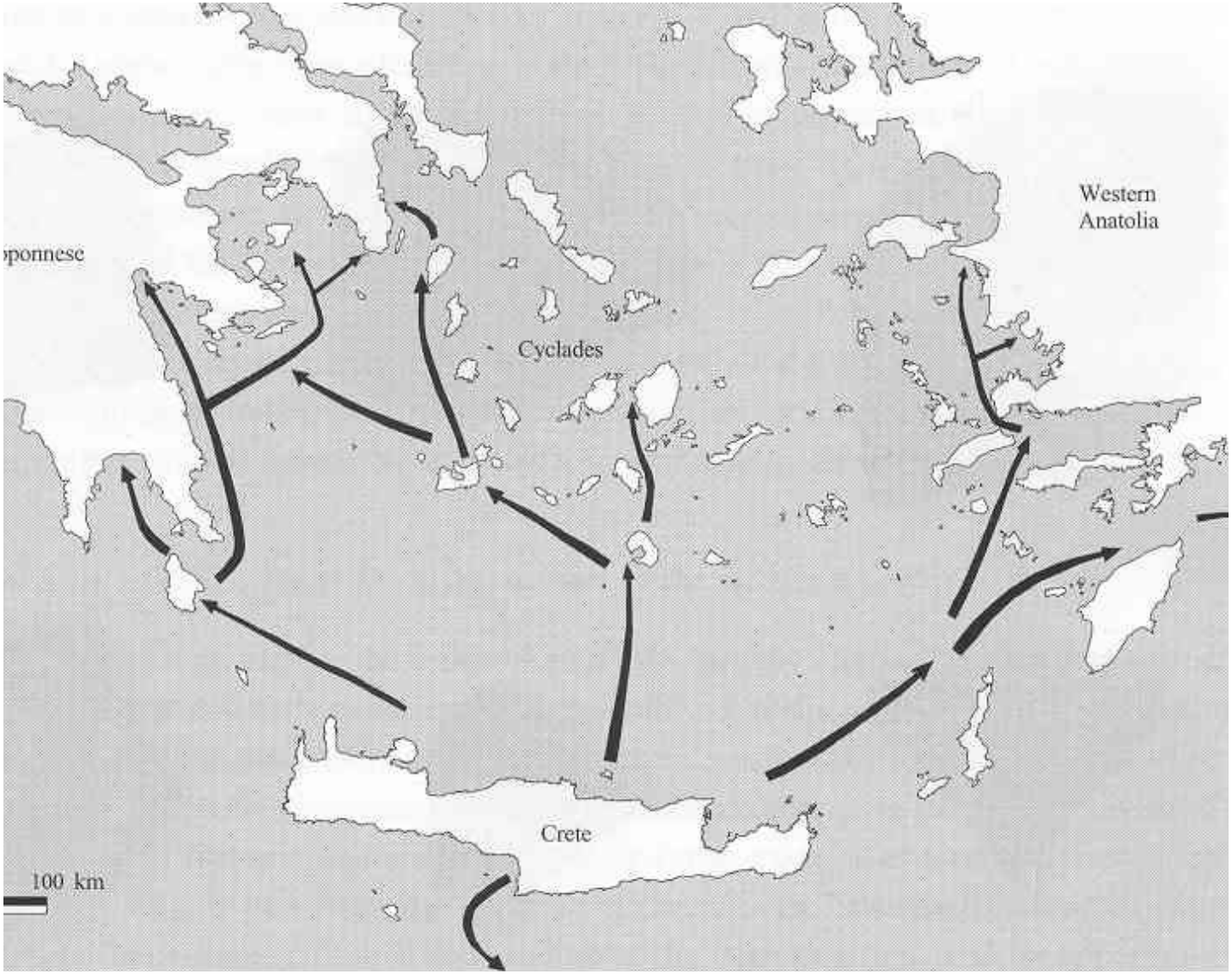
- clear temporal delineation
- Aegean physically largely self-contained (Egypt?)
- sail replaces oar

Questions of interest

In the context of ‘Minoanisation’

- what is the connection between macro-scale development of regional networks and emergence of primary centres?
- what can explain the variability in Cretan influence across Aegean?
- etc.

