2023

Network Science: Eye Spy Networks

Worlds of Connections SEPA

NETWORK SCIENCE

Eye Spy Networks

Activity guide for facilitators

WORLDS OF CONNECTIONS
SCIENCE EDUCATION PARTNERSHIP AWARD
SUPPORTED BY THE NATIONAL INSTITUTES OF HEALTH

University of Nebraska Lincoln

EYE SPY NETWORKS

Next Generation Science Standards*

Crosscutting Concept *4. Systems and system models*. A system is an organized group of related objects or components; models can be used for understanding and predicting the behavior of systems.

*Next Generation Science Standards is a registered trademark of WestEd. Neither WestEd nor the lead states and partners that developed the Next Generation Science Standards were involved in the production of this product, and do not endorse it.

Objective

Youth will identify components of network graphs and interpret relationships modeled by the network graphs. They will develop curiosity (ask questions) about why there are connections in some places and not in other places; why there are different colors; shapes, and sizes, and how/if the model helps us understand the phenomenon.

Materials

Per club

- Network graph images with legends for interpretation and source citations (see **Example Network Images,** pp. 11–29)
- Painter's tape

Per group (2–4 youth)

- Paper
- Writing utensils
- **Handout 1 – Thinking Prompts** (p. 10)

Anticipatory Set

Note: A strength of the "noticing and wondering" strategy used in this activity is that it is inclusive—all youth can notice and wonder about things. Youth can feel empowered when what they notice, wonder, and question is recognized by facilitators and peers. Therefore, thank youth when they contribute something, and if appropriate, mention appreciation for insights, curiosity, observations, and making connections. You might also ask, "Can you tell me more about that?" There are no "right" answers in noticing and wondering activities. Scientists notice phenomenon, then build models and wonder about relationships; they then design studies to answer questions that they develop while tinkering with the models.

We're going to explore models of phenomena and how models can help us understand the world around us.

- *What is a model? Why do you think people would use models?*
- *How would you create a model of the characters in a movie?*
- *How would you model who talks to whom at a party?*
- *How would you model which birds share food with specific other birds?*

Procedure

Set-up

1. Create stations around the room with one pair of seemingly different network images (e.g., brain network and *Frozen* network, flavor network and underground railway network) per station. If needed, use painter's tape to attach the images to desks or hang them on the walls.
2. Place a copy of **Handout 1 – Thinking Prompts** at each station.
3. Provide paper and writing utensils for youth to record observations
4. Create groups of 2 to 4 participants.

Activity 1 — Notice & Wonder with Network Models

Note: See the **Quick Reference on VIPS** (p. 9) for big-picture ideas about using network models. This may be helpful for you as a facilitator.

1. Assign each group to a station with network models.
2. At the stations, ask participants to describe the two images (e.g., "trees" or "bus route") and what they notice and wonder about the graphs. (See **Hand-out 1 – Thinking Prompts.**) Youth can use paper and writing utensils to record their observations and/or one person can record observations for the whole group. Group members can tell one another what they see and what stands out to them based on what they have already learned about networks. They can also describe what might be missing that they expect to see. Encourage youth to tell a story about what they see happening in the models.
   a. Encourage and acknowledge participants noticing patterns in the images (e.g., *I agree, there are* so many *connections!*).
   b. Ask participants to list as many things that they can possibly wonder about the images (e.g., *Why are there different sizes?*).
   c. Encourage comparisons, such as:
      i. *How are the phenomena similar or different from each other?*
      ii. *How are the models/representations similar or different from each other?*
3. Have groups rotate through stations.
4. Once participants have visited each of the stations to notice and wonder about

images, ask them to individually think about the networks and network models.
   a. *Did the network pairs all have something in common?*
   b. *Were there some networks that you want to know more about?*
   c. *Are any similarities or differences surprising? In what way?*

Differentiation/Extension

Think, pair, share a story

1. Instruct each youth to select one of the networks or network models.
2. Give youth some time to explore their model in more depth to create a description/story based upon what they notice and wonder.
   a. *Does the model help you see flows through the connections?*
   b. *Does the model help you see which nodes are more or less important (e.g. which ones make useful connections)?*
   c. *What would happen to the other parts of the model if edges/lines was removed or added (i.e. interdependence)?*
   d. *Is it easier or harder to describe the phenomena using the network models?*
3. Have youth pair up and tell each other about the models that they explored. Guiding questions are in the **Quick Reference on VIPS** (p. 9) and **Handout 1 –Thinking Prompts** (p. 10).
4. Encourage youth to find differences and commonalities in their phenomena and models.

Reflection Questions for Discussion/Debrief

Note: You could point out that these questions are easier to answer with sparse networks (e.g. *Frozen*) than more complex networks (e.g. mobile phone connections). You could also talk about how network scientists use summary statistics (e.g., average number of steps it takes to get from one node to another) if the networks are too big or too dense to represent with pictures.

Welcome individuals or pairs of youth to share their observations, explanations, and/or stories of their observed networks.

Have a group discussion:

- *What did you discover?*
- *What do you want to know more about?*
- *What was surprising about exploring the network maps?*
- *What other phenomena might you want to map with networks?*

- *What other kinds of models, other than networks, might you be interested in to help explore phenomena?*
- *Are there other examples of networks that you know about and want to share?*

Career/Future Application

The process of analyzing complex systems using network models may inspire youth to think about fields related to complex systems (e.g., biochemistry, biology, pharmacological research, public health, transportation, animal behavior, One Health, epidemiology, sociology, and supply chain analysis).

Careers include **epidemiologist** (studying how diseases spread), **intelligence analyst** (using network analyses to study collusion), **robotic engineer**, and careers in **marketing** (using social influence to get people interested in new products) and **transportation/supply chain management**.

Background

So what?

Modeling a complex system using a network graph model can help people understand the properties of the system. The origin of network science is based in graph theory, a branch of mathematics. Before Leonard Euler, a mathematician known as the father of graph theory, turned the Seven Bridges of Königsberg puzzle into a graph, people thought the only way to solve it would be to trace every possible route among the bridges.

Graph theory has many applications that span multiple topics and fields. Any system can be represented using a network model, which sometimes reveals patterns or insights that are missing when we examine a phenomenon without turning it into a network graph. Examples include figuring out the shortest path between two nodes, how many colors are necessary for a map if no border countries should be the same color, and if there are clusters or hubs that can be relevant for disseminating information or stopping the spread of disease.

Seeing phenomena as complex systems and modeling/analyzing the systems as network graphs allows for comparisons across seemingly disparate phenomena (i.e. scope). Network graphs/models also reveal properties that may not be evident without the network formulation. For example, networks can show how a seemingly stable food web suddenly collapses (percolation), why someone has power because they are the only connection between two groups that want to do business (bridges), how rumors can ripple quickly through a school (externalities), how groups can form in which members are closely connected to each other and separate from others outside of the group (clusters), how some groups have lots of connections and others are loosely connected (density), how some vertices can have many more connections than others (hubs), how some animals depend upon eating other animals to survive in a food web (interdependence), and how seemingly large numbers of vertices can have short paths between them because of a few hubs (small world properties).

Vocabulary

Note: The vocabulary terms are helpful for the activity facilitator to learn the scientific language used in the activity and within the network science community. You can decide if you want to emphasize vocabulary or not.

Network science
An approach to answering difficult questions in many fields (e.g., social science, economics, biology, mathematics, and computer science); the study of connections that are often complex and hard to see. Combines graph theory from mathematics and software tools from computer science with applications in multiple disciplines.

