Finding Hidden Structure in Complex Networks

Yong-Yeol "YY" Ahn
@yy

SCHOOL OF INFORMATICS AND COMPUTING
INDIANA UNIVERSITY
Bloomington

When are we living?

Most populated countries

1,300,000,000+

1,200,000,000+

300,000,000+

Most populated countries

	1,300,000,000+
	1,200,000,000+
	900,000,000+
	500,000,000+
	300,000,000+

Billions of people

recording their social life

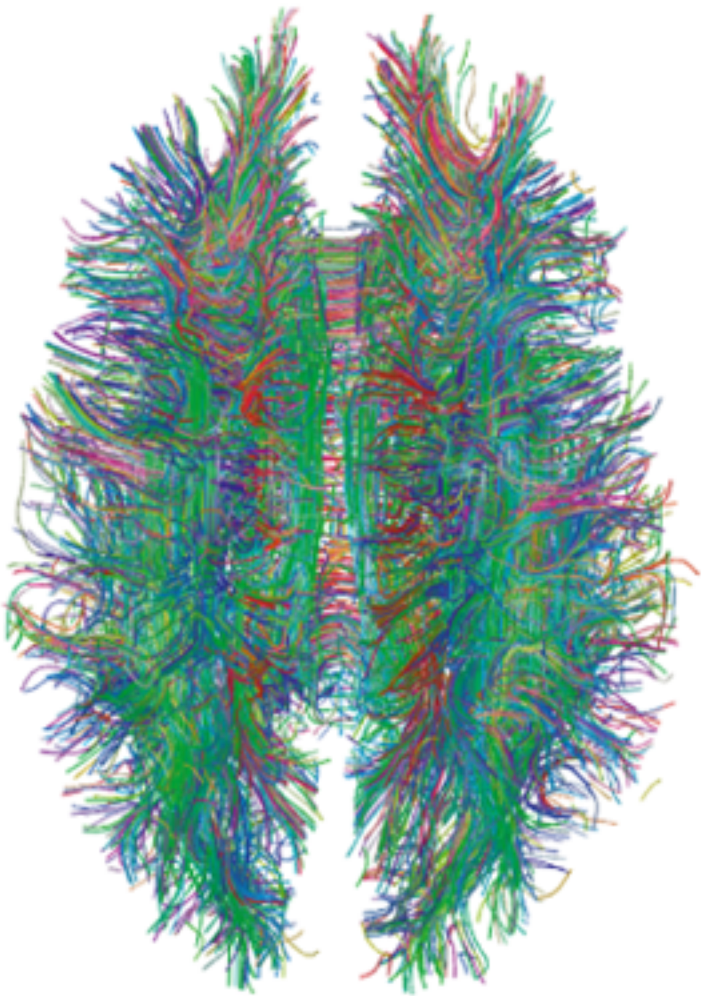
in **Bits**.

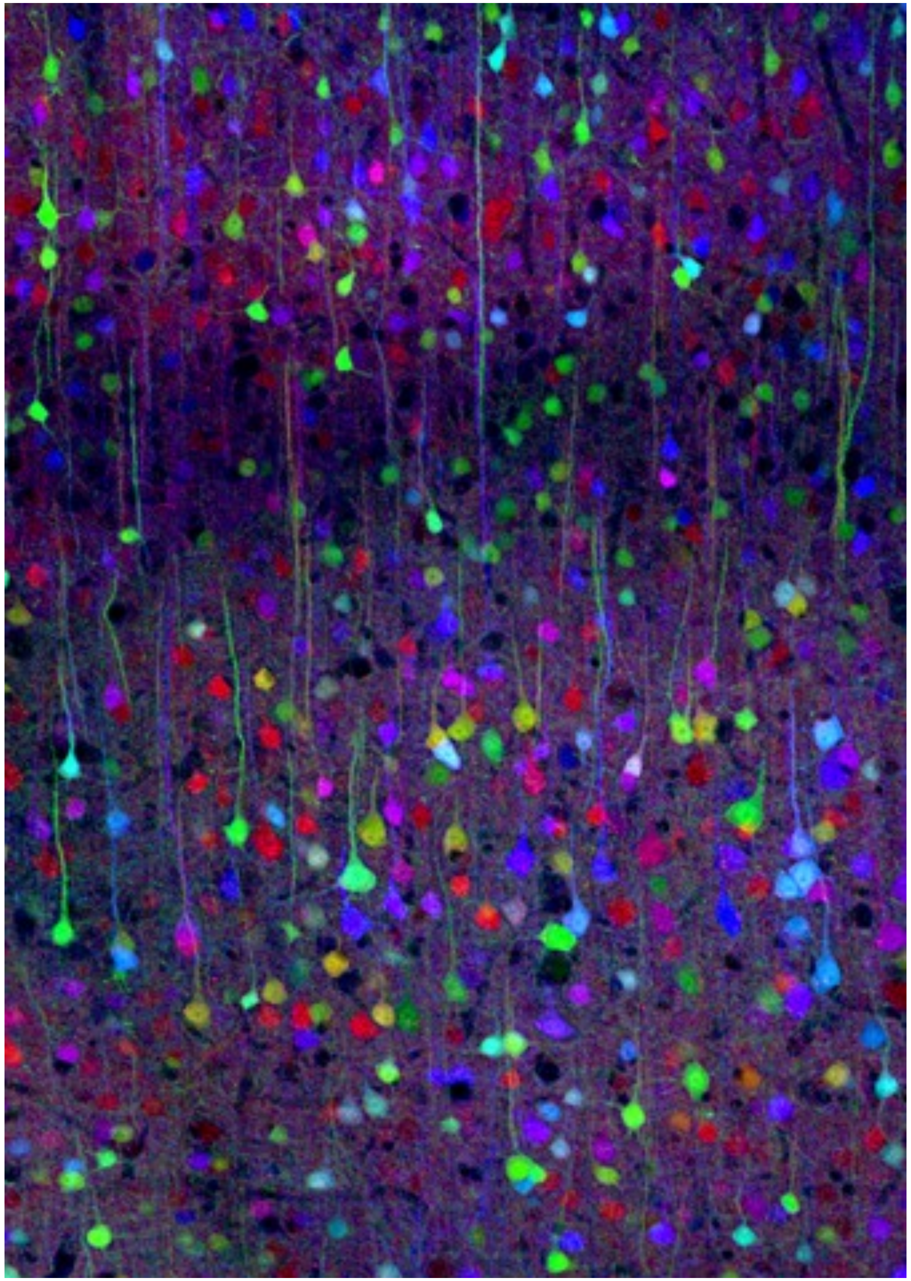
Billions of people

publishing their life.

40421551 40421561 40421571 40421581 40421591 40421601 40421611 40421621 40421631 40421641 40421651 40421661 40421671 40421681
tgagcagacctatataagatggttatgaagattcacacagcggctcatgcctgtgatcccagcactttgggaggctgaggcaagtggagcacctgagatcatgagttcaagaccagcctggccaacatggtgaaaccccatctcta


$1000





BIG DATA

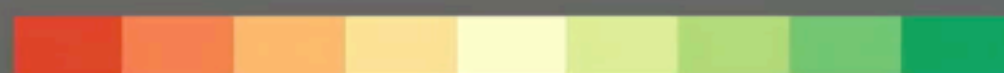
BIG DATA

↓

INFORMATION


GOLD
"SWISS PRALINES"
NET WT
300g - 10.5oz
GOLDKENN

Pulse of the Nation:
U.S. Mood Throughout the Day inferred from Twitter

Less Happy  More Happy

http://www.ccs.neu.edu/home/amislove/twittermood

BIG DATA

SOCIETY

LIFE

BIG DATA

ECONOMY

LIFE
SOCIETY
ECONOMY

BIG DATA

LIFE
SOCIETY
ECONOMY

BIG DATA

COMPLEX
SYSTEMS

COMPLEX SYSTEMS

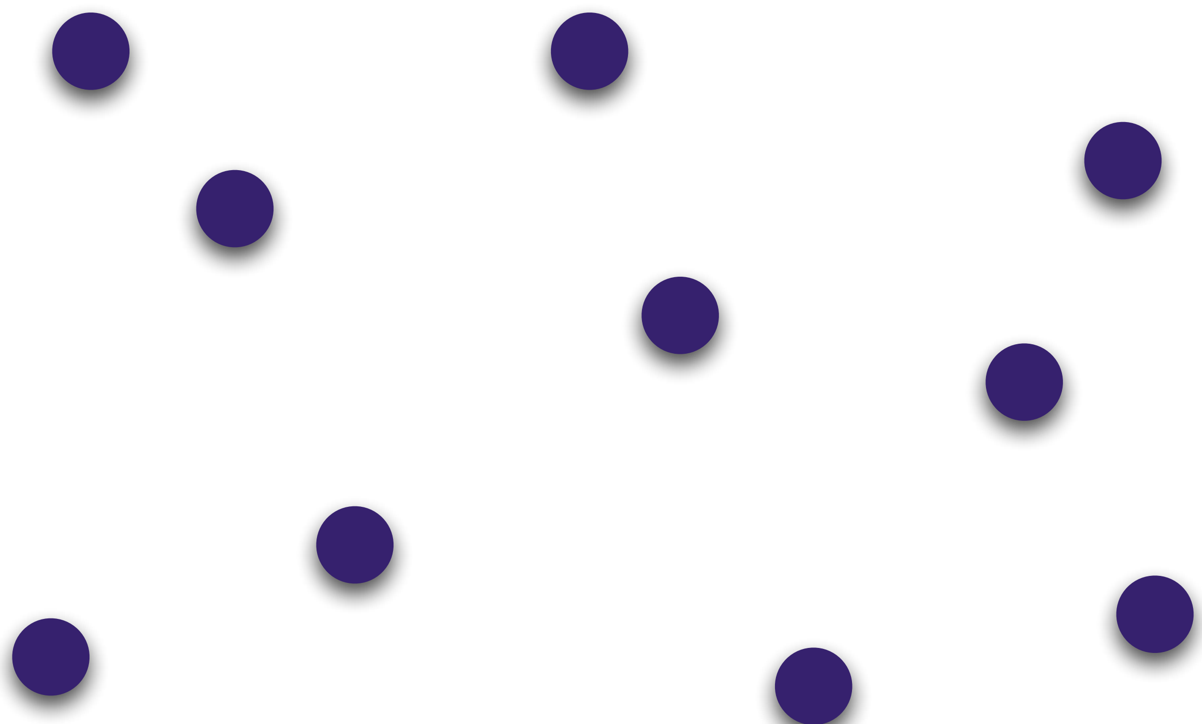
COMPLEX SYSTEMS

MANY parts,

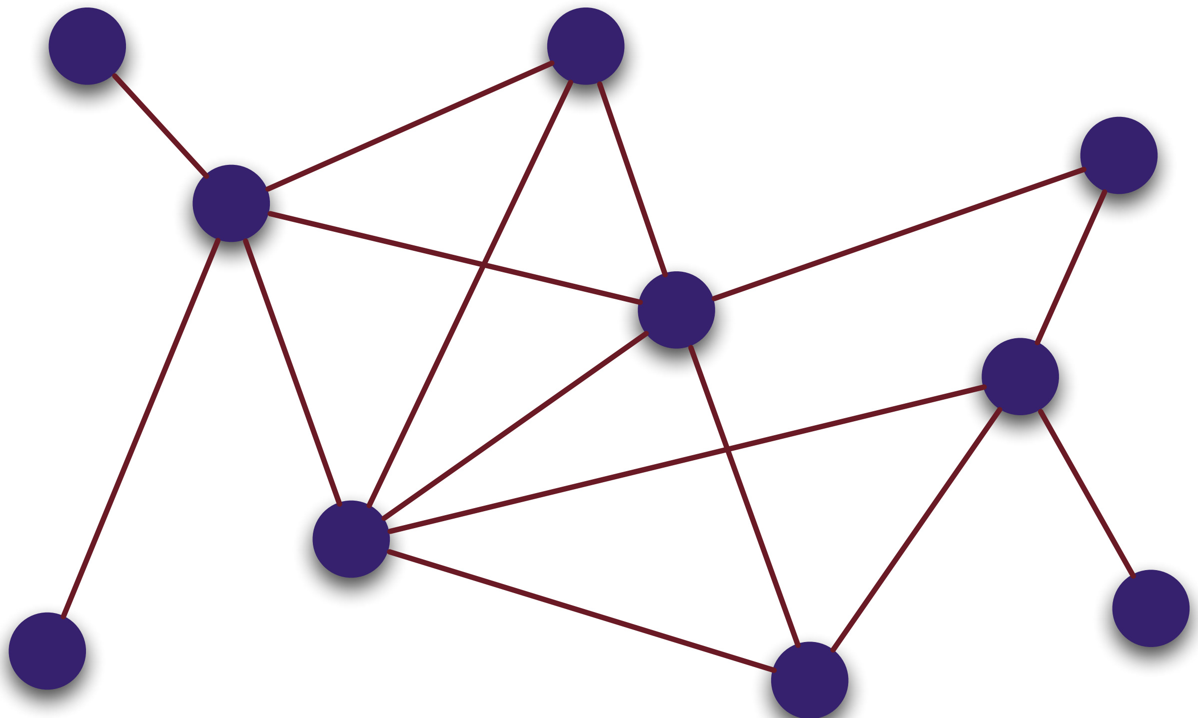
INTERACTING with each other

in **NON-TRIVIAL WAYS**

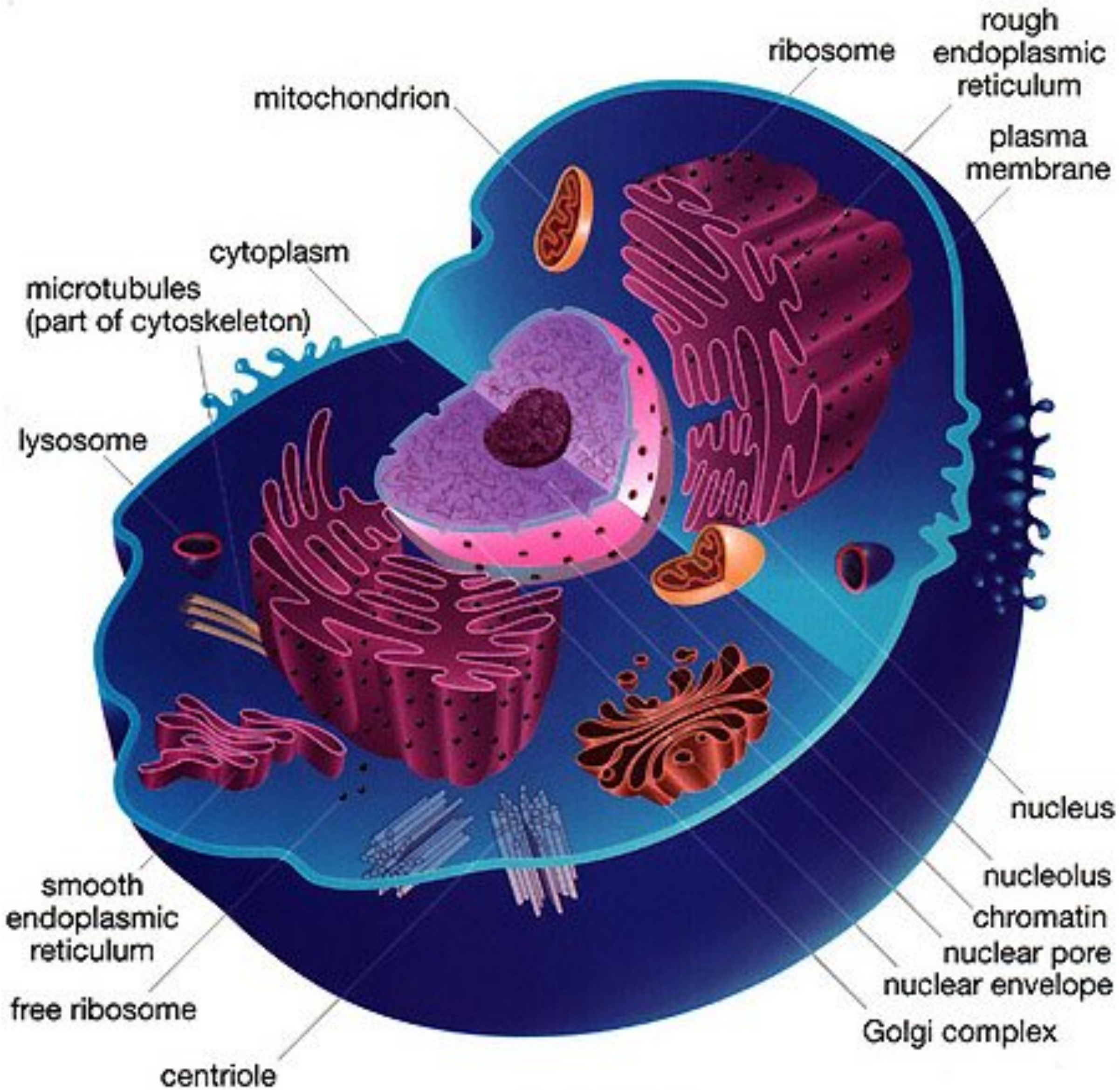
NETWORKS



Nodes

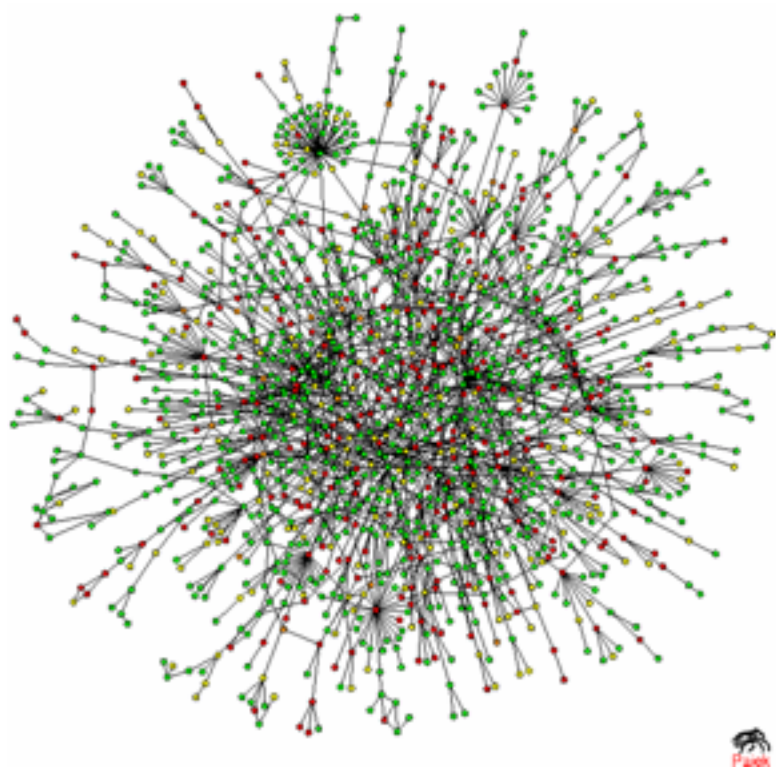


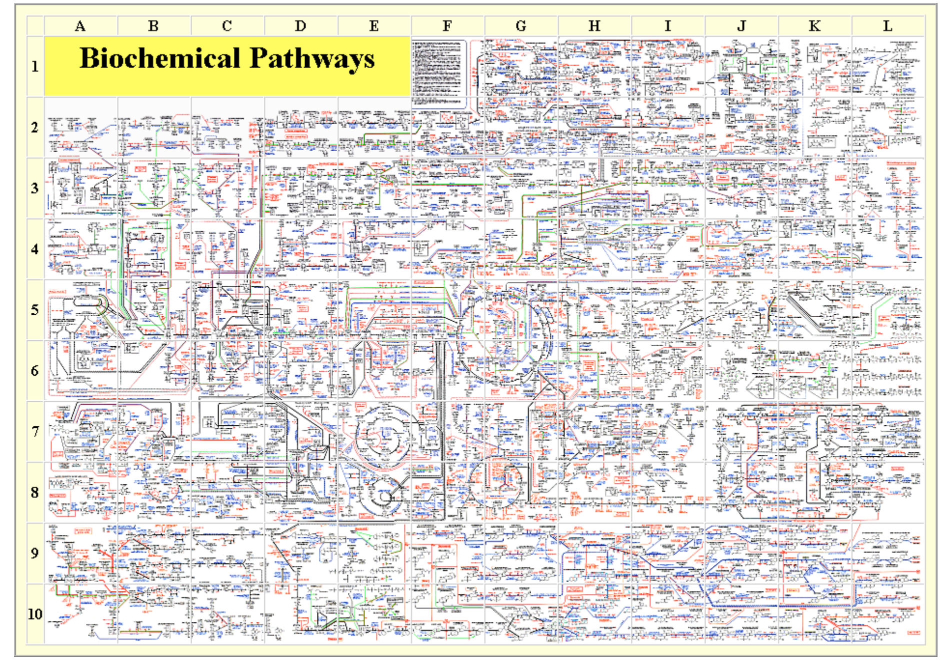
Links (edges) between nodes

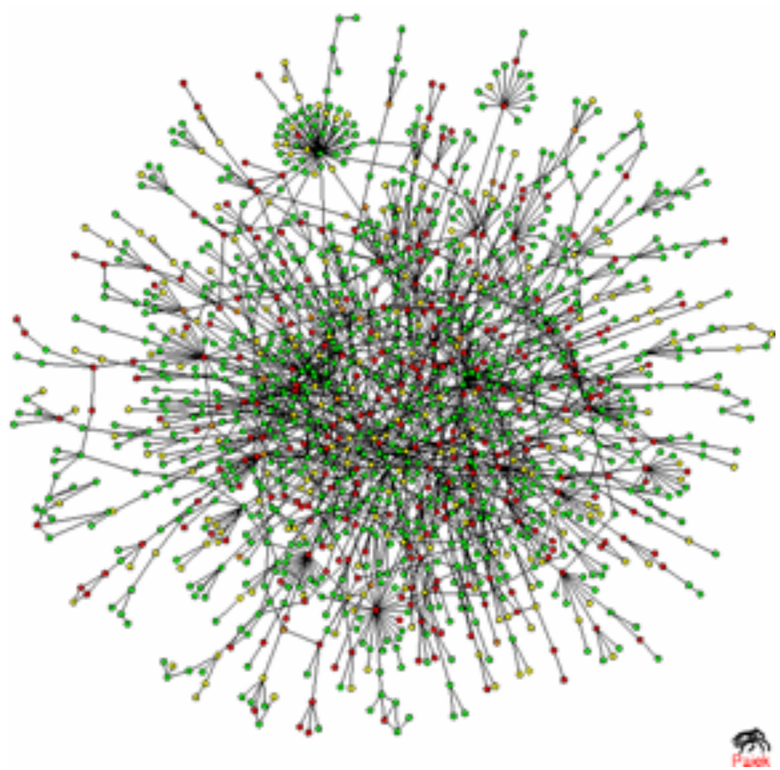

ribosome
rough endoplasmic reticulum
mitochondrion
plasma membrane
cytoplasm
microtubules (part of cytoskeleton)
lysosome
nucleus
nucleolus
chromatin
nuclear pore
nuclear envelope
Golgi complex
smooth endoplasmic reticulum
free ribosome
centriole

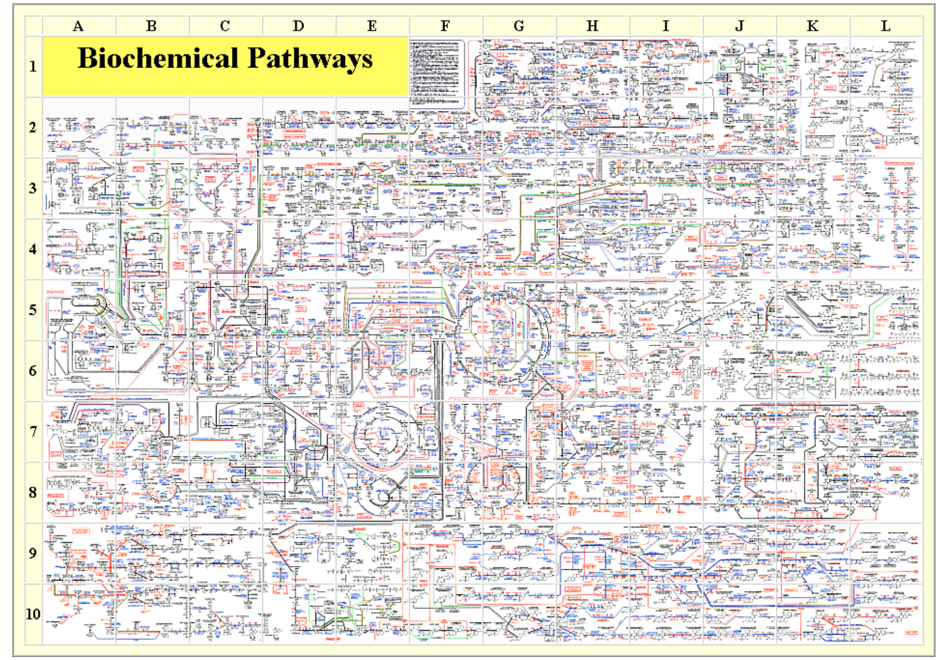
Immune response
Inflammatory response
Receptor activity
Developmental process
Receptor linked signal transduction
TBP
Cell adhesion
Plasma membrane
Regulation of signal transduction
Vacuole
Lysosome
PU.1
RNA splicing
FOS/JUN
NRF1
Nucleus
Transcription factor activity
Regulation of transcription
Response to chemical stimulus
YY1
NFYA,B,C
TFDP1
E2F1-5
Protein binding
MYB
Chromatin
Chromosome
Mitosis
Cell cycle
Microtubule cytoskeleton

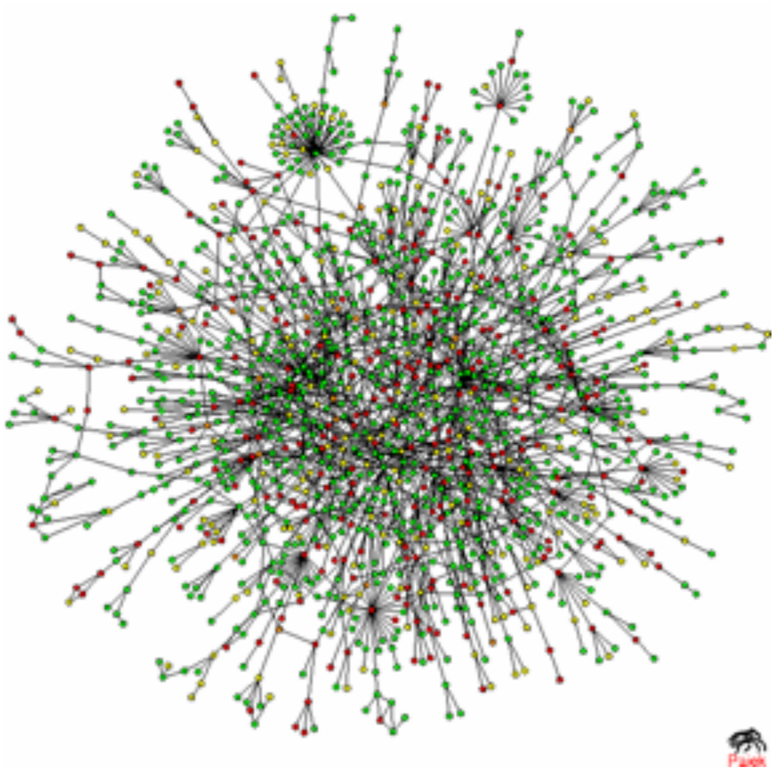

Immune response
Inflammatory response
Receptor activity
Developmental process
Receptor linked signal transduction
TBP
Cell adhesion
Plasma membrane
Regulation of signal transduction
Vacuole
Lysosome
RNA splicing
NRF1
Nucleus
Transcription factor activity
Regulation of transcription
Response to chemical stimulus
NFYA,B,C
YY1
TFDP1
Protein binding
E2F1-5
MYB
Chromatin
Chromosome
Mitosis
Cell cycle
Microtubule cytoskeleton