Schematically : (Broodbank 2000)



Q. How do we convert this schematic picture into a Network?

More concretely

How, in the MBA Aegean, does

- Social organisation
- Geography
- Marine technology

lead to

- population distribution
- local link strengths
- site importance
- 'cultural transmission'

i.e. 'local' and 'global' properties

The latter will be explicable in terms of relative importance of 'weak' and 'strong' links - variants of 'small world' networks

Can go some of the way as follows:

Social Organisation

We would like the global properties of networks to emerge from local properties, from as bottom-up as possible

Our assumptions about social organisation determine the nature of our model.

- Global (whole network)
- Macroscopic (whole islands)
- Mesoscopic (communities on islands)
- Microscopic (household/individual)

Increased complexity

Approaches:

Agent-based modelling: Microscopic/individuals upwards

Too difficult – too many different levels of aggregation

If agent-based modelling is ‘statistical mechanics’, our approach is more ‘thermodynamical’ – equations of state.

We begin with Mesoscopic (island communities) upwards

Our approach:

Non-agent-based modelling; 'Imperfect' rational choice models

- Rational choice – 'optimisation' of a cost/benefit function (social 'potential') *H* – 'agency'
- 'Imperfect' in that there is volatility. Stochastic optimisation – non-predictive
- Adiabatic evolution — slow exogenous change - permits 'tipping points'

Q. How do we enumerate mesoscopic sites?

Potentially, a few hundred

Distance scales relevant to us:

1. Meso-scale – intra-island e.g. hamlets

2. Macro-scale – inter-island e.g. global network
   -previous pictures

Assumption:

Meso-scale can be subsumed into the macro-scale in the sense that the cumulative effect of interactions at the meso-level can be represented by simple interactions at the macro-scale - 'block –renormalisation'

Not universal (Broodbank's EBA Cyclades does not have it)

- conditioned by technology and society

Middle Bronze Age Aegean (2000 – 1500 BC)

Assumption:

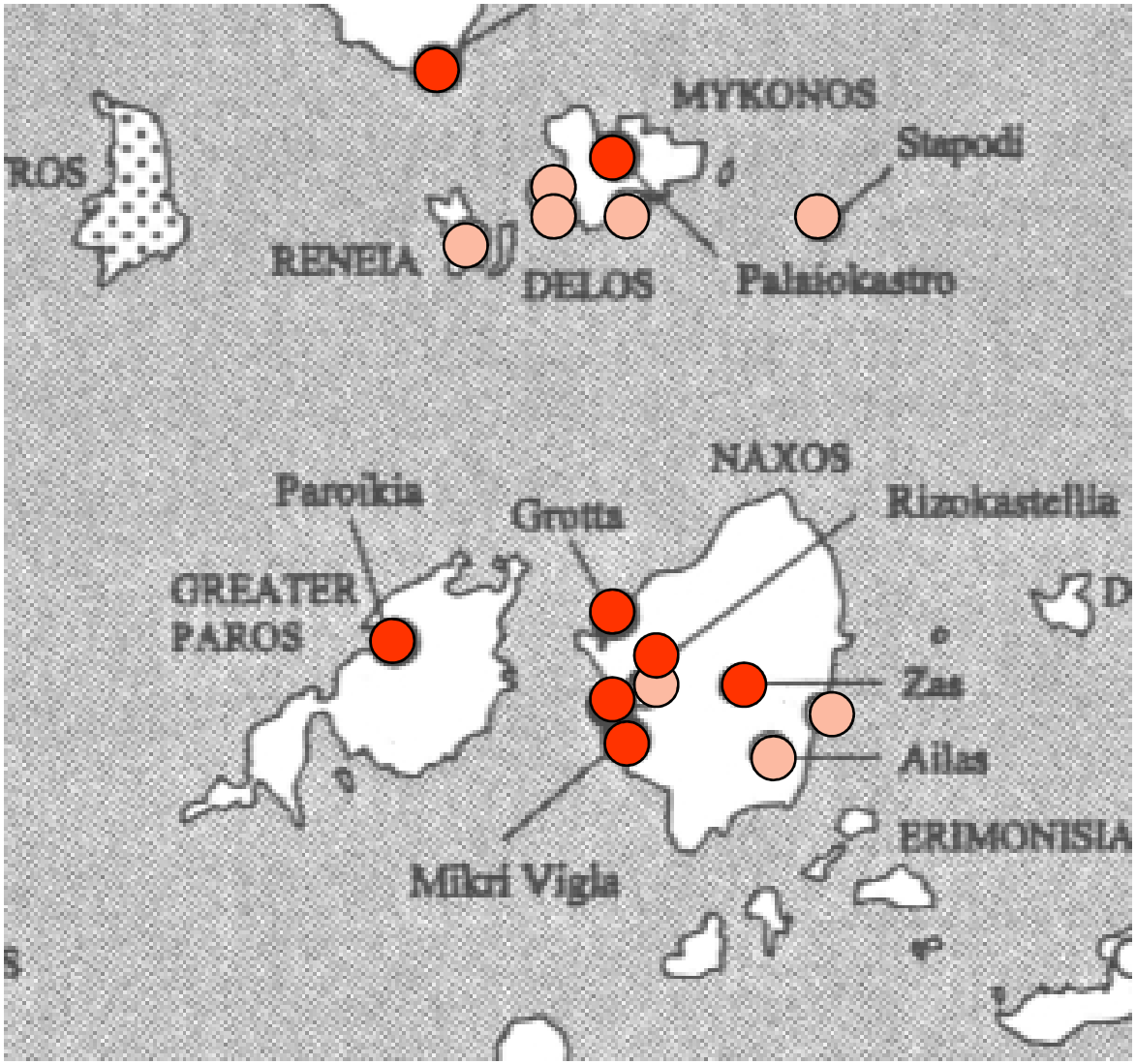
Sail (harbours?) suggests island-to-island interaction rather than hamlet-to-hamlet interaction

One site per island e.g. Naxos

BUT several sites for Crete and mainland

How can we ignore the meso-level?

