Formalizing the notion of ‘innovation’ in an evolutionary model

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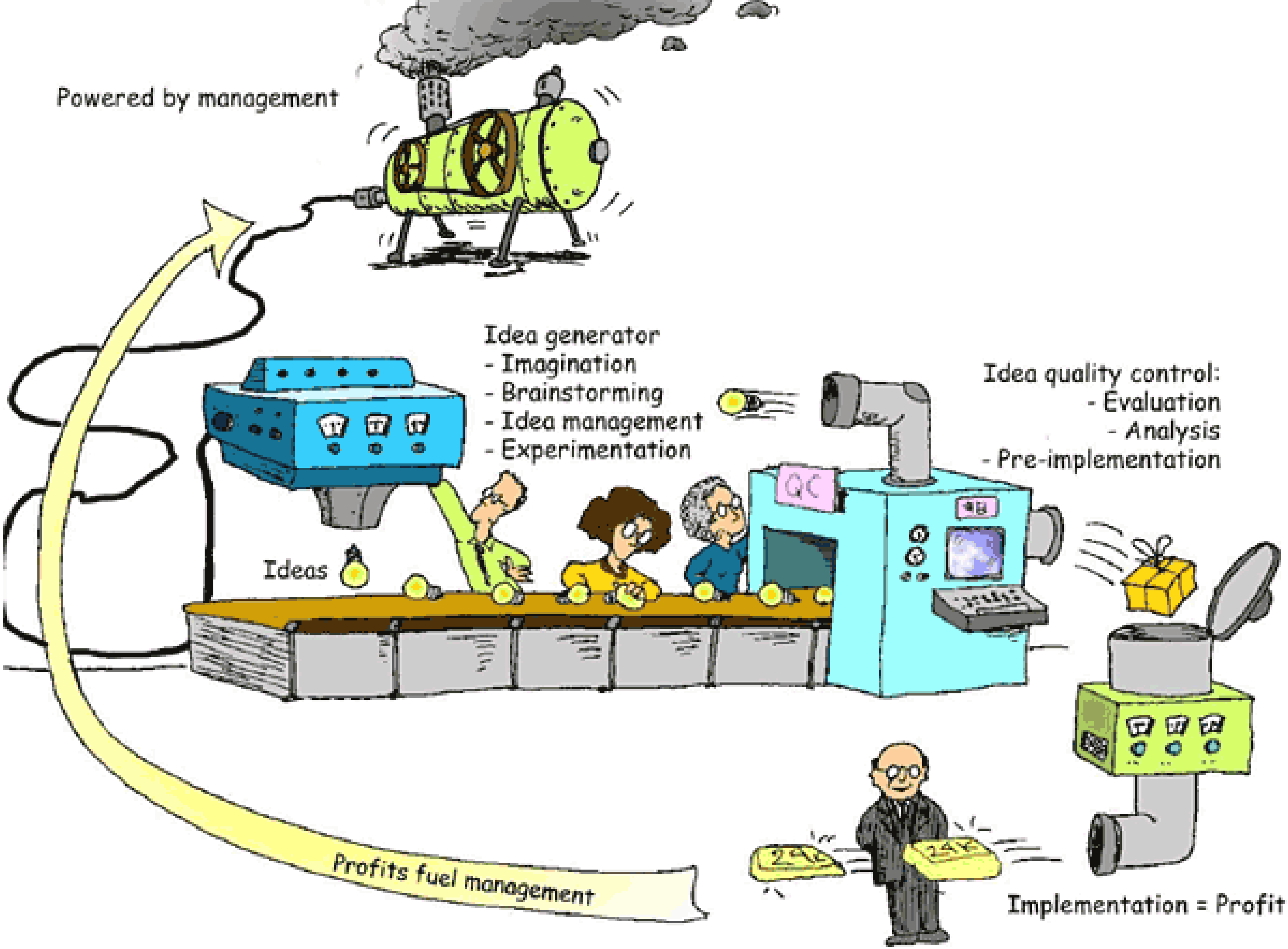


The Corporate Innovation Machine

Source: http://www.jpb.com/innovation/index.php

Innovation (everyday usage)

"Something new that brings about a change"

Examples

- artifacts that humans build (wheel, steam engine, computer)
- processes (agriculture, manufacture of steel)
- the world of ideas (discovery of zero, law of gravitation)
- social organization (money, parliamentary democracy)

In biology, "evolutionary innovation"

- photosynthesis
- multicellularity
- eye

Birth of a star, origin of the earth are not considered innovations. "Innovation" seems to presuppose an evolutionary context.

Innovation can have both constructive and destructive consequences.

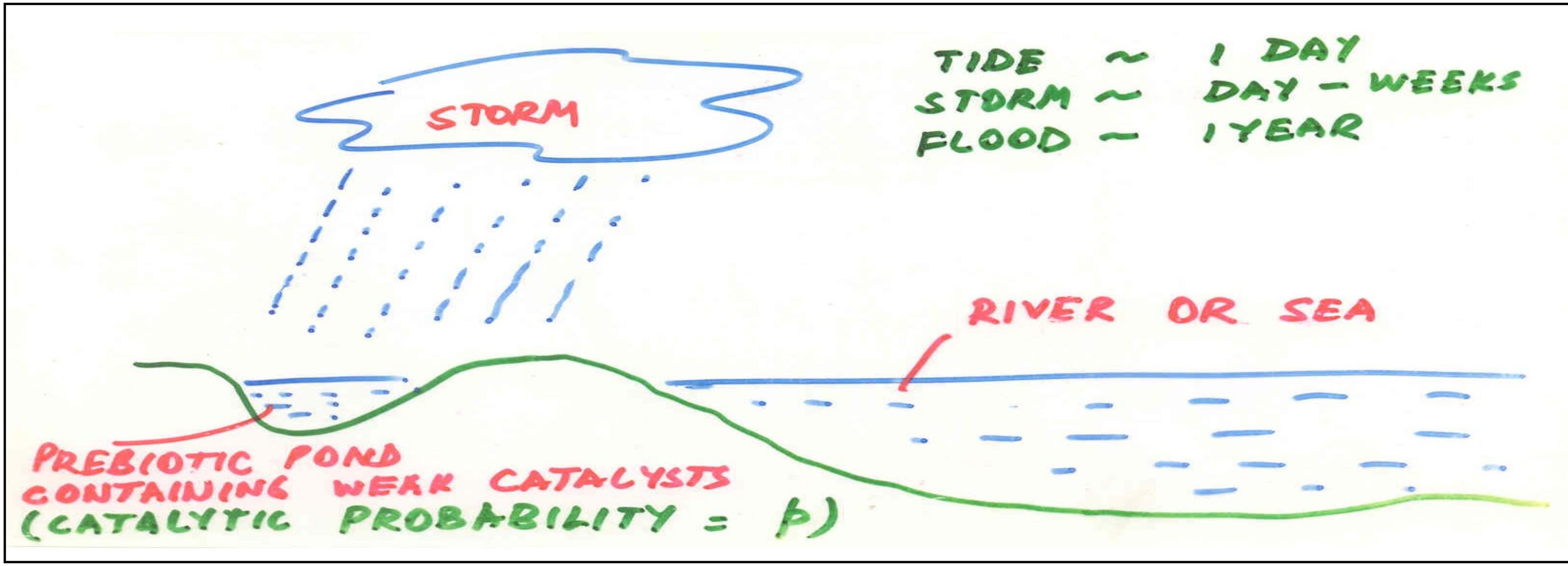
- Automobile destroyed the horse drawn carriage industry.
- Aerobic organisms out competed anaerobic organisms.

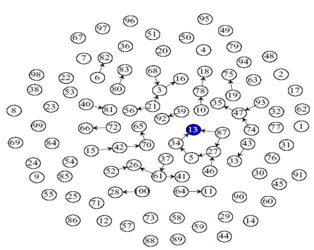
Success of innovation depends on the context.

Successful innovation then changes the context.

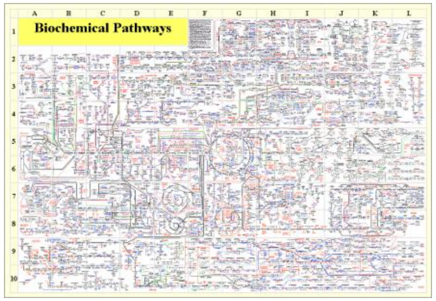
Will describe a mathematical model that captures this two faced nature of innovation and its dynamical relationship with the context.

The model (based on the origin of life problem -- emergence of pre-biotic chemical organization)



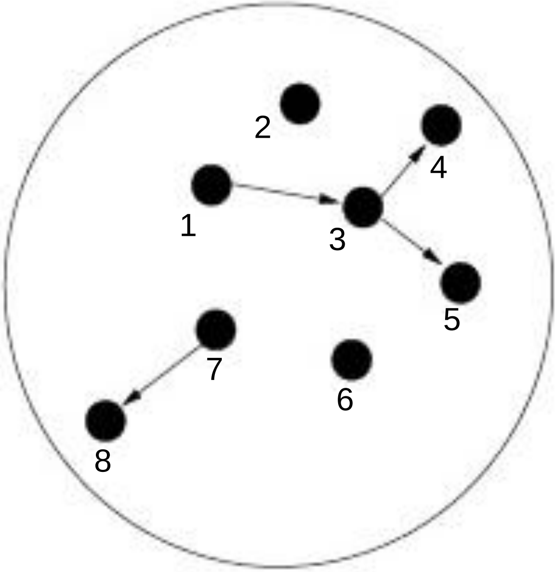


100-500 million years



Variables of the model

A graph of interacting molecular species



An arrow from node j to i implies that j is a catalyst for the production of i, and then

$$c_{ij} = 1$$

The absence of an arrow from j to i implies that

$$c_{ij} = \mathbf{0}$$

The s x s matrix $C = (c_{ij})$ is the adjacency matrix of the graph

s is the number of molecular species

Each species i has a population y_i or a relative population x_i

The variables $\boldsymbol{x}$ and $\boldsymbol{C}$ characterize the chemical organization in the pond and they change with time.

Initialization: $\boldsymbol{C_{ij}}$ **= 1** with probability p**,** p is the "catalytic probability"

= 0 with probability **1-** p $m = ps =$ average connectivity

$\boldsymbol{x_i}$ are chosen randomly

Dynamical rules

1. Keeping C fixed, let the relative populations $\boldsymbol{x}$ change with time according to

$$\frac{dx_i}{dt} = \sum_{j=1}^{s} c_{ij} x_j - x_i \sum_{j,k=1}^{s} c_{jk} x_k$$ (catalytic dynamics)

C_{ij} = 1 if molecule j is a catalyst for the production of molecule i
= 0 otherwise