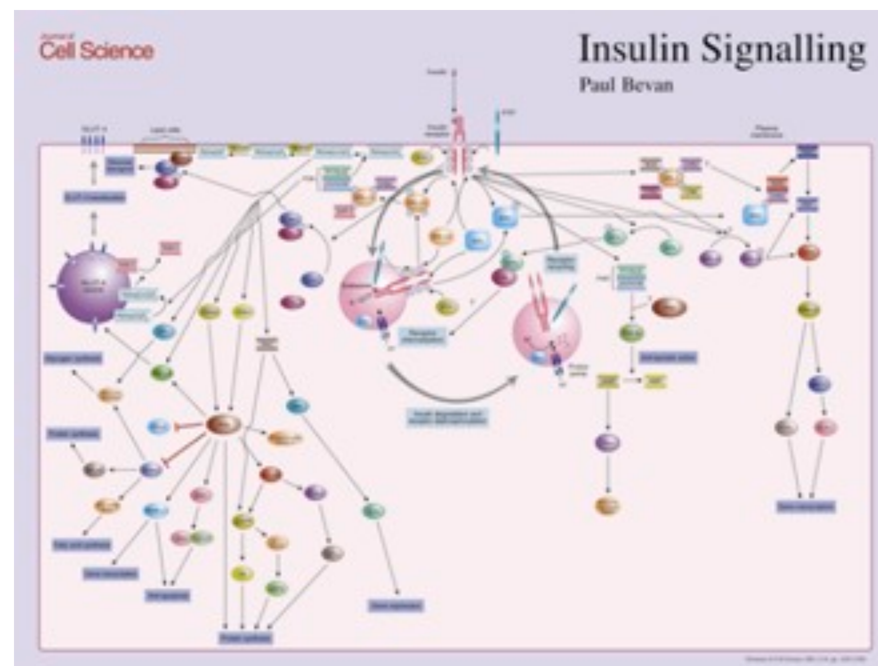

Pajek

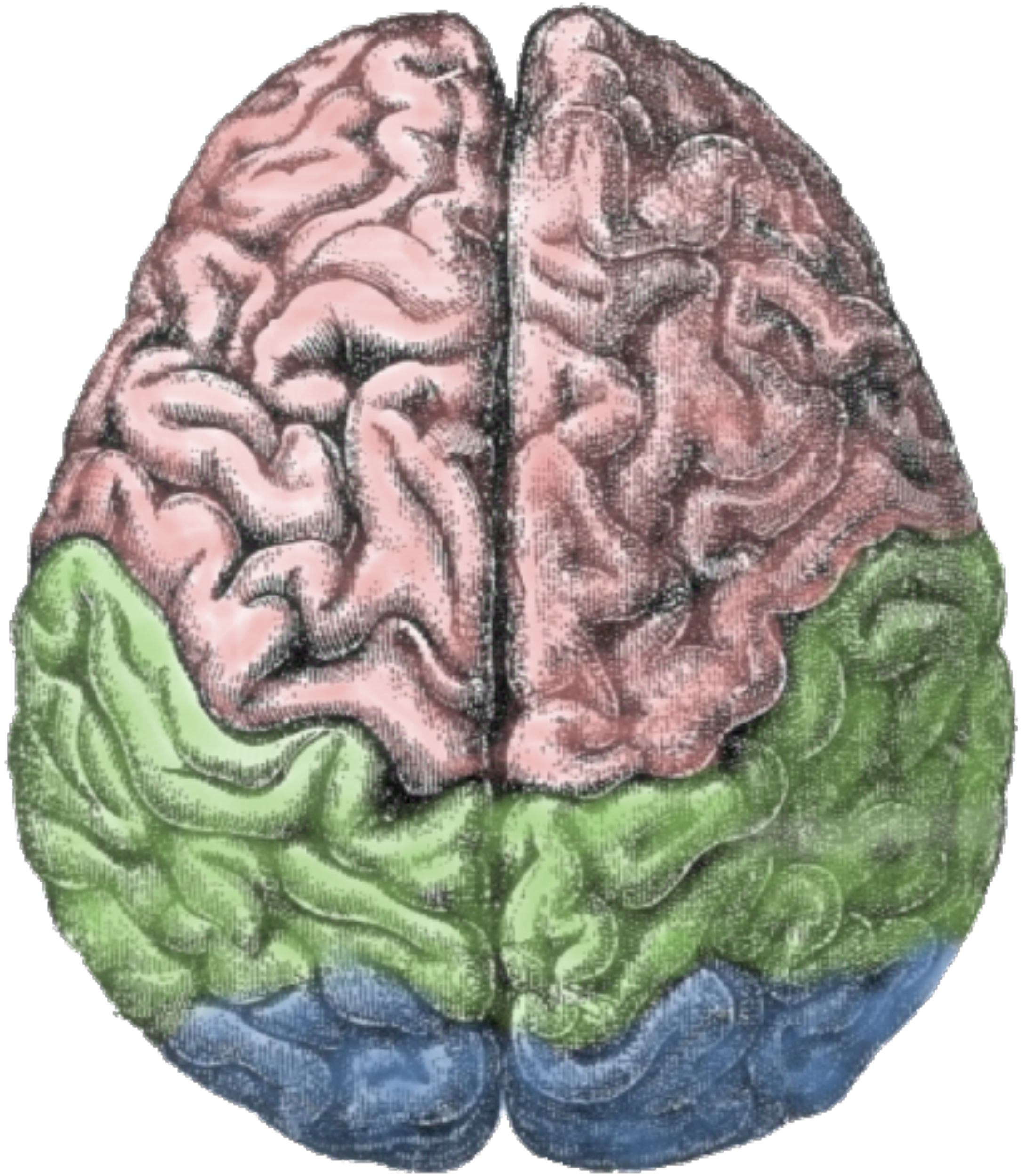

Biochemical Pathways



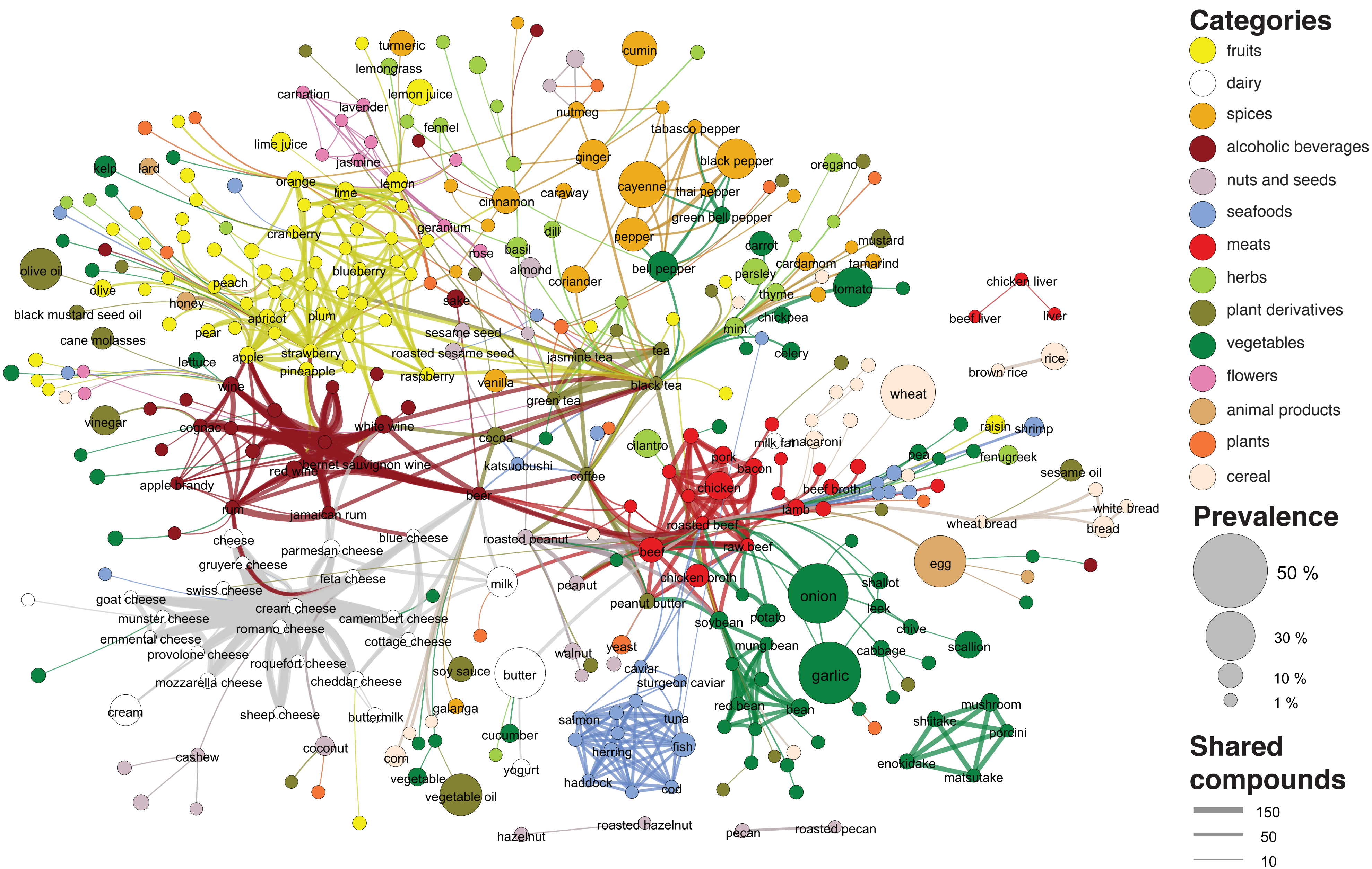

Biochemical Pathways
A B C D E F G H I J K L
1 2 3 4 5 6 7 8 9 10




Cell Science
Insulin Signalling
Paul Bevan



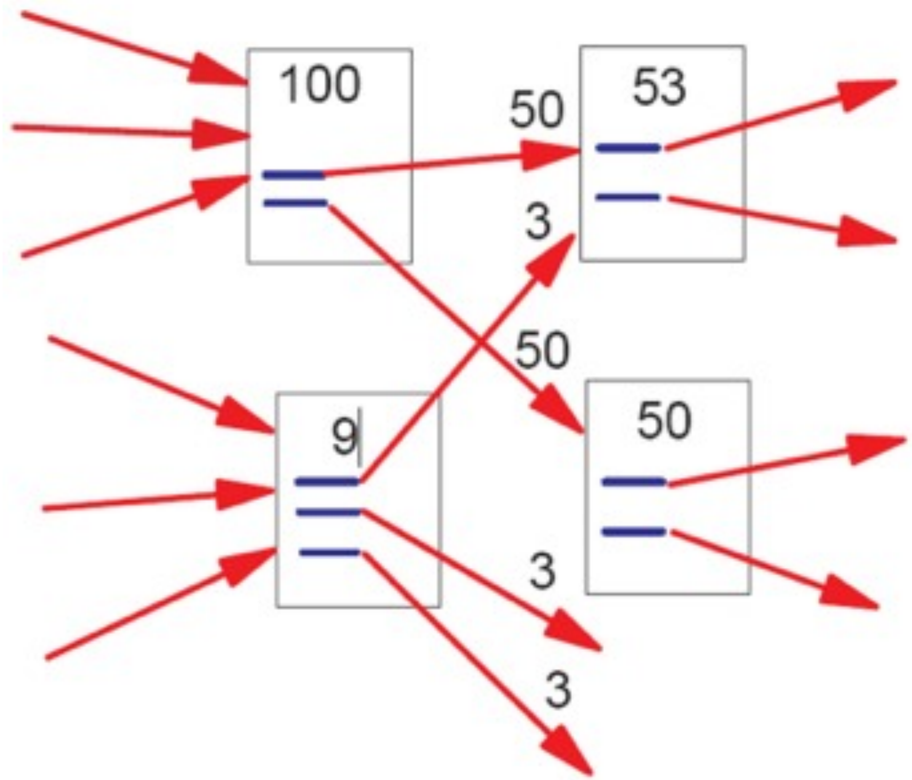

facebook
December 2010



Y.-Y. Ahn, S. Ahnert, J. P. Bagrow, A.-L. Barabási, *Sci. Rep.* 2011

So what?

Google



Pagerank =
Random walk problem on a network

Can we understand a
complex system

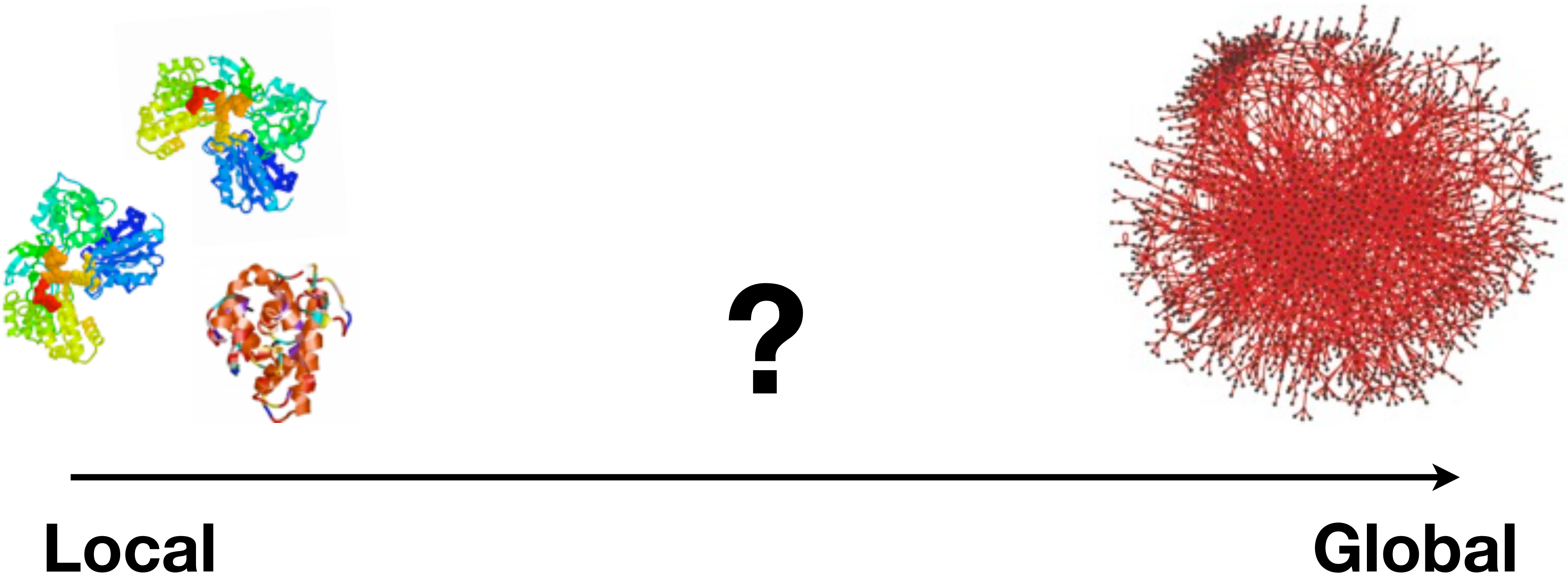
without knowing the **structure**
of it?

NETWORKS

Local **Global**


Local
Global


Local
Global


?
Local
Global

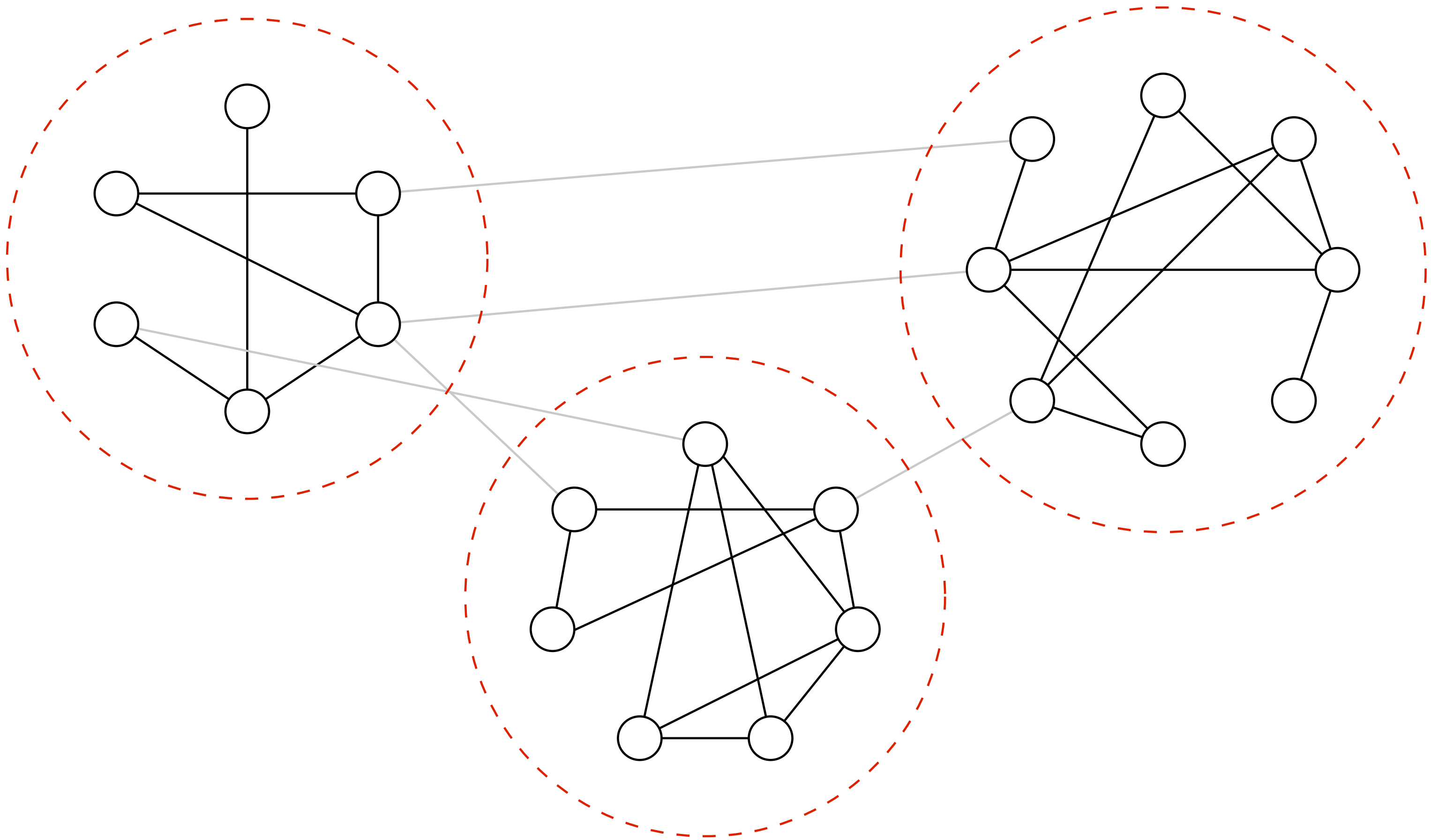
Network Communities

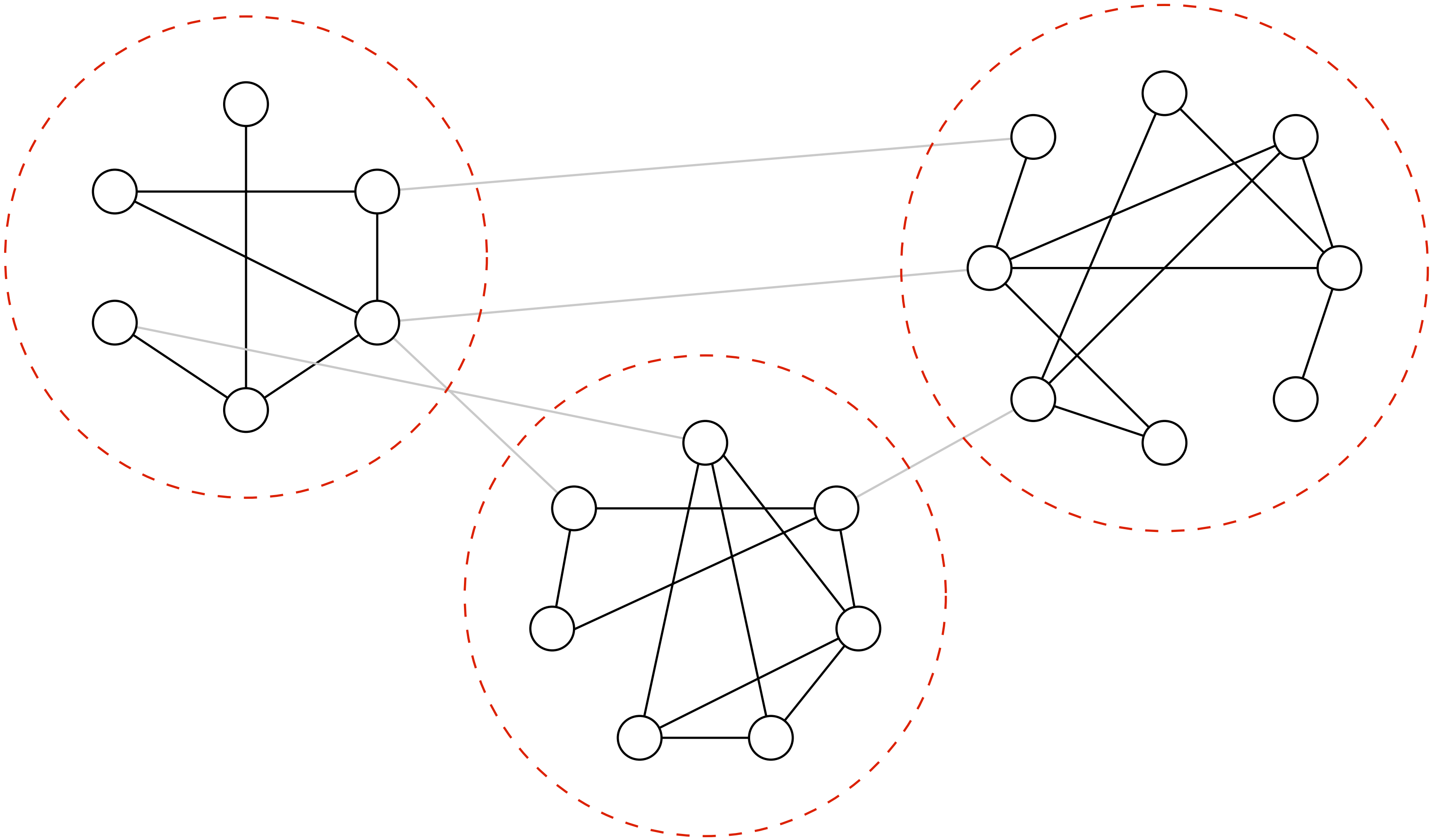
Communities

Biological modules

Social circles

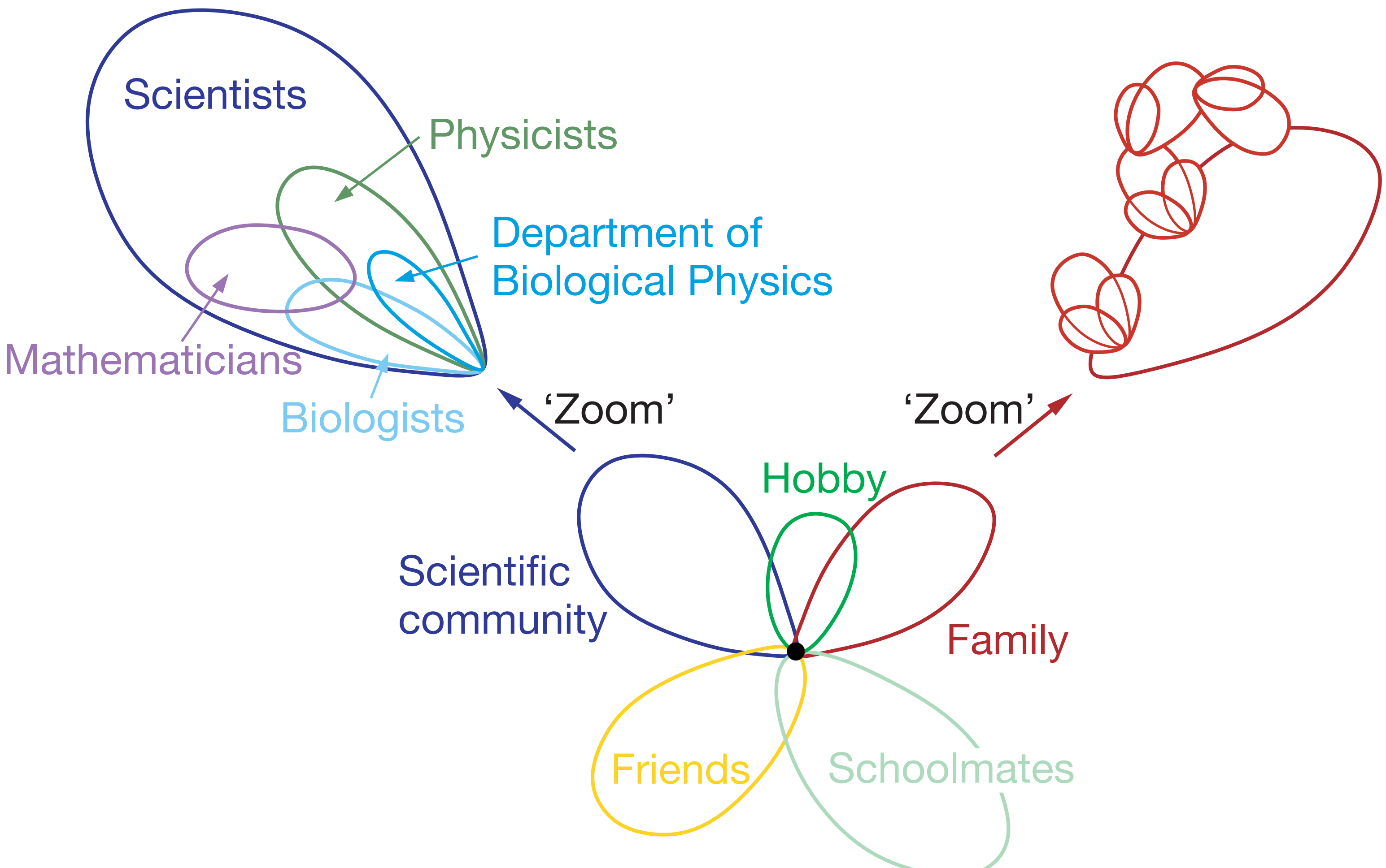
"a group of densely interconnected nodes" “a group of densely interconnected nodes”



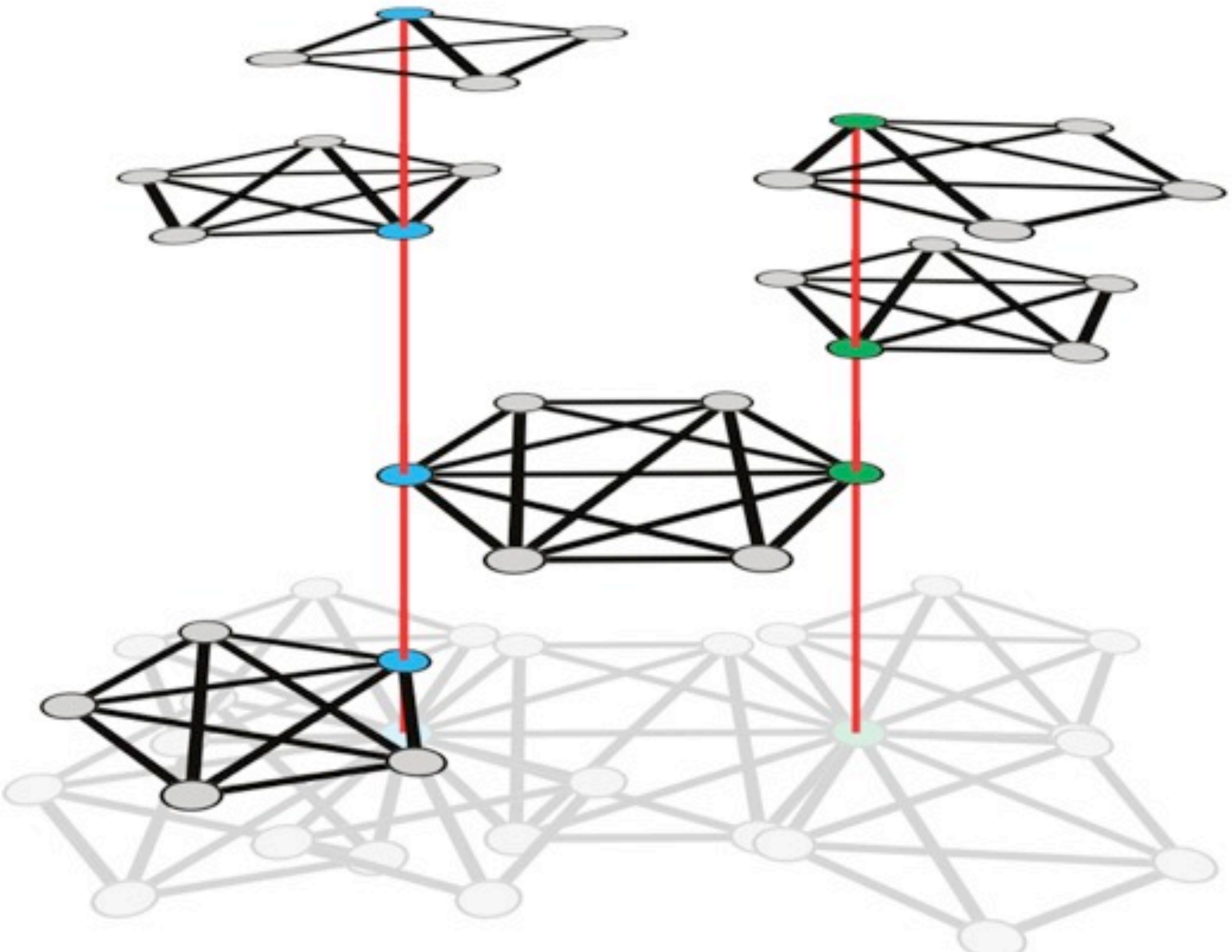


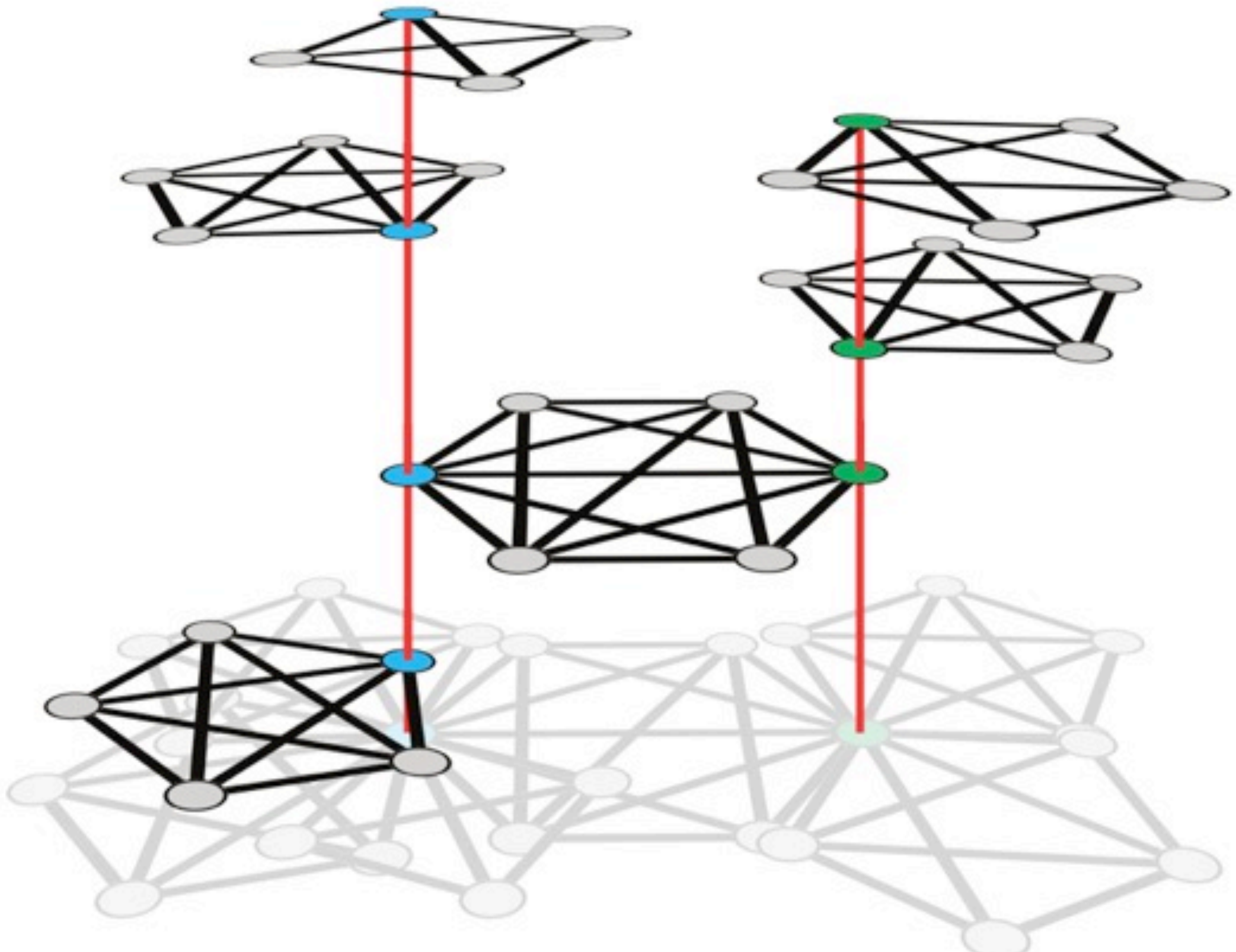
Hundreds of community detection methods

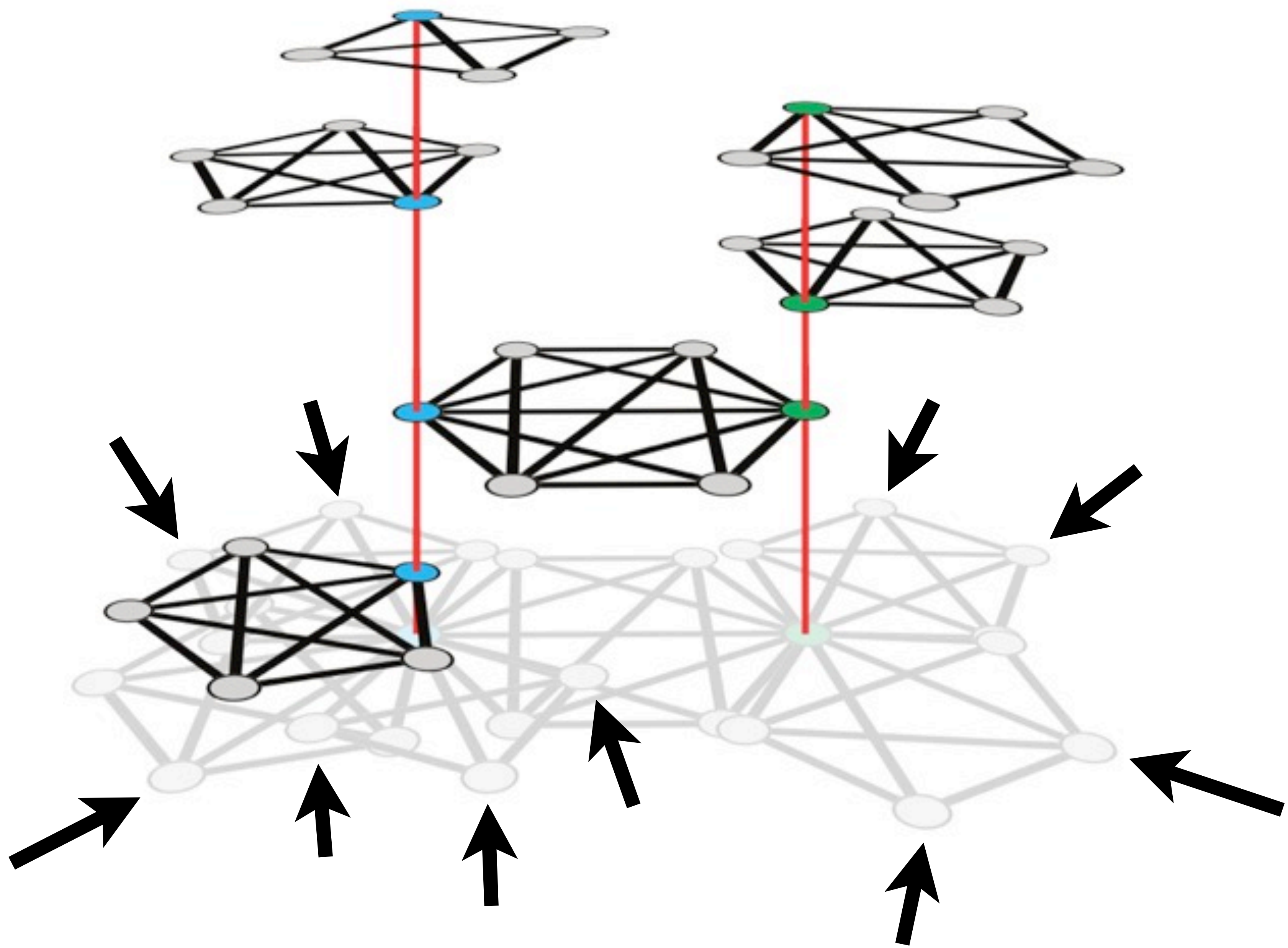
Then, why bother?