Consider Naxos



major site

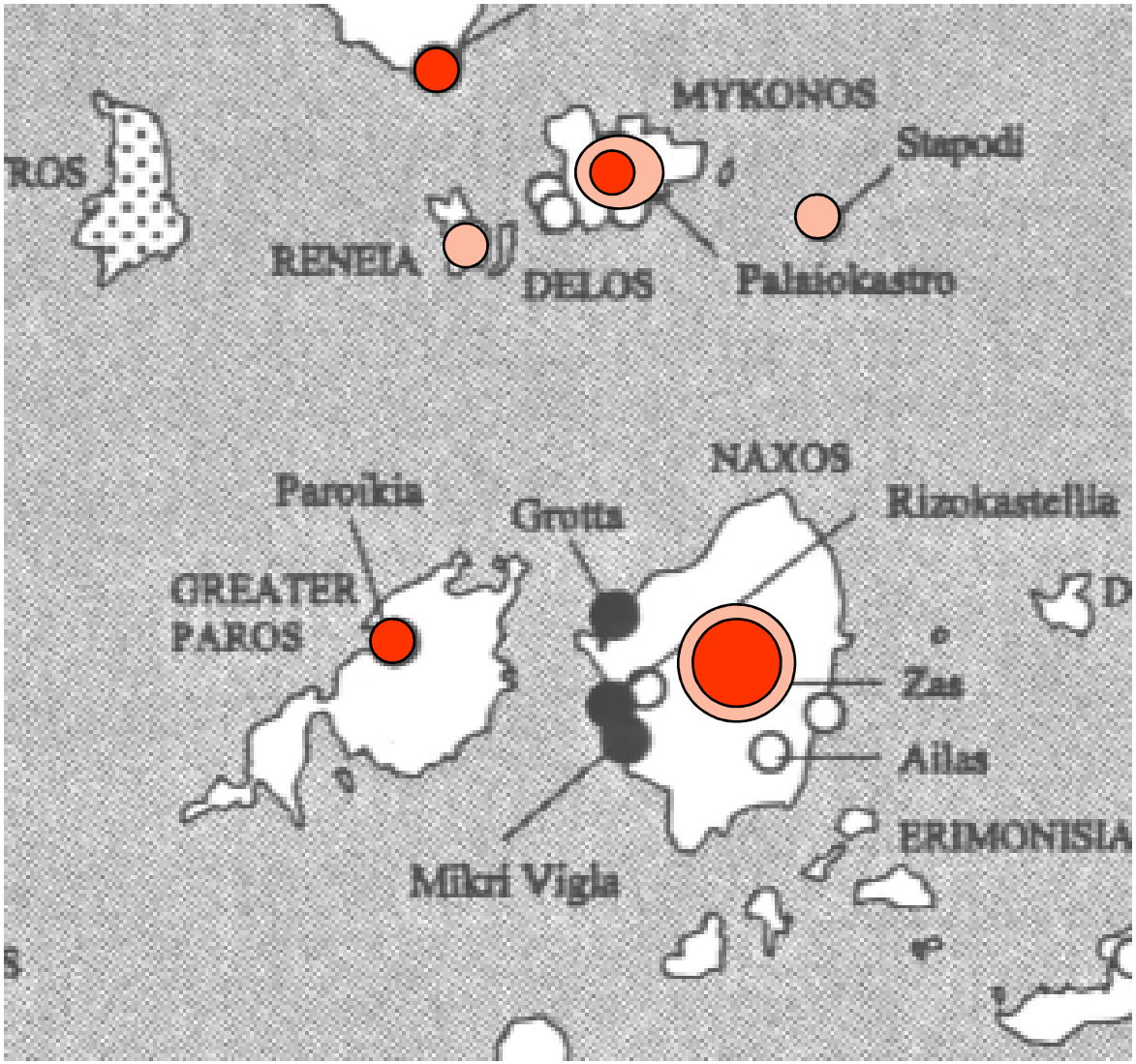
limited or uncertain data

unknown sites

Need to make individual archaeological sites invisible at both

- vertex level
- link level

Step I : ‘Centre of mass’ approximation



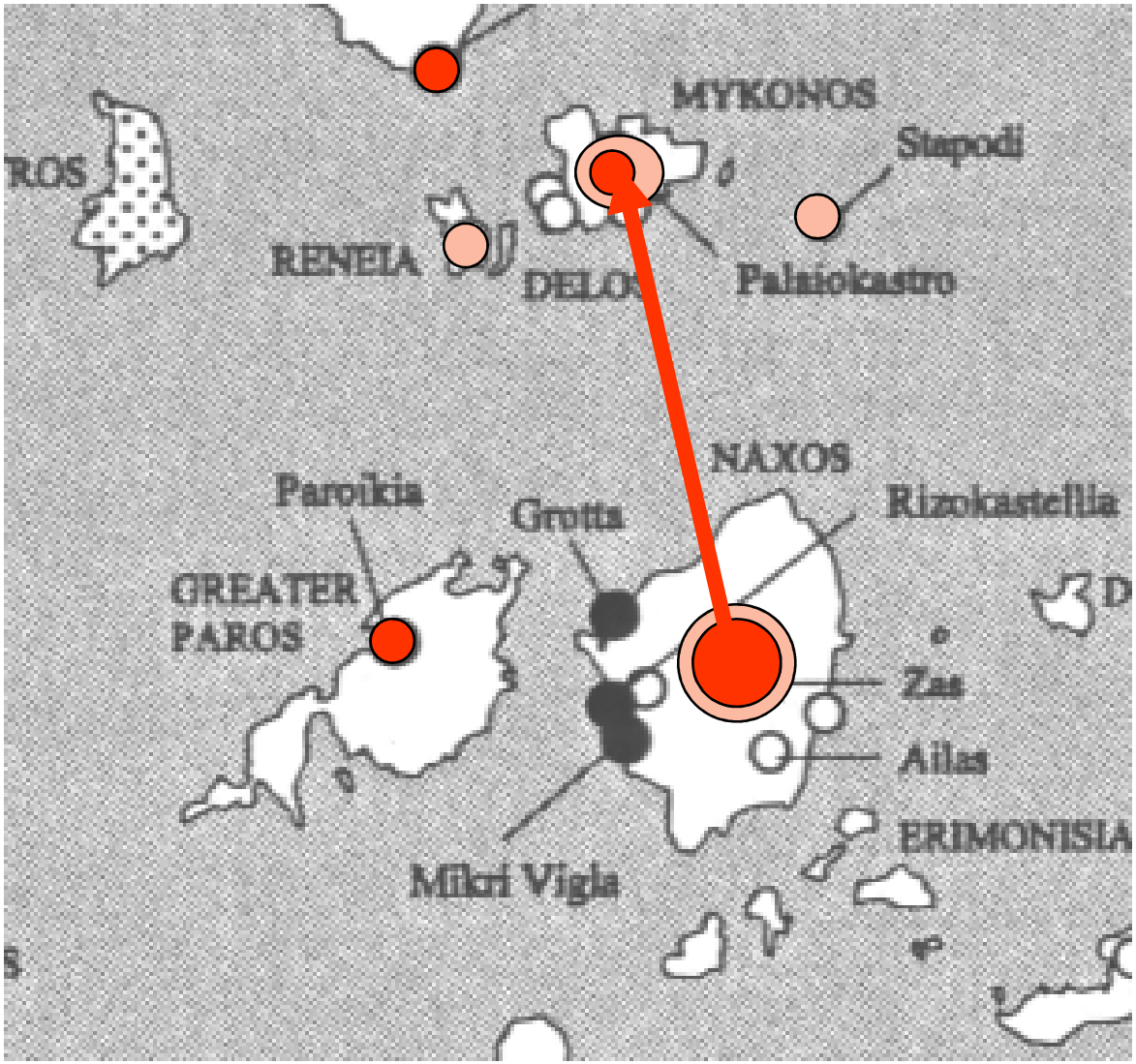
Assume that resource exploitation/population is extensive

That is, there is no benefit and no penalty in resource exploitation in communities splitting or amalgamating

‘The whole is just the sum of the parts.’

We can replace individual sites by an aggregate site

At link level



Replace clusters of individual links between individual sites by single link(s) between collective sites

‘Gravity’ Model !

Main Implications:

- Homophily: - Large connects to large (and small to small)

  Benefits of a link are proportional to the product of exploited resources/ populations at sites at the end of the link.

- We minimise the effects of our ignorance

  e.g. if a major site is discovered we do not have to include it, since island-wide output can be distributed as we wish