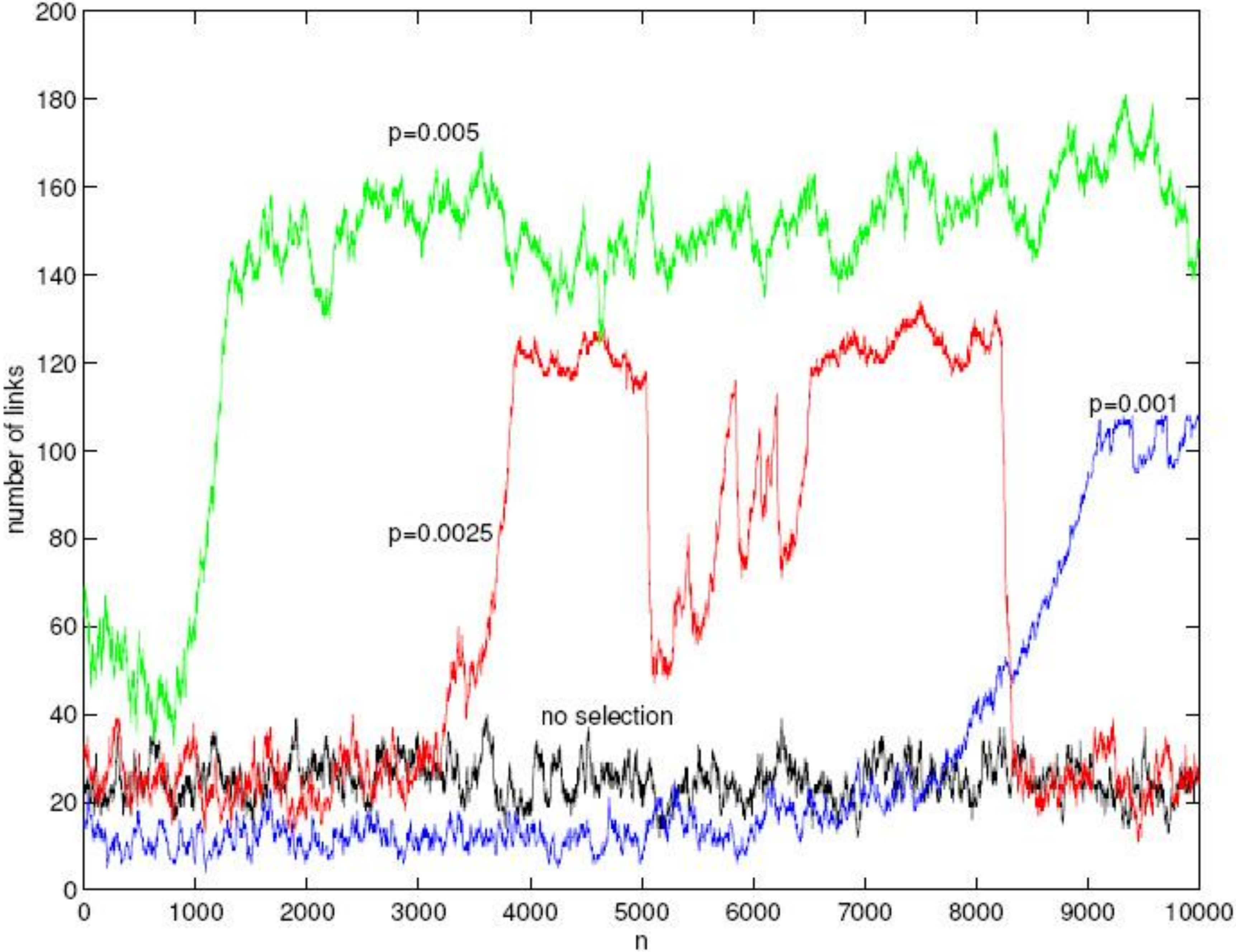
Let the populations reach a steady state (attractor is a fixed point, and is an eigenvector of C corresponding to its largest eigenvalue – Perron Frobenius eigenvalue)

2. Now change C

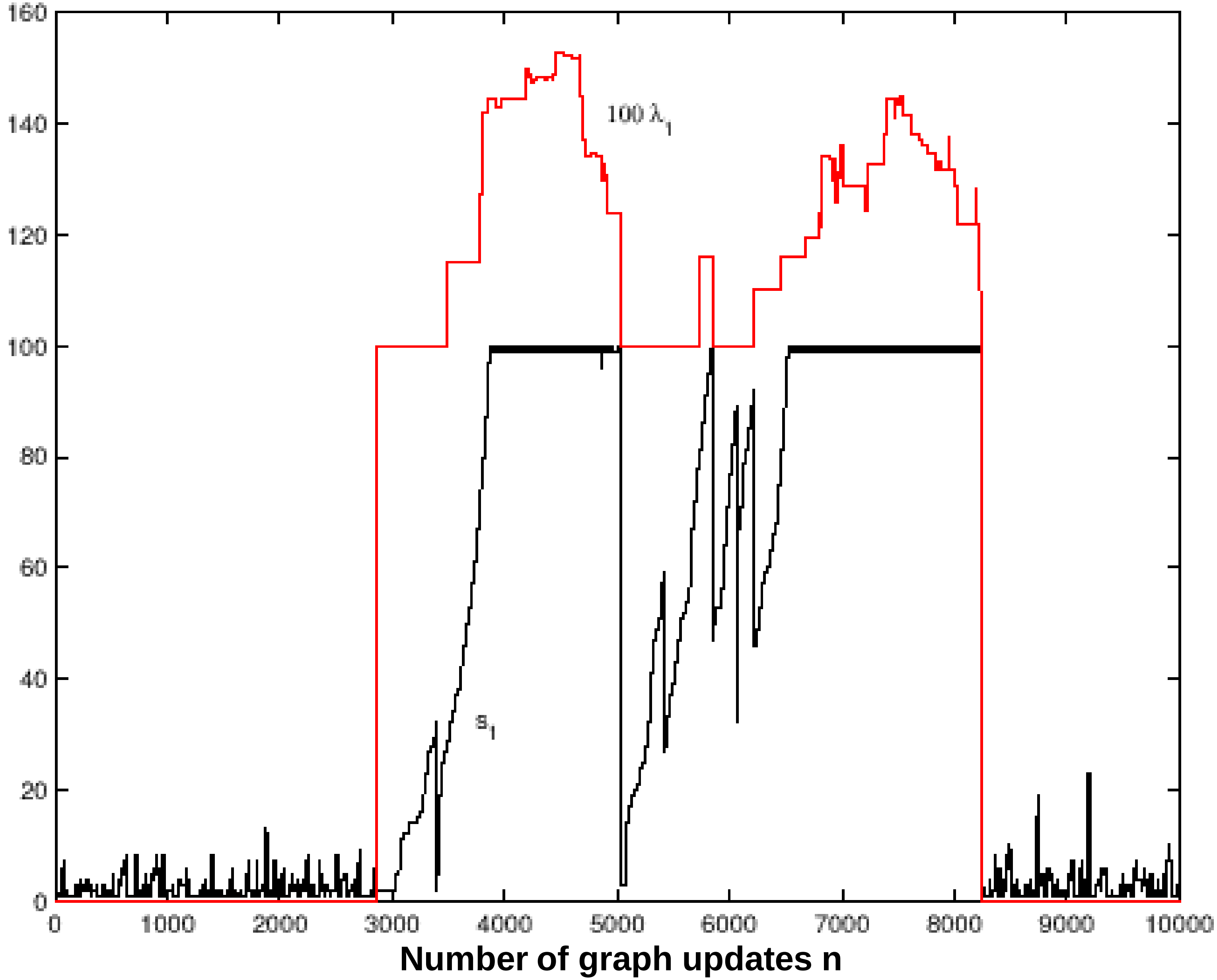
(a) Remove the node with the least population along with all its links (selection; tide washes out the least populated molecular species)

(b) Introduce a new node whose connections to the existing nodes are made randomly with prob p (introduction of novelty; tide brings in a new molecule)

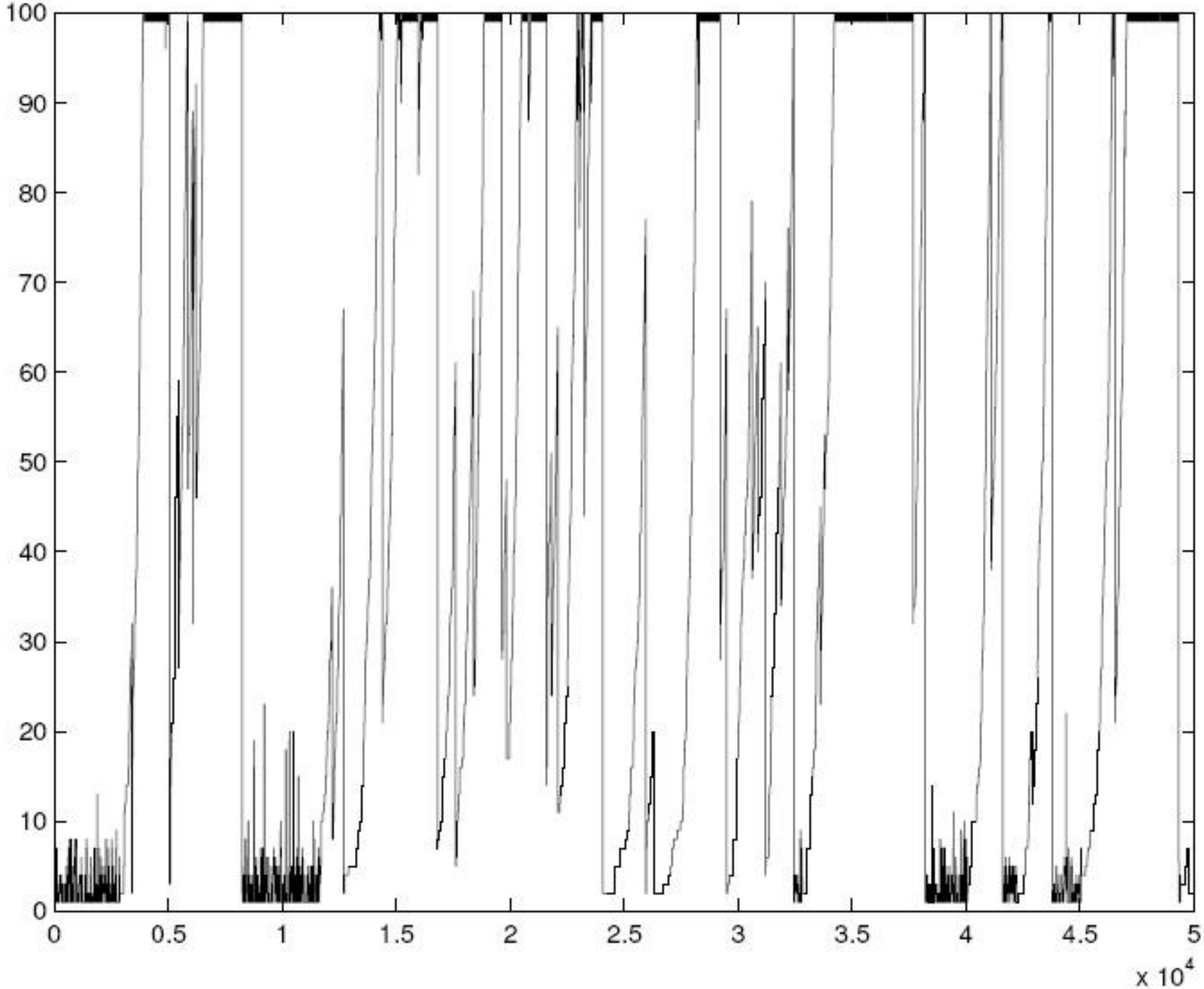
3. Iterate steps 1 and 2



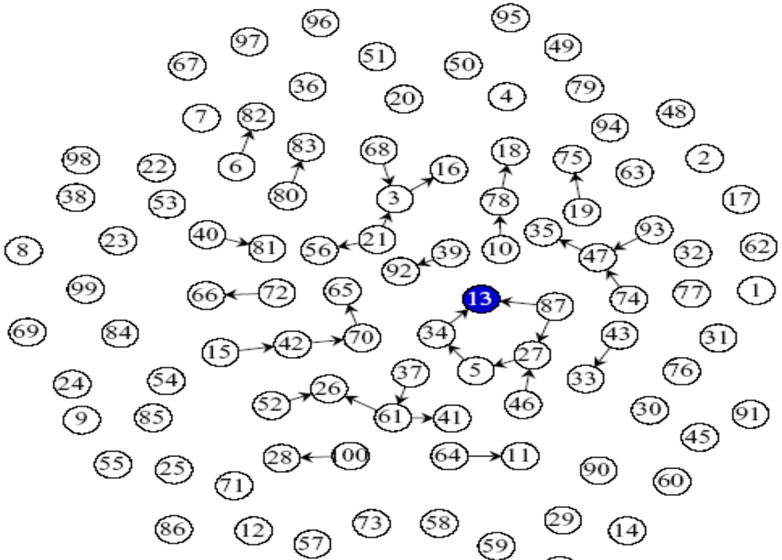
p=0.005
p=0.0025
p=0.001
no selection
number of links
n
0
20
40
60
80
100
120
140
160
180
200
0
1000
2000
3000
4000
5000
6000
7000
8000
9000
10000