Network
1) A set of relationships; 2) show how things are connected; 3) reveals hidden information.

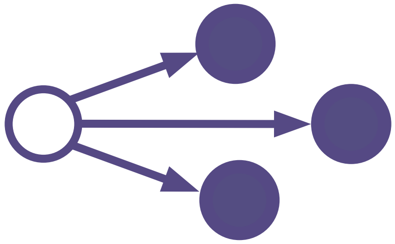
Vertex (vertices)
Also called a node, usually drawn as a circle; can represent different things in a network (e.g., people in a community, animals in an ecosystem, cells in the body).

Edges

The lines connecting vertices in a network that represent a relationship. Arrows can indicate the direction of the relationship. The first example below shows an undirected edge; the second example shows a directed edge.

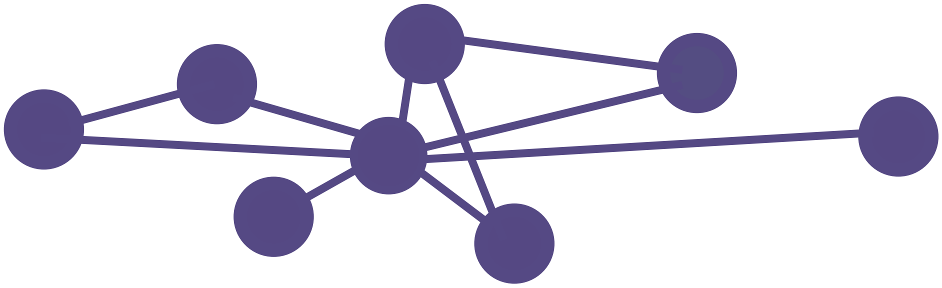
Degree

The number of lines a vertex has connected to it. The leftmost vertex pictured below has a degree of three:



Graph

Any set of vertices and the lines that run through them; a network is sometimes defined as a graph with characteristics (like names) assigned to it.



Graph theory

The theory of mathematics that deals with graphs. Graph theory is important to network science because it is used to describe the parts of a network and its properties.

System

"A system is a group of interacting, interrelated, and interdependent components that form a complex and unified whole" (Benson and Jost 2019). "Systems may interact with other systems; they may have sub-systems and be a part of larger complex systems" (NGSS Lead States 2013).

References

Next Generation Science Standards crosscutting concepts

NGSS Lead States. (2013). APPENDIX G: Crosscutting concepts in the Next Generation Science Standards. In *Next Generation Science Standards: For States, By States.* Washington, DC: National Academies Press.

System definition

Benson, T., and T. Jost. (2019). Introduction to systems thinking for early childhood. Waters Center for Systems Thinking CEELO Leadership Academy, Washington D.C., July 3—Aug 1, 2019. http://ceelo.org/wp-content/uploads/2019/08/CEELO_2019Cohort5Workbook.pdf

Network model of a suburban backyard food web

National Geographic Society. Who's in my backyard? *National Geographic*, https://education.nationalgeographic.org/resource/whos-my-backyard/

Network graph model of the main characters in *Frozen*

Holme, P., M. Porter, and H. Sayama. (2019). Who is the most important character in *Frozen*? What networks can tell us about the world. *Front. Young Minds*. 7:99. doi.org/10.3389/frym.2019.00099

Underground fungal network graph model

Hansford, D. (2017). The wood wide web. *New Zealand Geographic 148*(Nov–Dec-2017), https://www.nzgeo.com/stories/the-wood-wide-web/

Mongabay Kids. (2022, Dec 1). Mapping the fantastic fungi networks under our feet. *Mongabay Kids*. https://kids.mongabay.com/mapping-the-fantastic-fungi-networks-under-our-feet/

See a video explanation of fungal networks at the following link:

BBC News. (2018, Jun 29). How trees secretly talk to each other - BBC News [Video]. YouTube, https://www.youtube.com/watch?v=yWOqeyPIVRo

Fly brain network graph model

eLife. (2020). *Reconstructing the brain of fruit flies.* eLife, 9 Oct 2020. https://elifesciences.org/digests/57443/reconstructing-the-brain-of-fruit-flies

Rubin, G.M. (2020, Jan 22). *Unveiling the biggest and most detailed map of the fly brain yet.* Howard Hughes Medical Institute. https://www.hhmi.org/news/unveiling-the-biggest-and-most-detailed-map-of-the-fly-brain-yet

Bus route network graph model

City of Lincoln, Nebraska. (2022). StarTran Saturday service effective August 2022. *City of Lincoln, Nebraska*, https://www.lincoln.ne.gov/files/sharedassets/public/ltu/startran/route-brochures/all-saturday-routes.pdf

London Underground (Central) map network graph model

London & Partners. Free London travel maps. *Visit London: Official Visitor Guide,* https://www.visitlondon.com/traveller-information/getting-around-london/london-maps-and-guides/free-london-travel-maps

Flavor network graph model

Ahn, Y., S.E. Ahnert, J.P. Bagrow, & A. Barabási. (2011). *Sci. Rep. 1*(196). https://www.nature.com/articles/srep00196

Brain network graph model

Bassett, D.S., and M.S. Gazzaniga. (2011). Understanding complexity in the human brain. *Trends Cogn Sci. 15*(5):200-9. doi.org/10.1016/j.tics.2011.03.006.

Besseling et al. (2014). Delayed convergence between brain network structure and function in rolandic epilepsy. *Front. Hum. Neurosci.* 8. https://www.frontiersin.org/articles/10.3389/fnhum.2014.00704/full

Johns Hopkins Medicine. *Brain anatomy and how the brain works.* Johns Hopkins Medicine. https://www.hopkinsmedicine.org/health/conditions-and-diseases/anatomy-of-the-brain

Kocevar, G., L. Suprano, C. Stamile, S. Hannoun, P. Founrneret, O. Revol, F. Nusbaum, and D. Sappry-Marinier. (2019). Brain structural connectivity correlates with fluid intelligence in children: A DTI graph analysis. *Intelligent.* 72:67-95. https://doi.org/10.1016/j.intell.2018.12.003

Neuroscience News. (2017, May 25). *Researchers identify brian network organization changes.* Neuroscience News. https://neurosciencenews.com/organize-changes-network-6767/

Telesford, Q.K., S.L. Simpson, J.H. Burdette, et al. (2011). The brain as a complex system: Using network science as a tool for understanding the brain. *Brain Connectivity 1*(4), 295–308. Doi.org/10.1089/brain.2011.0055

Loneliness clusters in the Framingham social betwork graph model

Cacioppo, J.T., J.H. Fowler, N.A. Christakis. (2009). Alone in the crowd: The structure and spread of loneliness in a large social network. *J Pers Soc Psych 97*(6), 977-991. doi.org/10.1037/a0016076

Human disease network and disease gene network graph model

Goh, K., M.E. Cusick, D. Valle, B. Childs, M. Vidal, and A. Barabasi. (2007). The human disease network. *PNAS*. www.pnas.org/cgi/doi/10.1073/pnas.0701361104

Bird community structure network graph model

Shizuka, D., and D.R. Farine. (2016). Measuring the robustness of network community structure using assortativity. *Anim. Behav. 112*(Feb-2016), 237-246. https://doi.org/10.1016/j.anbehav.2015.12.007

Cocktail party network, clusters of congested airports network, and communities in Belgium mobile phone network graph models

Barabási, A. (2016). *Network Science*. Cambridge University Press: Cambridge, UK. http://networksciencebook.org

***Thinking Like a Parrot* network graph model**

Bond, A.B., and J.Diamond. (2019). *Thinking Like a Parrot: Perspectives from the Wild*. Chicago, IL: The University of Chicago Press.