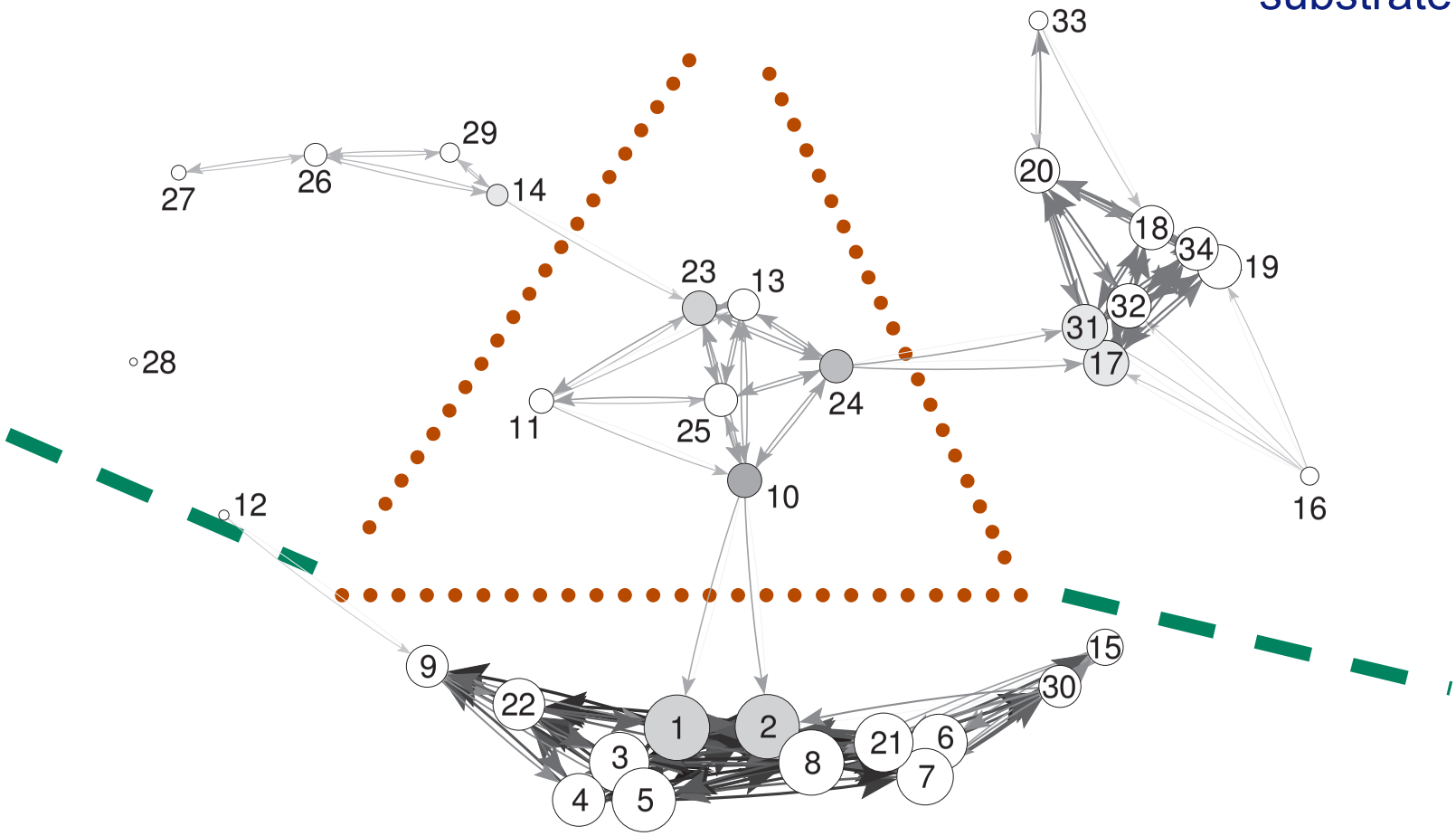
  Desirable since archaeological record is very patchy

Choose 34 sites

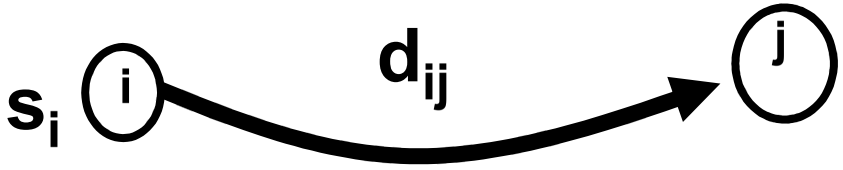
Gravity models very Robust

Exemplary network in our model

Same strongly connected regions = same physical network substrate



Network Description – sites *i =1,2,..N*



Physical inputs: Geography

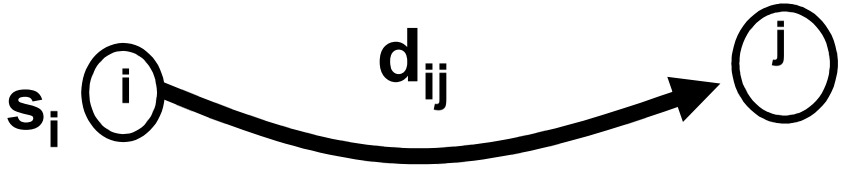
- d_{ij} Fixed distance between sites

  - may be physical but may include penalties for prevailing winds, currents, land travel, ...