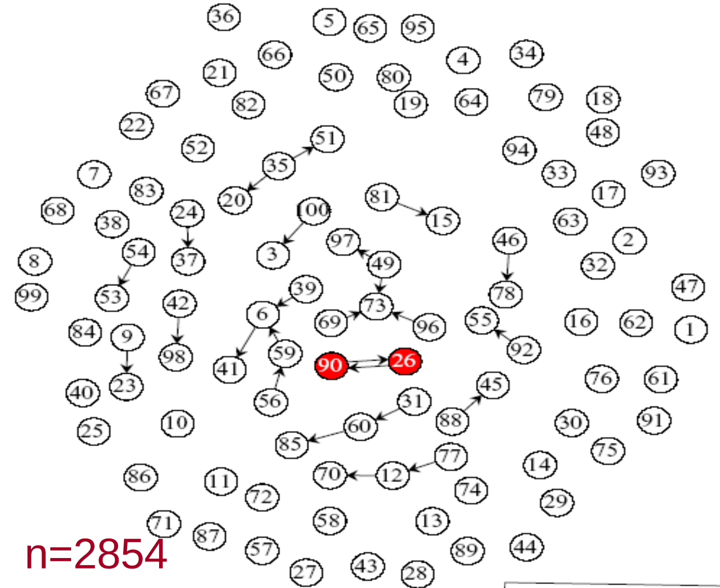
Black curve: Number of nodes with relative populations > 0
Red curve: Perron-Frobenius eigenvalue of the graph



100
90
80
70
60
50
40
30
20
10
0
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
x 10^4

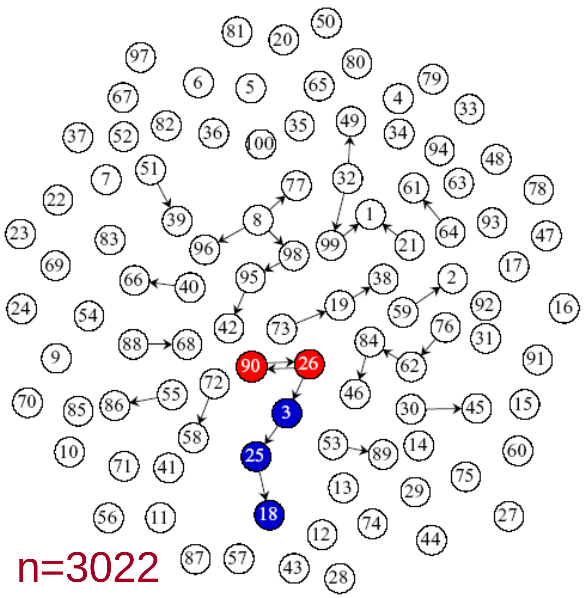


n=1

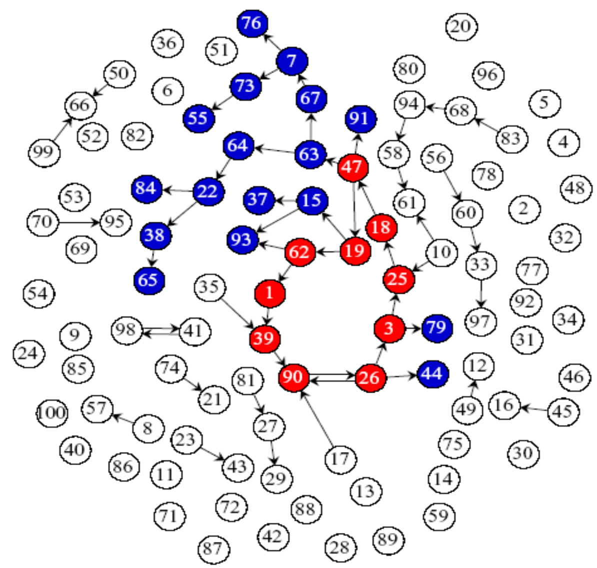


n=2854

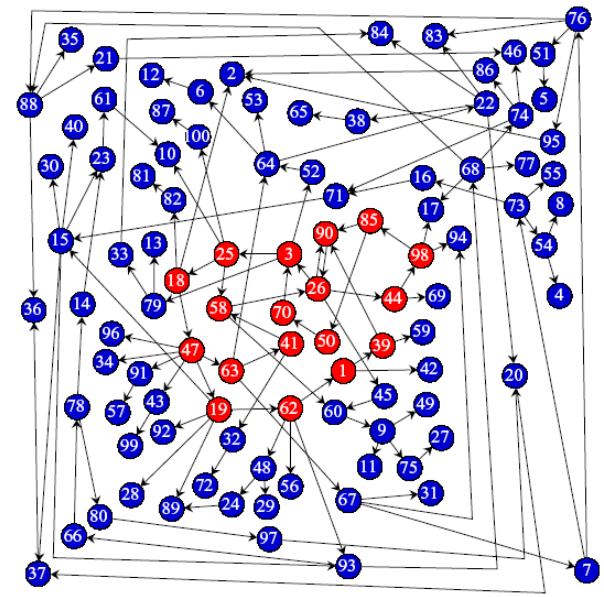
A small autocatalytic set (ACS) appears by chance. Its cooperative structure means that both its nodes
do well (the ACS is a replicator), hence both survive. .



n=3022



n=3489

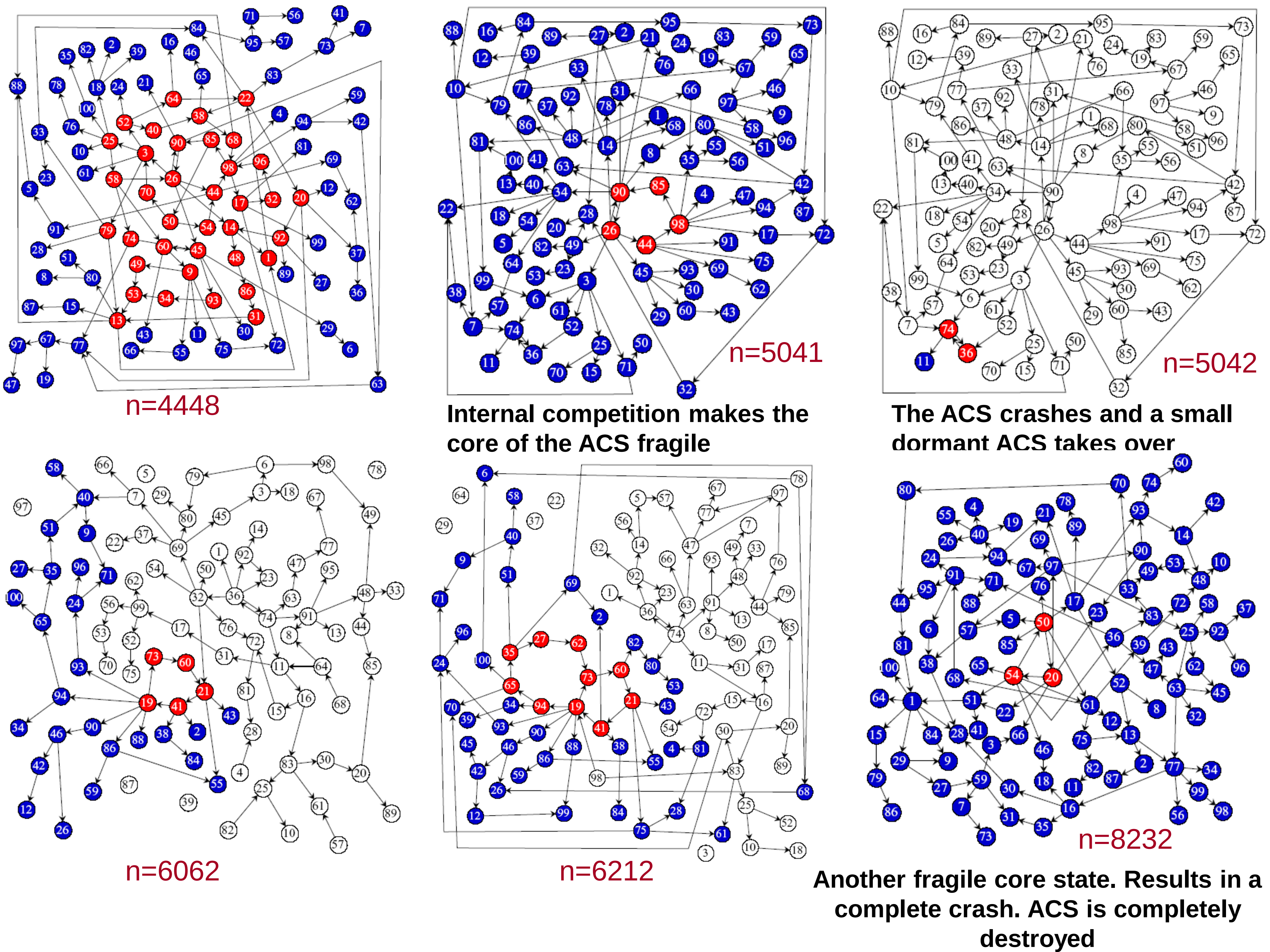


n=3880

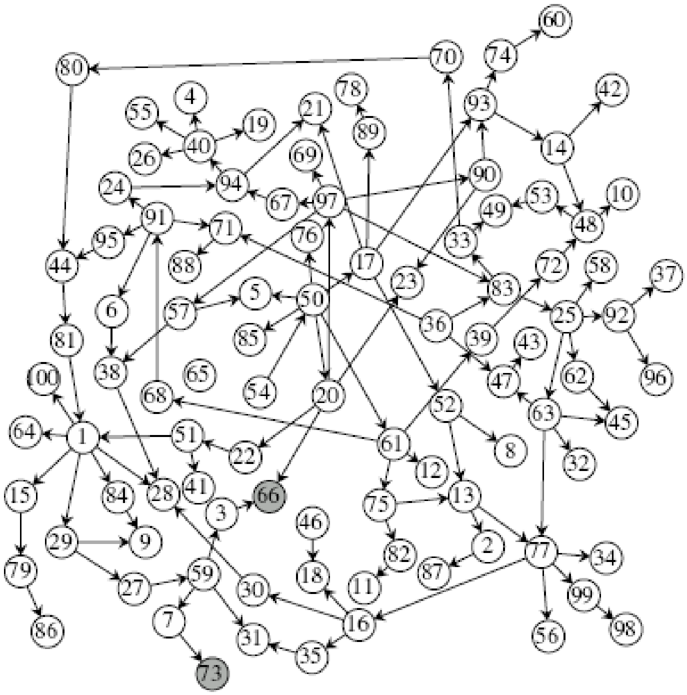
The ACS is the seed from which growth of complexity and structure occurs

ACS eventually takes over the whole pond

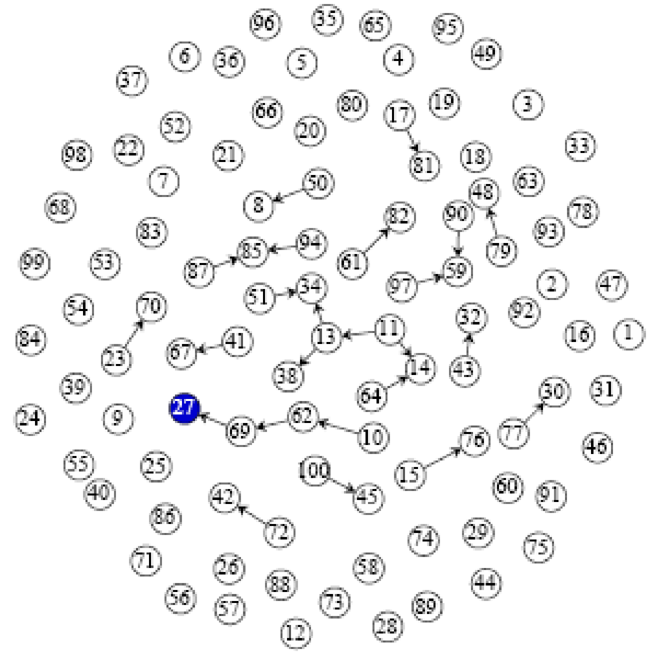
Evolution of a prebiotic chemical organization



n=4448
n=5041
Internal competition makes the core of the ACS fragile
n=5042
The ACS crashes and a small dormant ACS takes over
n=6062
n=6212
n=8232
Another fragile core state. Results in a complete crash. ACS is completely destroyed



n = 8233



n = 10000

Innovation

‘Novelty’ enters the system at one point in the dynamics: when the new node is brought in and its links with the existing nodes are chosen randomly