Structure of the human retina model

Davson, H., E.S. Perkins, A. Augustyn, et al. (2022). Human eye. *Encycolpaedia Britannica*. https://www.britannica.com/science/human-eye/The-retinal-image

Retina colorized model

Zhang, X., B. Chen, A.H. Ng, J. Tanner, D. Tay, K. So, R.A. Rachel, N. Copeland, N. Jenkins, and J. Huang. (2005). Transgenic mice expressing cre-recombinase specifically in retinal rod bipolar neurons. *IOVS* 46, 3515-20. https://doi.org/10.1167/iovs.04-1201

There are many more possible network graphs—and this blog has some fun examples

Jones, C. All Things Graphed. http://allthingsgraphed.com/

Funding

The development of this activity was supported in part by the *Worlds of Connections* Science Education Partnership Award [R25GM129836 (2018–2023)] at the University of Nebraska–Lincoln, funded by the National Institute of General Medical Sciences of the National Institutes of Health. This content is solely the responsibility of the authors and does not necessarily represent the official views of the National Institutes of Health or the University of Nebraska.

SEPA SCIENCE EDUCATION PARTNERSHIP AWARD SUPPORTED BY THE NATIONAL INSTITUTES OF HEALTH

WORLDS OF CONNECTIONS

UNIVERSITY OF Nebraska Lincoln

Visualization, Interdependence, Position, and Scope (VIPS) Reference Guide

This guide is designed to give activity leaders the core themes for using network models to analyze systems.

Visualization

- What does the image represent?
- What are the nodes/vertices or what do the nodes represent? (Could be trees, neurons, story characters, friends, family, planets, chemicals, countries, bus stops, airports, etc.)
- What are the edges—what connects nodes? In other words, what are the ties? (Could be friendship, advice-seeking, dendrites, genes, mycelium, gravity, roads, information-sharing, chemical bonds, bytes, touching, territory, trade routes, etc.)

Interdependence

- What flows or moves through the system?
- Does a change in one node/vertex (e.g. remove it, change properties, change resources, drop or add connections) result in a change for other nodes/vertices?
- Do nodes/vertices have ways to gain more or avoid more if they want to by changing themselves only, or do they need other nodes or connections to change to achieve their goals?

Position

- If a node/vertex was removed, would that make a difference for any other nodes/edges?
- If a node/vertex was added, would that make a difference for any other nodes/edges?
- Does it matter which nodes/vertices or which ties/edges are removed or added for flows/distribution from node to node?

Scope

- Compare networks of different phenomena. Do the ideas of nodes/vertices; ties/edges; direction of flow (one-way, two-way, mutual); the position in a network of nodes; the presence or absence of ties; or other characteristics of the networks work in the same way or differently for different phenomena?
- What makes such phenomena systems? Think about what is similar or different among phenomena such as flavor combinations, genes and diseases, genetic inheritance, tree communication, disease spread, and/or support from and conflicts among family members.

Handout 1 – Thinking Prompts

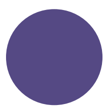
First look: What do you notice in each image? What do you wonder about each image?

Second look: What can you SPY in each image?

- All network graphs will have at least one vertex and one edge. Can you SPY at least one vertex in each graph?
- Can you figure out a degree for a vertex? (See below.)
- Do you have questions about the image or what it represents?
- What do you notice about colors and shapes in the network graph?
- Do you SPY anything that explains what the graph represents?

Vertex (vertices)

Also called a node, usually drawn as a circle; can represent different things in a network (e.g., people in a community, animals in an ecosystem, cells in the body, etc.).

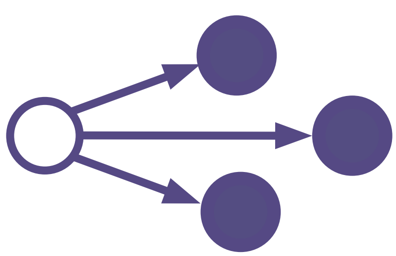


Edges

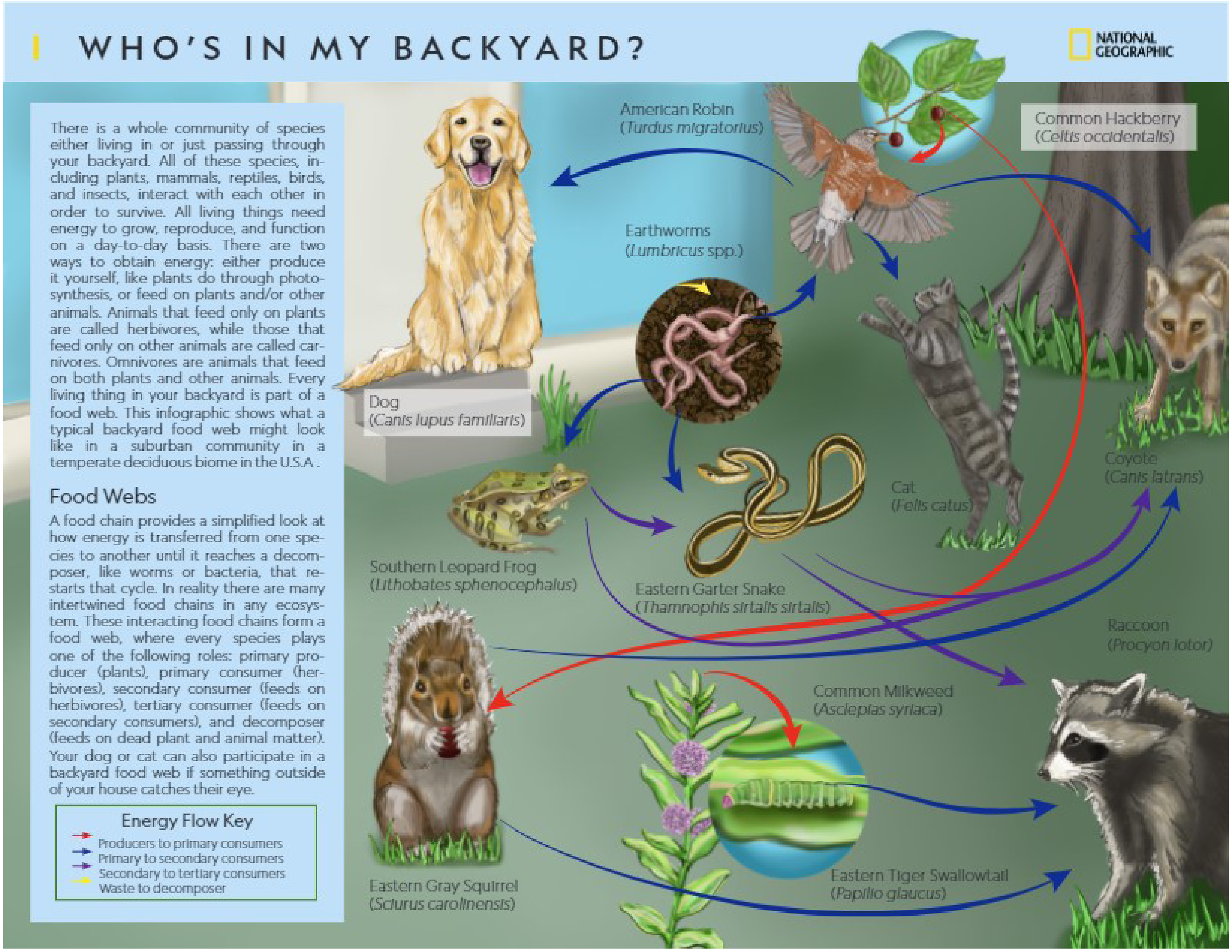
The lines connecting vertices in a network that represent a relationship. Arrows can indicate the direction of the relationship. The first example below shows an undirected edge; the second example shows a directed edge (represented by an arrow).