G. Palla, I. Derényi, I. Farkas & T. Vicsek, *Nature* (2005)

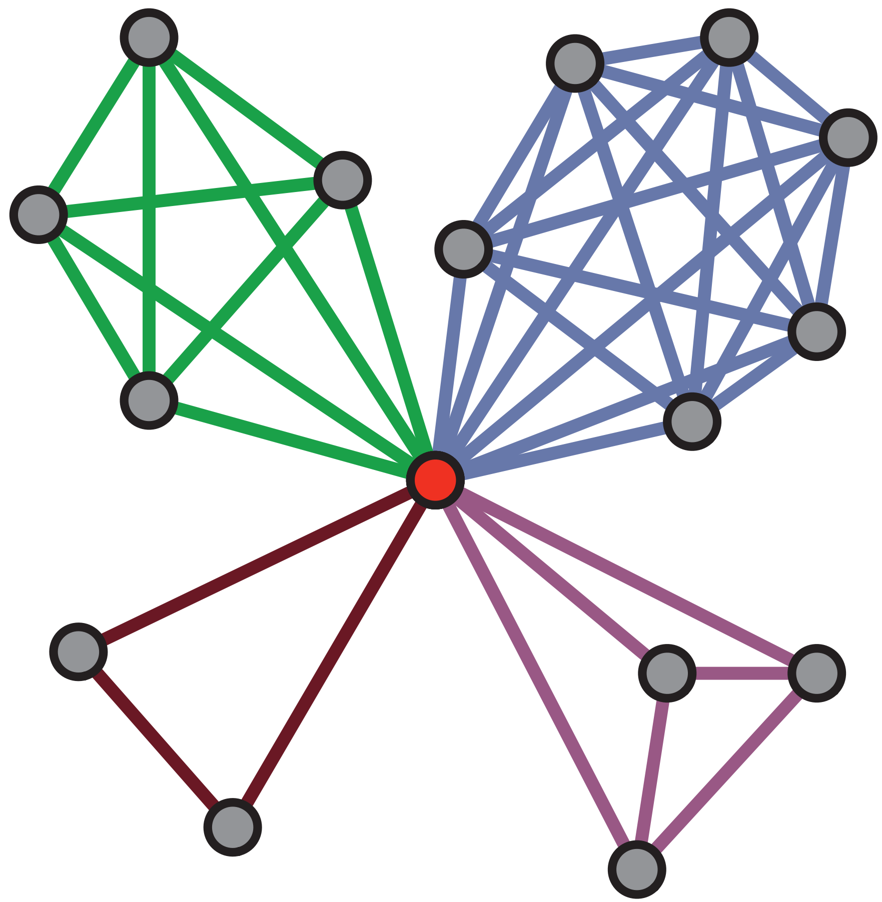




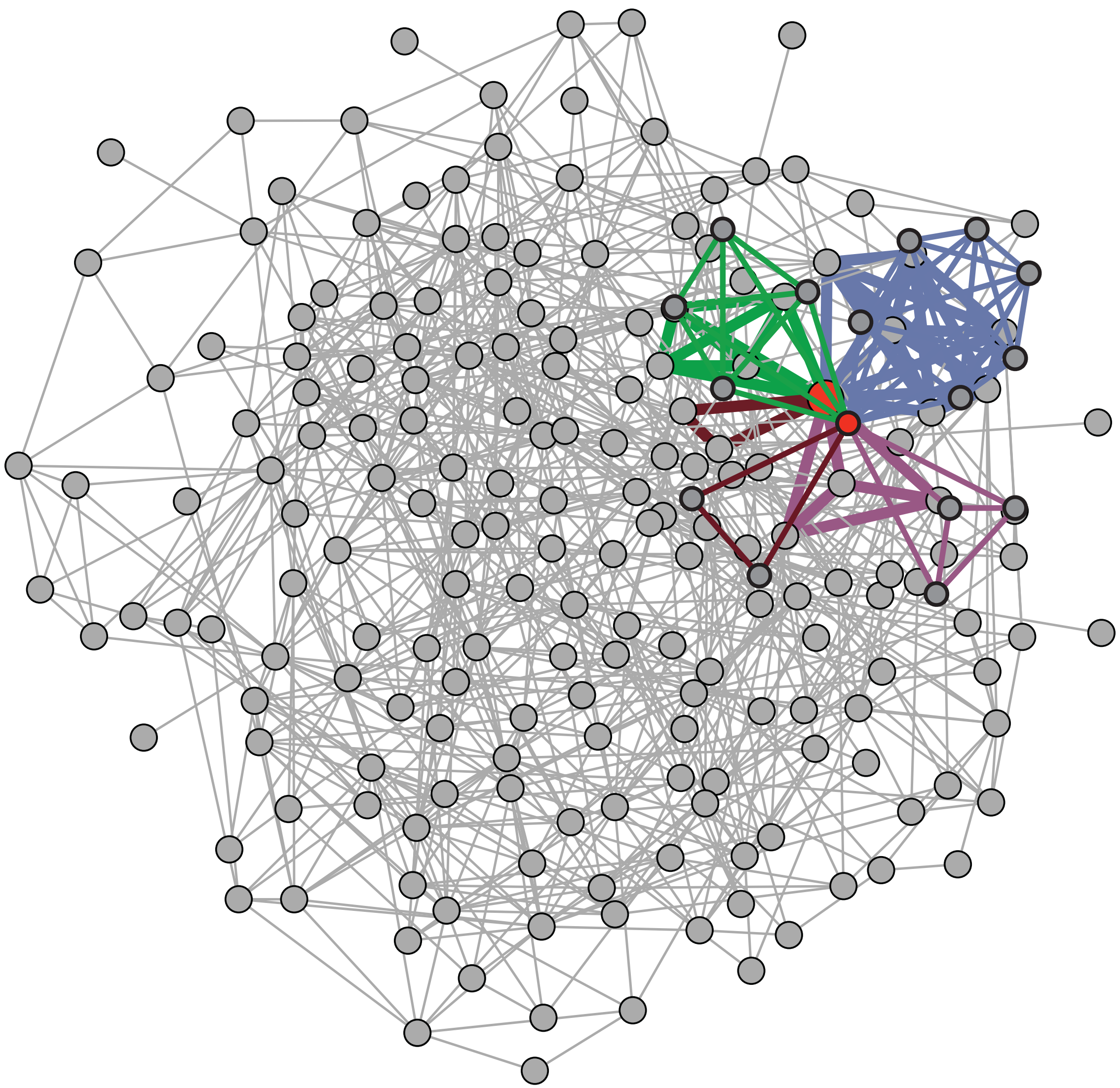


Overlap is **pervasive.**

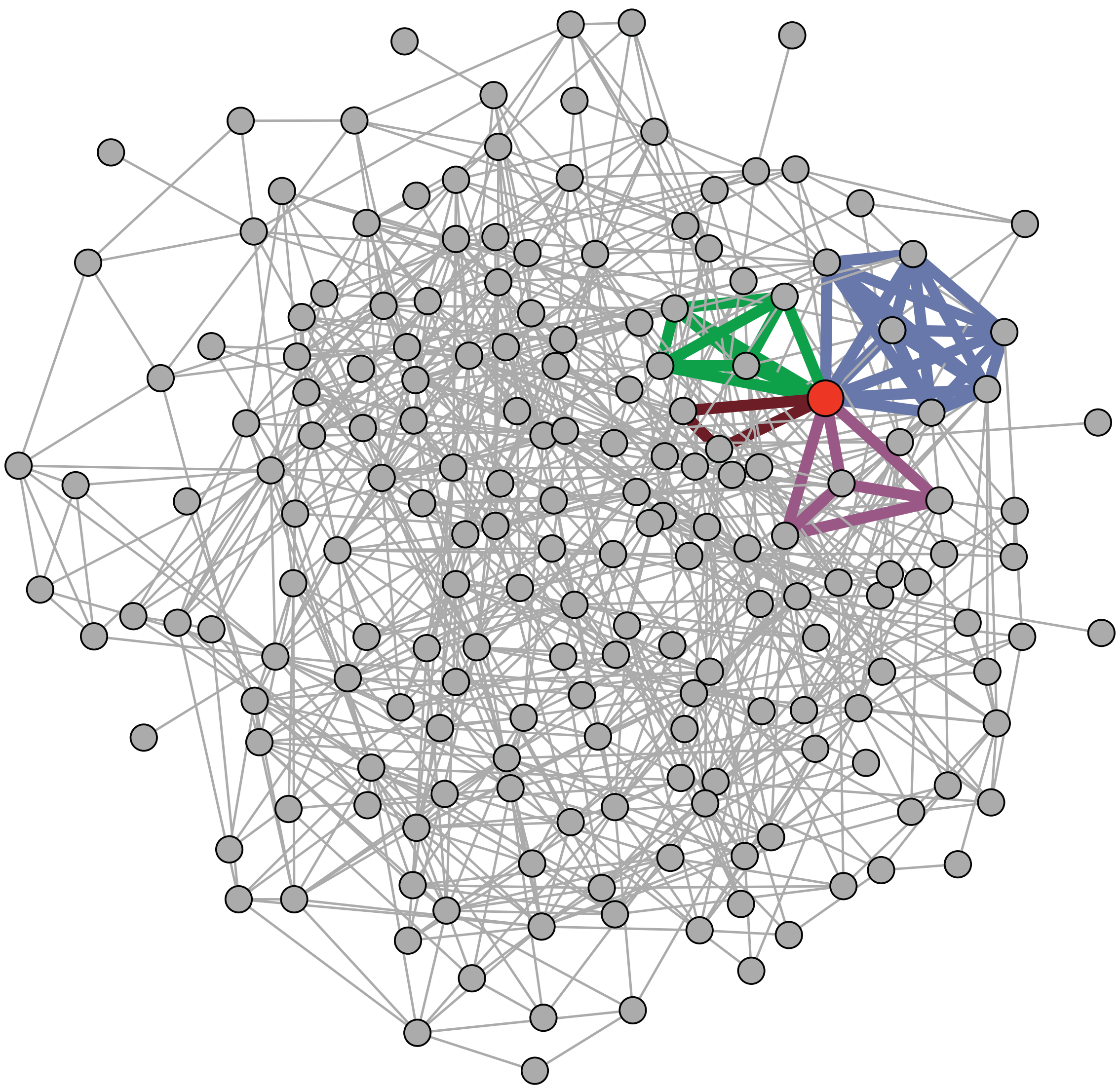
Simple local structure

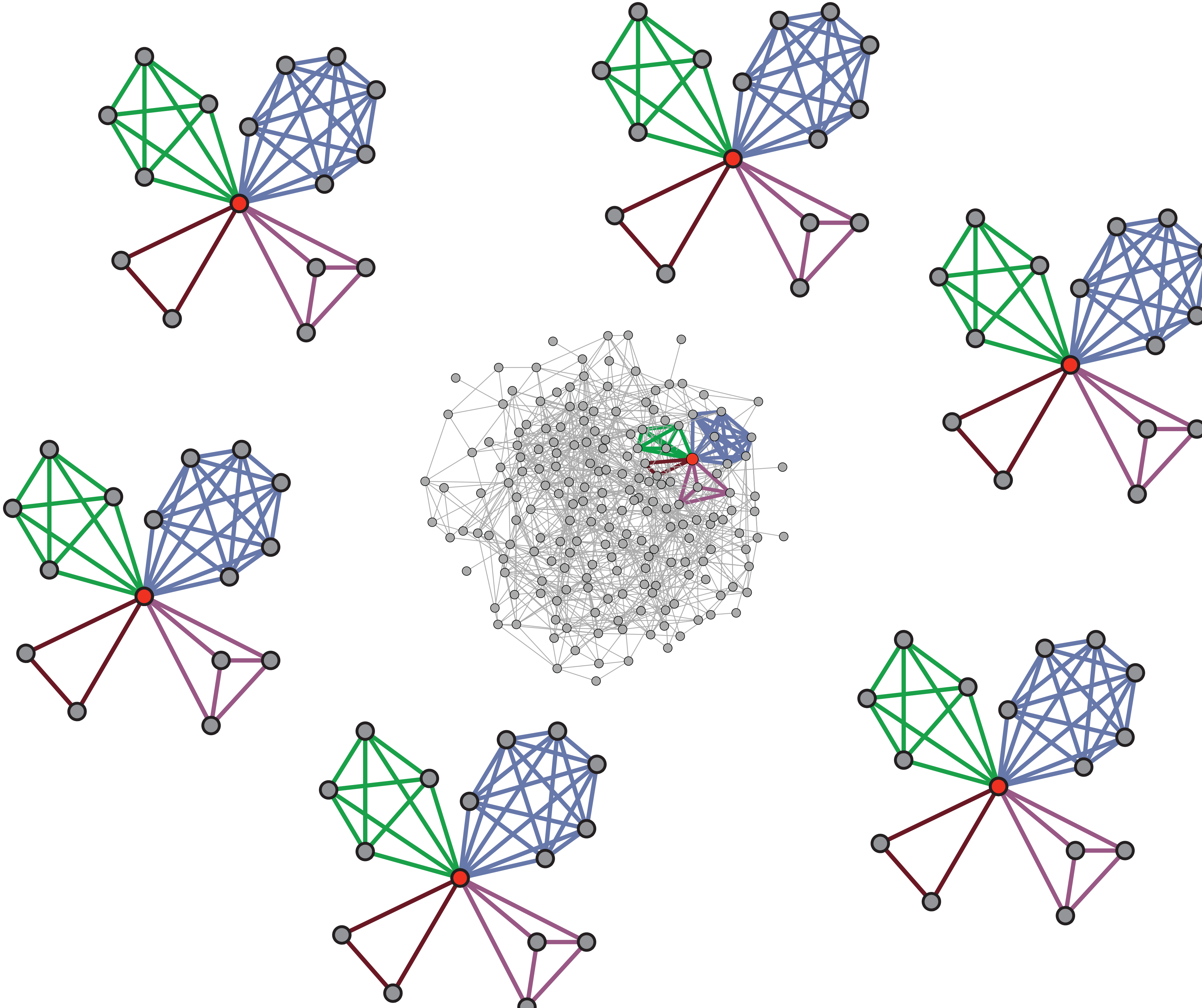


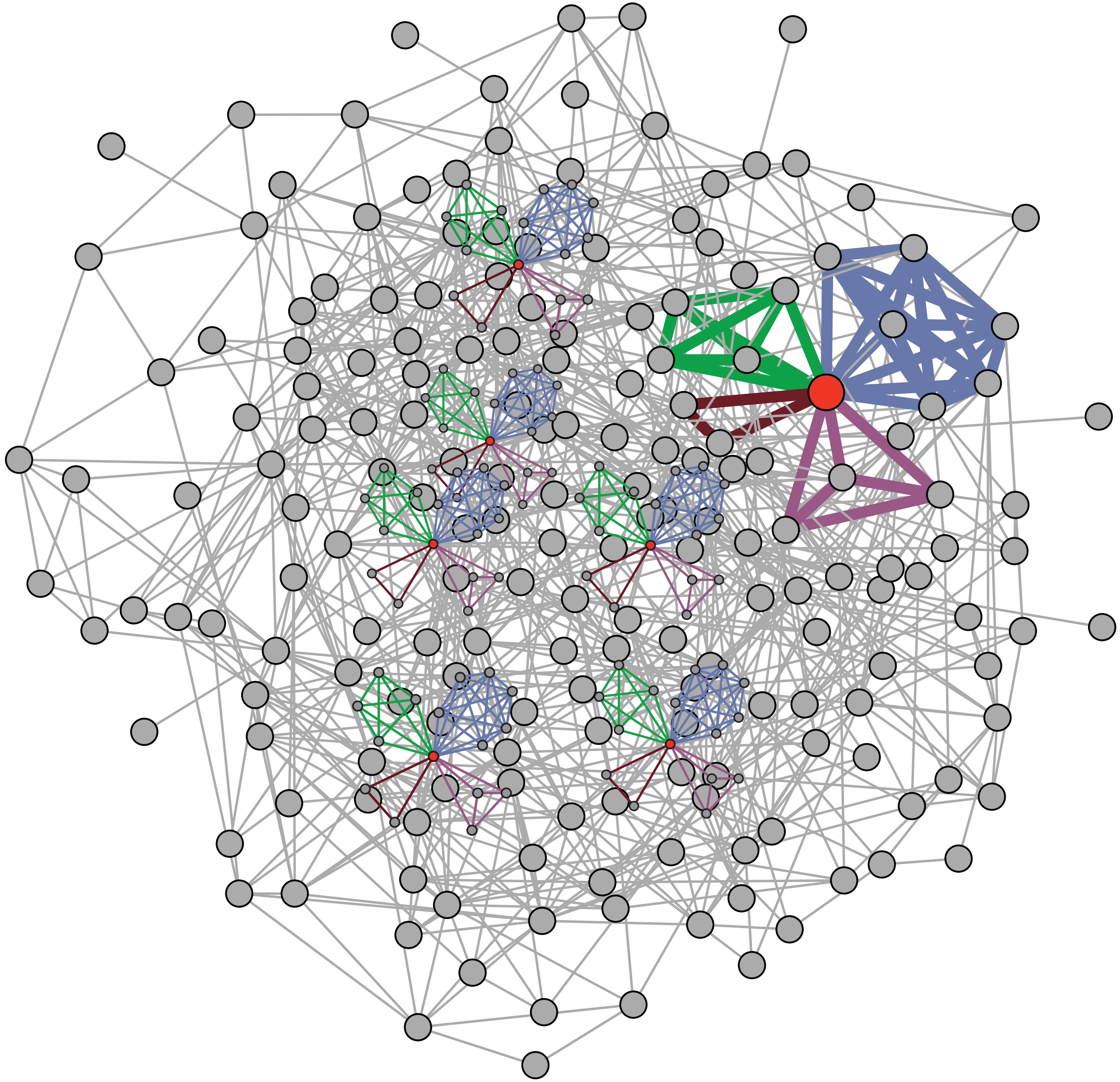
Complex global structure



Complex global structure







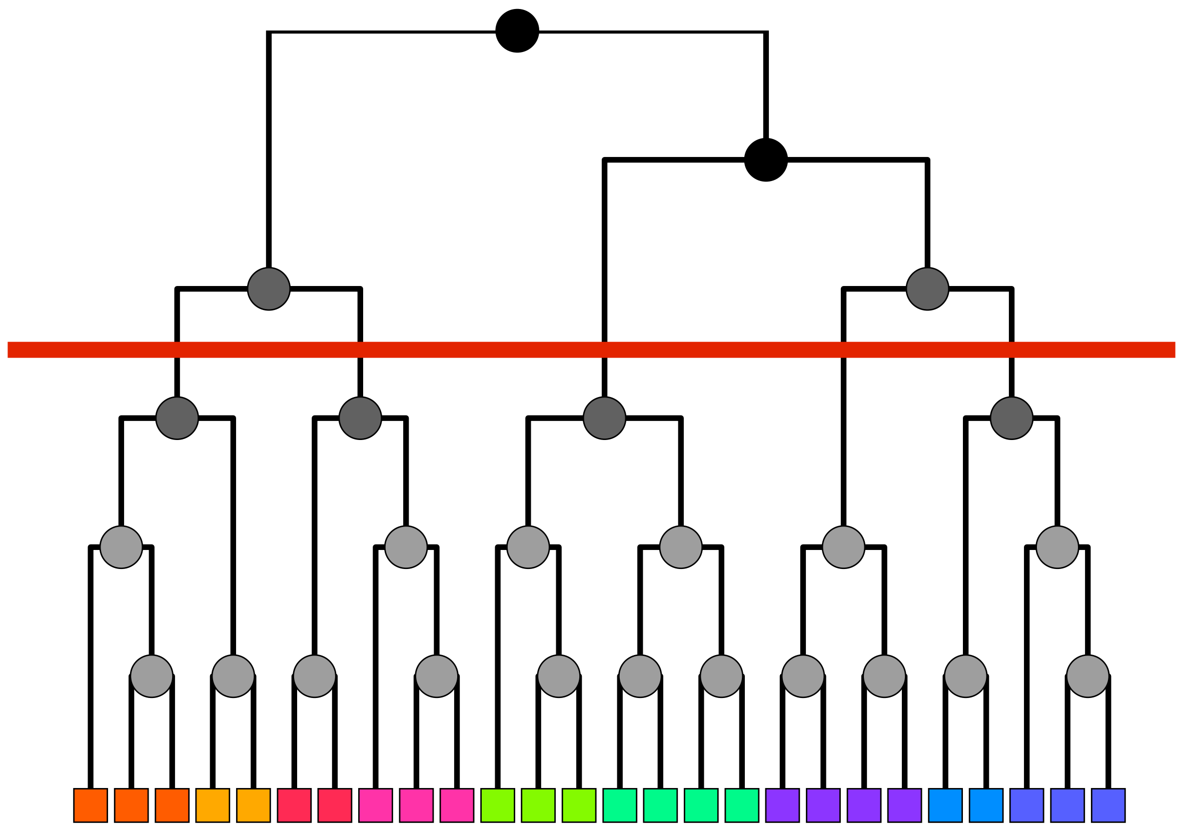
Here is the

PROBLEM.

Communities exist.

Hierarchical structure exists.

Hierarchy implies
disjoint communities.



Hierarchical community structure

Hierarchy $\not\longrightarrow$ Communities

Hopeless?

Solution:
Use **LINKS**

Solution:

Use **LINKS**

Solution:
Use **Links**

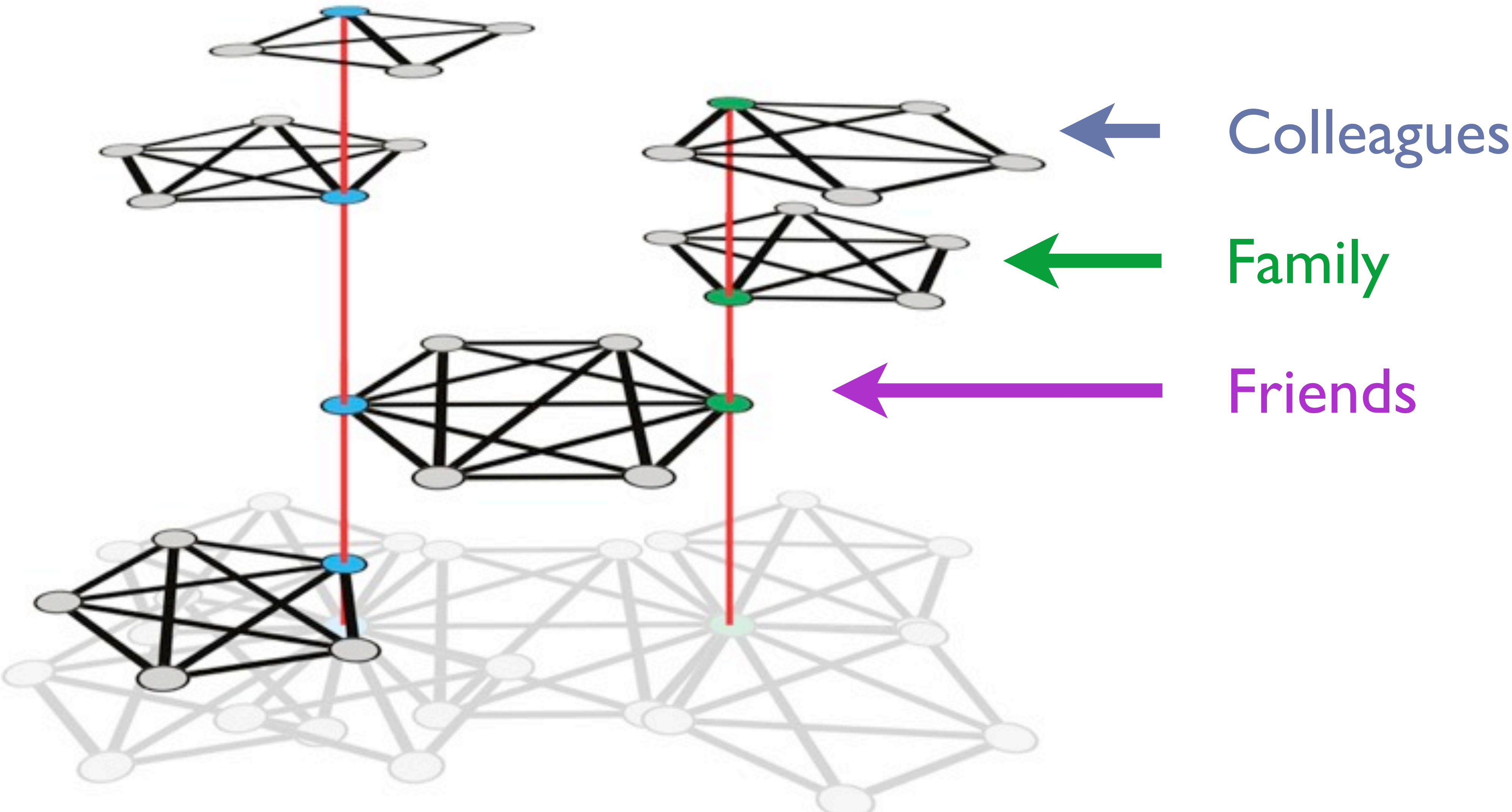
"a group of densely interconnected nodes"

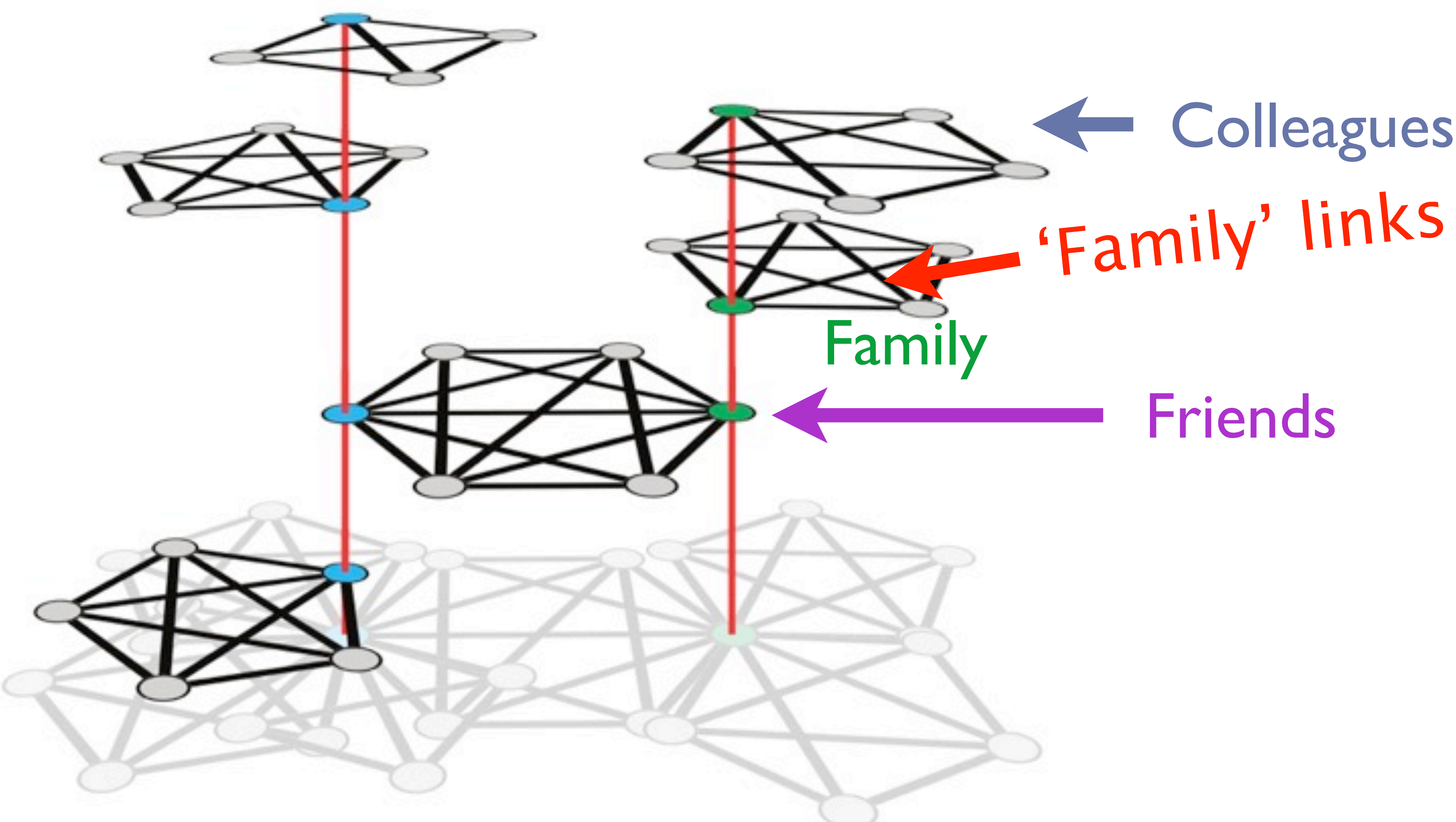
Our solution:
Use **Links**

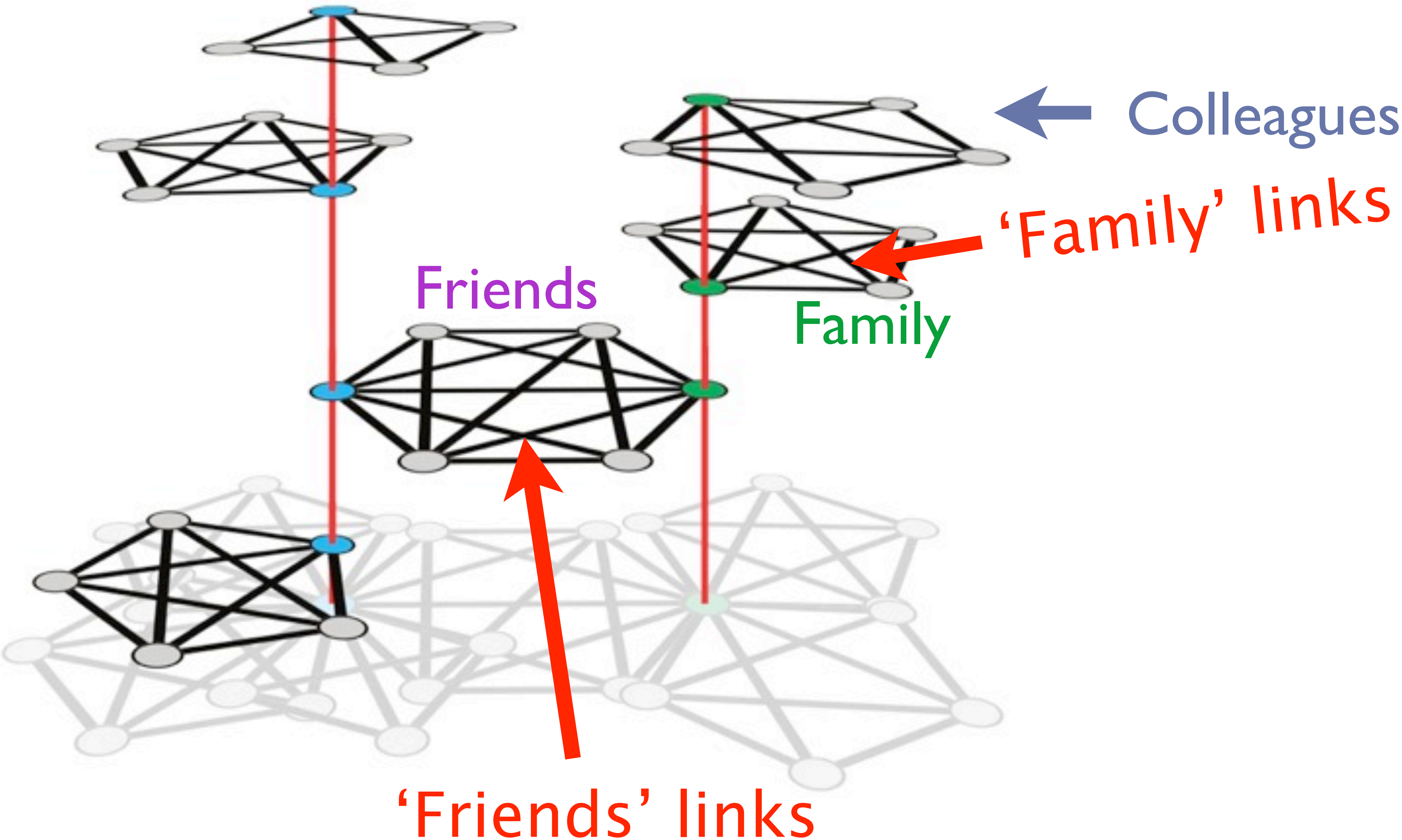
"a group of densely interconnected ~~nodes~~ LINKS"