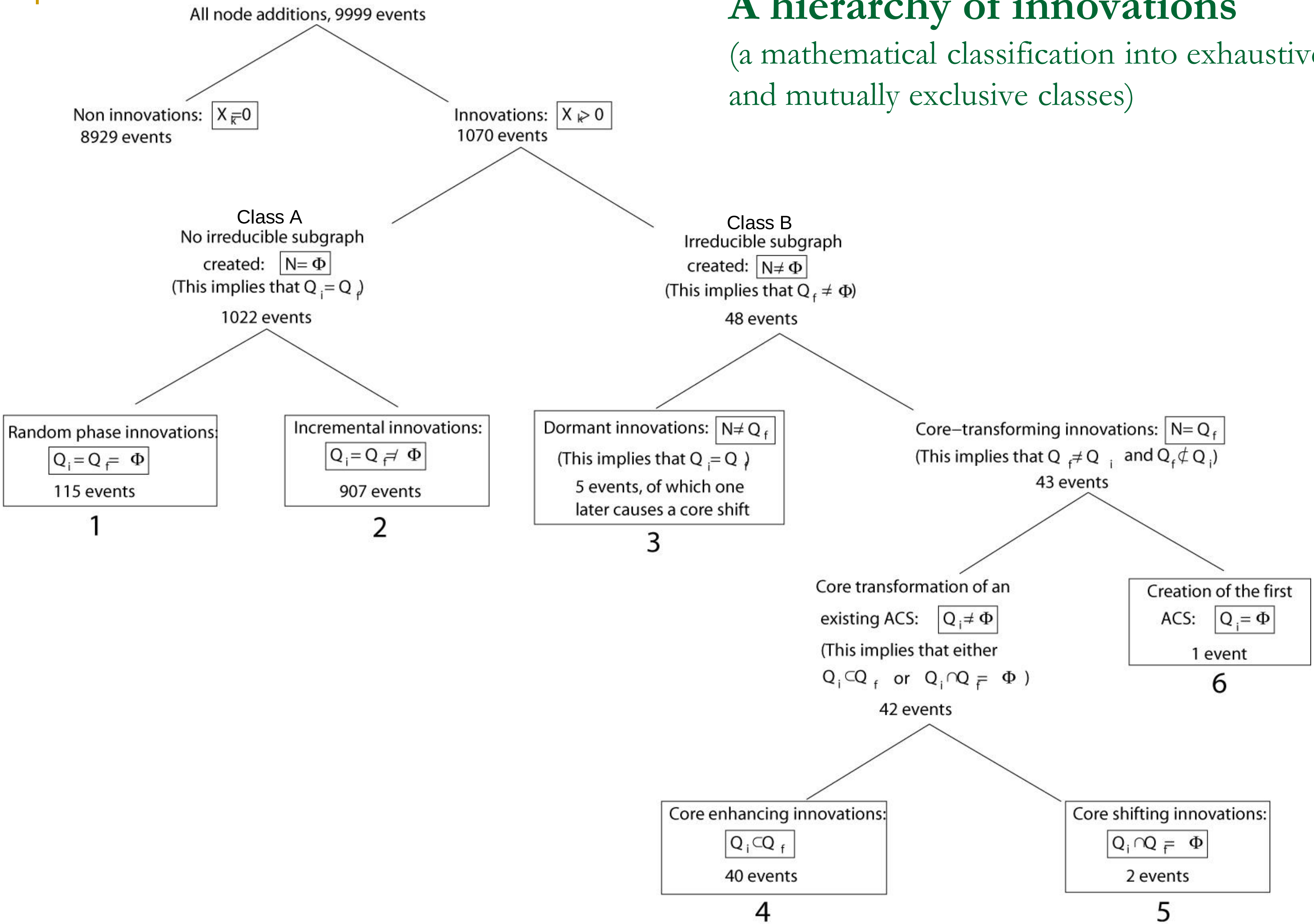
Not every new thing qualifies as an ‘innovation’

A node addition will be called an **innovation** if the new node

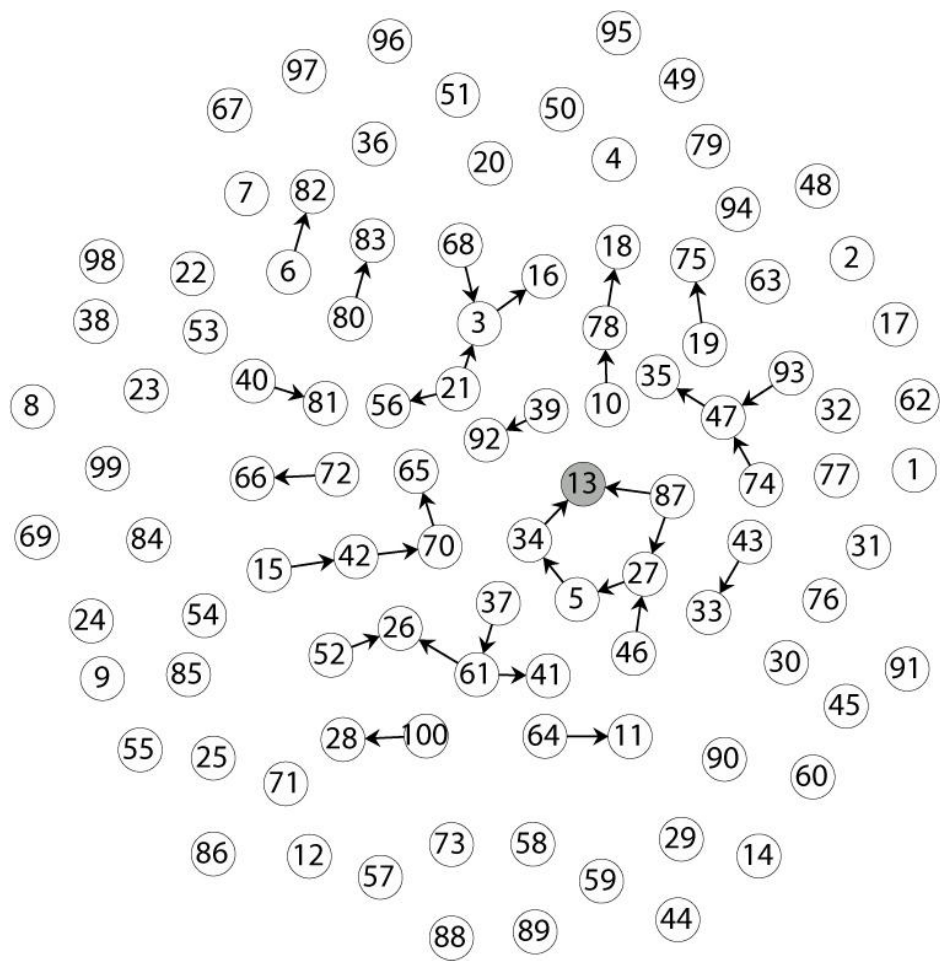
has a nonzero relative population in the next steady state
(There needs to be some ‘performance’ criterion for something to qualify as ‘innovation’)

A hierarchy of innovations

(a mathematical classification into exhaustive and mutually exclusive classes)