Degree

The number of lines a vertex has connected to it. The leftmost vertex pictured below has a degree of three:



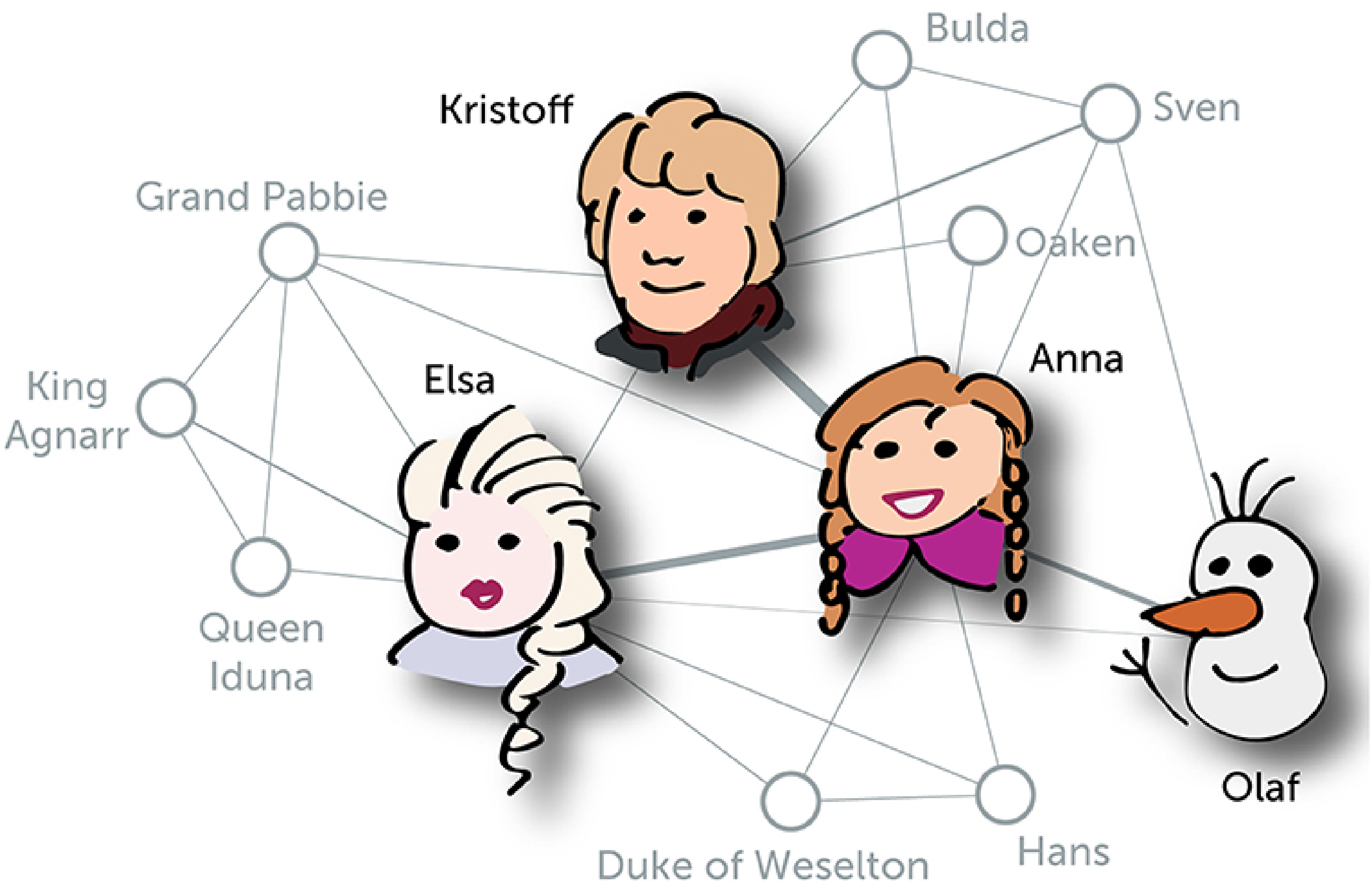
Example Network Images



Network model of a suburban backyard food web

In this network model of a backyard food web, the **nodes** represent producers (e.g., milkweed); consumers (e.g., squirrels); and decomposers (e.g., earthworms). The directed edges represent the flow of energy from one species to another when feeding. The **red directed edges** represent energy flow from producers to primary consumers (herbivores); the **blue directed edges** represent energy flow from primary consumers to secondary consumers (who feed on herbivores); and the **purple directed edges** represent energy flow from secondary consumers to tertiary consumers (who feed on secondary consumers). The **yellow directed edge** represents energy flow from waste to decomposers (who feed on dead plant and animal matter).

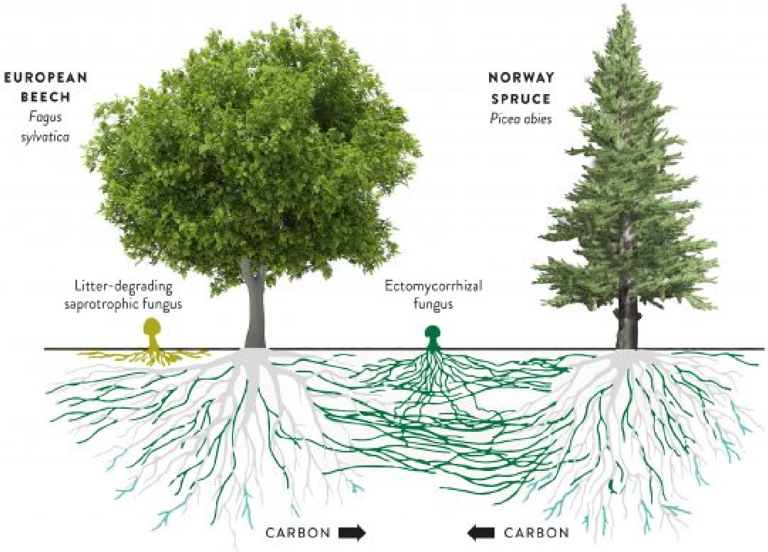
Source: National Geographic Society. Who's in my backyard? *National Geographic*, https://education.nationalgeographic.org/resource/whos-my-backyard/