LINK

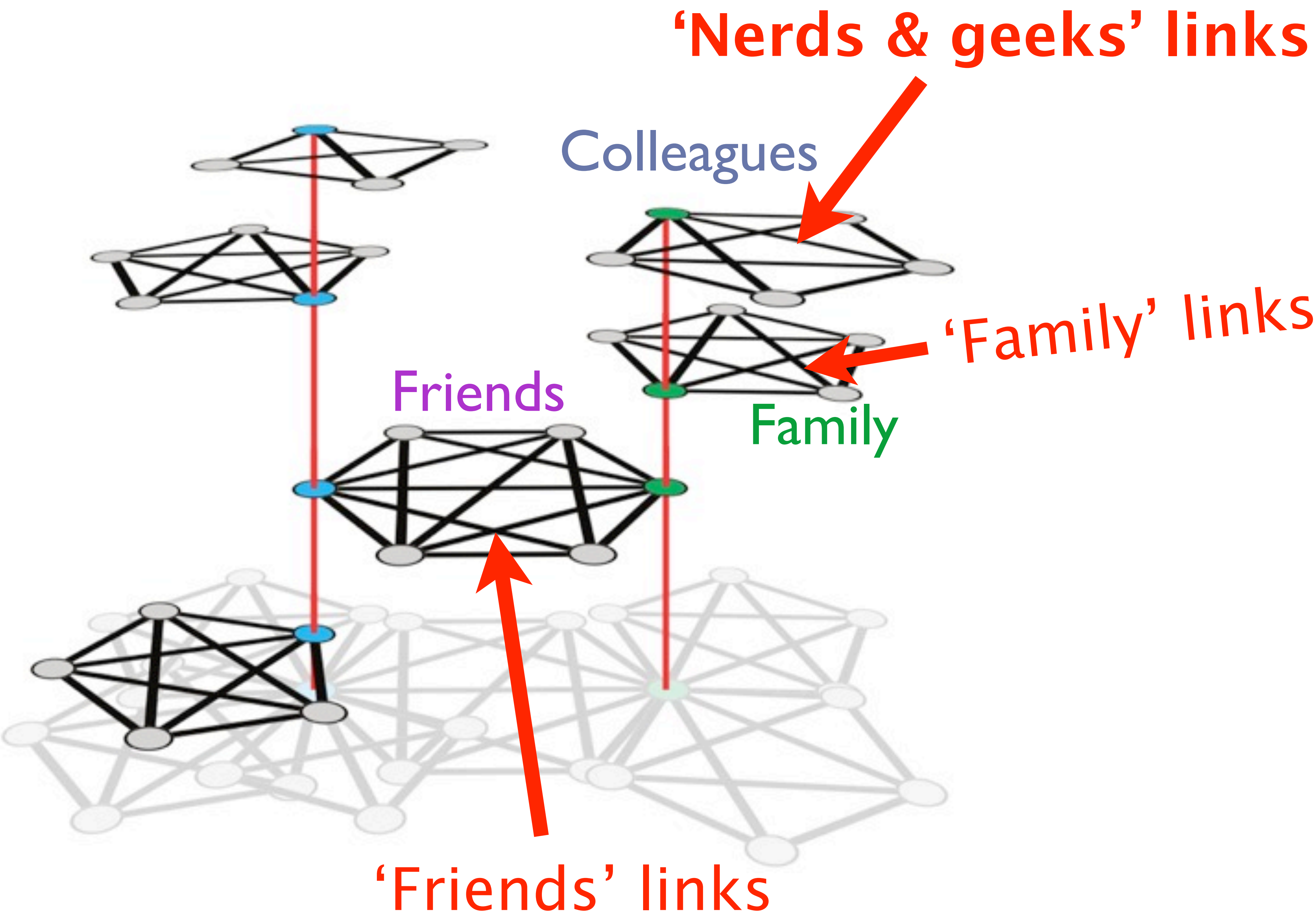
communities


Colleagues
Family
Friends


Colleagues
'Family' links
Family
Friends



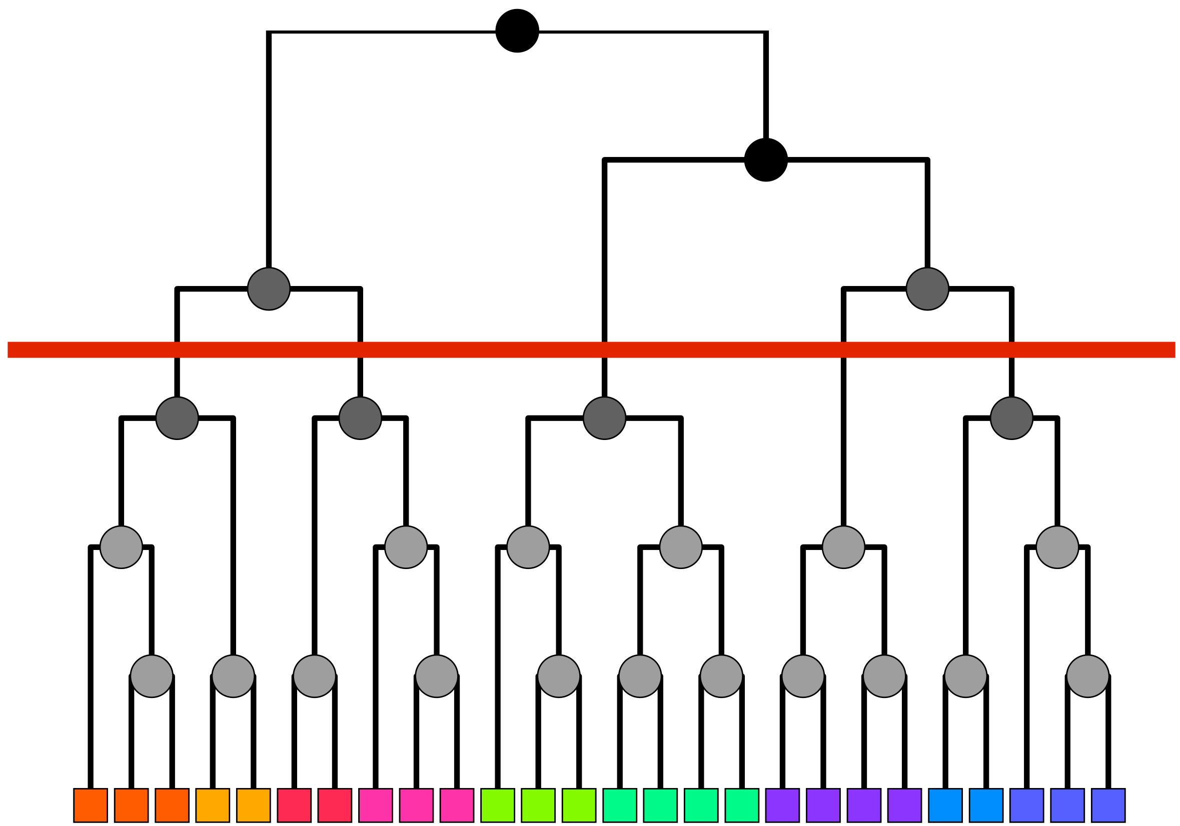
Colleagues
'Family' links
Friends
Family
'Friends' links


'Nerds & geeks' links
Colleagues
'Family' links
Friends
Family
'Friends' links

Nodes: multiple membership

Links: unique membership

Hierarchy implies **disjoint communities.**



Hierarchy $\not\longrightarrow$ Communities

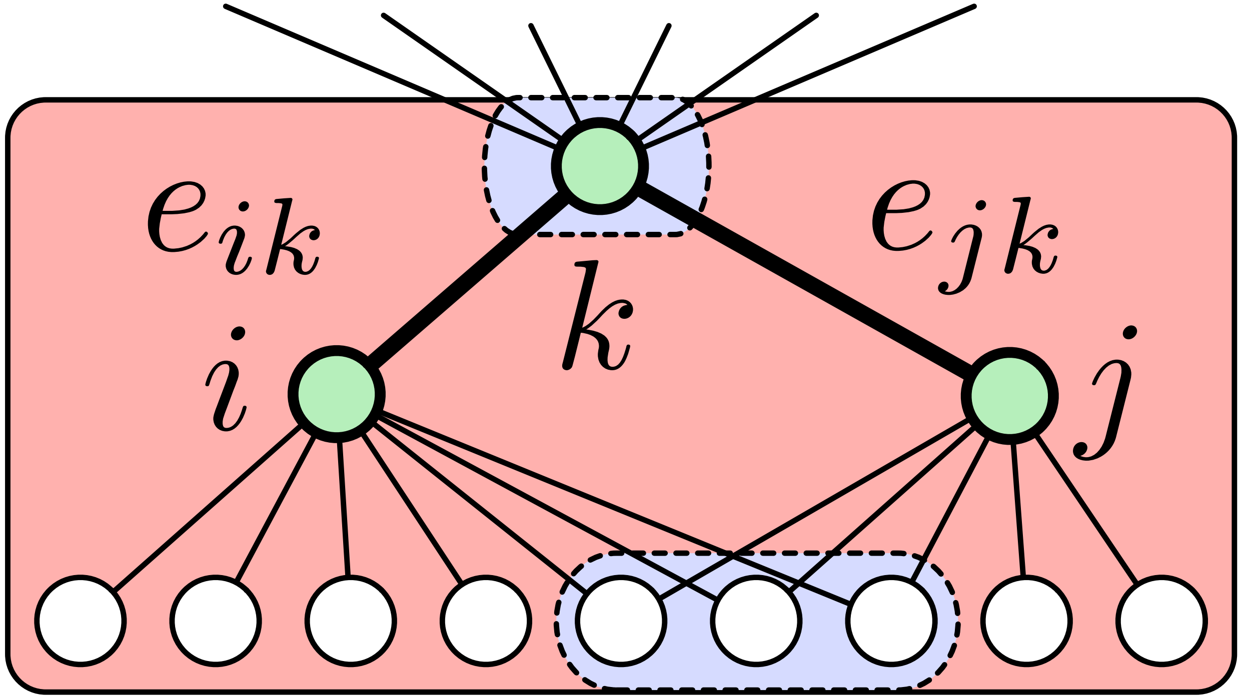
Hierarchy → Communities

So, How?

Similarity between links

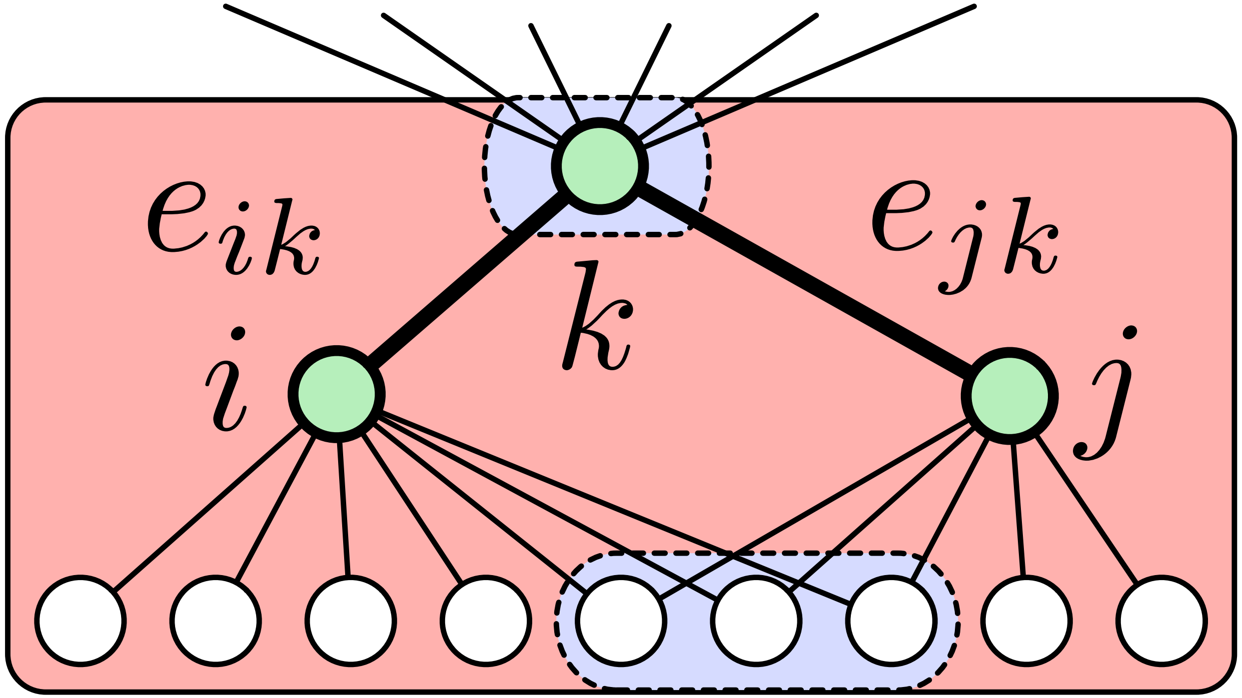
$\downarrow$

Hierarchical Clustering



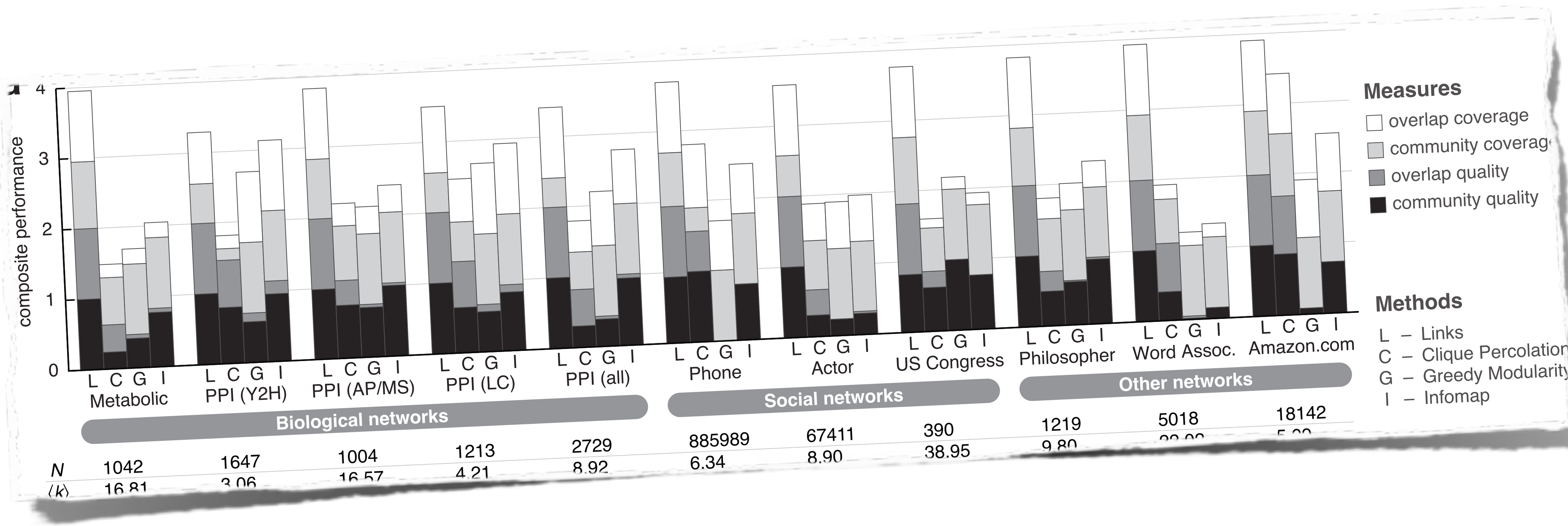
$$n_+(i) \equiv \{x \mid d(i,x) \leq 1\}$$

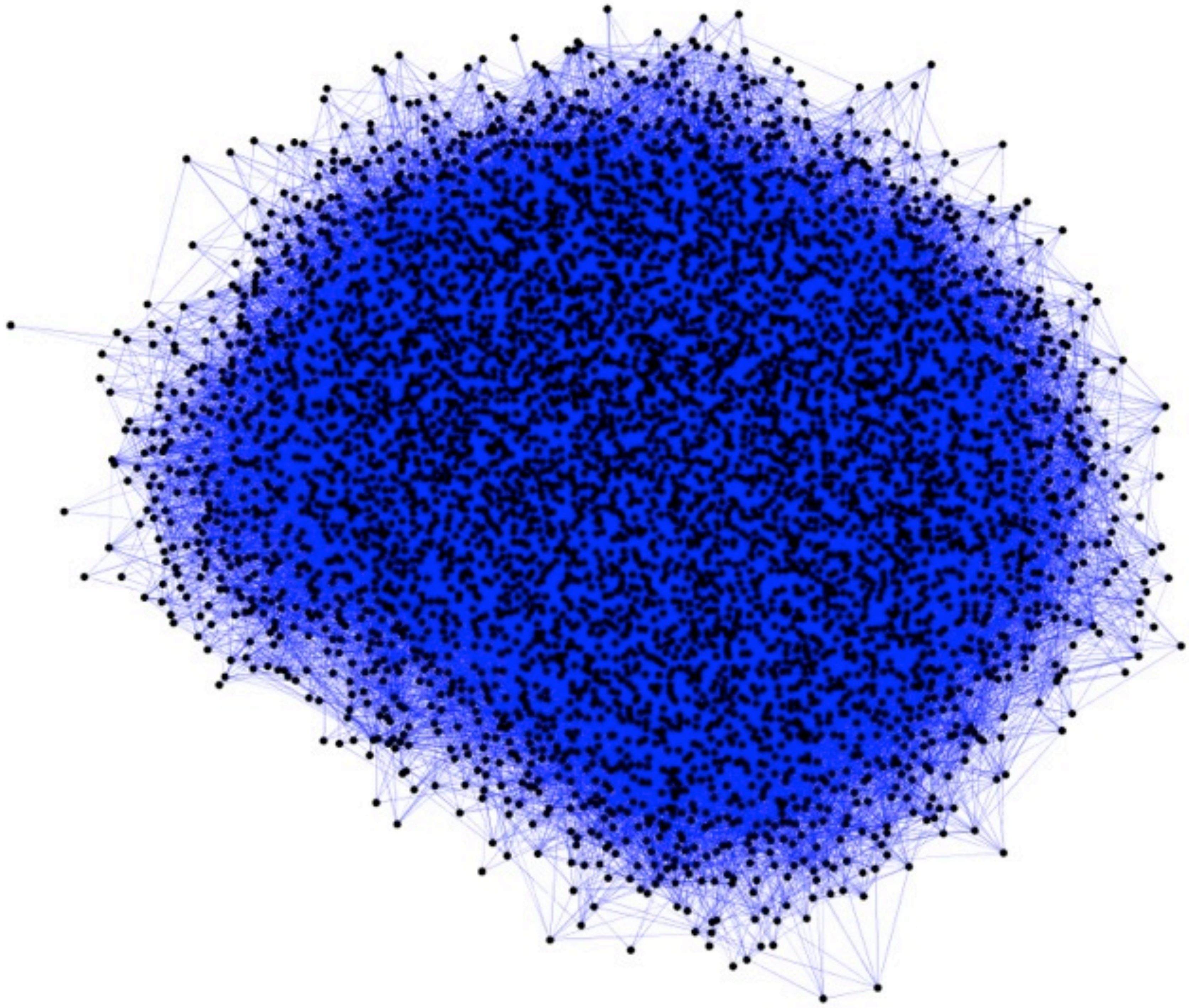
$$S(e_{ik}, e_{jk}) = \frac{|n_+(i) \cap n_+(j)|}{|n_+(i) \cup n_+(j)|}$$

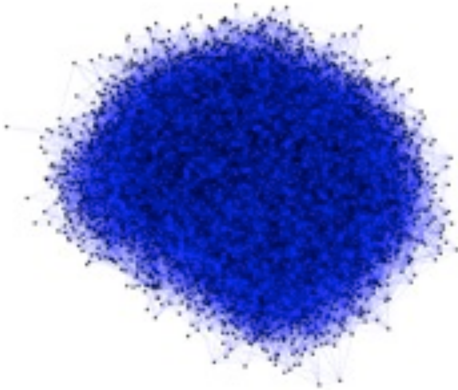


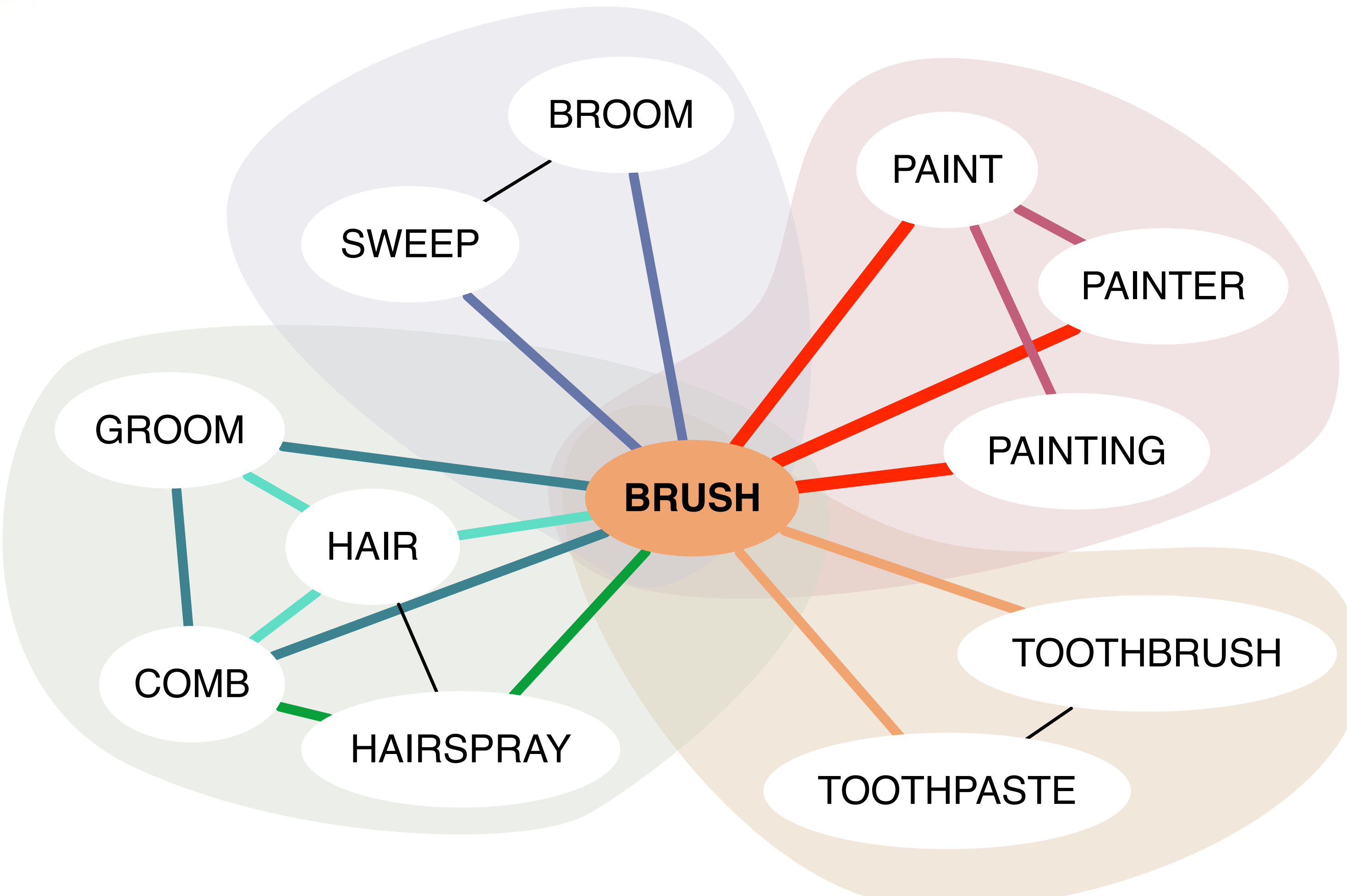
$$n_+(i) \equiv \{x \mid d(i,x) \leq 1\}$$

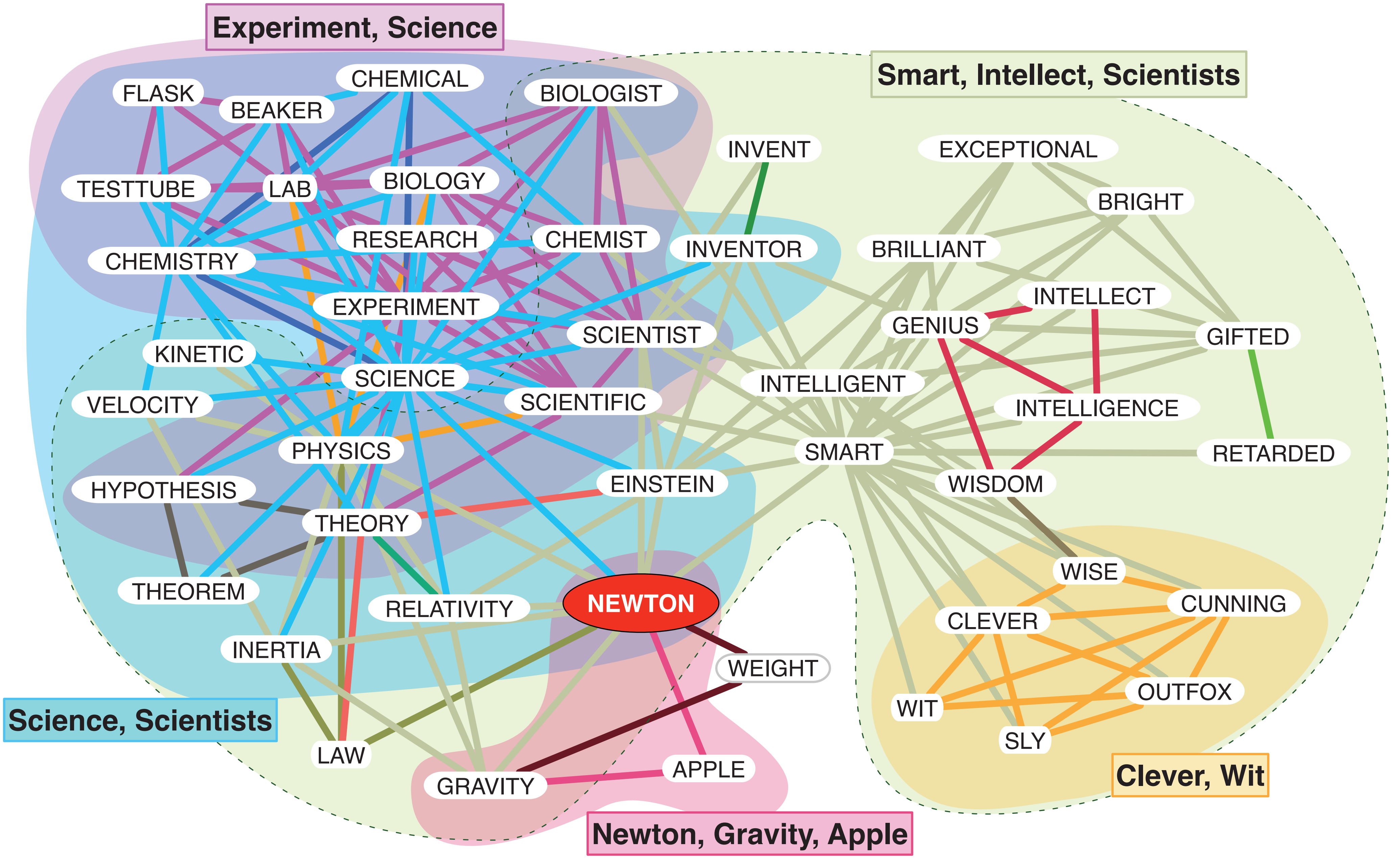
$$S(e_{ik}, e_{jk}) = \frac{|n_+(i) \cap n_+(j)|}{|n_+(i) \cup n_+(j)|} \qquad \frac{4}{12}$$