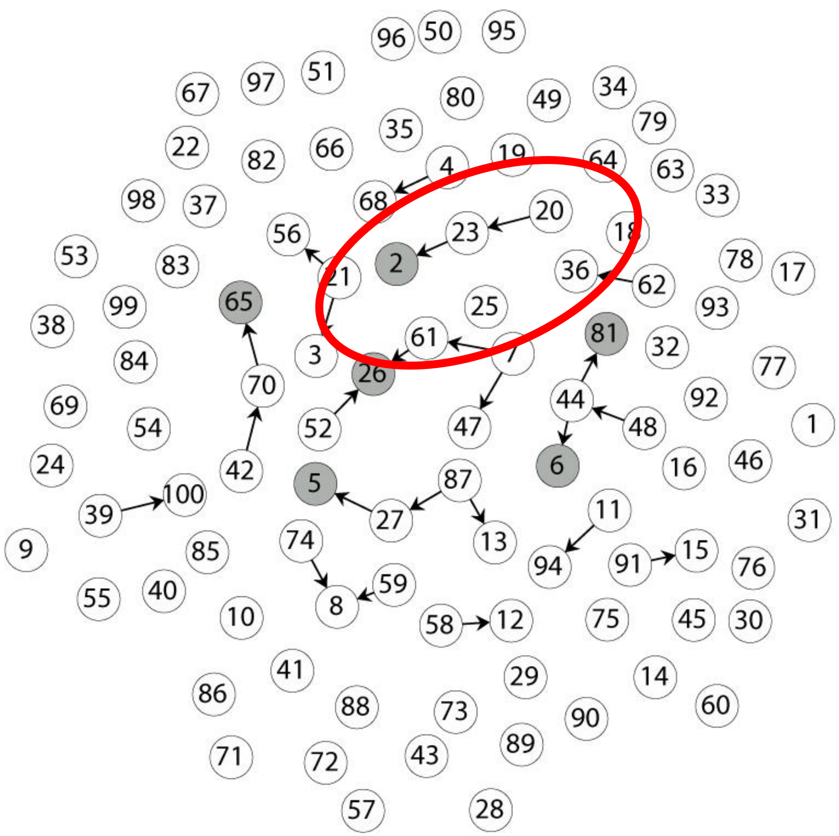


n = 1

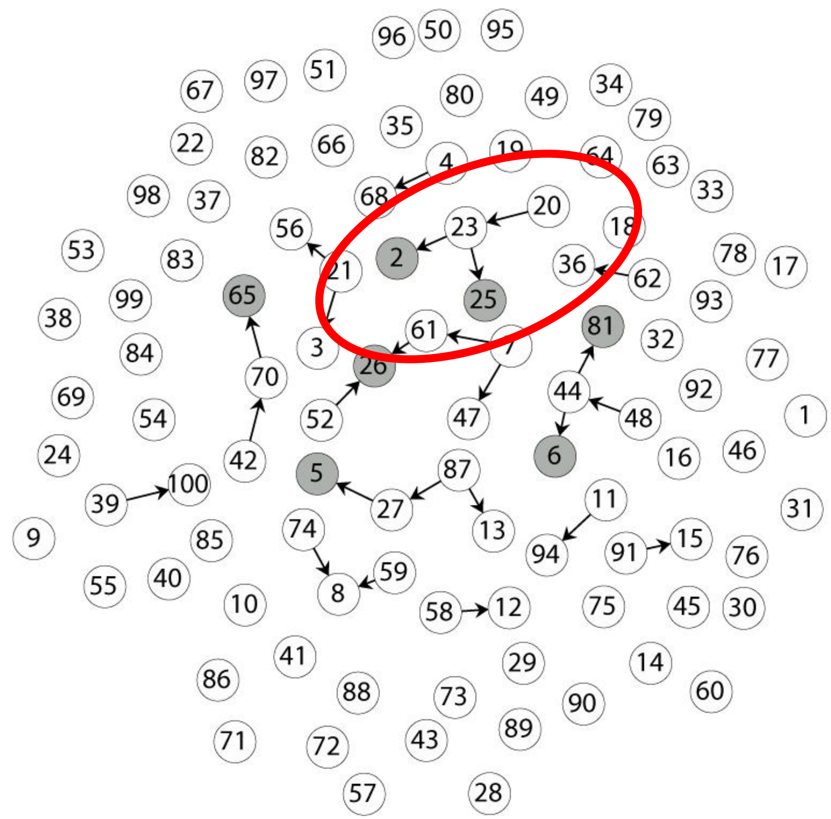


Initially, a random, sparse, graph

n = 78

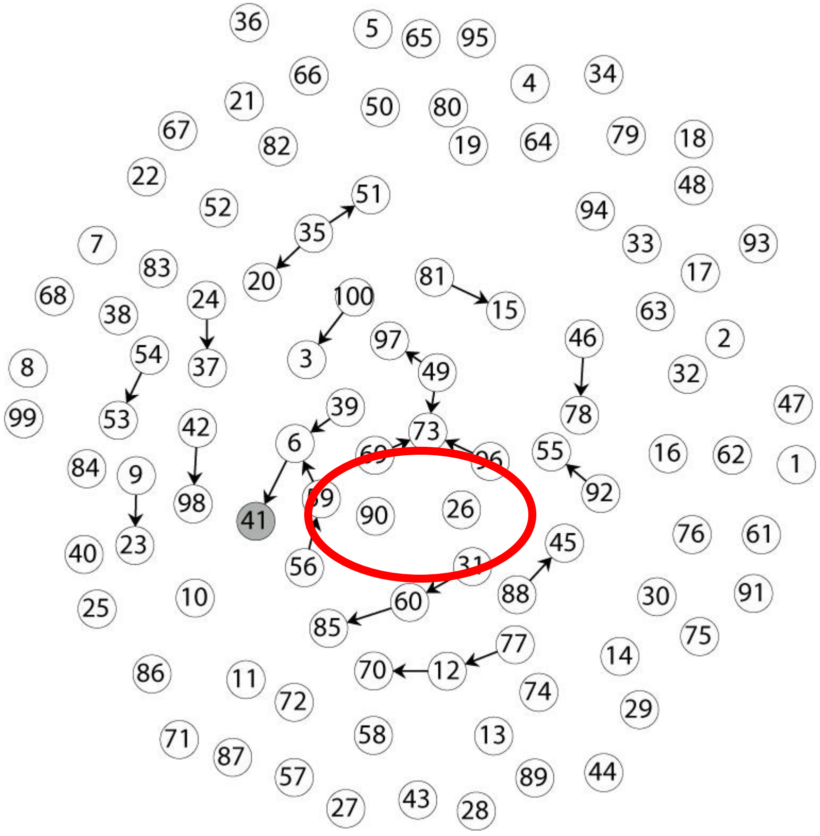


n = 79

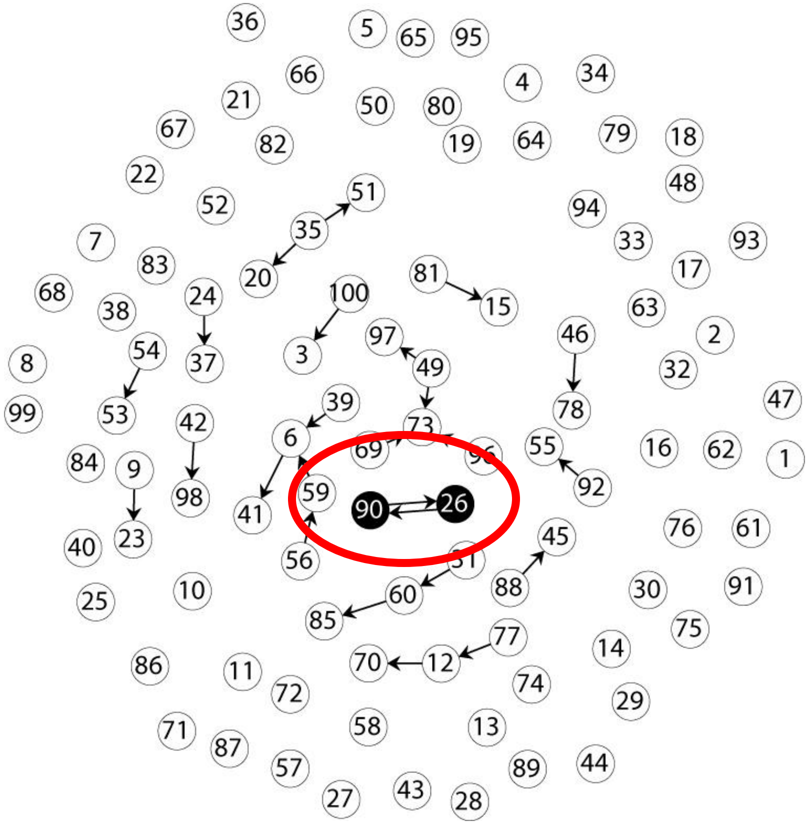


A random phase innovation: Uncaring and unviable (shortlived) winners

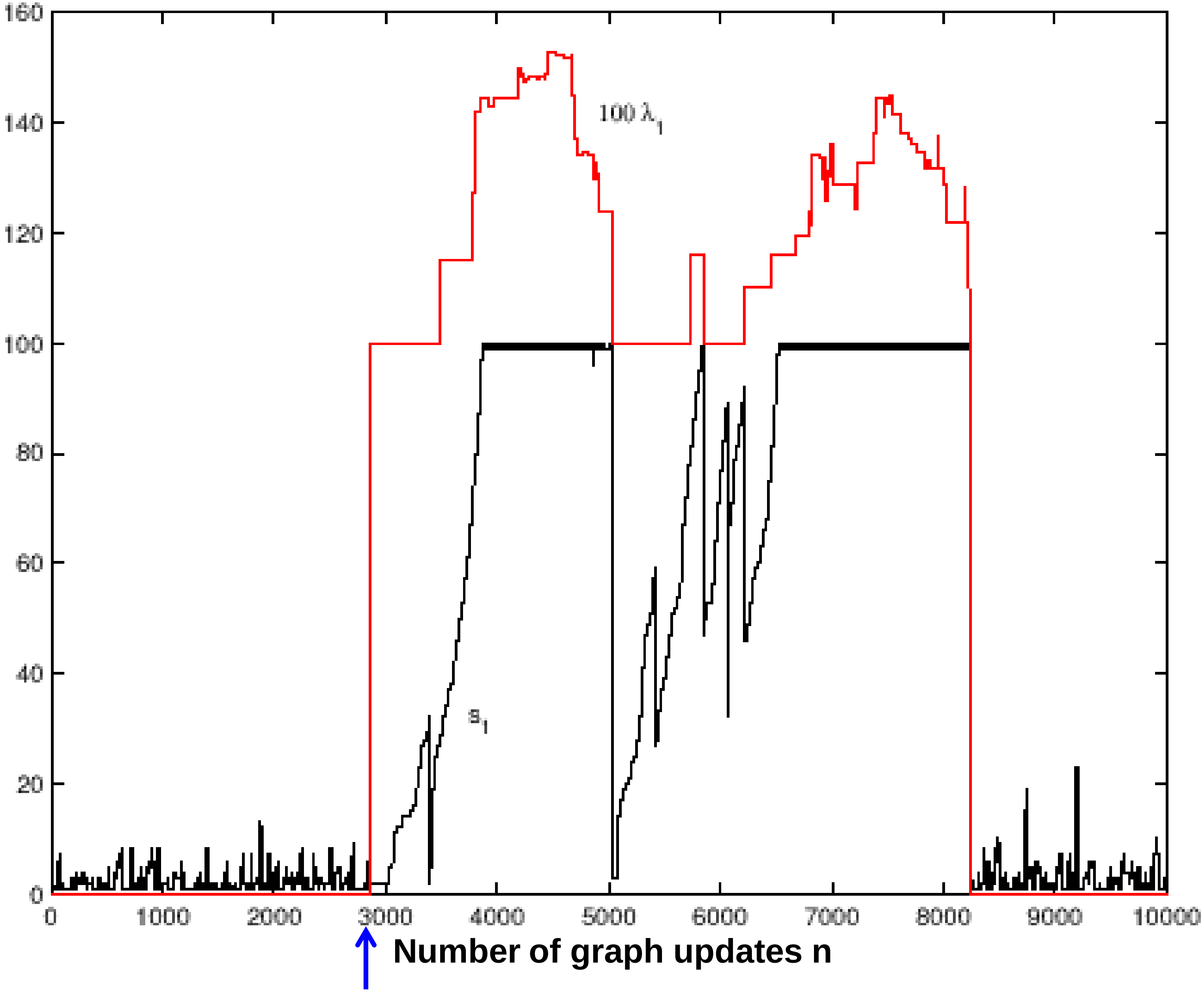
n = 2853



n = 2854



Birth of an organization: creation of the first ACS

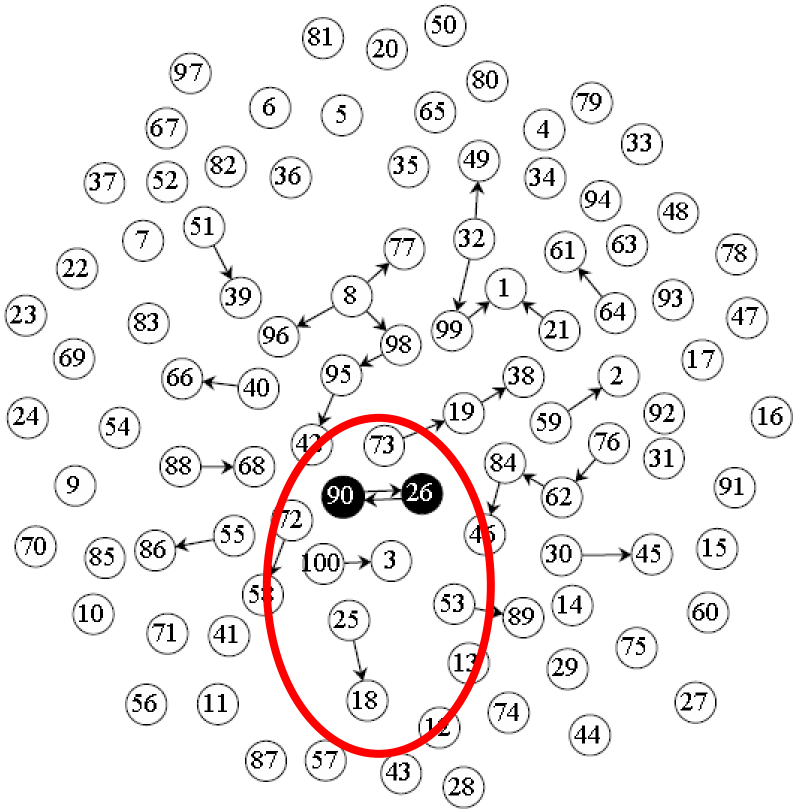


Number of graph updates n

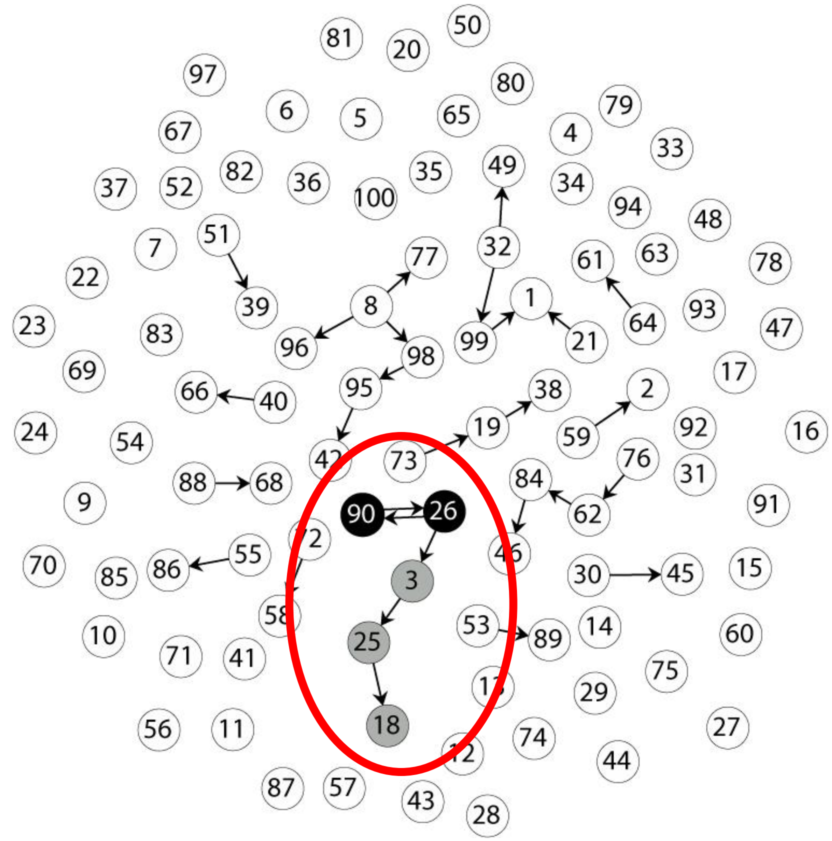
Black curve: Number of nodes with relative populations > 0