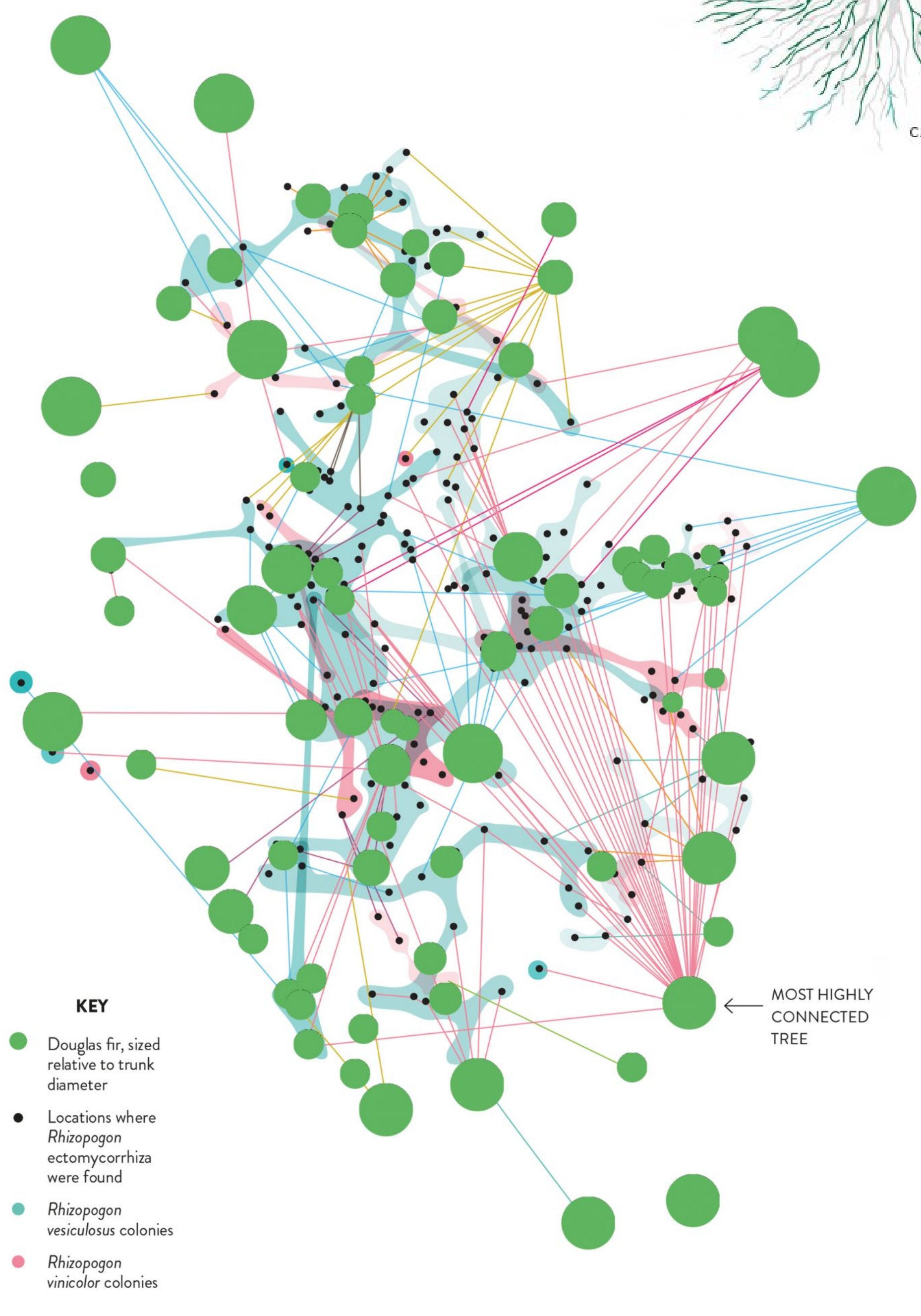


Network graph of the main characters in *Frozen*
The **nodes** of this network represent the people who are a part of the network such as Anna, Elsa, Kristoff, Olaf, and Hans. The **edges** or **links** are the lines that connect the main characters together if they talk to each other. The more that they say to each other during the movie, the thicker the line between the two characters.

Source: Holme, P., M. Porter, and H. Sayama. (2019). Who is the most important character in *Frozen*? What networks can tell us about the world. *Front. Young Minds*. 7:99. doi.org/10.3389/frym.2019.00099

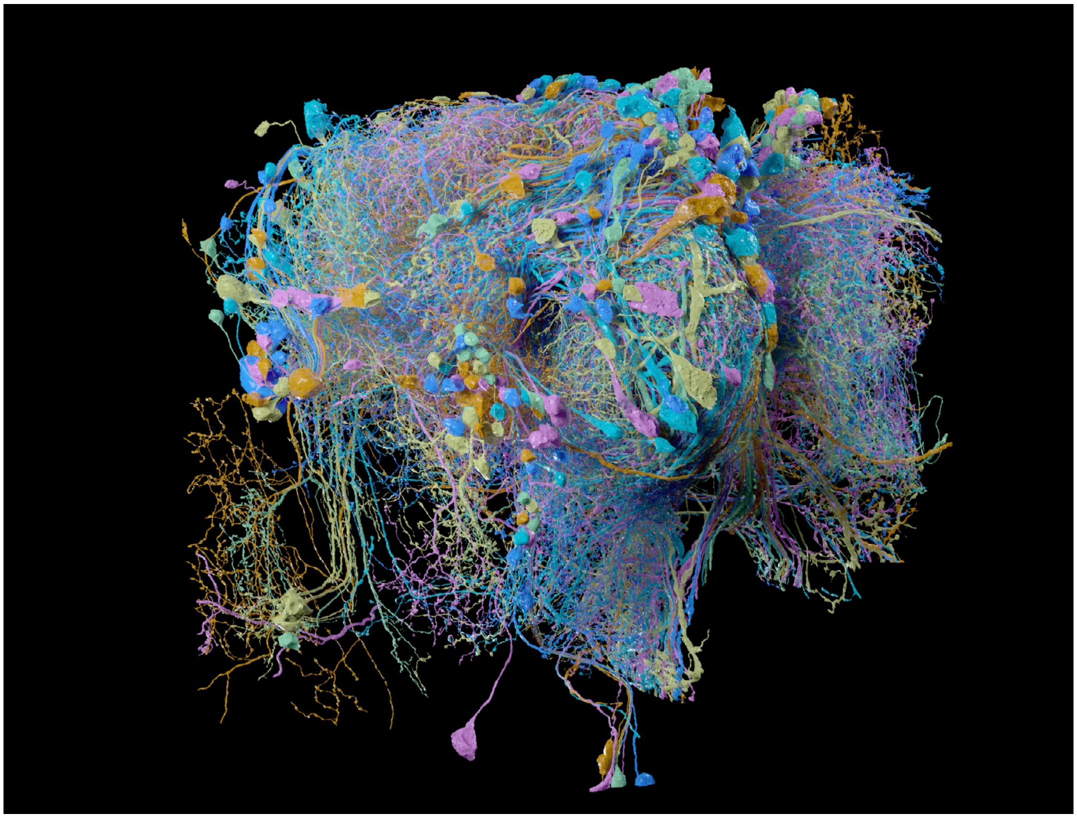
Underground fungal network graph
The **nodes** of the network are the European beech trees, Norway spruce trees, ectomycorrhizal fungus (a type of fungus that is commonly found living in symbiosis with pine and fir trees), and the litter-degrading saprotrophic fungus.





The mycorrhizal fungi act as the **edges (links)** of the network connecting the roots of the trees to the surrounding soil. Carbon molecules move between the nodes through the fungi. The mycorrhizal fungi help the trees by storing carbon and moving nutrients and water through the network. By connecting to the tree roots, the fungi get sugars they need to survive.