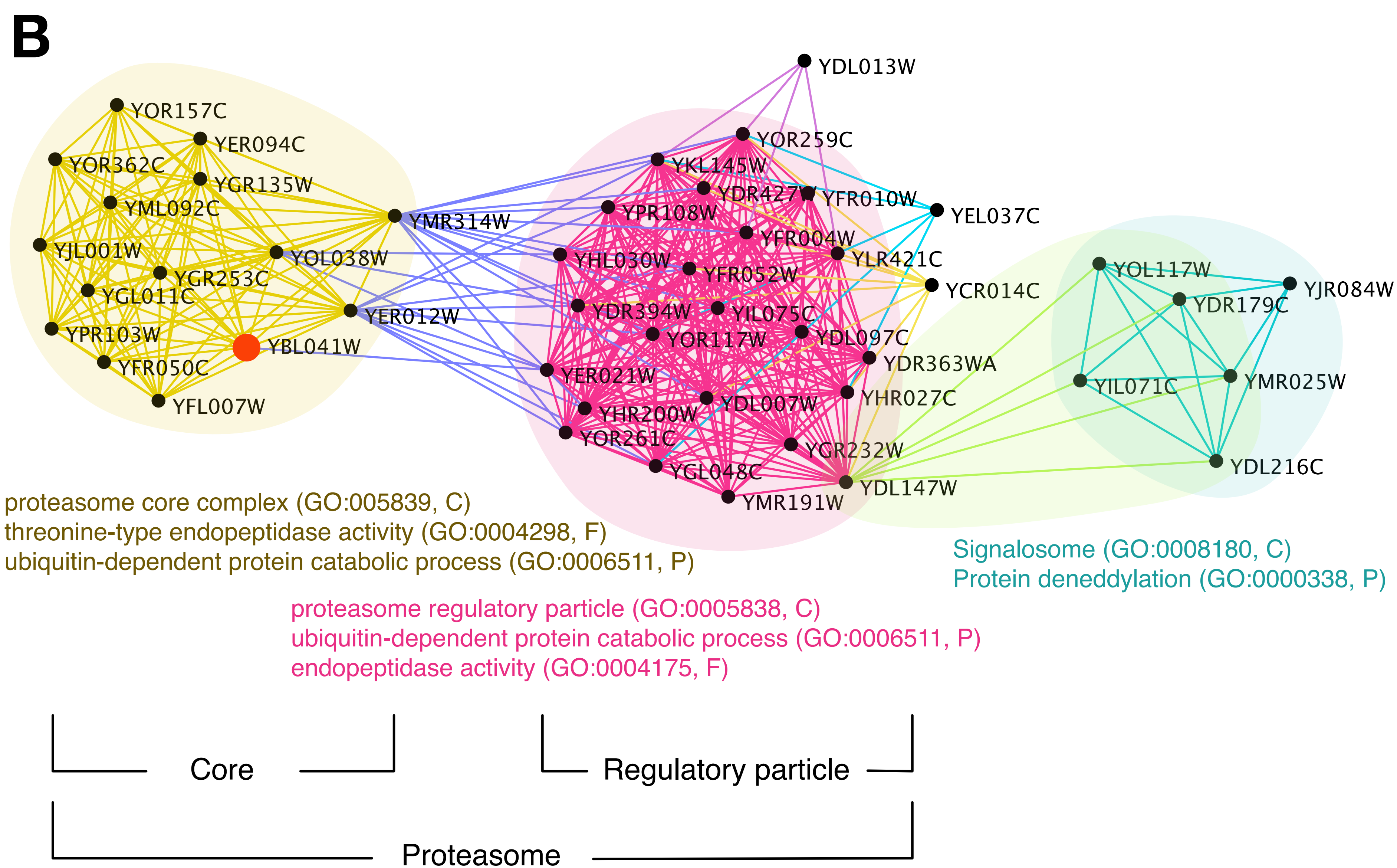

composite performance
0
1
2
3
4
Measures
overlap coverage
community coverage
overlap quality
community quality
Methods
L – Links
C – Clique Percolation
G – Greedy Modularity
I – Infomap
L C G I
Metabolic
PPI (Y2H)
PPI (AP/MS)
PPI (LC)
PPI (all)
Phone
Actor
US Congress
Philosopher
Word Assoc.
Amazon.com
Biological networks
Social networks
Other networks
N
⟨k⟩
1042
16.81
1647
3.06
1004
16.57
1213
4.21
2729
8.92
885989
6.34
67411
8.90
390
38.95
1219
9.80
5018
18142





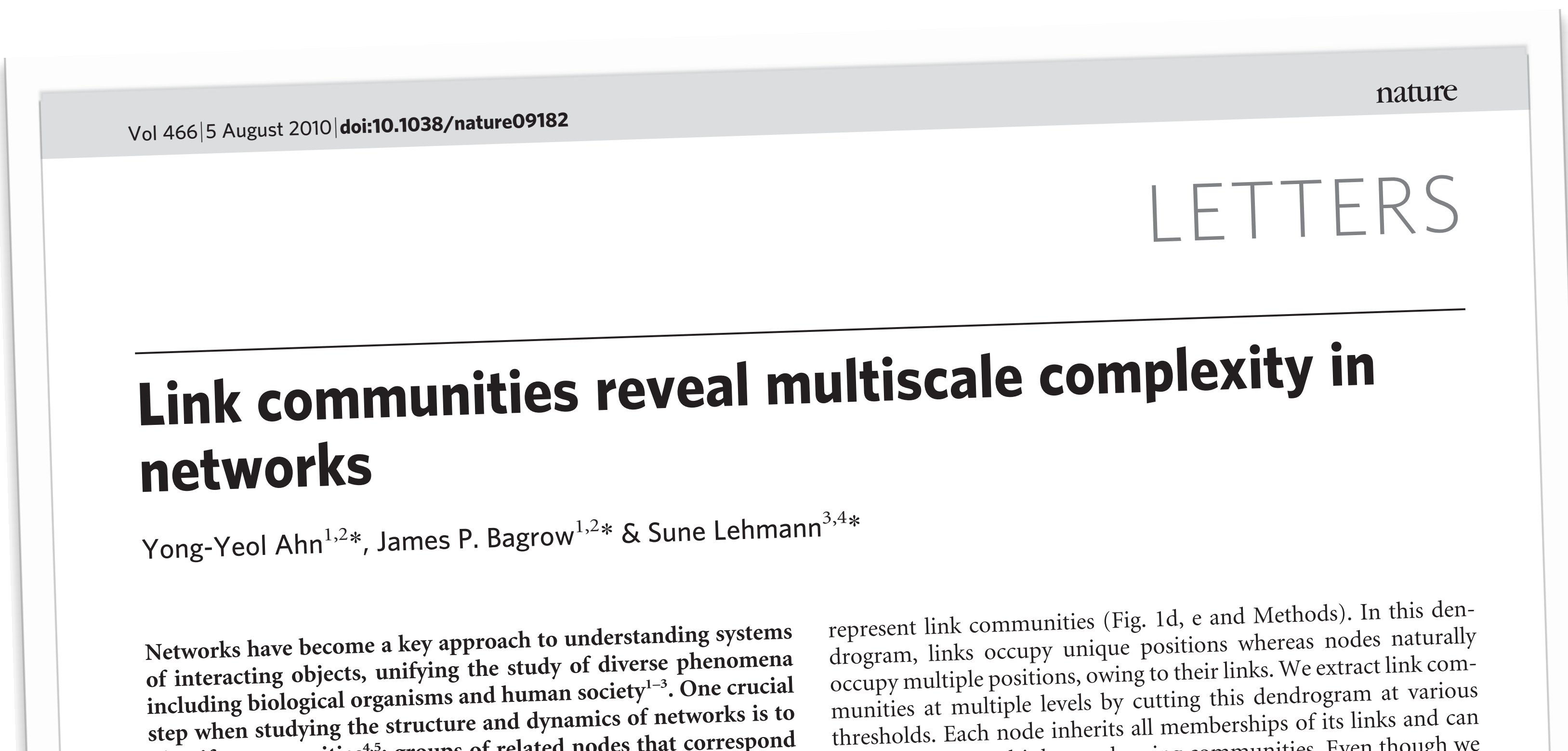

BROOM
SWEEP
PAINT
PAINTER
PAINTING
GROOM
HAIR
BRUSH
COMB
HAIRSPRAY
TOOTHBRUSH
TOOTHPASTE


Experiment, Science
Smart, Intellect, Scientists
Science, Scientists
Newton, Gravity, Apple
Clever, Wit
FLASK
BEAKER
CHEMICAL
BIOLOGIST
INVENT
EXCEPTIONAL
TESTTUBE
LAB
BIOLOGY
BRIGHT
RESEARCH
CHEMIST
INVENTOR
BRILLIANT
CHEMISTRY
EXPERIMENT
INTELLECT
GENIUS
GIFTED
SCIENTIST
KINETIC
SCIENCE
INTELLIGENT
VELOCITY
SCIENTIFIC
INTELLIGENCE
PHYSICS
SMART
RETARDED
HYPOTHESIS
EINSTEIN
WISDOM
THEORY
THEOREM
WISE
RELATIVITY
NEWTON
CUNNING
CLEVER
INERTIA
WEIGHT
OUTFOX
WIT
SLY
LAW
APPLE
GRAVITY


B
YOR157C
YER094C
YOR362C
YGR135W
YML092C
YJL001W
YOL038W
YGR253C
YGL011C
YER012W
YPR103W
YBL041W
YFR050C
YFL007W
YMR314W
YDL013W
YOR259C
YKL145W
YDR427W
YFR010W
YEL037C
YPR108W
YFR004W
YLR421C
YHL030W
YFR052W
YCR014C
YDR394W
YIL075C
YOR117W
YDL097C
YDR363WA
YER021W
YHR027C
YHR200W
YDL007W
YOR261C
YGR232W
YGL048C
YDL147W
YMR191W
YOL117W
YJR084W
YDR179C
YIL071C
YMR025W
YDL216C
proteasome core complex (GO:005839, C)
threonine-type endopeptidase activity (GO:0004298, F)
ubiquitin-dependent protein catabolic process (GO:0006511, P)
Signalosome (GO:0008180, C)
Protein deneddylation (GO:0000338, P)
proteasome regulatory particle (GO:0005838, C)
ubiquitin-dependent protein catabolic process (GO:0006511, P)
endopeptidase activity (GO:0004175, F)
Core
Regulatory particle
Proteasome

Summary

- Networks matter.
- Relationships are fundamental.


Vol 466 | 5 August 2010 | doi:10.1038/nature09182

nature

LETTERS

Link communities reveal multiscale complexity in networks

Yong-Yeol Ahn[1,2]*, James P. Bagrow[1,2]* & Sune Lehmann[3,4]*

Networks have become a key approach to understanding systems of interacting objects, unifying the study of diverse phenomena including biological organisms and human society[1–3]. One crucial step when studying the structure and dynamics of networks is to

represent link communities (Fig. 1d, e and Methods). In this dendrogram, links occupy unique positions whereas nodes naturally occupy multiple positions, owing to their links. We extract link communities at multiple levels by cutting this dendrogram at various thresholds. Each node inherits all memberships of its links and can

Part II

WARNING

This presentation may contain appetizing material.

“Tell me what you eat, and I will tell you what you are.”

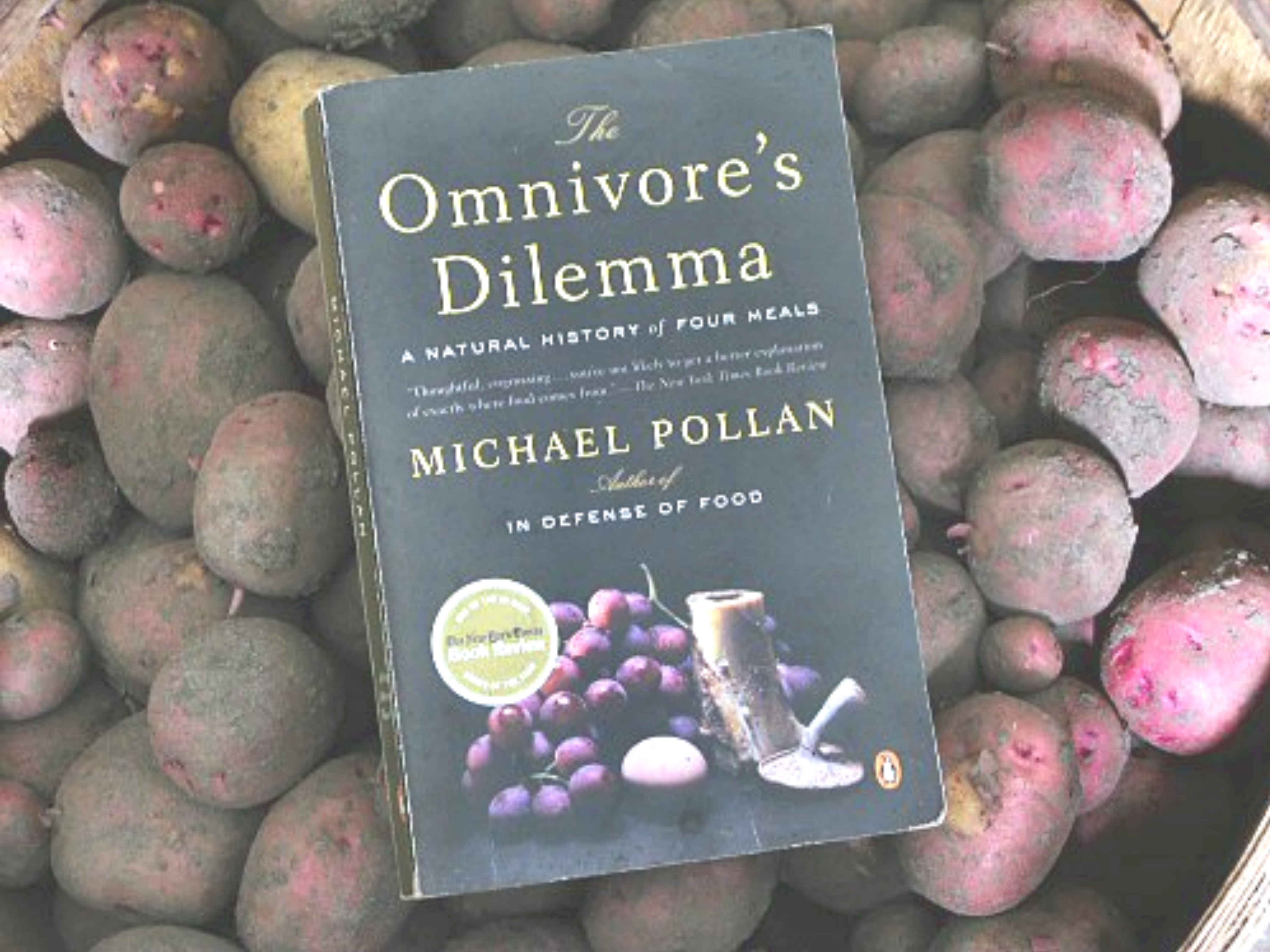
Jean Anthelme Brillat-Savarin
(1755-1826)

What do we eat?


Tender hamburger bun, made from scratch and toasted in beef suet
Hamburger glaze of suet, pureed tomato confit, beef stock, and smoked salt
Maitake mushroom, sautéed in beef suet
Romaine lettuce infused sous vide with liquid hickory smoke
Vacuum-compressed heirloom tomato
Cheese single made from aged Emmental, Comté, and wheat ale
Short-rib patty ground to vertically align the grain
Crimini mushroom ketchup with honey, horseradish, fish sauce, ginger, and allspice

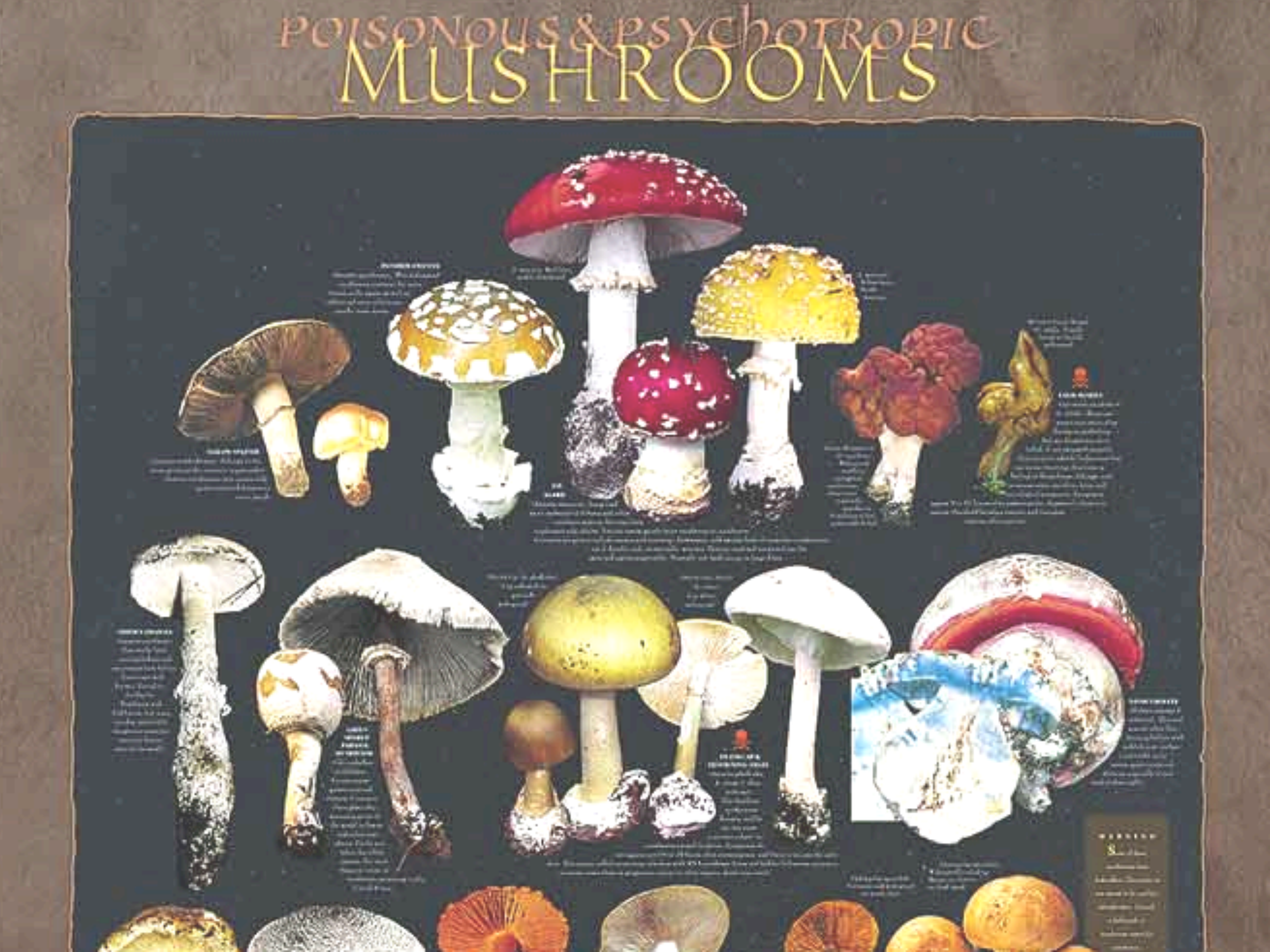
We are

Omnivores.


The Omnivore's Dilemma
A NATURAL HISTORY of FOUR MEALS
MICHAEL POLLAN
Author of
IN DEFENSE OF FOOD


Friendship
All Natural
Sour
Cream
TABASCO


2005 WWW.51WALL.COM


POISONOUS & PSYCHOTROPIC
MUSHROOMS

How do we choose

what to eat?

Because it’s delicious!

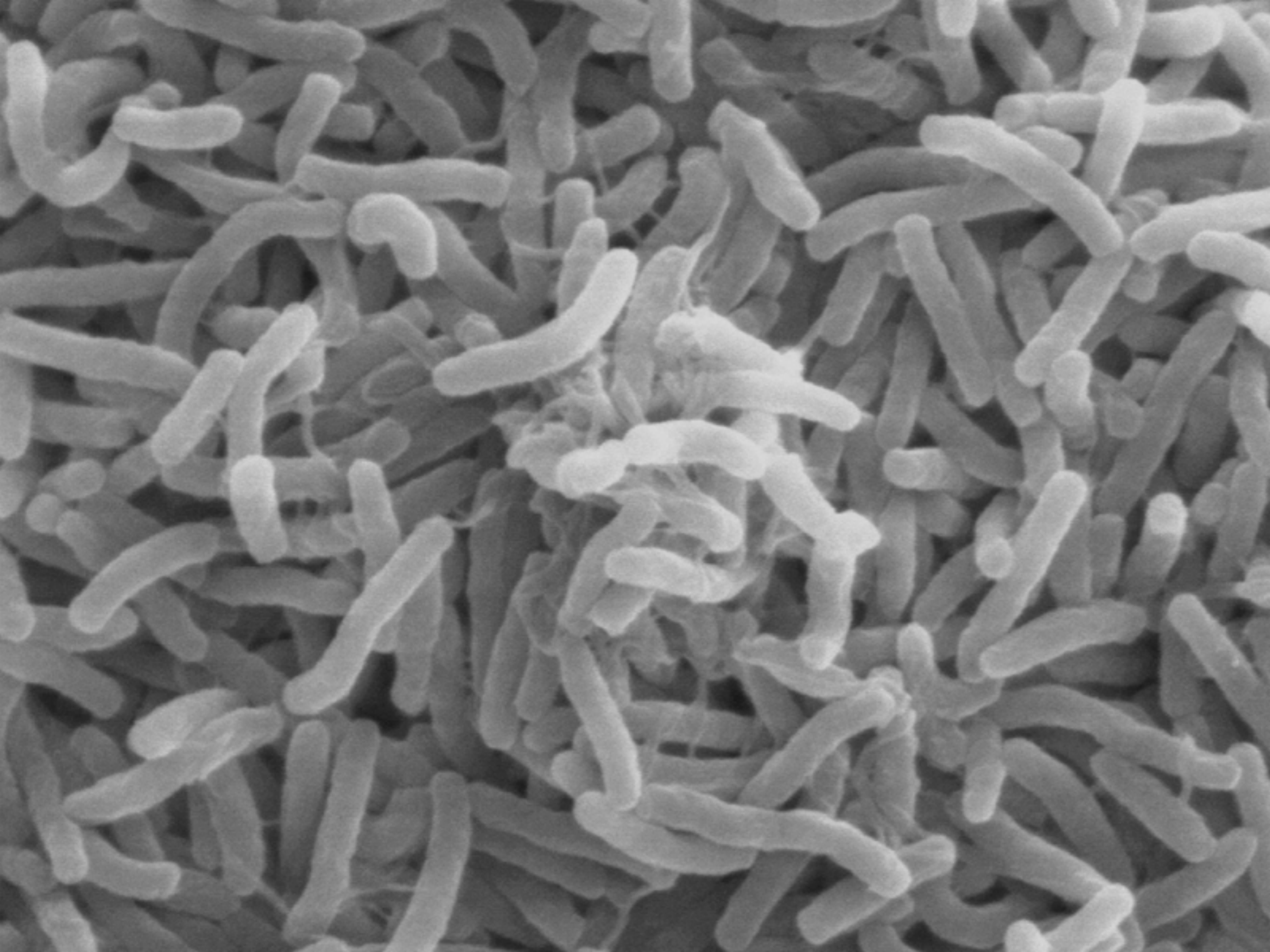
Why is it delicious?

Energy!


Sweet + Fat
= **AWESOME**

Energy

Why do we eat
spices?



Darwinian Gastronomy: Why We Use Spices

Spices taste good because they are good for us

Paul W. Sherman and Jennifer Billing

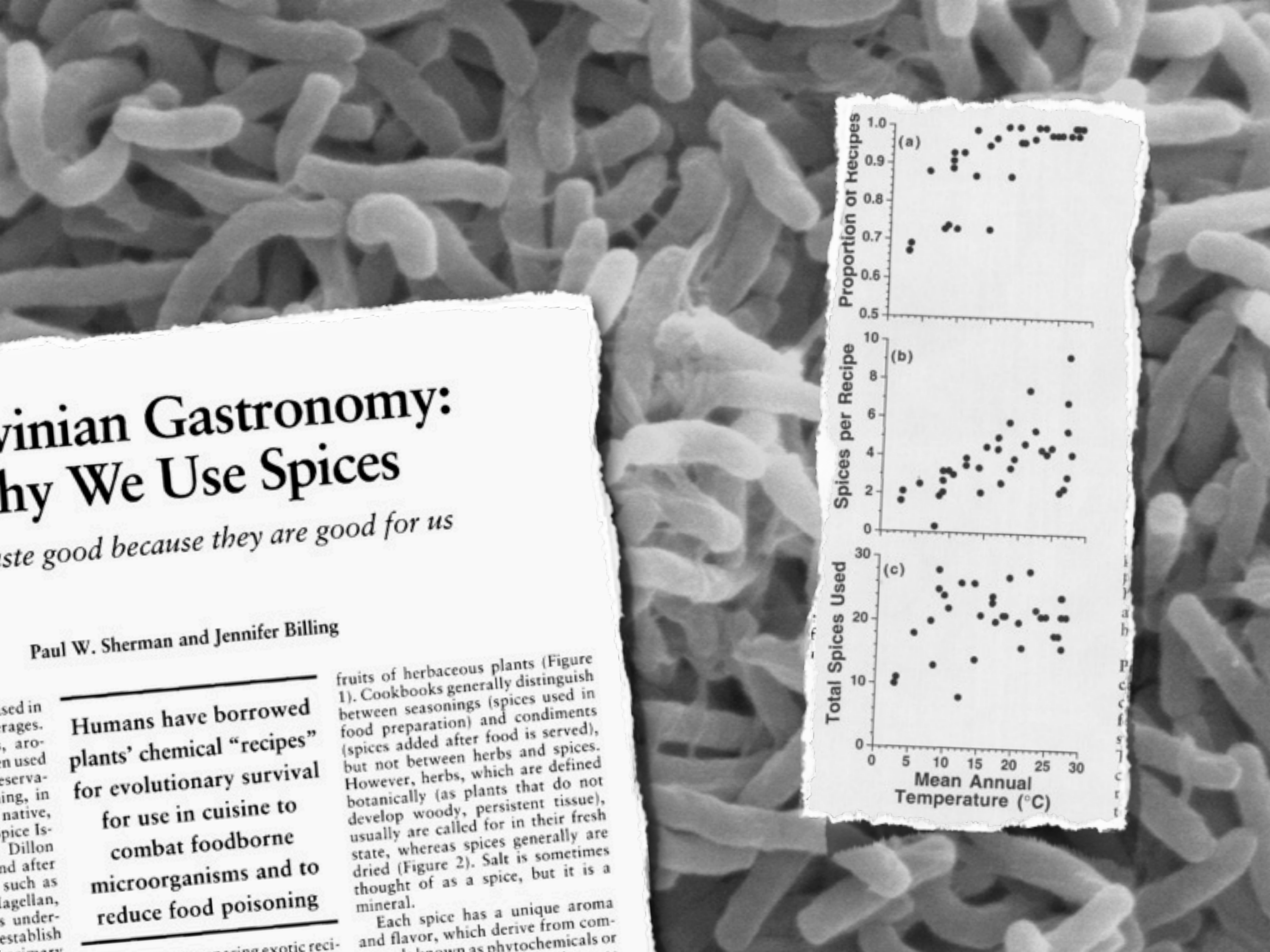
Spices are plant products used in flavoring foods and beverages. For thousands of years, aromatic plant materials have been used in food preparation and preservation, as well as for embalming, in areas where the plants are native, such as Hindustan and the Spice Islands (Govindarajan 1985, Dillon and Board 1994). During and after the Middle Ages, seafarers such as Marco Polo, Ferdinand Magellan, and Christopher Columbus undertook hazardous voyages to establish ... ports in primary

Humans have borrowed plants' chemical "recipes" for evolutionary survival for use in cuisine to combat foodborne microorganisms and to reduce food poisoning

... or preparing exotic reci-

fruits of herbaceous plants (Figure 1). Cookbooks generally distinguish between seasonings (spices used in food preparation) and condiments (spices added after food is served), but not between herbs and spices. However, herbs, which are defined botanically (as plants that do not develop woody, persistent tissue), usually are called for in their fresh state, whereas spices generally are dried (Figure 2). Salt is sometimes thought of as a spice, but it is a mineral.

Each spice has a unique aroma and flavor, which derive from compounds known as phytochemicals o...



vinian Gastronomy:
hy We Use Spices

ste good because they are good for us

Paul W. Sherman and Jennifer Billing

Humans have borrowed plants' chemical "recipes" for evolutionary survival for use in cuisine to combat foodborne microorganisms and to reduce food poisoning

fruits of herbaceous plants (Figure 1). Cookbooks generally distinguish between seasonings (spices used in food preparation) and condiments (spices added after food is served), but not between herbs and spices. However, herbs, which are defined botanically (as plants that do not develop woody, persistent tissue), usually are called for in their fresh state, whereas spices generally are dried (Figure 2). Salt is sometimes thought of as a spice, but it is a mineral.

Each spice has a unique aroma and flavor, which derive from com-

So, sweet, fatty, spicy, and?

Are there any other
principles
that transcend individuals
and cultures?

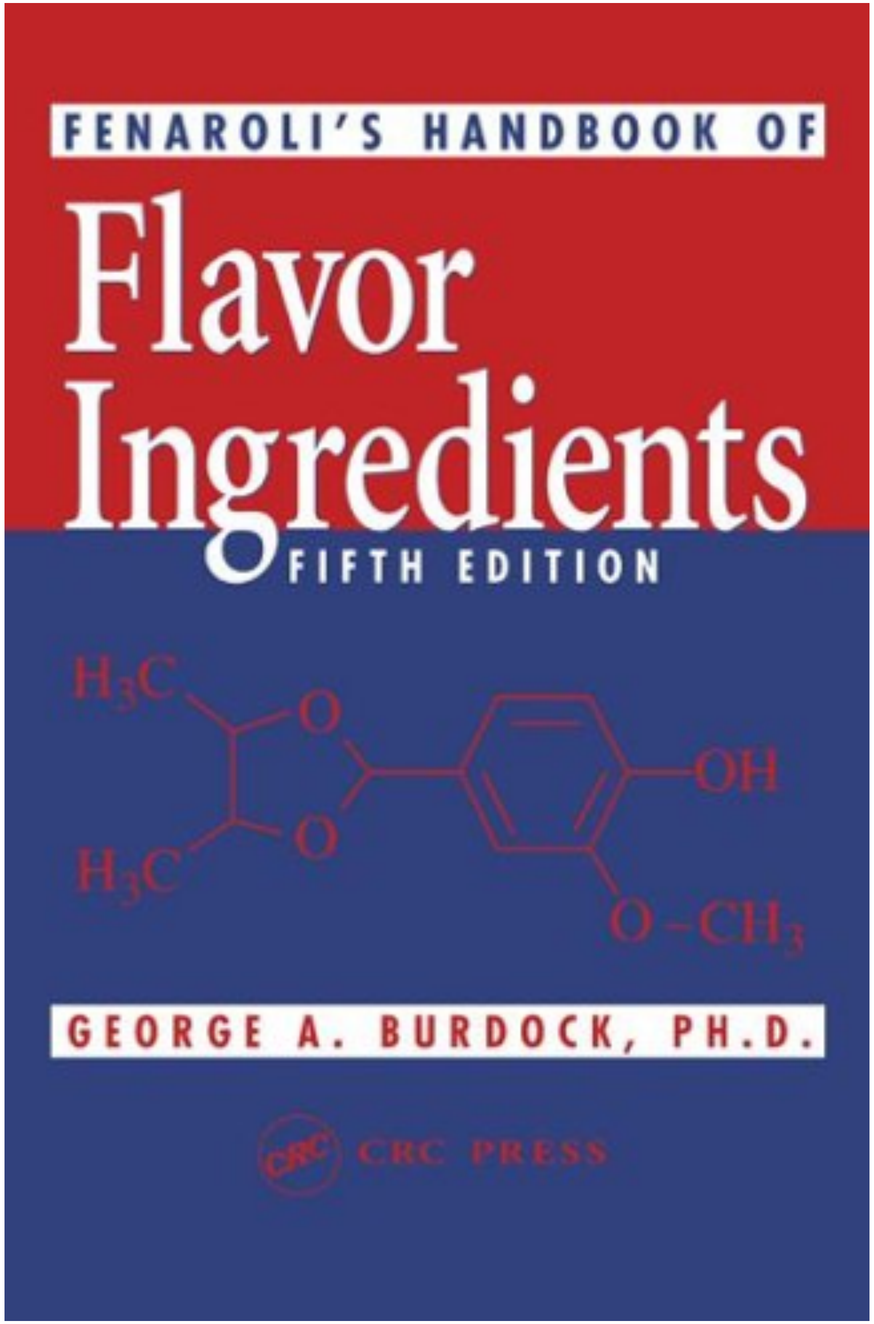
Food Pairing Hypothesis

"Two ingredients taste good together **if they share flavor compounds**"

François Benzi, Heston Blumenthal

Is it really true?