Red curve: Perron-Frobenius eigenvalue of the graph

n = 3021

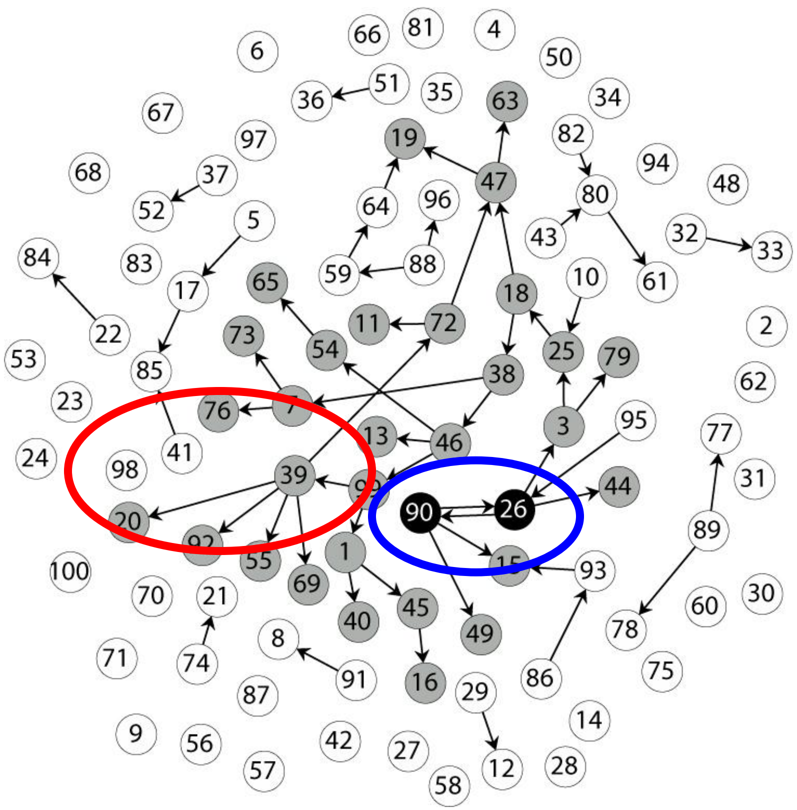


n = 3022

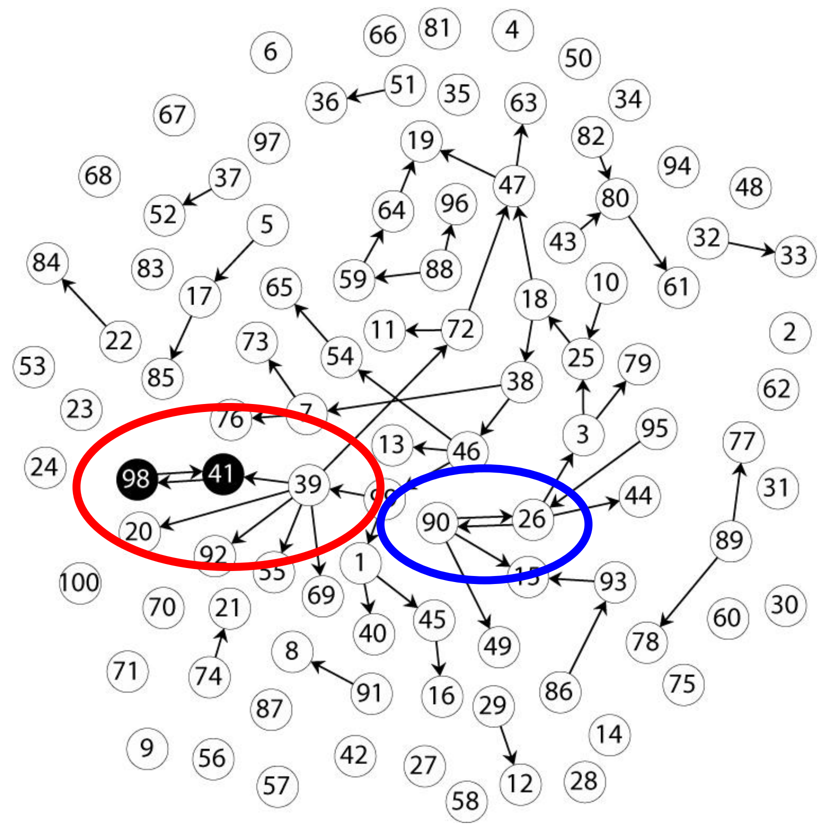


Expansion of the organization at its periphery: Incremental innovation

n = 3386

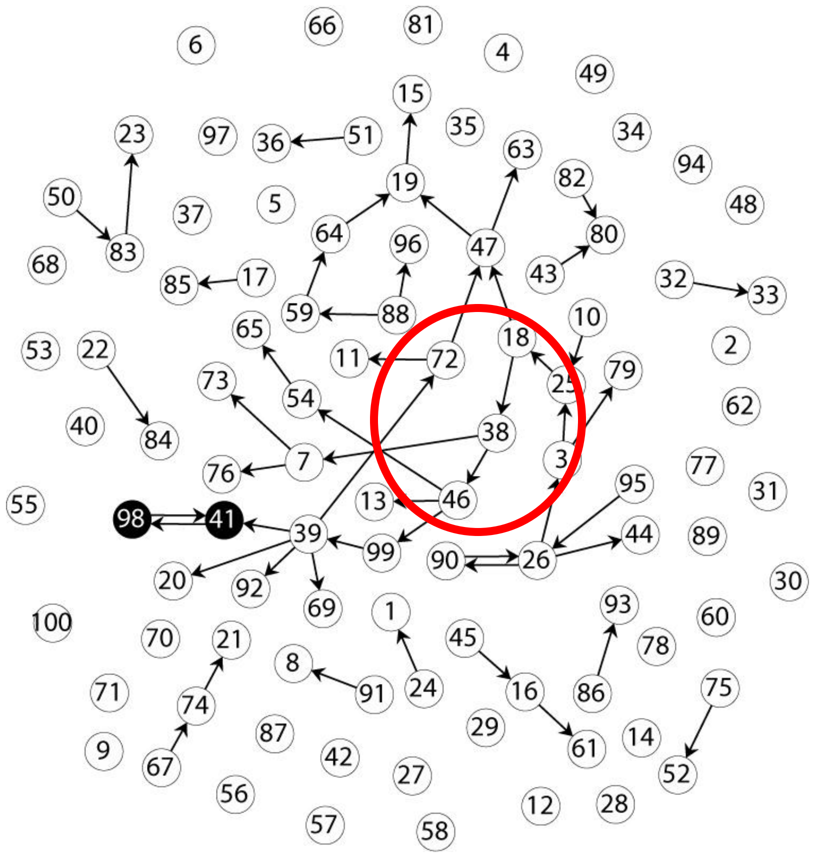


n = 3387

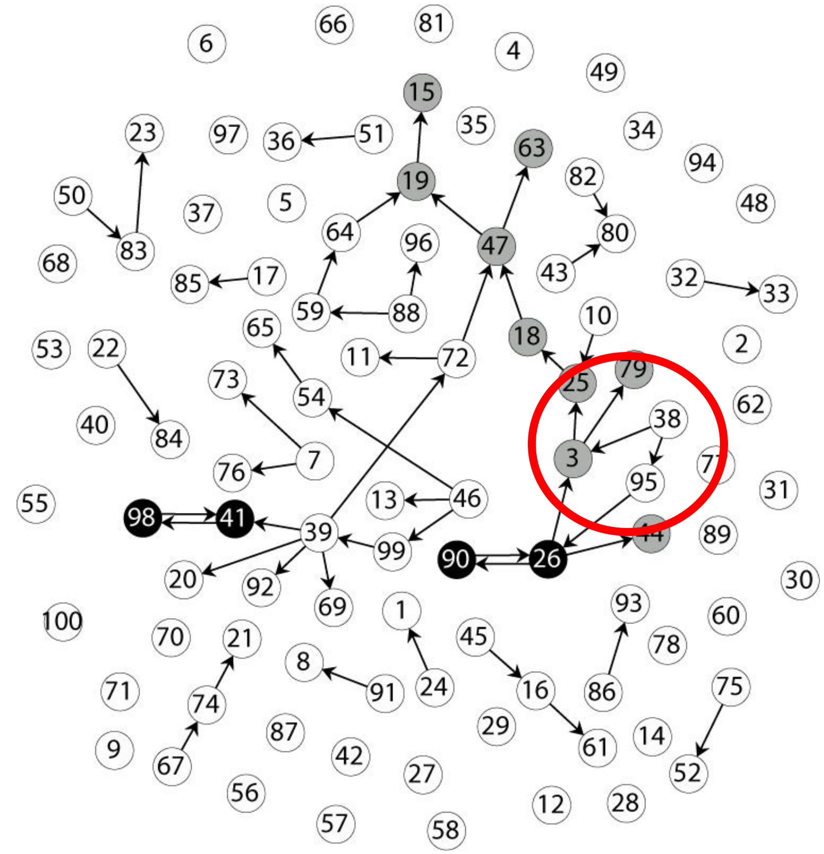


Core shift 1: Takeover by a new competitor

n = 3402

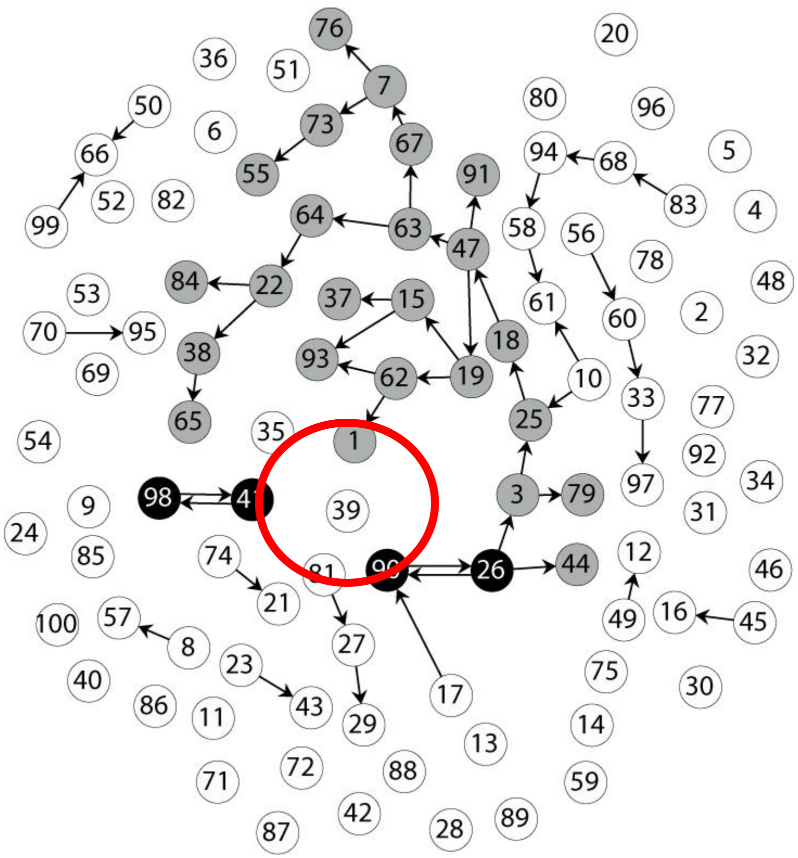