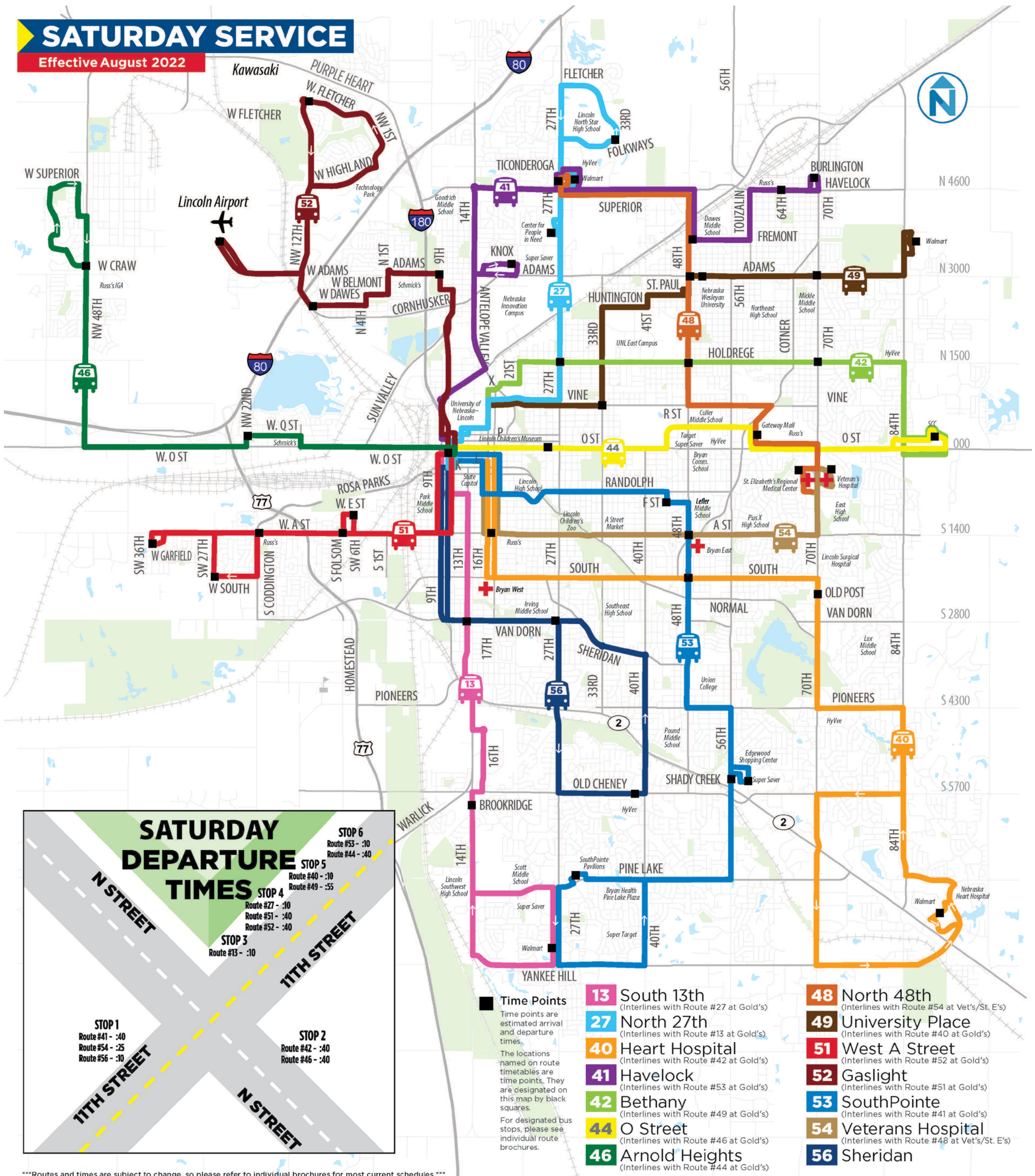
Source: Hansford, D. (2017). The wood wide web. *New Zealand Geographic 148*(Nov–Dec-2017), https://www.nzgeo.com/stories/the-wood-wide-web/
Parts of the image description were also paraphrased from the following source: Mongabay Kids. (2022, Dec 1). Mapping the fantastic fungi networks under our feet. *Mongabay Kids*. https://kids.mongabay.com/mapping-the-fantastic-fungi-networks-under-our-feet/



Fly brain network
This wiring diagram, or connectome, outlines roughly 25,000 neurons in the brain of a female fruit fly and pinpoints where the neurons connect. Though incomplete (representing about one-third of the brain), this network was the biggest and most detailed map of the fly brain when this image was first published in 2020.The **nodes** in the network are the neurons in the fly brain. The **edges** of the network are the synapses that connect the neurons. There are so many neurons, dendrites, and synapses connecting them that it may be hard to see each connection.

How do scientists map the fly brain? In a special room built to dampen noise, behind several sets of locked doors and floor-length curtains, eight microscopes imaged the fly brain. The microscopes, designed to capture data over minutes or hours, needed to run continuously for months or years to image an entire fly brain. After nearly a decade of refinement, the image-collection process could consistently result in sharp images that revealed the fly brain's neural network in detail. Scientists used a technique called focused-ion beam scanning electron microscopy to capture images of the fly brain: focused ion beams from the microscopes milled away fine layers of tissue, snapping images of each layer. Scientists then used computer programs to stitch the image back together, creating the network model. Each neuron is a different color in the model to show where the neurons start and end.

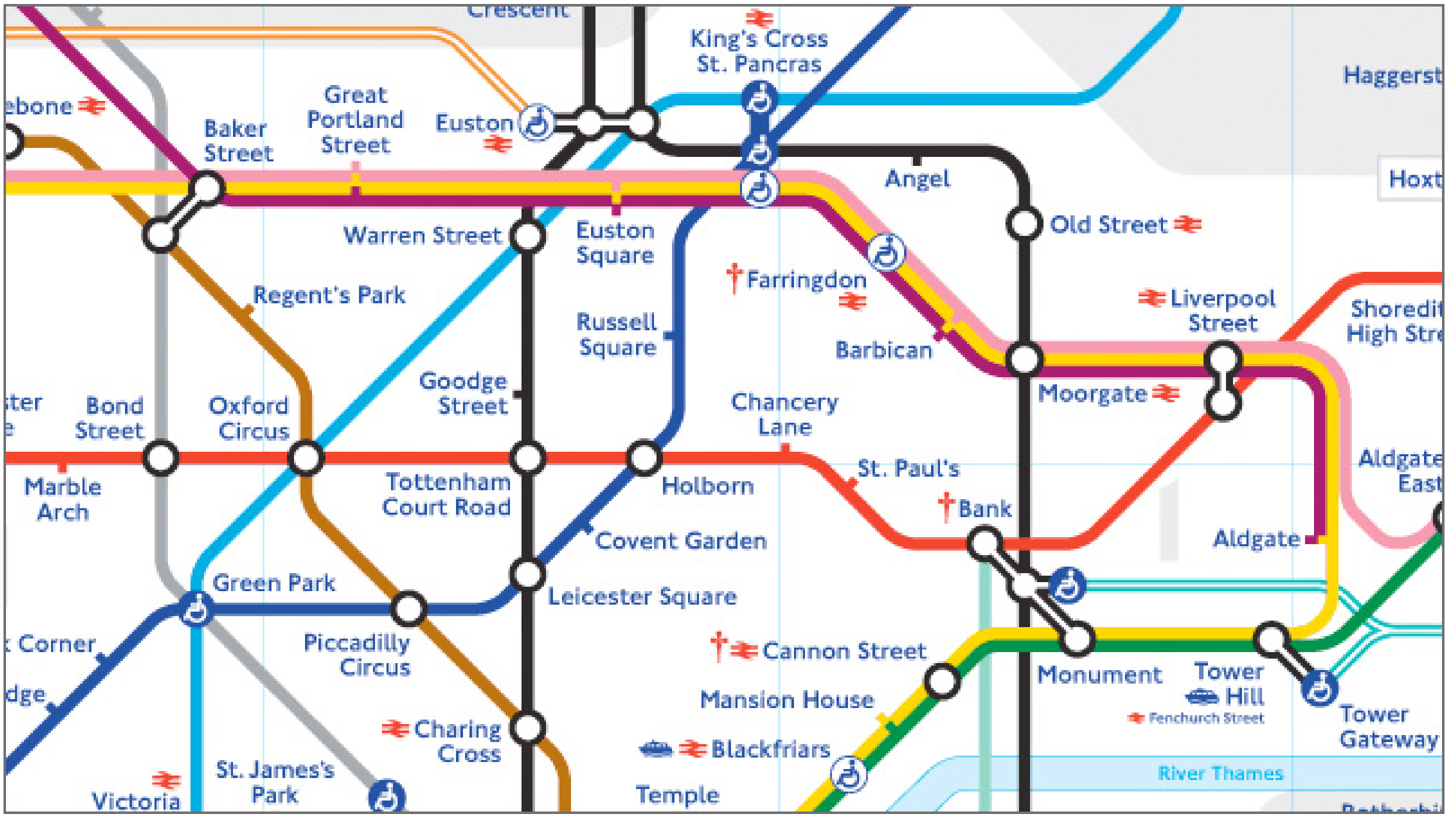
Image source: eLife. (2020). *Reconstructing the brain of fruit flies.* eLife, 9 Oct 2020. https://elifesciences.org/digests/57443/reconstructing-the-brain-of-fruit-flies
Description source: Rubin, G.M. (2020, Jan 22). *Unveiling the biggest and most detailed map of the fly brain yet.* Howard Hughes Medical Institute. https://www.hhmi.org/news/unveiling-the-biggest-and-most-detailed-map-of-the-fly-brain-yet