Systematic approach



Flavor compounds

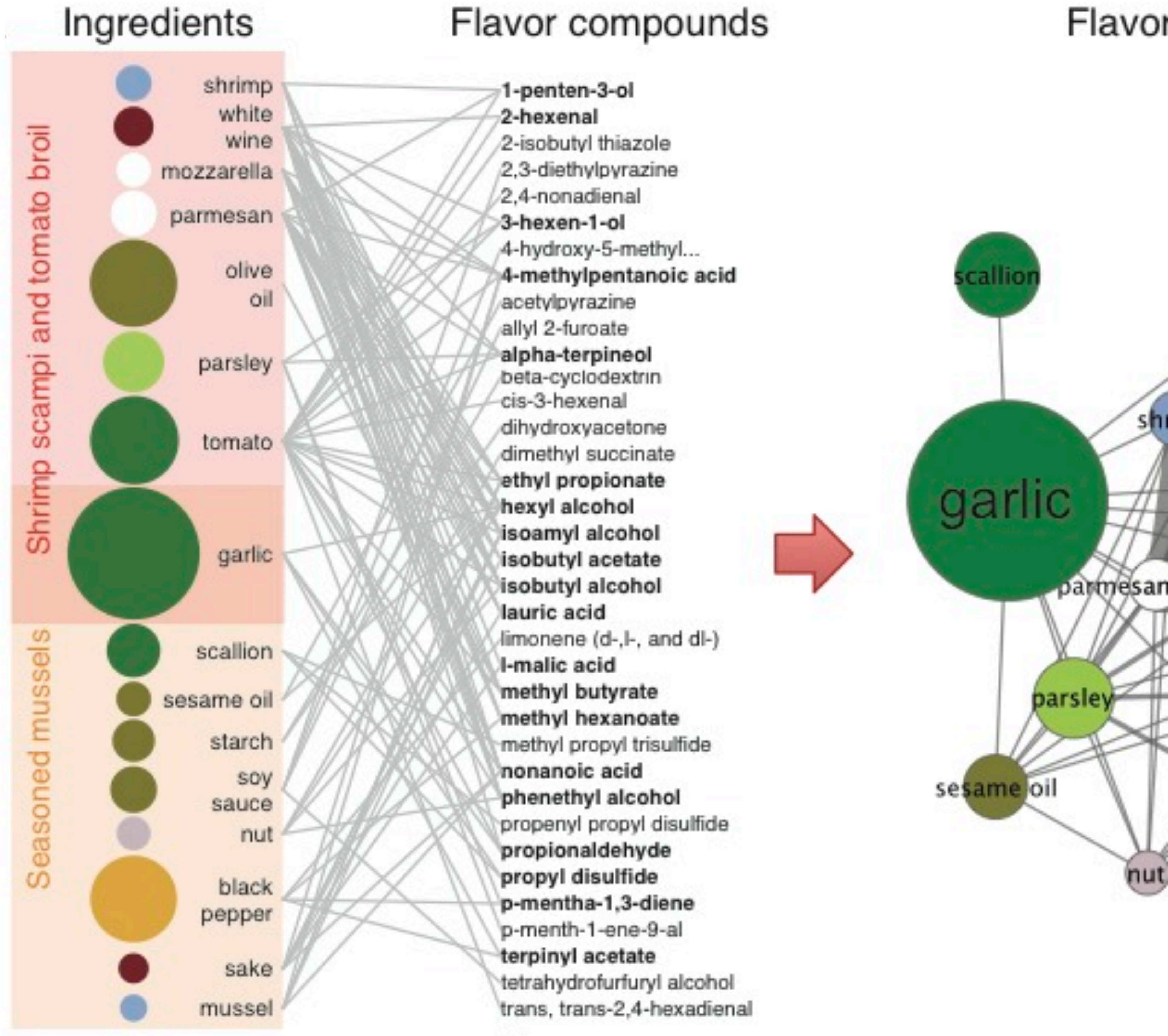
|

Ingredients

G. A. Burdock, G. Fenaroli, *Fenaroli's Handbook of Flavor Ingredients* (5th ed., CRC Press).

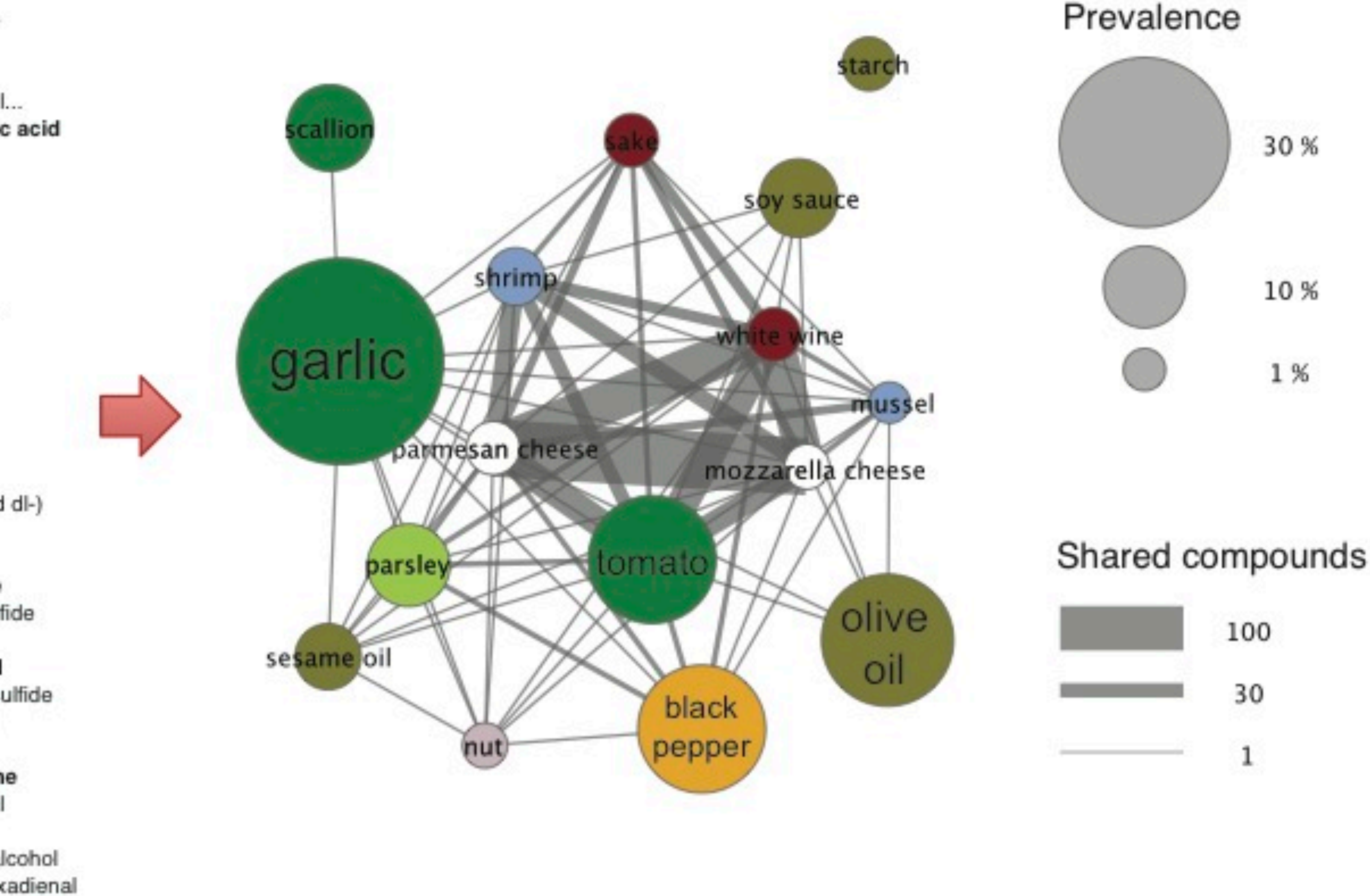
381 ingredients

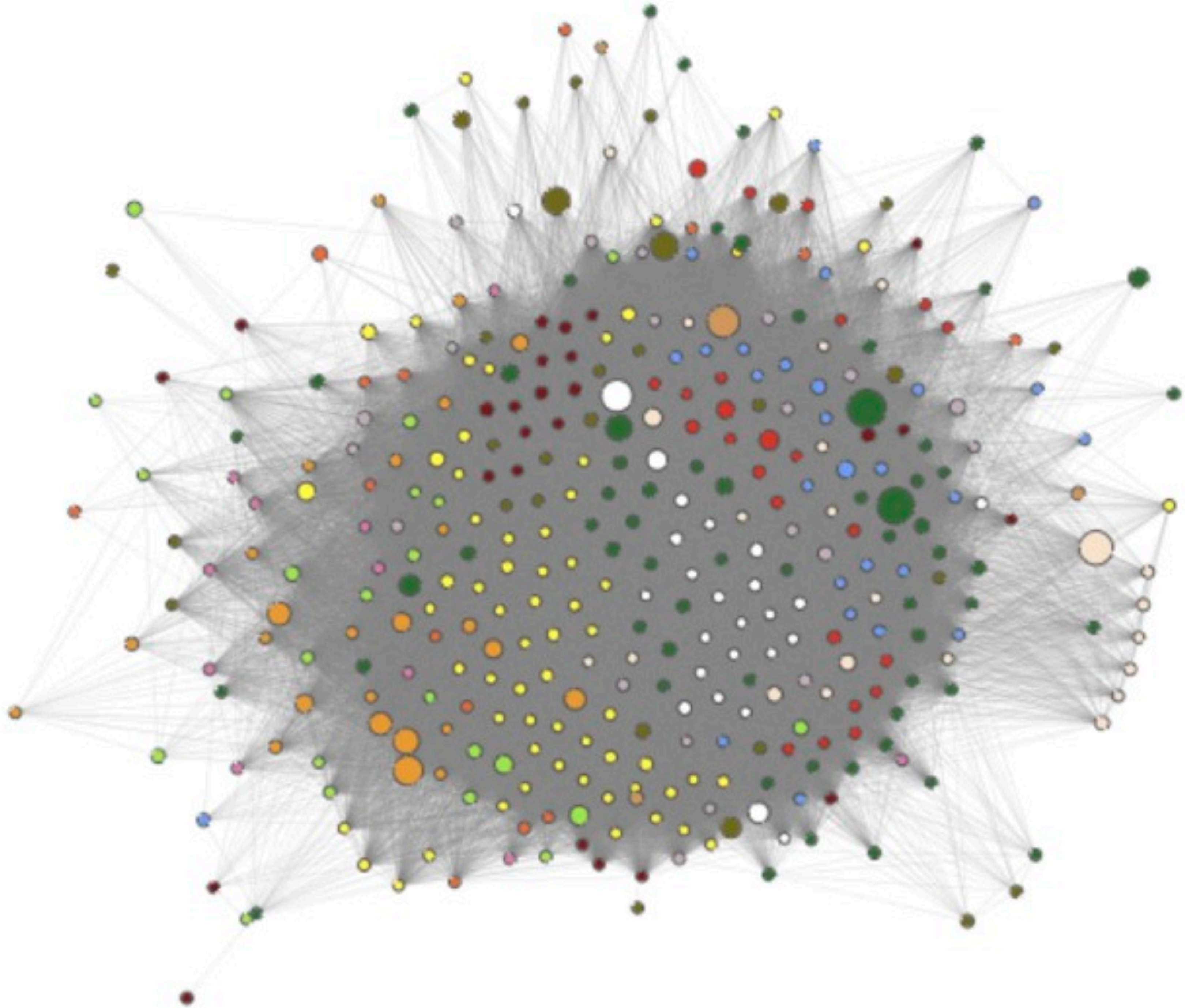
1,201 flavor compounds


Ingredients
Flavor compounds
Flavor
Shrimp scampi and tomato broil
Seasoned mussels
shrimp
white wine
mozzarella
parmesan
olive oil
parsley
tomato
garlic
scallion
sesame oil
starch
soy sauce
nut
black pepper
sake
mussel
1-penten-3-ol
2-hexenal
2-isobutyl thiazole
2,3-diethylpyrazine
2,4-nonadienal
3-hexen-1-ol
4-hydroxy-5-methyl...
4-methylpentanoic acid
acetylpyrazine
allyl 2-furoate
alpha-terpineol
beta-cyclodextrin
cis-3-hexenal
dihydroxyacetone
dimethyl succinate
ethyl propionate
hexyl alcohol
isoamyl alcohol
isobutyl acetate
isobutyl alcohol
lauric acid
limonene (d-,l-, and dl-)
l-malic acid
methyl butyrate
methyl hexanoate
methyl propyl trisulfide
nonanoic acid
phenethyl alcohol
propenyl propyl disulfide
propionaldehyde
propyl disulfide
p-mentha-1,3-diene
p-menth-1-ene-9-al
terpinyl acetate
tetrahydrofurfuryl alcohol
trans, trans-2,4-hexadienal
...
scallion
garlic
parmesan
parsley
sesame oil
nut

ounds

Flavor network





Network Backbone:

“keeping only the significant links”

Extracting the multiscale backbone of complex weighted networks

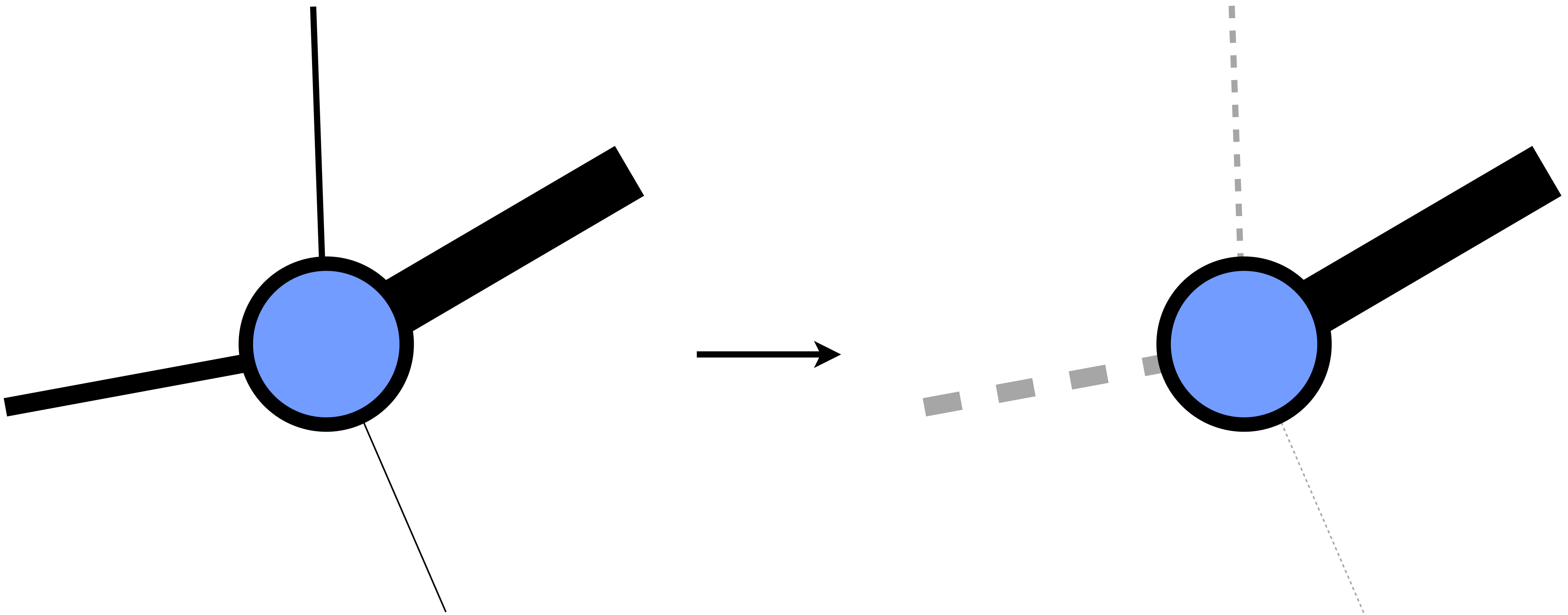
M. Ángeles Serrano[a,1], Marián Boguñá[b], and Alessandro Vespignani[c,d]

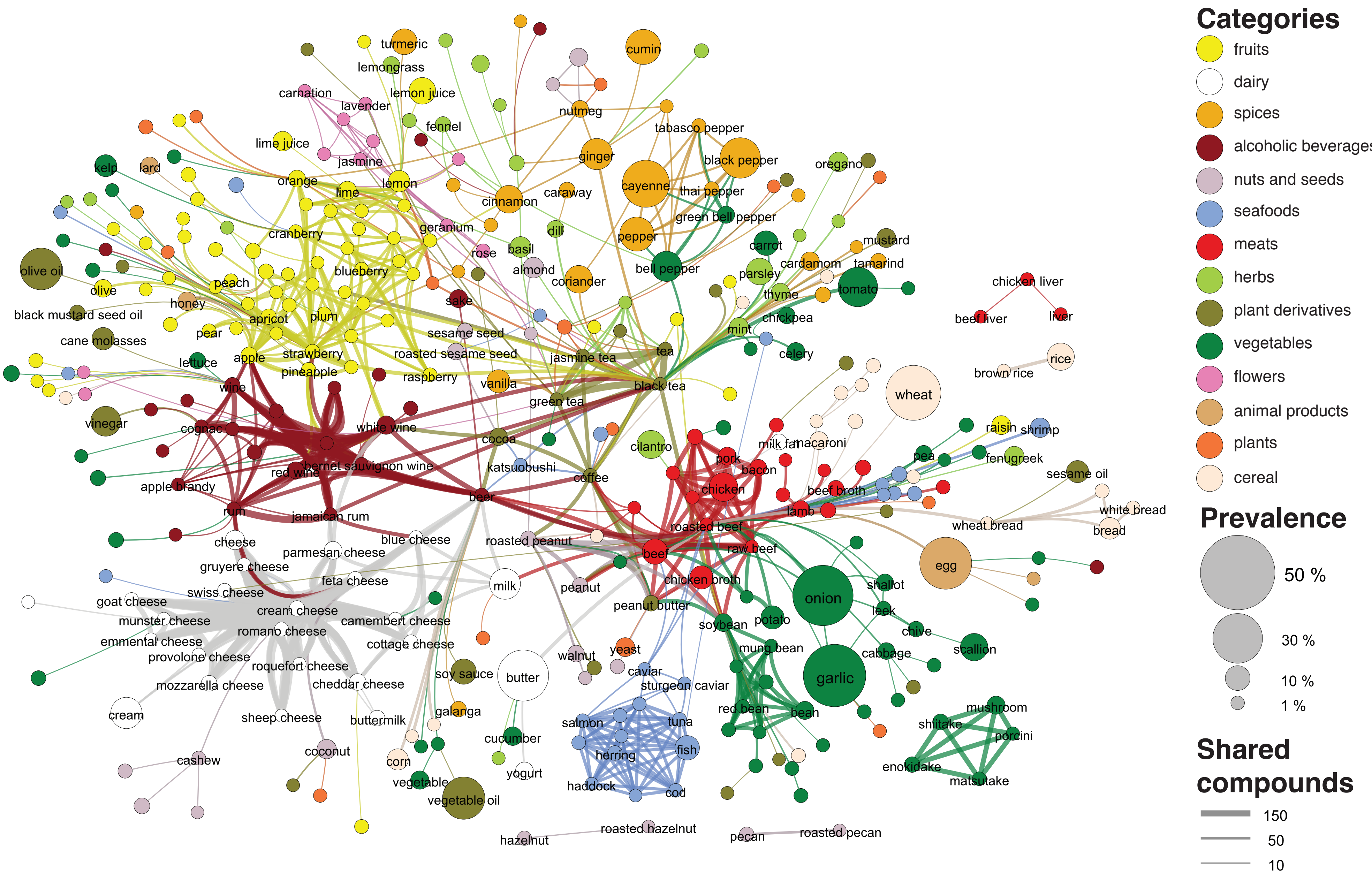
[a]Instituto de Física Interdisciplinar y Sistemas Complejos, Consejo Superior de Investigaciones Científicas-Universitat Illes Balears, E-07122 Palma de Mallorca, Spain; [b]Departament de Física Fonamental, Universitat de Barcelona, Martí i Franquès 1, 08028 Barcelona, Spain; [c]Center for Complex Networks and Systems Research, School of Informatics, Indiana University, 919 East 10th Street, Bloomington, IN 47406; and [d]Complex Networks Lagrange Laboratory, Institute for Scientific Interchange, 10133 Torino, Italy

Edited by Peter J. Bickel, University of California, Berkeley, CA, and approved March 2, 2009 (received for review September 9, 2008)

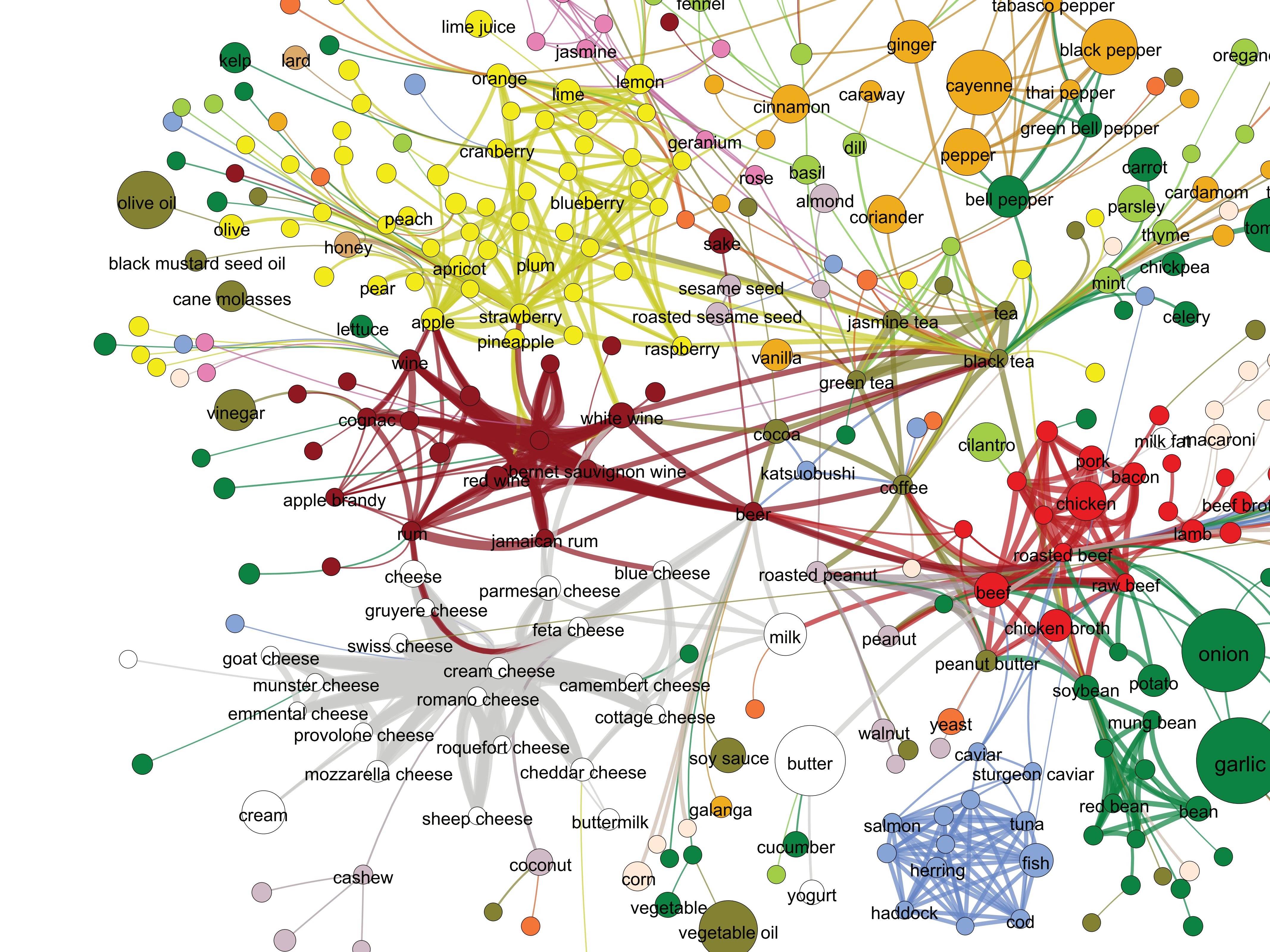
A large number of complex systems find a natural abstraction in the form of weighted networks whose nodes represent the elements of the system and the weighted edges identify the presence of an interaction and its relative strength. In recent years, the study of an increasing number of large-scale networks has highlighted the statistical heterogeneity of their interaction pattern, with degree

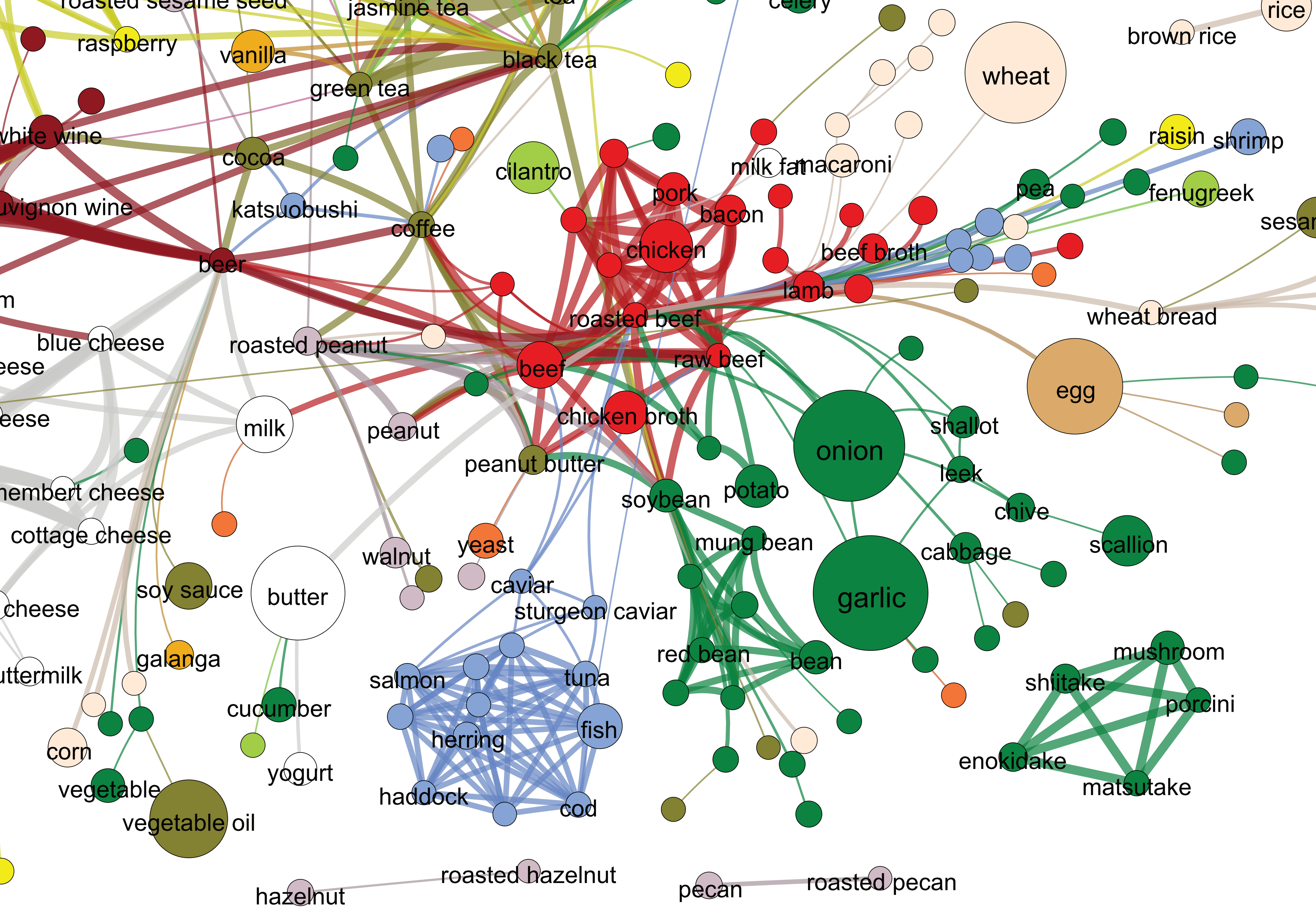
on thresholding would simply overlook the information present above or below the arbitrary cutoff scale. Although this issue would not be a major drawback in networks where the intensities of all the edges are independently and identically distributed, the cutoff of the $P(\omega)$ tail would destroy the multiscale nature of more realistic networks where weights are locally correlated on edges incident to



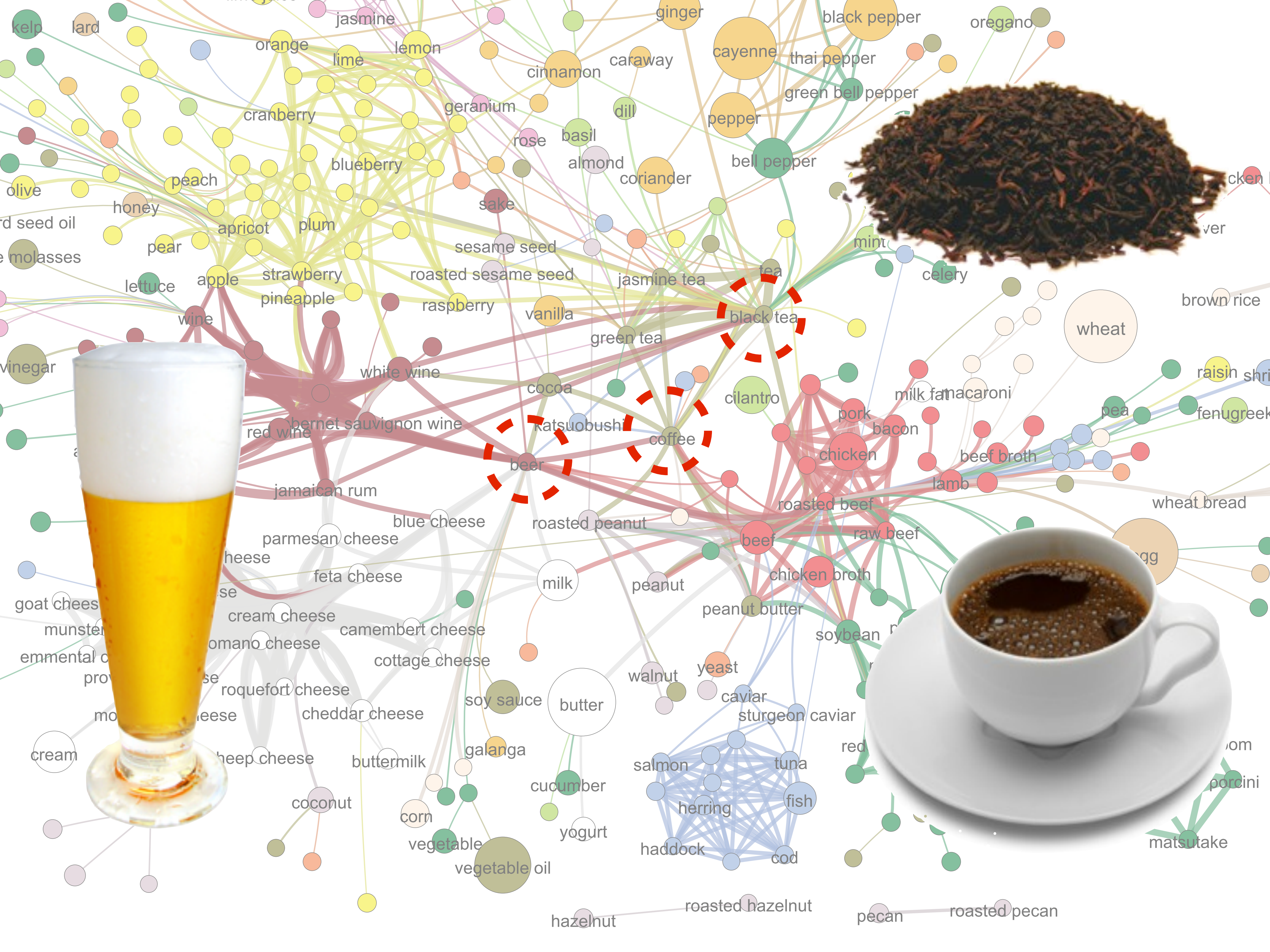


turmeric
lemongrass
carnation
lavender
lemon juice
fennel
nutmeg
cumin
tabasco pepper
lime juice
jasmine
ginger
black pepper
oregano
kelp
lard
orange
lime
lemon
cinnamon
caraway
cayenne
thai pepper
green bell pepper
cranberry
geranium
dill
pepper
carrot
mustard
rose
basil
almond
coriander
bell pepper
cardamom
tamarind
olive oil
blueberry
parsley
tomato
peach
olive
thyme
chicken liver
honey
sake
chickpea
black mustard seed oil
apricot
plum
beef liver
liver
pear
sesame seed
mint
cane molasses
tea
celery
rice
apple
strawberry
roasted sesame seed
jasmine tea
lettuce
brown rice
pineapple
raspberry
vanilla
black tea
wine
wheat
green tea
vinegar
cognac
white wine
raisin
shrimp
cocoa
milk fat
macaroni
cilantro
pork
pea
fenugreek
katsuobushi
bacon
cabernet sauvignon wine
red wine
coffee
sesame oil
chicken
apple brandy
beef broth
beer
white bread
lamb
rum
jamaican rum
wheat bread
roasted beef
bread
cheese
blue cheese
roasted peanut
raw beef
egg
parmesan cheese
beef
gruyere cheese
feta cheese
chicken broth
shallot
swiss cheese
milk
peanut
onion
goat cheese
cream cheese
peanut butter
leek
munster cheese
camembert cheese
soybean
potato
chive
romano cheese
emmental cheese
cottage cheese
mung bean
yeast
scallion
walnut
cabbage
provolone cheese
roquefort cheese
caviar
garlic
soy sauce
butter
mozzarella cheese
cheddar cheese
sturgeon caviar
mushroom
galanga
red bean
cream
sheep cheese
buttermilk
salmon
tuna
bean
shiitake
porcini
cucumber
coconut
herring
fish
cashew
corn
enokidake
yogurt
matsutake
vegetable
haddock
cod
vegetable oil
roasted hazelnut
roasted pecan
hazelnut
pecan
Categories
fruits
dairy
spices
alcoholic beverages
nuts and seeds
seafoods
meats
herbs
plant derivatives
vegetables
flowers
animal products
plants
cereal
Prevalence
50 %
30 %
10 %
1 %
Shared compounds
150
50
10