- s_i Fixed site capacity ('carrying capacity')

  - maximum local resources

Network Description



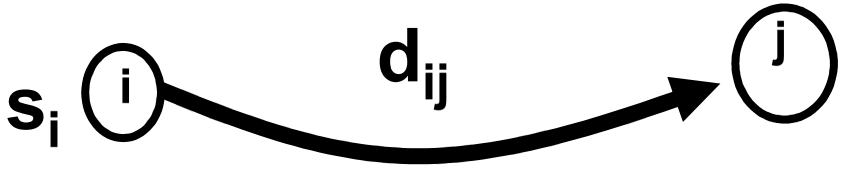
Physical inputs: Technology

- D: Distance scale for interaction by boat (sail)
  measures how long a single journey can be
  - perhaps how far one can travel in one day

  As a guess take D = 100km

- $V(d_{ij}/D)$: A 'nearest neighbour' function
  $V \approx 1$ for $d_{ij} < D$
  $V \approx 0$ for $d_{ij} > D$

Network Description



Physical inputs: Social interactions (Homophily/Gravity)

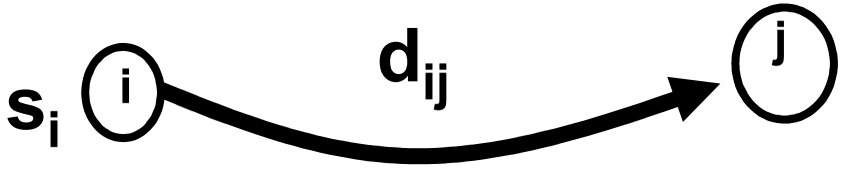
- There is a benefit proportional to

$$(s_i v_i).(e_{ij} V(d_{ij}/D)).(s_j v_j)$$

= (*Population of i* X *nearest neighbour potential* X *population of j*) e_{ij}

for establishing a link between sites *i* and *j*

Network Description



Physical inputs: Social interactions

Obviously more – use of local resources

– cost of maintaining population

– cost of maintaining links

Key point: 'Gravity' + penalties for overexploitation

⟹ potential ' instability'

Network Description

Local outputs: 'population' and 'trade'

- v_i : Variable site occupation *fraction* ('detrended population')

  $\Rightarrow$ Site Weight $S_i = s_i\, v_i$ (= Site `*population*')

- e_{ij} : Fractional Edge values $\boldsymbol{0 \le \Sigma_j e_{ij} \le 1}$
  probability of making a journey from site ***i*** to site ***j***

  $\Rightarrow$ Edge Weights ($s_i\, v_i\, e_{ij}$) = '*Trade*' (interaction) going from site ***i*** to site ***j***

  related to the number of journeys made from site *i* to site *j* if everyone makes one journey.

Network Description

Local site outputs: ‘strength’

- $w_i = \sum_j s_i v_i e_{ij}$: incoming *‘strength’* of the site *i,*

  related to number of incoming visits if everyone makes one journey
  - one measure of importance of site

Network Description

Global site outputs: ‘rank’ (‘traffic junction’)

Can construct (from powers of e_{ji} : ‘Adjacency’ or ‘transfer’ matrix.)

- the site (‘Google page’) rank r_i

  - corresponds to rate at which ‘random sailors’ travelling the network according to the probabilities e_{ji} pass through a site

    – ‘gateway communities’(?)

Network Description

Global site outputs: 'influence' ('car parking')

Can construct (from powers of e_{ji} : 'Adjacency' or 'transfer' matrix.)

- The site 'influence' I_i

  - corresponds to the number of random sailors that arrive at a site (ever) if each sailor takes only a (prescribed) limited number of 'hops' in his travel

  – one aspect of 'cultural transmission' (?)

Global questions:

1. Thinking of the network as mappings from ‘geography (+)’ to ‘social interaction’, to what extent do they primarily reflect the geography?

   i.e. what are the exceptions to the first guess that large sites have large influence and short distances mean strong links

2. Where do the networks sit in the continuum between (‘scale free’) networks with a few large nodes and networks characterised by the existence of weak links between strong clusters, etc.

3. How do they evolve?

4. What is the role of instability?

5. etc.,