Lincoln, NE Saturday bus routes

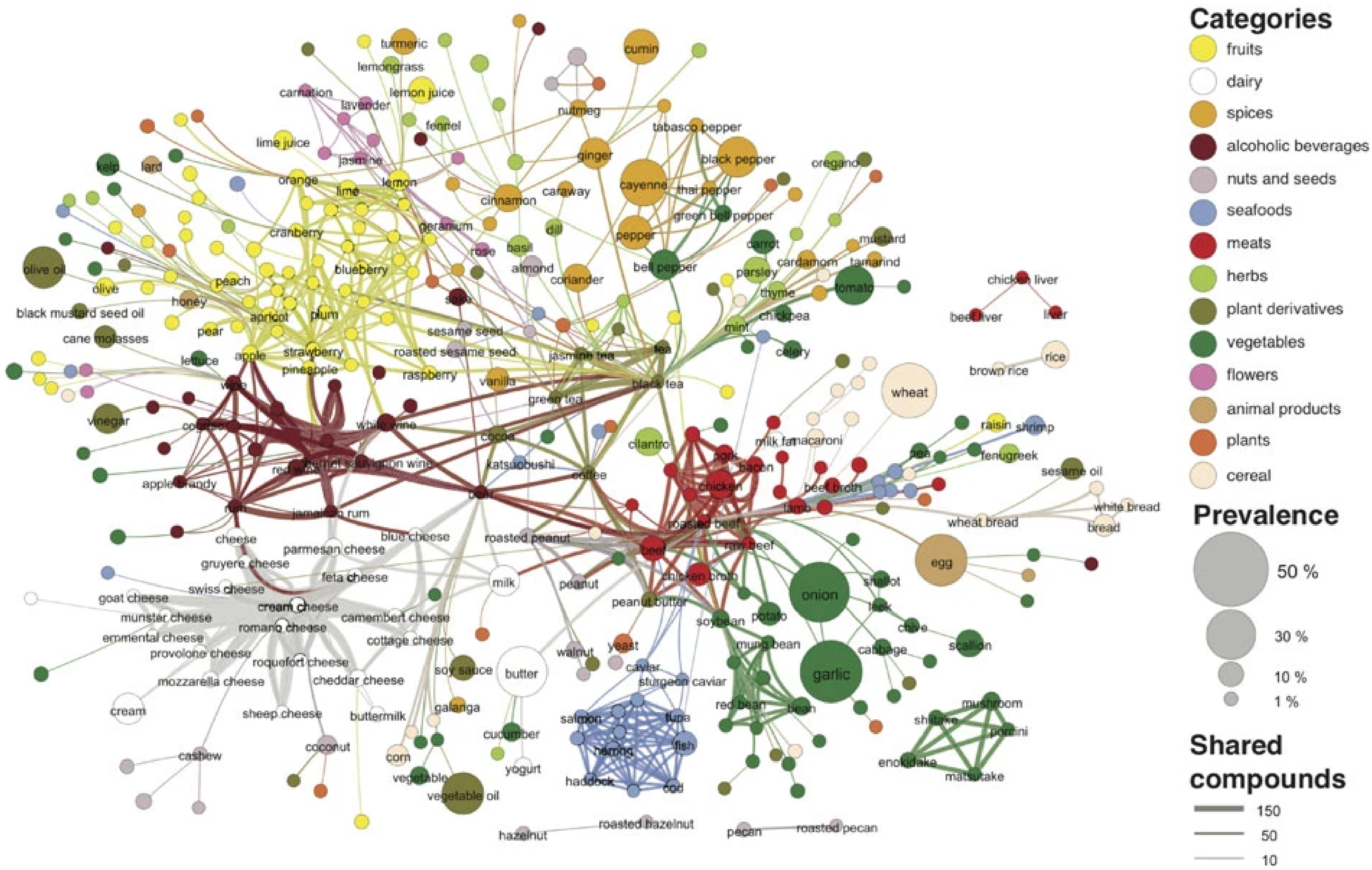
Each bus stop is a **node**, the roads are the **edges/links** connecting the bus stops, and the buses "flow through" the network carrying people from place to place. Different colors represent different routes that buses take through the roads from bus stop to bus stop. The small black squares show the scheduled time stops for each bus route.

Source: City of Lincoln, Nebraska. (2022). StarTran Saturday service effective August 2022. *City of Lincoln, Nebraska*, https://www.lincoln.ne.gov/files/sharedassets/public/ltu/startran/route-brochures/all-saturday-routes.pdf



London Underground (Central) map network graph:
In this network of the London Underground, the circles on the map are the **nodes** that represent the Underground stations. The different colored paths are the **edges** that connect the network and represent the railway paths between Underground stations. Trains carry people through the system.