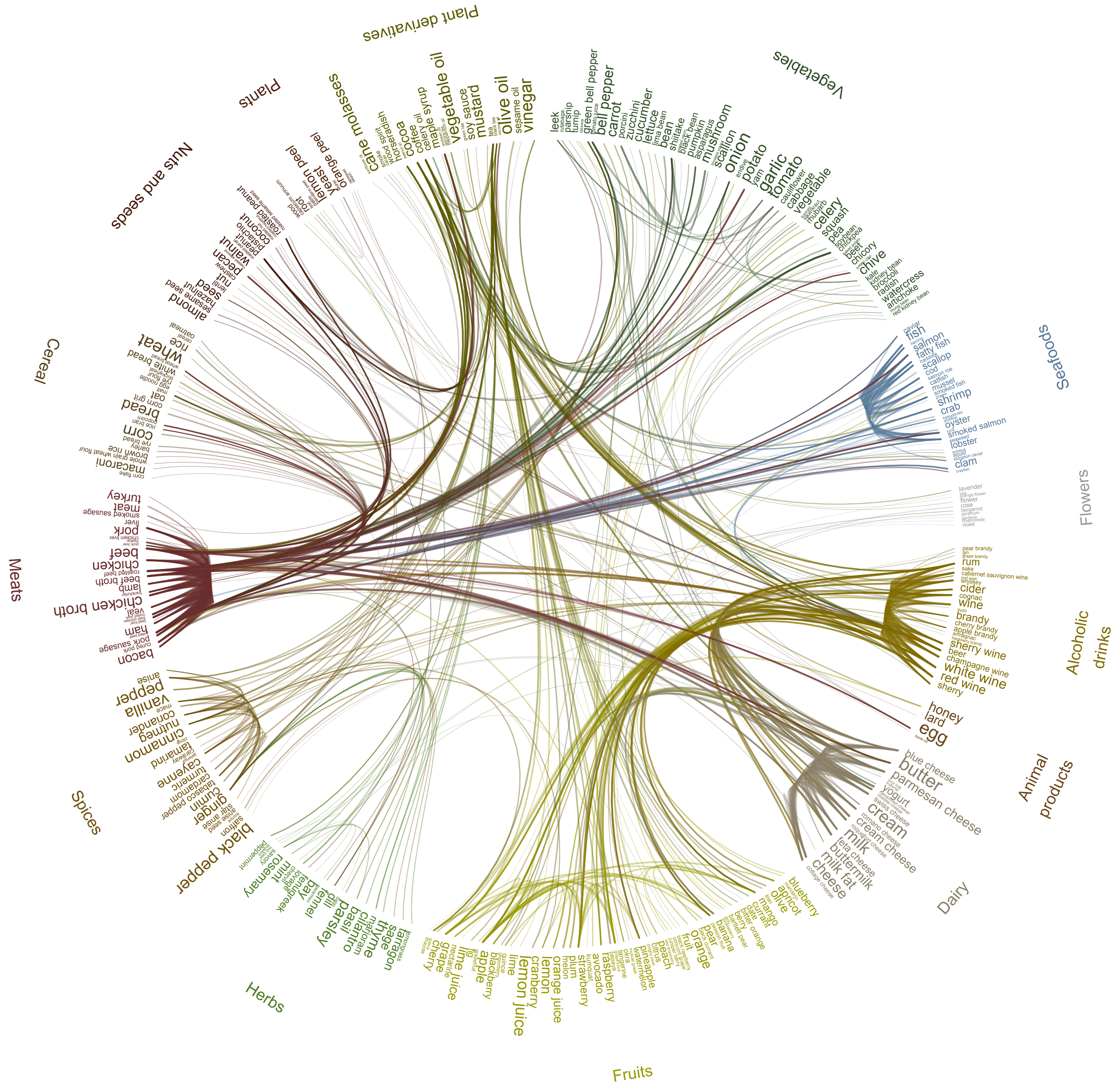

fennel
tabasco pepper
lime juice
jasmine
kelp
lard
orange
lemon
lime
ginger
black pepper
oregan
cayenne
caraway
cinnamon
thai pepper
green bell pepper
geranium
cranberry
dill
pepper
carrot
rose
basil
almond
bell pepper
cardamom
olive oil
blueberry
parsley
coriander
tom
peach
olive
honey
thyme
sake
black mustard seed oil
apricot
plum
chickpea
pear
sesame seed
mint
cane molasses
strawberry
roasted sesame seed
jasmine tea
tea
celery
lettuce
apple
pineapple
raspberry
vanilla
black tea
wine
green tea
vinegar
cognac
white wine
cocoa
cilantro
milk fat
macaroni
pork
bacon
katsuobushi
red wine
bernet sauvignon wine
coffee
chicken
apple brandy
beef brot
beer
rum
jamaican rum
lamb
roasted beef
cheese
blue cheese
roasted peanut
parmesan cheese
beef
raw beef
gruyere cheese
feta cheese
milk
peanut
chicken broth
swiss cheese
onion
goat cheese
cream cheese
peanut butter
munster cheese
camembert cheese
soybean
potato
romano cheese
emmental cheese
cottage cheese
mung bean
walnut
yeast
provolone cheese
roquefort cheese
soy sauce
butter
caviar
garlic
sturgeon caviar
mozzarella cheese
cheddar cheese
red bean
bean
cream
galanga
salmon
tuna
sheep cheese
buttermilk
cucumber
fish
herring
coconut
cashew
corn
yogurt
vegetable
haddock
cod
vegetable oil



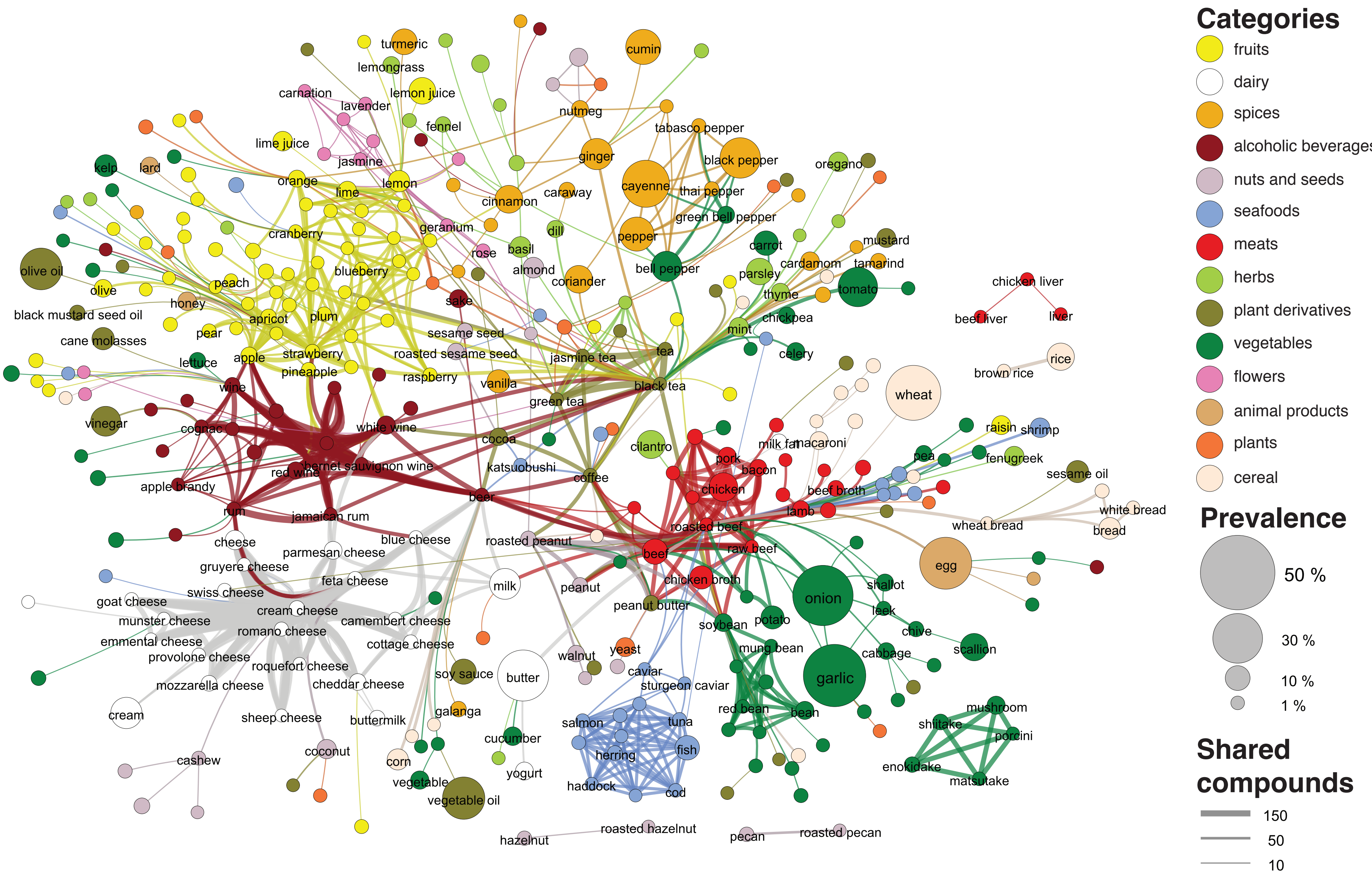
jasmine tea
celery
rice
raspberry
vanilla
black tea
brown rice
wheat
green tea
white wine
cocoa
cilantro
milk fat
macaroni
raisin
shrimp
pork
pea
fenugreek
katsuobushi
coffee
bacon
chicken
beef broth
beer
lamb
roasted beef
wheat bread
blue cheese
roasted peanut
beef
raw beef
egg
milk
chicken broth
shallot
peanut
onion
peanut butter
leek
soybean
potato
chive
cottage cheese
mung bean
scallion
walnut
yeast
cabbage
caviar
soy sauce
butter
garlic
cheese
sturgeon caviar
galanga
red bean
bean
mushroom
salmon
tuna
shiitake
cucumber
porcini
fish
herring
corn
enokidake
yogurt
vegetable
matsutake
haddock
cod
vegetable oil
roasted hazelnut
roasted pecan
hazelnut
pecan



kelp
lard
jasmine
orange
lime
lemon
ginger
black pepper
oregano
cayenne
caraway
cinnamon
thai pepper
green bell pepper
cranberry
geranium
dill
pepper
rose
basil
blueberry
almond
coriander
bell pepper
peach
olive
honey
sake
plum
apricot
pear
molasses
sesame seed
mint
roasted sesame seed
jasmine tea
tea
celery
lettuce
apple
strawberry
pineapple
raspberry
vanilla
black tea
brown rice
wine
wheat
green tea
vinegar
white wine
raisin
cocoa
cilantro
milk fat
macaroni
pork
pea
fenugreek
katsuobushi
red wine
coffee
bacon
chicken
beef broth
beer
lamb
jamaican rum
roasted beef
wheat bread
blue cheese
roasted peanut
parmesan cheese
beef
raw beef
feta cheese
milk
chicken broth
peanut
cream cheese
peanut butter
soybean
camembert cheese
cottage cheese
walnut
yeast
roquefort cheese
caviar
soy sauce
butter
sturgeon caviar
cheddar cheese
cream
galanga
salmon
tuna
buttermilk
porcini
cucumber
fish
coconut
herring
corn
yogurt
matsutake
vegetable
haddock
cod
vegetable oil
roasted hazelnut
pecan
roasted pecan
hazelnut



Plant derivatives
Vegetables
Seafoods
Flowers
Alcoholic drinks
Animal products
Dairy
Fruits
Herbs
Spices
Meats
Cereal
Nuts and seeds
Plants
cane molasses
cocoa
coffee
maple syrup
vegetable oil
soy sauce
mustard
olive oil
sesame oil
vinegar
leek
parsnip
turnip
green bell pepper
bell pepper
carrot
zucchini
cucumber
lettuce
bean
shiitake
pumpkin
asparagus
mushroom
scallion
onion
potato
yam
garlic
tomato
cauliflower
cabbage
vegetable
celery
squash
pea
chickpea
beet
chicory
chive
kale
broccoli
radish
watercress
artichoke
red kidney bean
fish
salmon
fatty fish
scallop
cod
catfish
mussel
smoked fish
shrimp
crab
oyster
smoked salmon
lobster
clam
lavender
flower
rose
violet
rum
sake
cabernet sauvignon wine
whiskey
cider
cognac
wine
brandy
cherry brandy
apple brandy
sherry wine
beer
champagne wine
white wine
red wine
sherry
honey
lard
egg
blue cheese
butter
parmesan cheese
yogurt
swiss cheese
cream
romano cheese
cream cheese
milk
feta cheese
buttermilk
milk fat
cheese
cottage cheese
blueberry
apricot
olive
mango
currant
date
bitter orange
berry
banana
pear
orange
fruit
peach
pineapple
watermelon
raspberry
avocado
strawberry
plum
melon
orange juice
lemon
cranberry
lemon juice
lime
blackberry
apple
fig
lime juice
nectarine
grape
cherry
tarragon
sage
thyme
marjoram
cilantro
basil
parsley
dill
fennel
bay
fenugreek
mint
rosemary
peppermint
black pepper
saffron
star anise
ginger
cumin
tabasco pepper
cardamom
turmeric
cayenne
caraway
tamarind
clove
cinnamon
nutmeg
coriander
mace
vanilla
pepper
anise
bacon
pork sausage
cured pork
ham
veal
chicken broth
lamb
beef broth
roasted beef
chicken
beef
pork
liver
smoked sausage
meat
turkey
corn flake
macaroni
whole grain wheat flour
brown rice
barley
rye bread
corn
rice bran
bread
corn grit
oat
egg noodle
rye flour
white bread
wheat bread
wheat
rice
cereal
oatmeal
almond
sesame seed
hazelnut
seed
lentil
nut
cashew
pecan
walnut
pistachio
coconut
roasted peanut
peanut
wood
root
lemon peel
yeast
orange peel



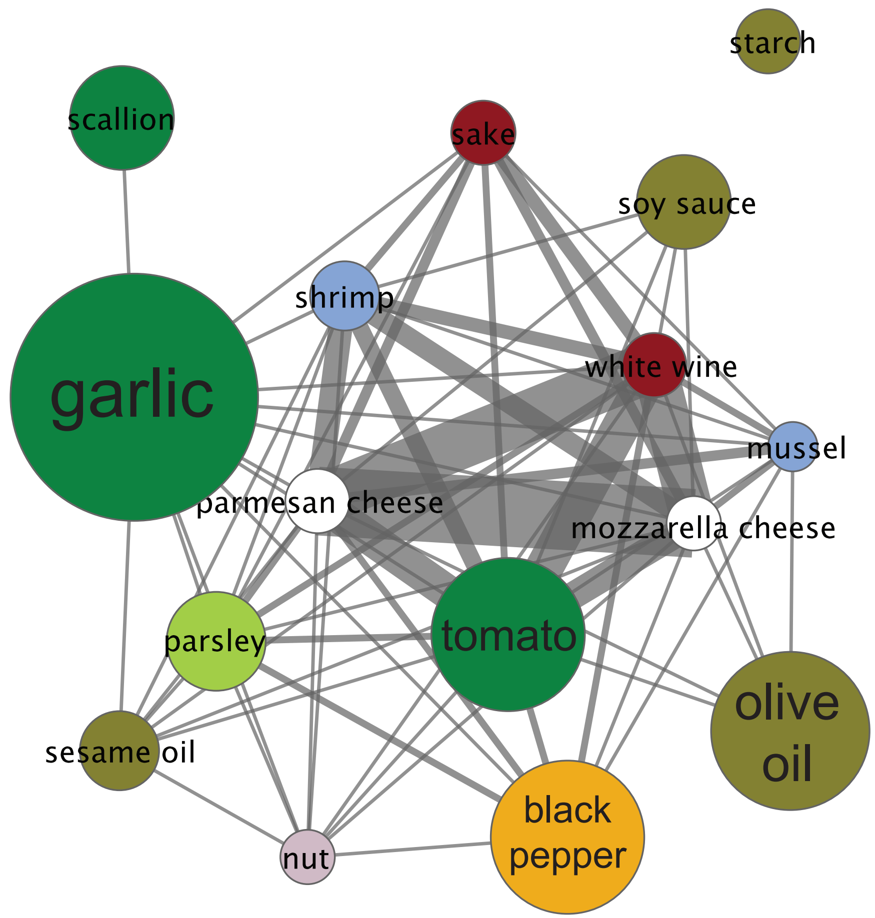
turmeric
lemongrass
carnation
lavender
lemon juice
cumin
nutmeg
fennel
tabasco pepper
lime juice
jasmine
ginger
black pepper
oregano
kelp
lard
orange
lime
lemon
cayenne
thai pepper
cinnamon
caraway
green bell pepper
geranium
cranberry
dill
pepper
carrot
mustard
rose
basil
almond
cardamom
tamarind
olive oil
blueberry
coriander
bell pepper
parsley
tomato
olive
peach
sake
thyme
chicken liver
black mustard seed oil
honey
apricot
plum
chickpea
beef liver
liver
pear
sesame seed
mint
cane molasses
jasmine tea
tea
celery
rice
roasted sesame seed
lettuce
apple
strawberry
brown rice
pineapple
raspberry
vanilla
black tea
wheat
wine
green tea
vinegar
raisin
shrimp
cognac
white wine
cocoa
milk fat
macaroni
cilantro
pork
pea
fenugreek
katsuobushi
cabernet sauvignon wine
red wine
bacon
sesame oil
coffee
chicken
apple brandy
beef broth
beer
white bread
lamb
wheat bread
rum
jamaican rum
roasted beef
bread
blue cheese
cheese
roasted peanut
raw beef
parmesan cheese
beef
egg
gruyere cheese
feta cheese
chicken broth
shallot
milk
peanut
onion
swiss cheese
goat cheese
cream cheese
peanut butter
leek
munster cheese
camembert cheese
soybean
potato
romano cheese
chive
emmental cheese
cottage cheese
mung bean
scallion
yeast
cabbage
provolone cheese
walnut
roquefort cheese
caviar
garlic
soy sauce
butter
mozzarella cheese
cheddar cheese
sturgeon caviar
cream
mushroom
galanga
red bean
sheep cheese
salmon
tuna
bean
buttermilk
shiitake
porcini
cucumber
coconut
herring
fish
cashew
corn
yogurt
enokidake
matsutake
vegetable
haddock
cod
vegetable oil
roasted hazelnut
roasted pecan
hazelnut
pecan
Categories
fruits
dairy
spices
alcoholic beverages
nuts and seeds
seafoods
meats
herbs
plant derivatives
vegetables
flowers
animal products
plants
cereal
Prevalence
50 %
30 %
10 %
1 %
Shared compounds
150
50
10

How can we know the preference of people?

Recipes!

56,498 recipes total

A recipe: a subgraph of the flavor network

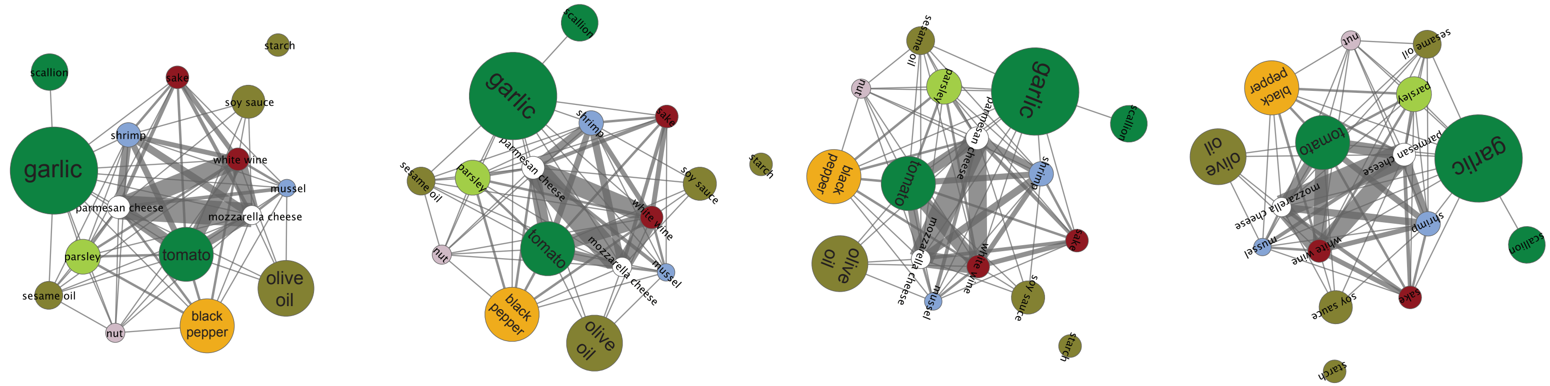


Food pairing hypothesis

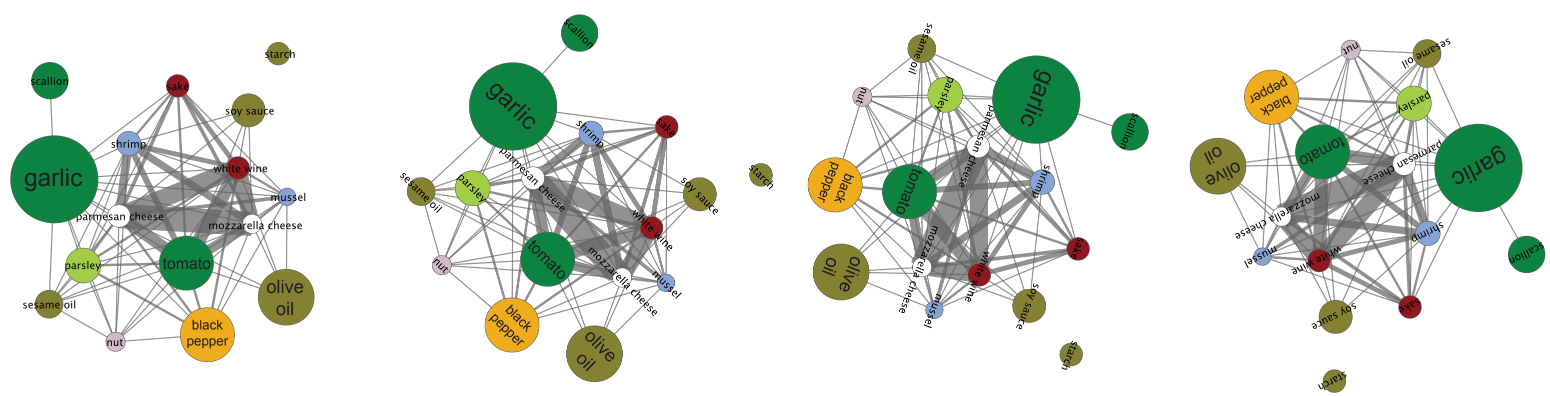
↓

Are these subgraphs (recipes) denser than random subgraphs?

Real
recipe
s



Random
recipes

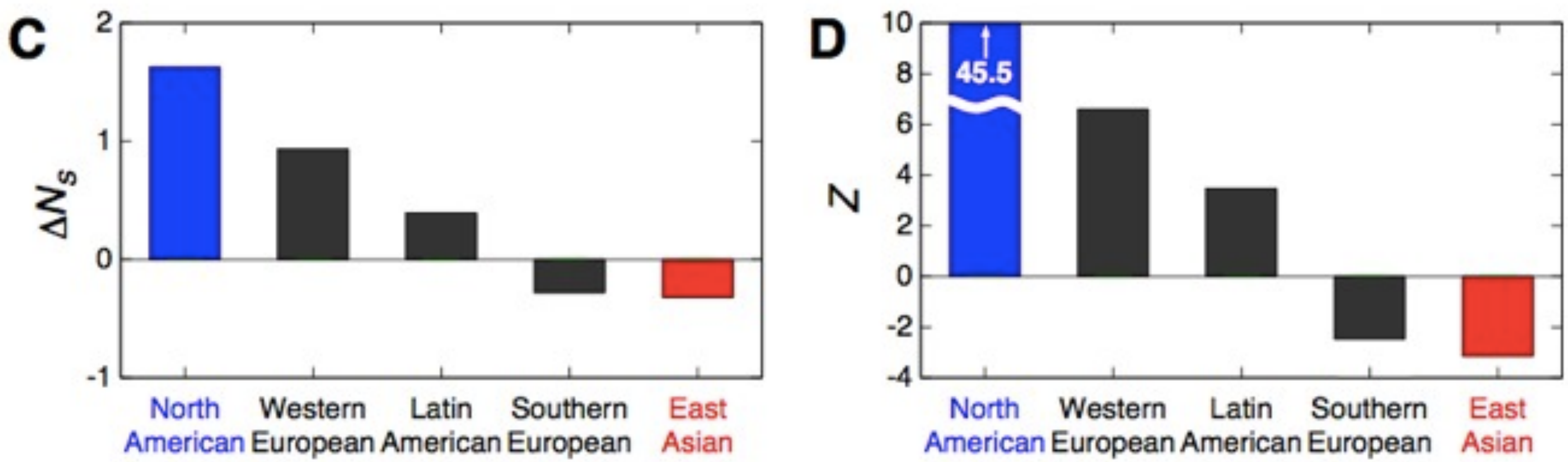


(ingredient frequency conserved)

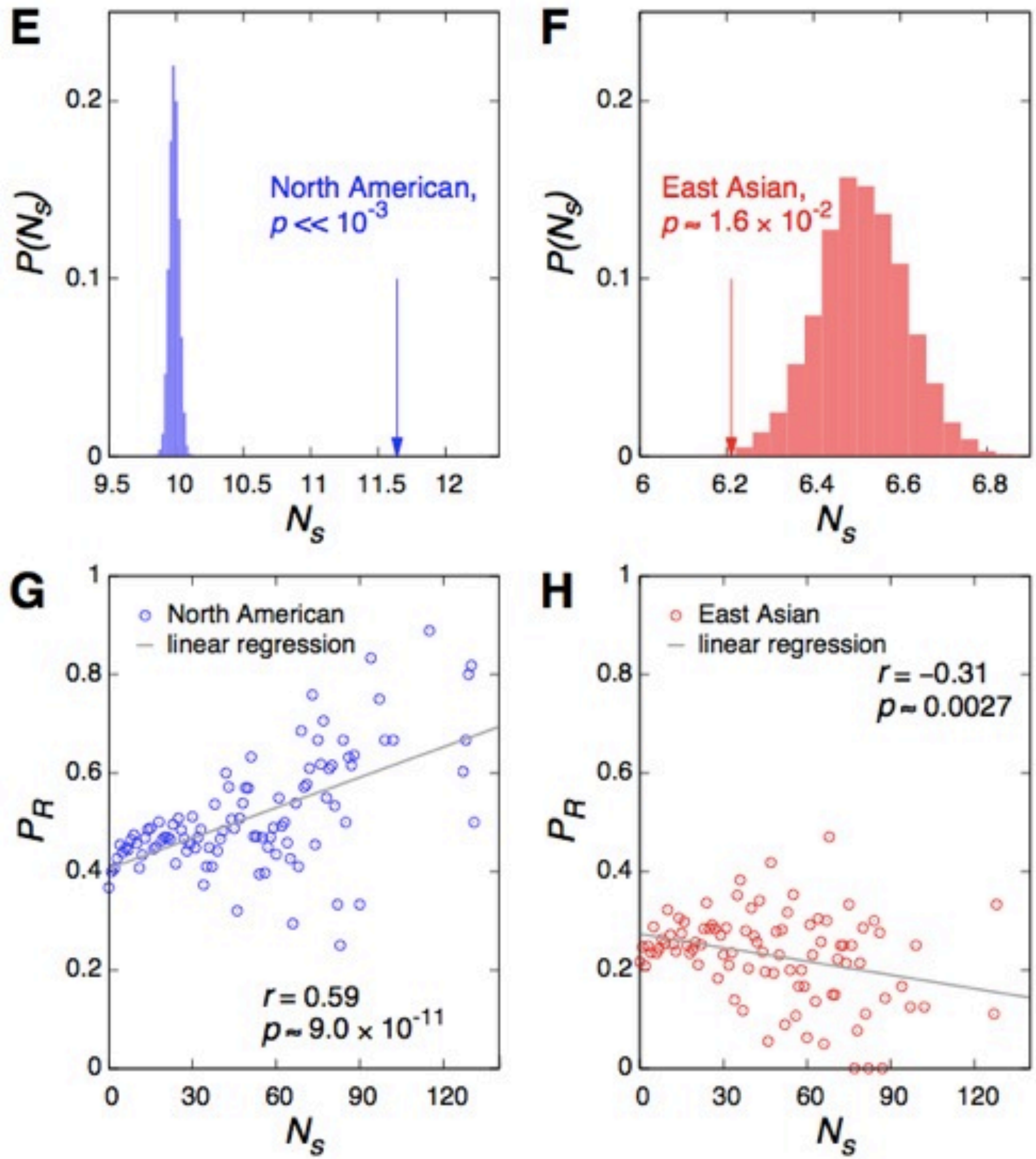
Are these subgraphs (recipes) denser than random subgraphs?