n = 3403

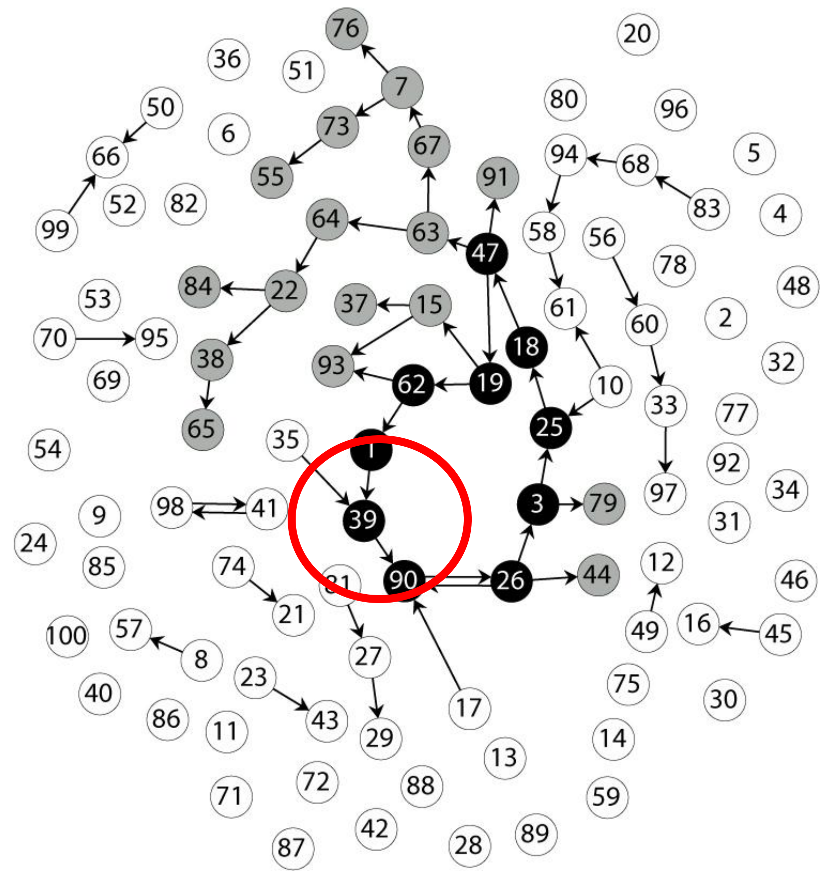


Revival of the old ACS

n = 3488

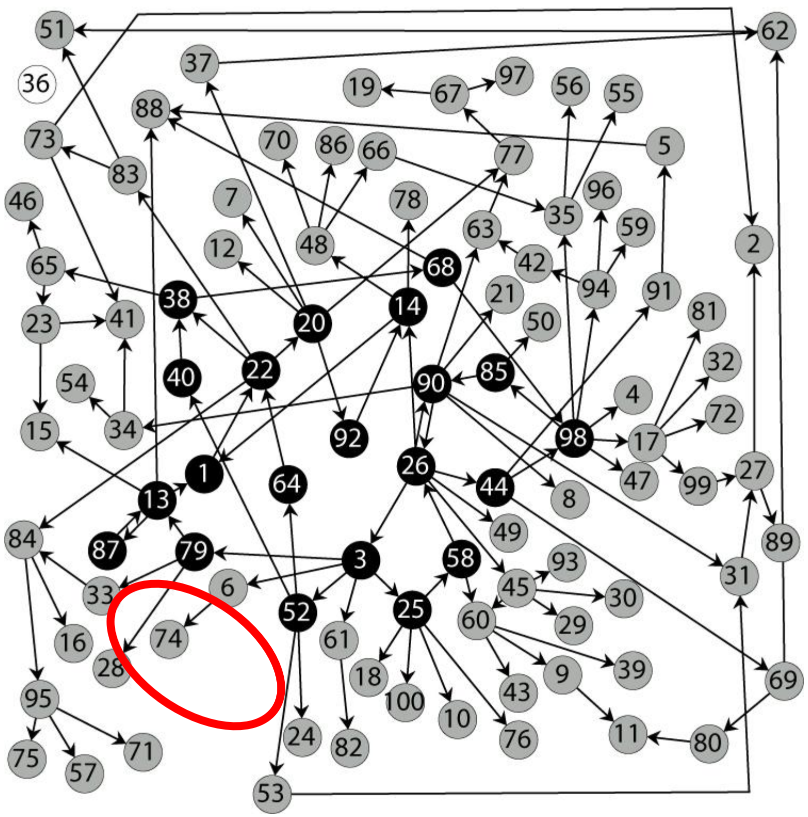


n = 3489

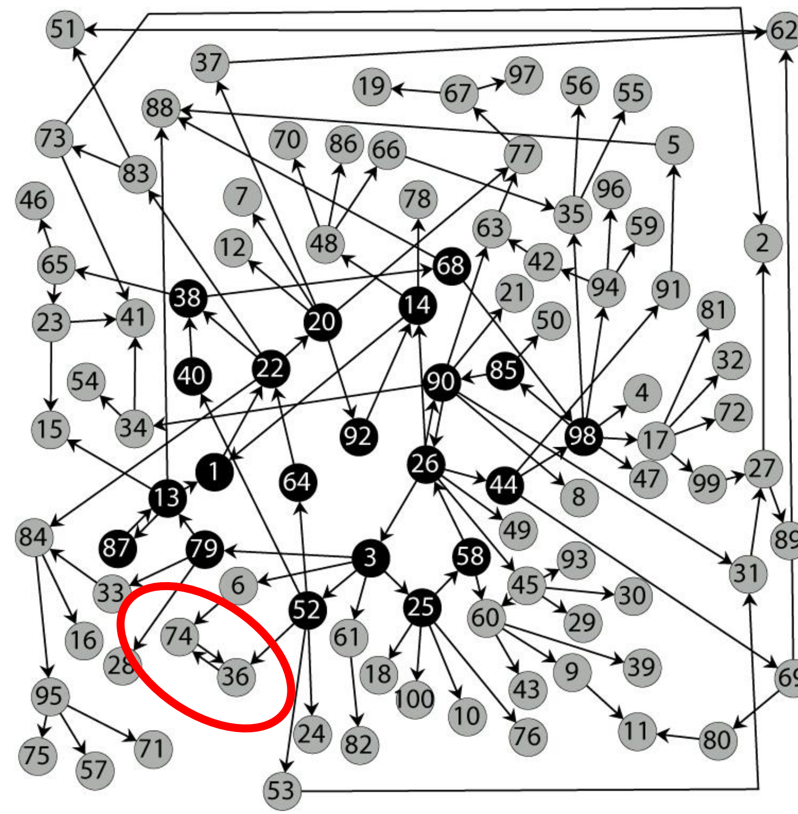


Growth of the core of the organization: Parasites become symbionts (core enhancing innovation)

n = 4695

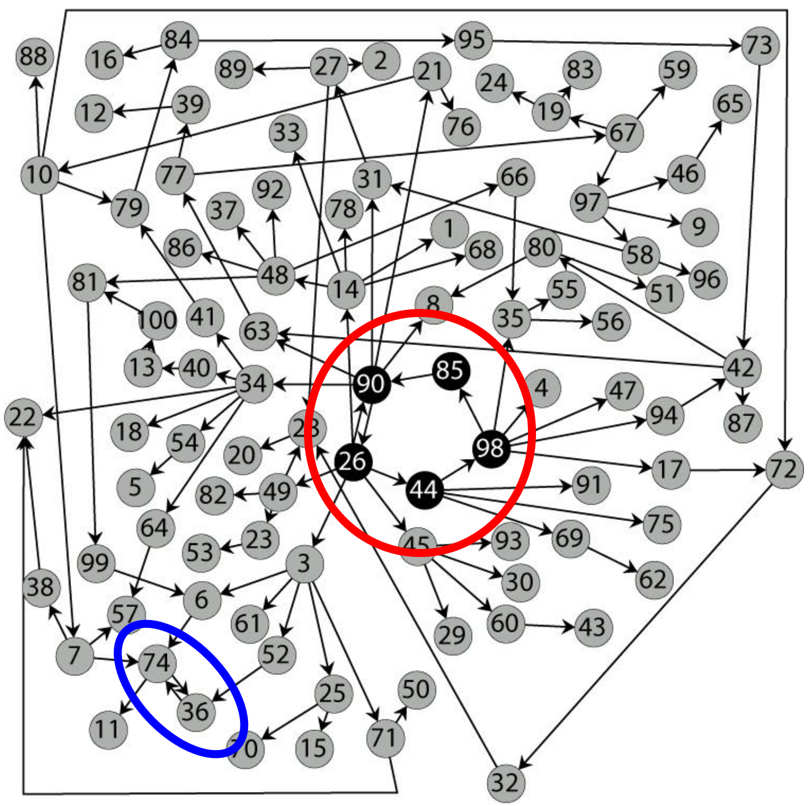


n = 4696

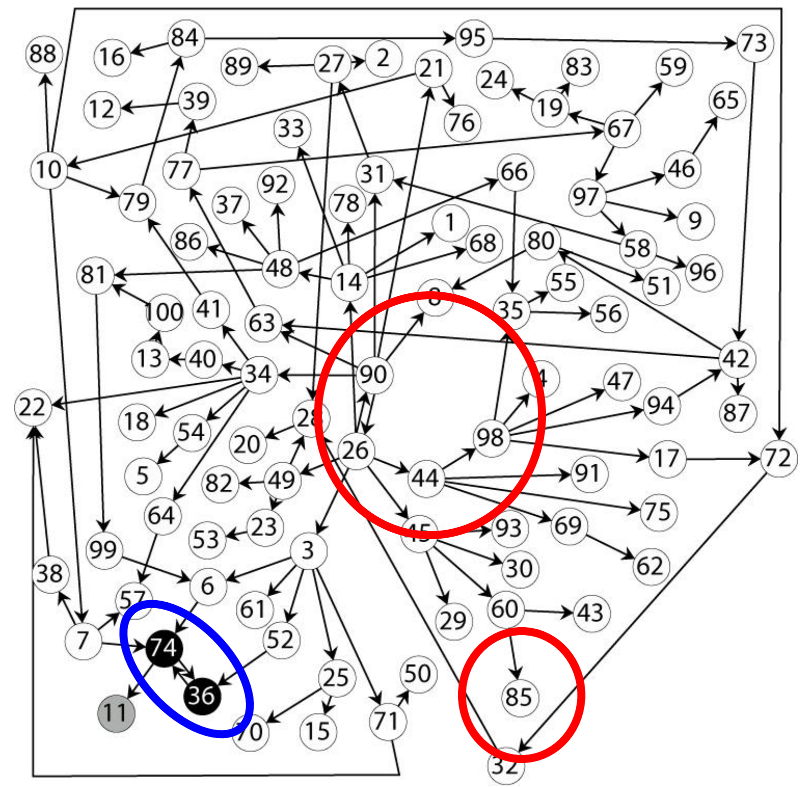


A small ACS appears in the periphery
(dormant innovation)