Yes & No

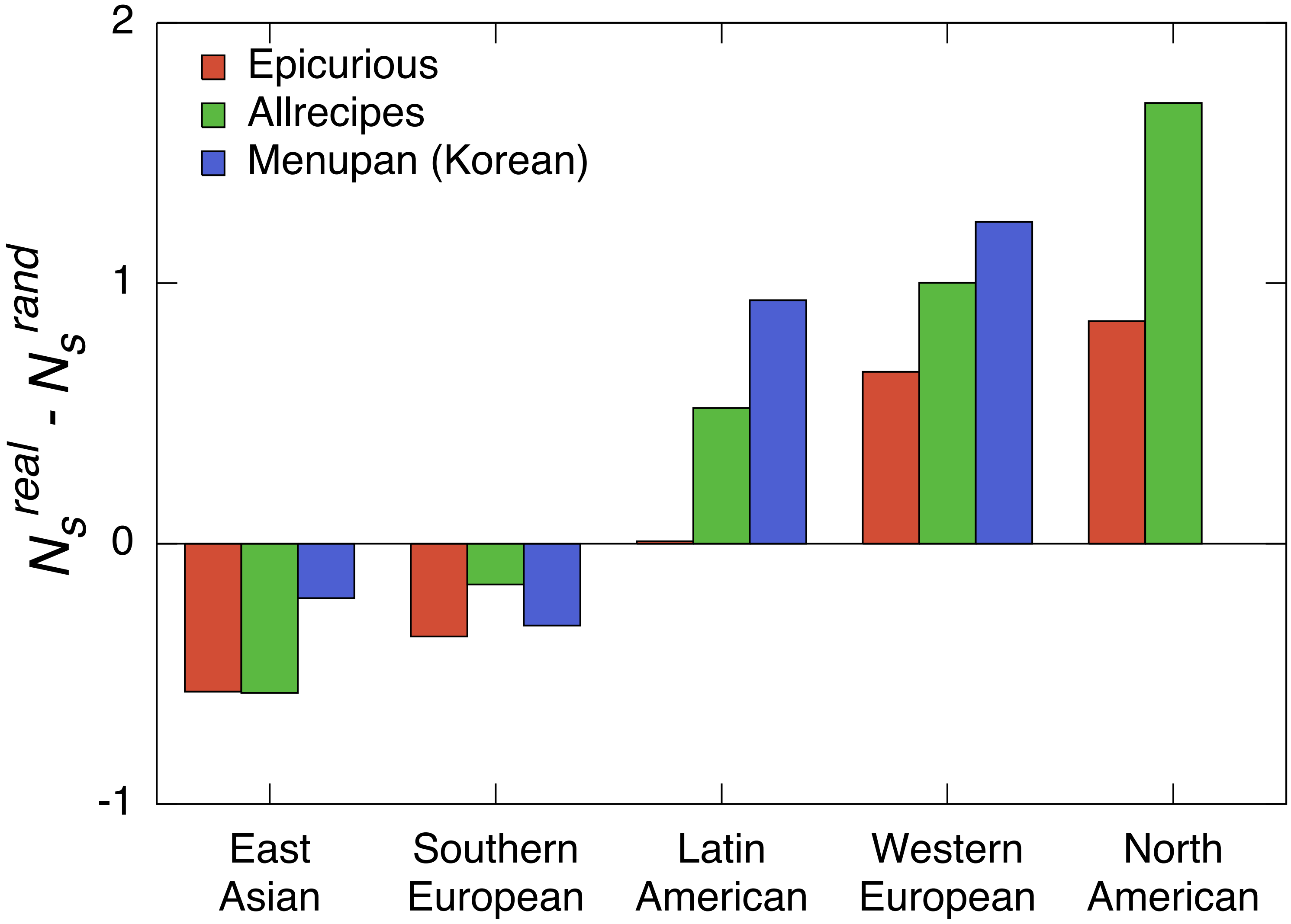
Cultural Variation



North American



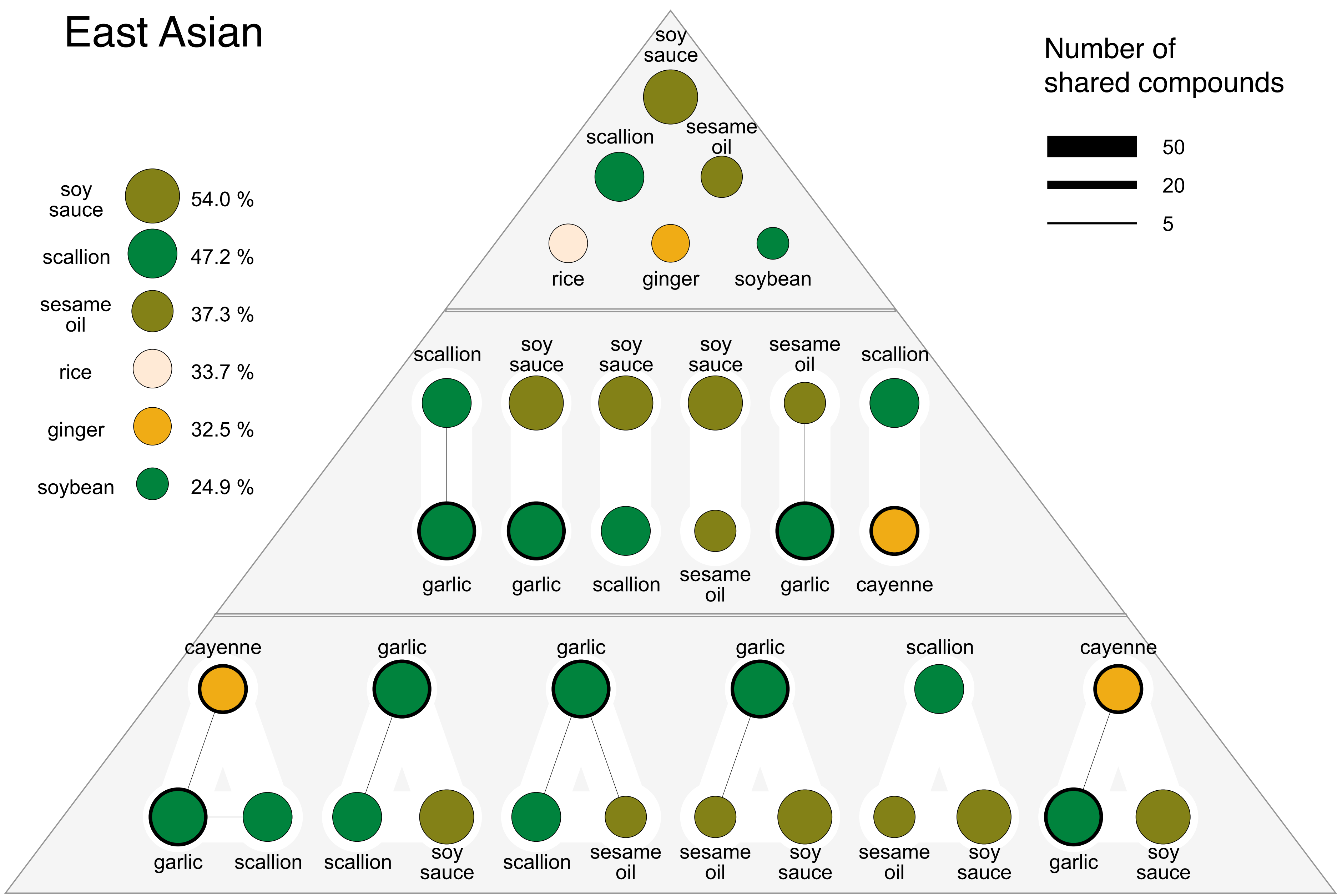
East Asian

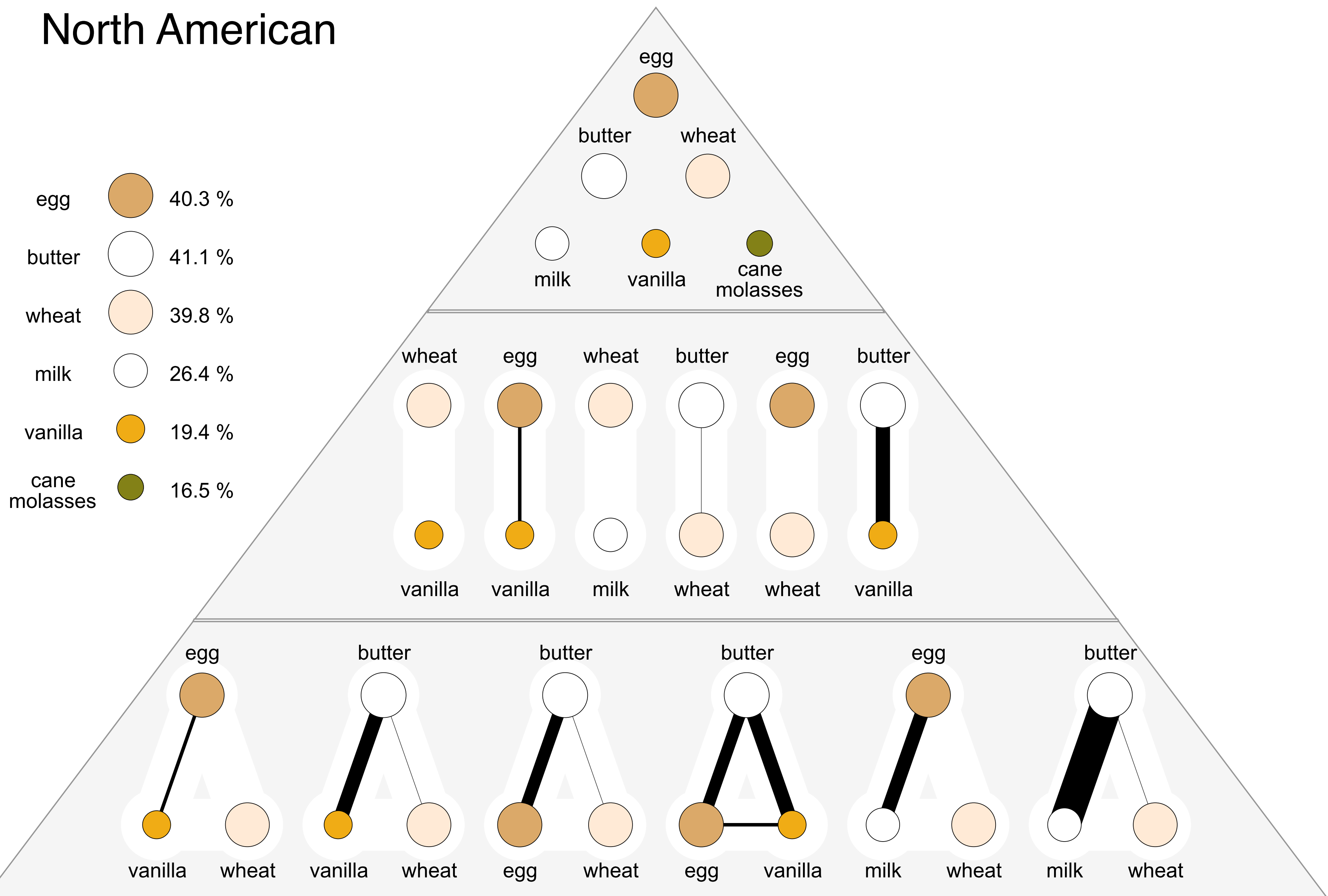


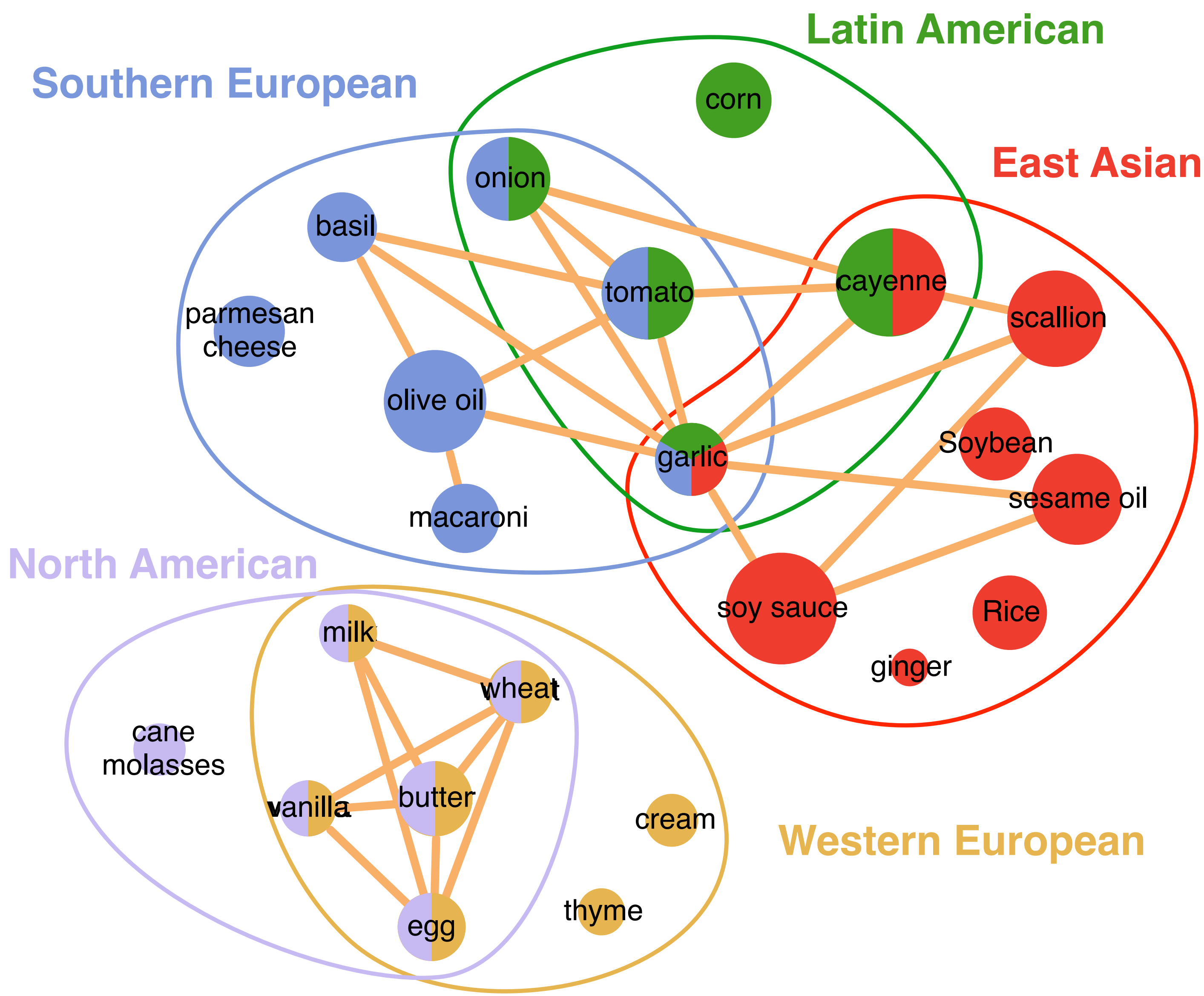
Epicurious
Allrecipes
Menupan (Korean)
$N_s^{real} - N_s^{rand}$
2
1
0
-1
East Asian
Southern European
Latin American
Western European
North American

Flavor principles

What are the most *authentic* ingredients in each cuisine?


East Asian
soy sauce
54.0 %
scallion
47.2 %
sesame oil
37.3 %
rice
33.7 %
ginger
32.5 %
soybean
24.9 %
Number of shared compounds
50
20
5
soy sauce
scallion
sesame oil
rice
ginger
soybean
scallion
garlic
soy sauce
garlic
soy sauce
scallion
soy sauce
sesame oil
sesame oil
garlic
scallion
cayenne
cayenne
garlic
scallion
garlic
scallion
soy sauce
garlic
scallion
sesame oil
garlic
sesame oil
soy sauce
scallion
sesame oil
soy sauce
cayenne
garlic
soy sauce


North American
egg 40.3 %
butter 41.1 %
wheat 39.8 %
milk 26.4 %
vanilla 19.4 %
cane molasses 16.5 %
egg
butter
wheat
milk
vanilla
cane molasses
wheat
vanilla
egg
vanilla
wheat
milk
butter
wheat
egg
wheat
butter
vanilla
egg
vanilla
wheat
butter
vanilla
wheat
butter
egg
wheat
butter
egg
vanilla
egg
milk
wheat
butter
milk
wheat

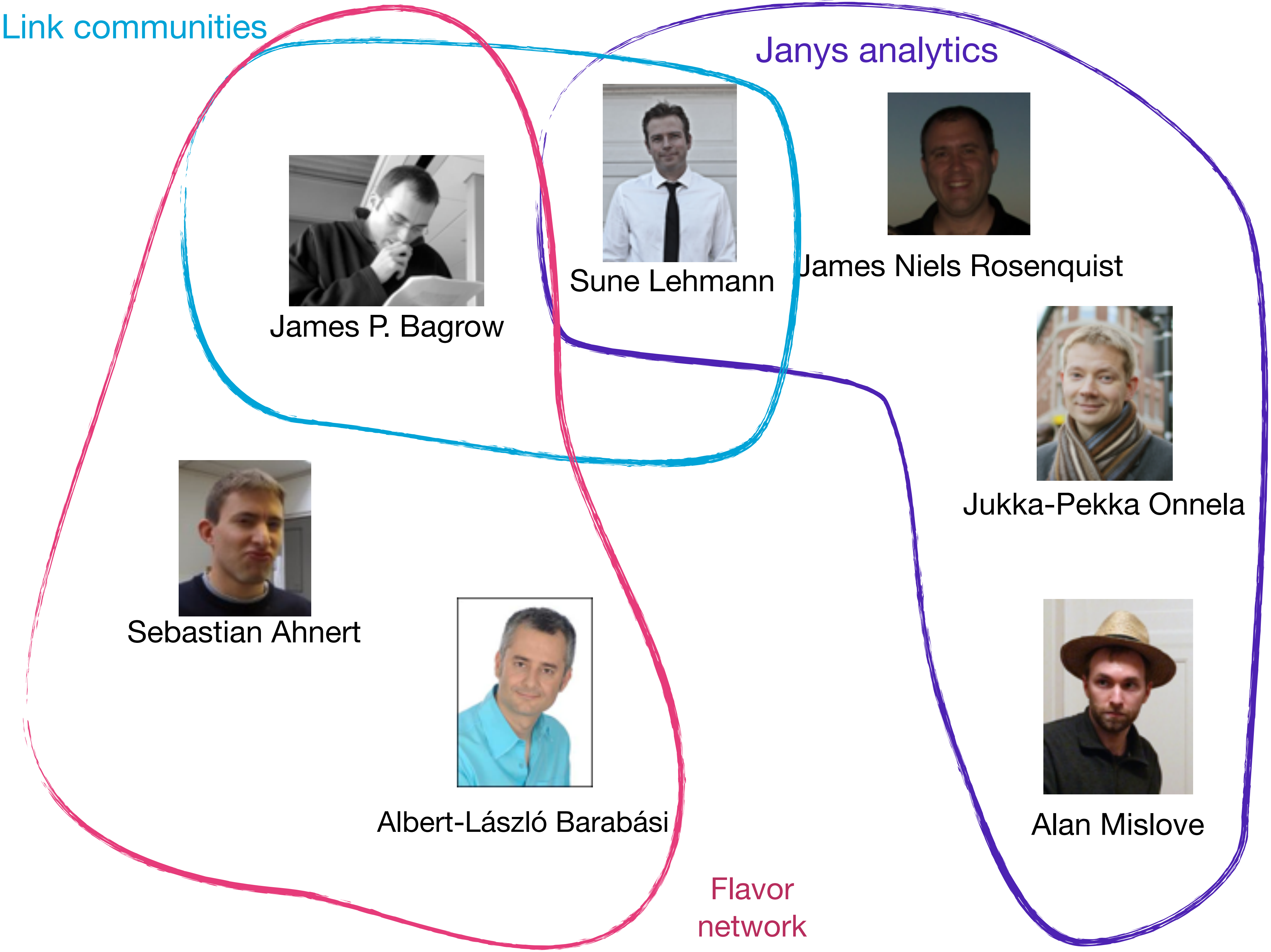


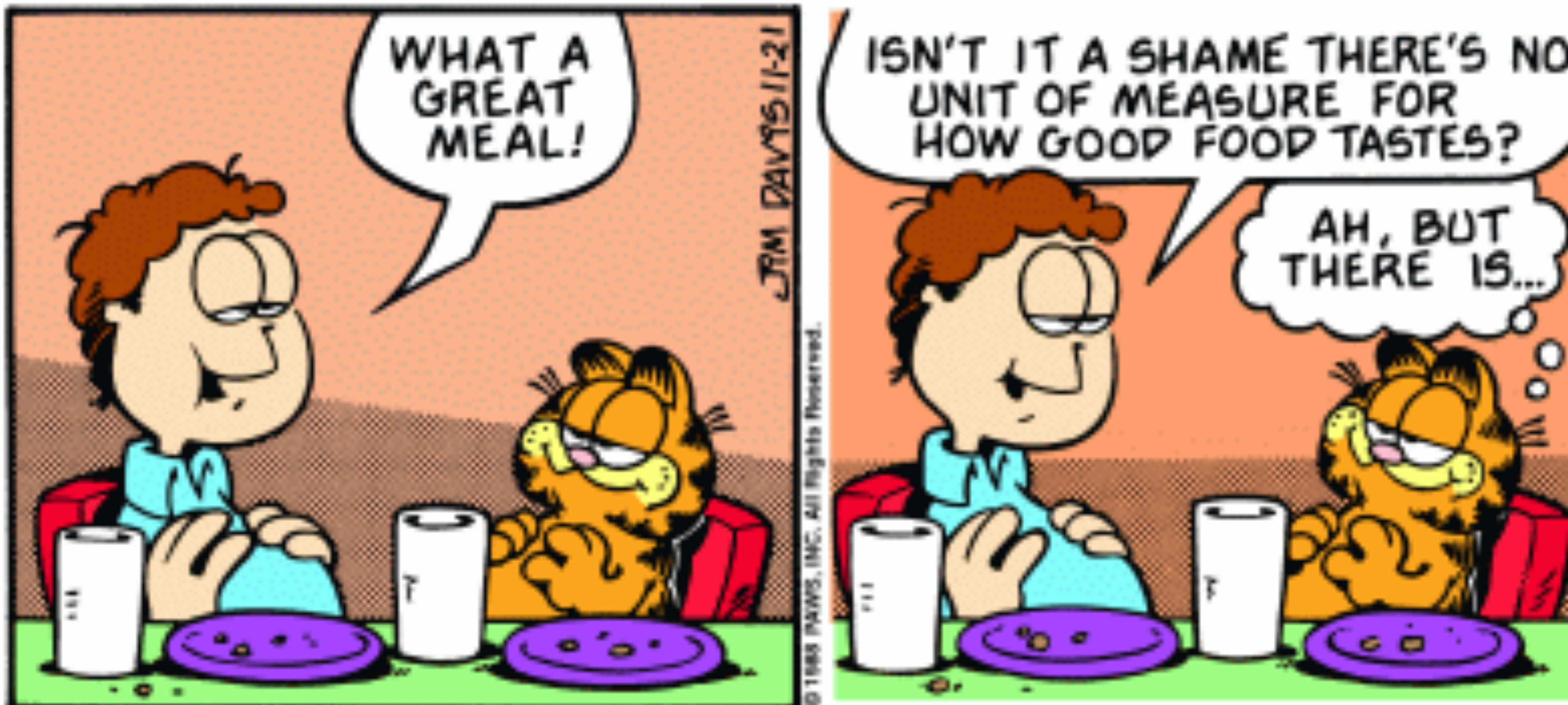
Latin American
Southern European
East Asian
North American
Western European
corn
onion
basil
tomato
cayenne
scallion
parmesan
cheese
olive oil
garlic
Soybean
sesame oil
macaroni
soy sauce
Rice
ginger
milk
wheat
cane
molasses
vanilla
butter
cream
thyme
egg

Summary

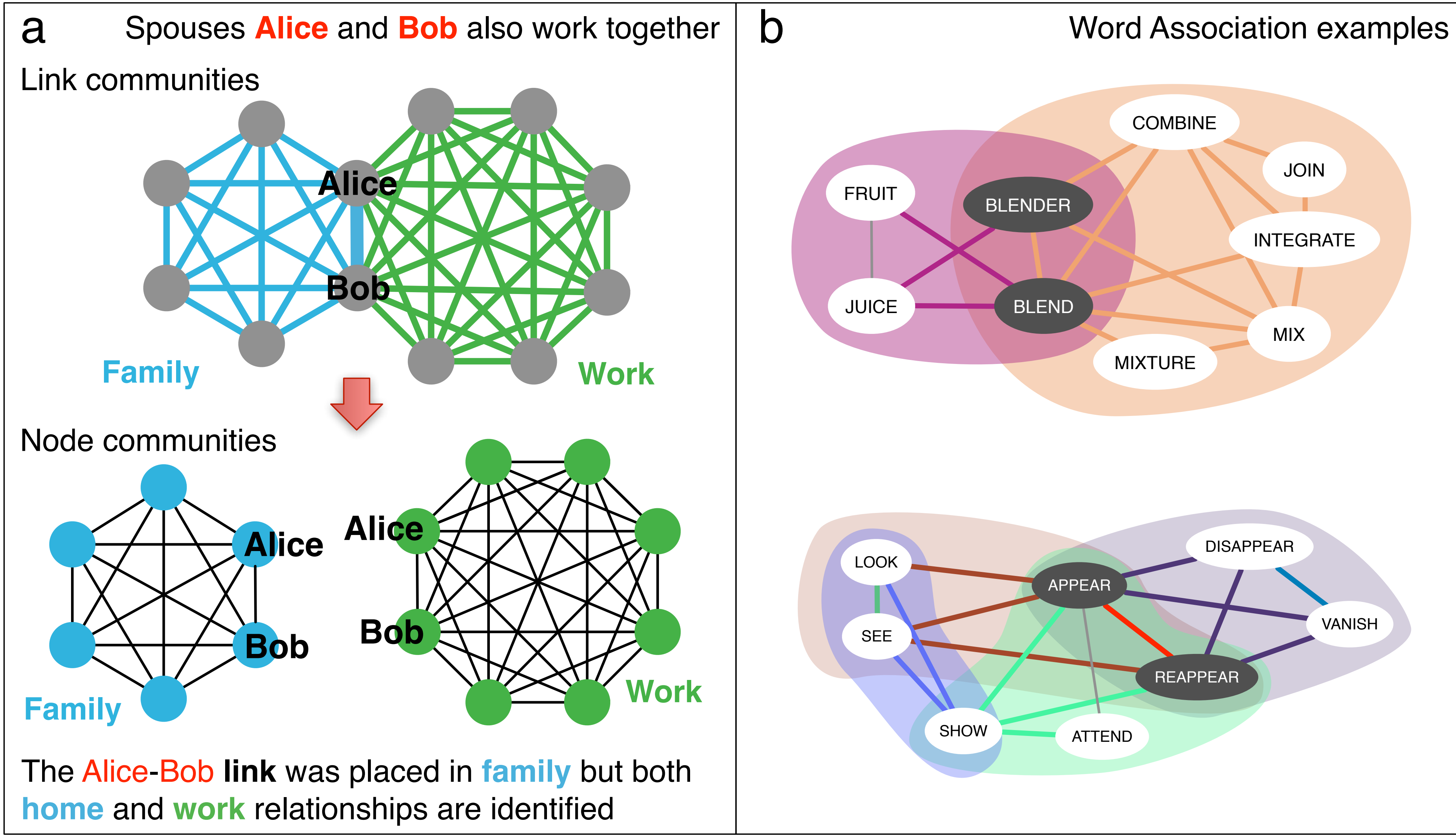
- Again, networks!
- We can study our food culture with data-driven & network-based approach.

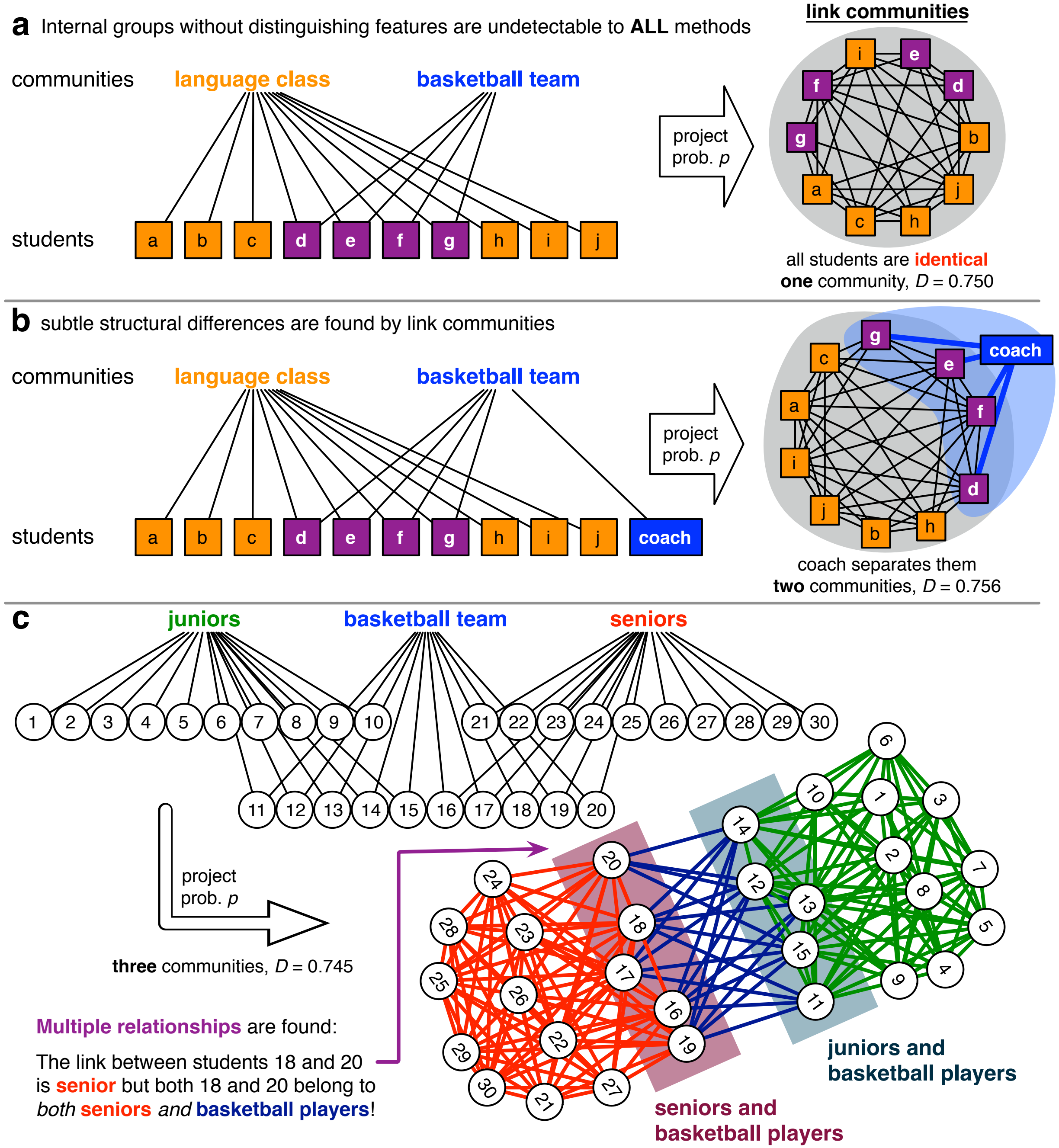
Acknowledgements


Link communities
Janys analytics
Sune Lehmann
James Niels Rosenquist
James P. Bagrow
Jukka-Pekka Onnela
Sebastian Ahnert
Albert-László Barabási
Alan Mislove
Flavor
network


WHAT A GREAT MEAL!
JIM DAVIS 11-21
ISN'T IT A SHAME THERE'S NO UNIT OF MEASURE FOR HOW GOOD FOOD TASTES?
AH, BUT THERE IS...


ISN'T IT A SHAME THERE'S NO UNIT OF MEASURE FOR HOW GOOD FOOD TASTES?
AH, BUT THERE IS...
IT'S CALLED A CALORIE


a
Spouses Alice and Bob also work together
Link communities
Alice
Bob
Family
Work
Node communities
Alice
Bob
Family
Alice
Bob
Work
The Alice-Bob link was placed in family but both home and work relationships are identified
b
Word Association examples
COMBINE
JOIN
FRUIT
BLENDER
INTEGRATE
JUICE
BLEND
MIX
MIXTURE
DISAPPEAR
LOOK
APPEAR
VANISH
SEE
REAPPEAR
SHOW
ATTEND


a Internal groups without distinguishing features are undetectable to ALL methods
link communities
communities
language class
basketball team
students
a b c d e f g h i j
project prob. p
all students are identical
one community, D = 0.750
b subtle structural differences are found by link communities
communities
language class
basketball team
students
a b c d e f g h i j coach
project prob. p
coach separates them
two communities, D = 0.756
c
juniors
basketball team
seniors
project prob. p
three communities, D = 0.745
Multiple relationships are found:
The link between students 18 and 20 is senior but both 18 and 20 belong to both seniors and basketball players!
seniors and basketball players
juniors and basketball players