n = 5041



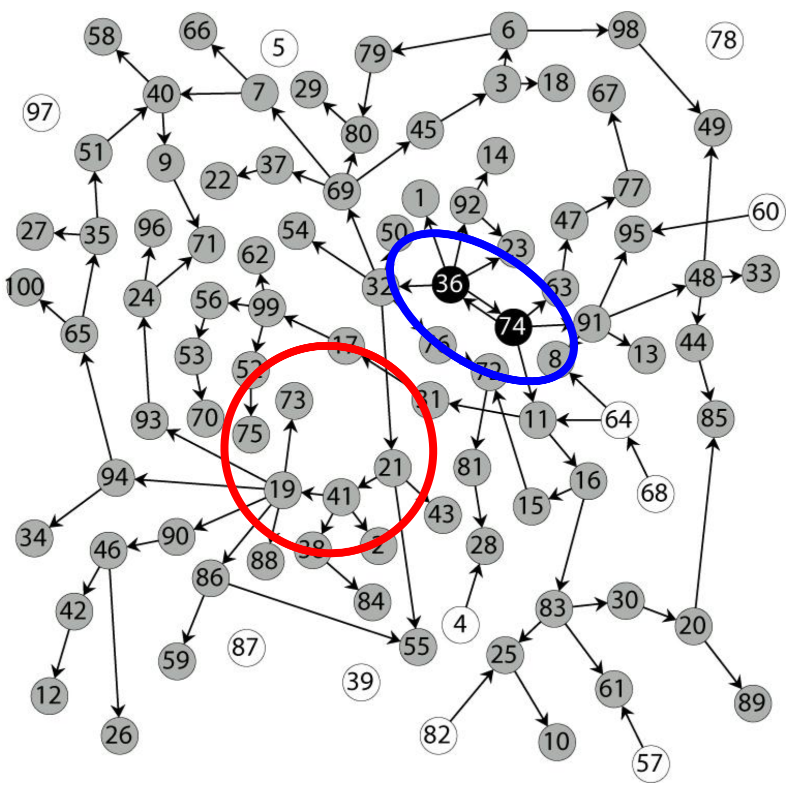
n = 5042



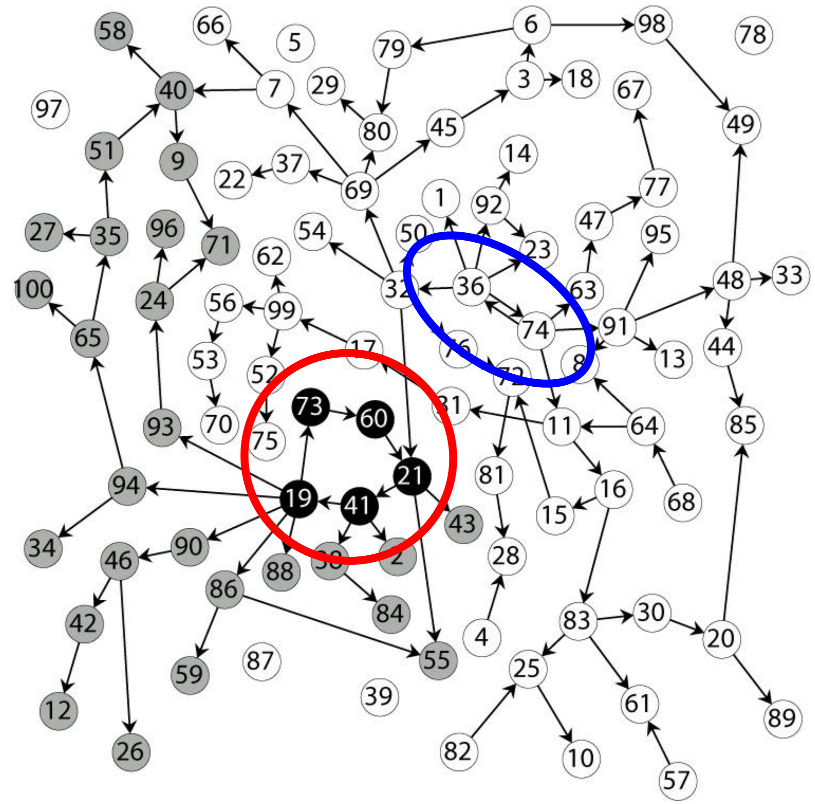
Core shift 2: Takeover by a dormant innovation

The flourishing of dormant phyla after the Permian extinction.

n = 6061

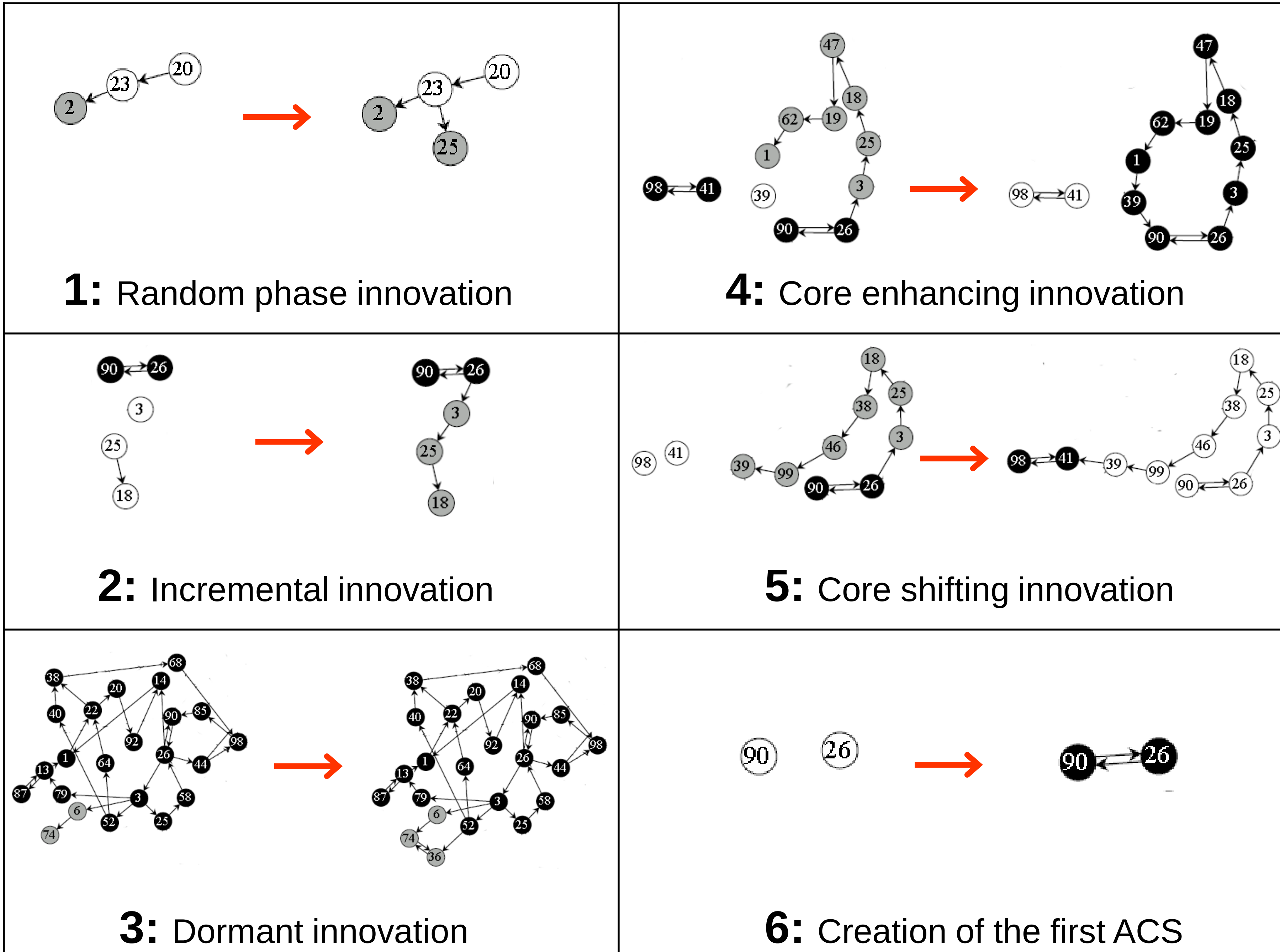


n = 6062



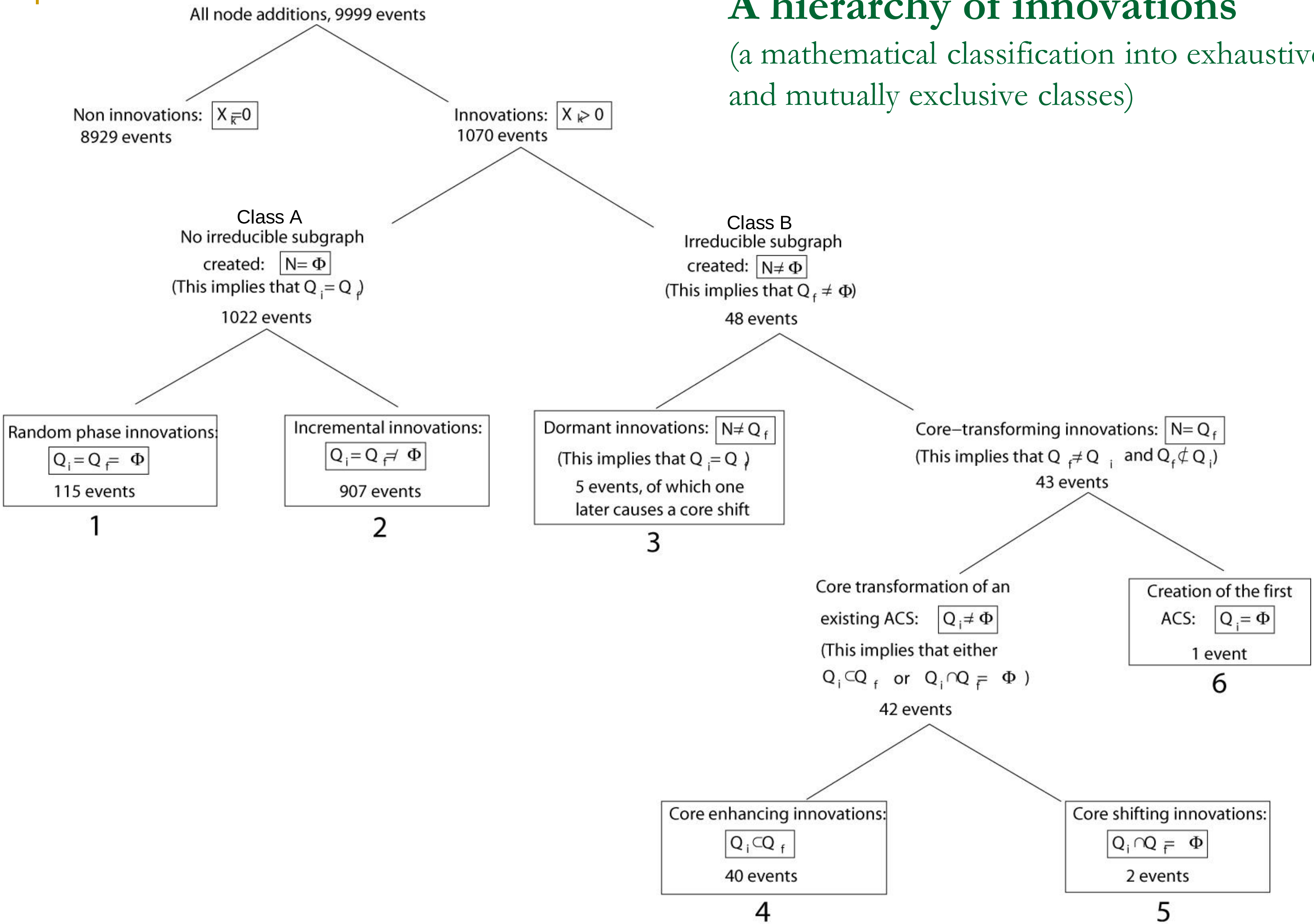
Another example of a core shifting innovation

The automobile causes the demise of the horse drawn carriage industry


1: Random phase innovation
4: Core enhancing innovation
2: Incremental innovation
5: Core shifting innovation
3: Dormant innovation
6: Creation of the first ACS

A hierarchy of innovations

(a mathematical classification into exhaustive and mutually exclusive classes)



Conclusions

- We have defined an innovation in structural-dynamical terms.
- The innovation depends on how the new node is linked to the existing nodes. Thus, it depends not only on the new links, but also on the 'context' in which the new node is embedded.
- Through a knowledge of how the node is linked to the existing graph we can qualitatively estimate the impact of this innovation.
- Innovations that modify the dynamics (flow patterns) on the network have the maximum impact. Typically these are those innovations that create new feedback loops.