Source: London & Partners. Free London travel maps. *Visit London: Official Visitor Guide,* https://www.visitlondon.com/traveller-information/getting-around-london/london-maps-and-guides/free-london-travel-maps

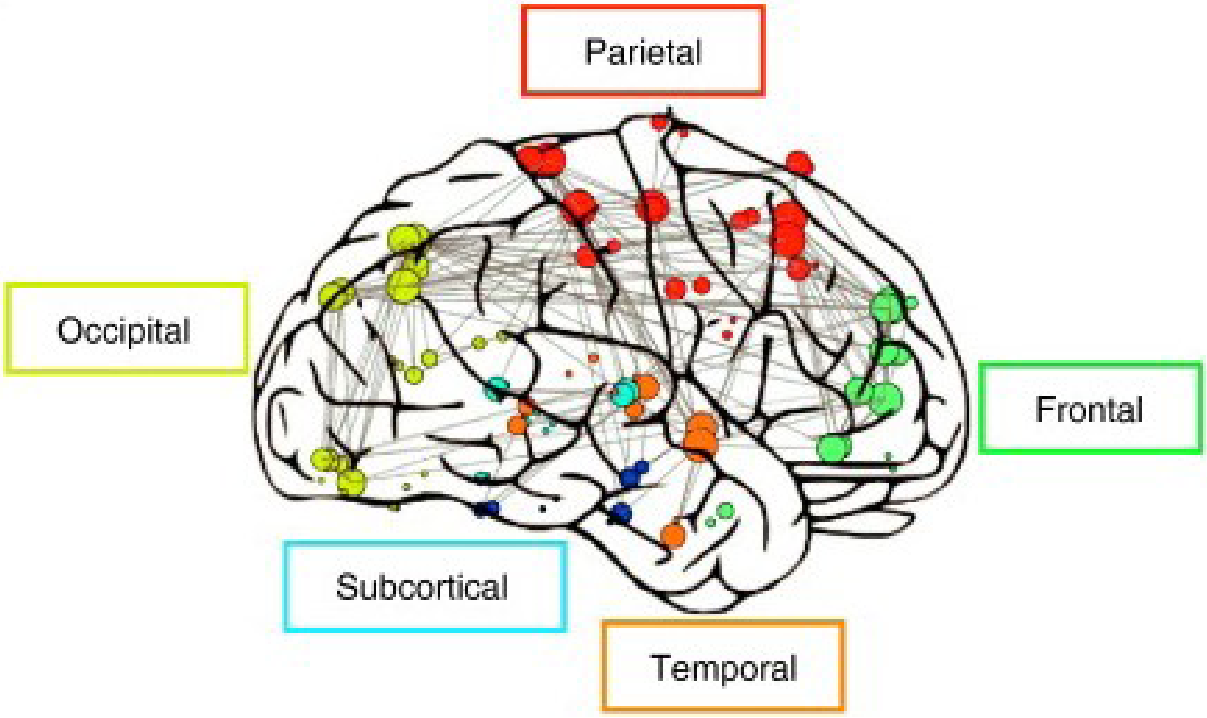


Flavor network graph

Each food is represented by a **node**, and the flavors are connected by **edges** if they share at least one compound. The more compounds that they share, the thicker the line. The more often a flavor occurs in a recipe (in other words, the more prevalent a flavor), the larger the node size.

Why create a network of flavors in recipes? This worldwide flavor network helps us understand how certain ingredients are combined in many different cuisines. Food scientists are interested in the "profiles" (flavor compositions) of different styles of food and can use a network such as this one to help them create new recipes or substitute ingredients in recipes. Artificial intelligence (e.g., machine learning) software programs can use the information in a network to generate possible new recipes.

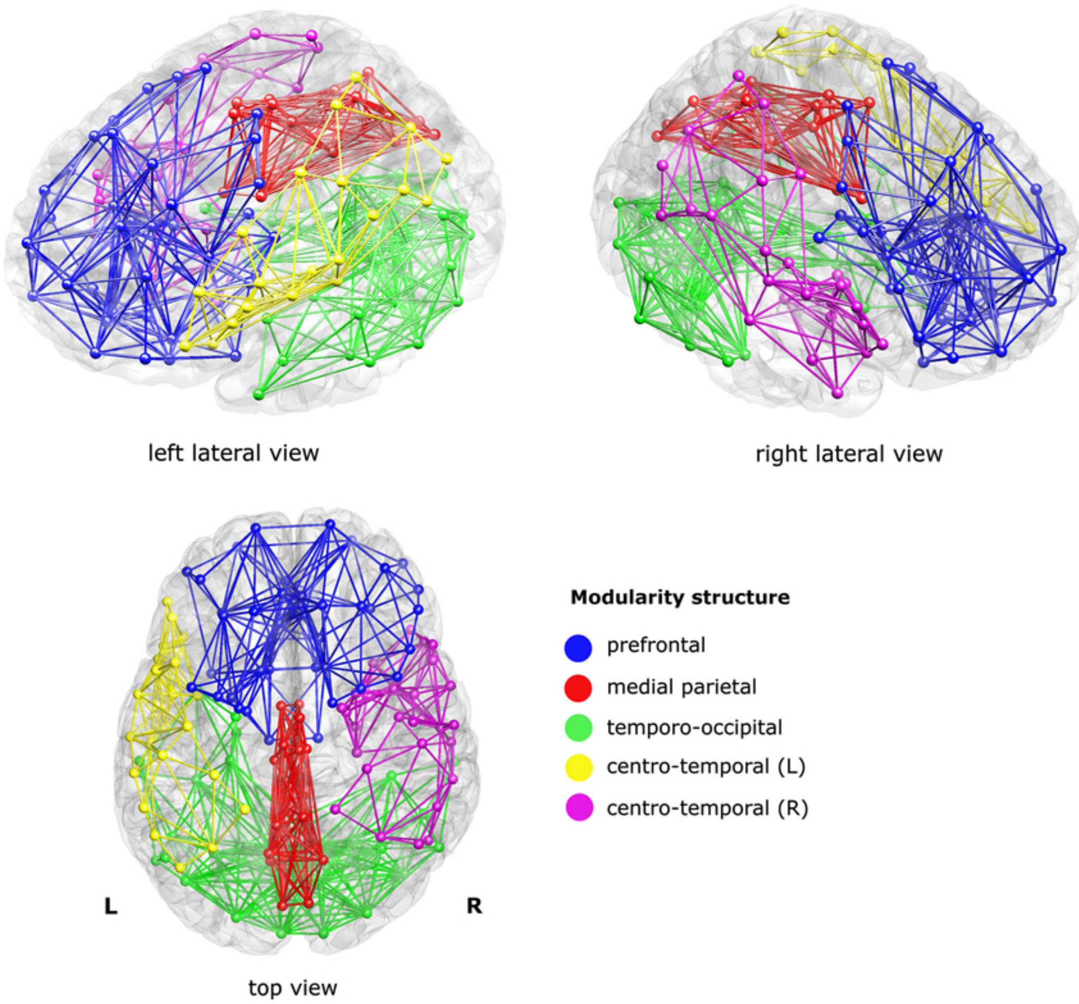
Source: Ahn, Y., S.E. Ahnert, J.P. Bagrow, & A. Barabási. (2011). *Sci. Rep. 1*(196). https://www.nature.com/articles/srep00196



Brain Network Graph 1
This network map of the human brain shows connections between neurons that communicate with each other through electrical signals. The **nodes** in the network represent the neurons, and the **links** represent physical connections between neurons that allow electrical charges to flow through the brain. Researchers continuously make new discoveries about how brains function using tools such as network mapping and imaging; therefore, it is a good idea to search the National Institutes of Health website to find more up-to-date models of the brain.

What do the lobes of the brain control? The different-colored nodes in this graph represent the different parts, or lobes, of the brain. The **green nodes** represent the frontal lobe, the largest lobe of the brain, which is involved in personality traits, decision-making, and movement. The **red nodes** represent the parietal lobe, which helps a person identify objects and understand where one's body is compared with objects around the person. The parietal lobe also helps the body interpret pain and touch and the brain understand spoken language. The **yellow-green nodes** represent the occipital lobe, which is involved with vision. The **orange nodes** represent the temporal lobes, the sides of the brain, which are involved in short-term memory, speech, musical rhythm, and to some degree, smell. Finally, the **light blue nodes** represent the subcortical structures in the brain which help the brain perform complex activities such as memory, emotion, pleasure and hormone production

Image source: Bassett, D.S., and M.S. Gazzaniga. (2011). Understanding complexity in the human brain. *Trends Cogn Sci. 15*(5):200-9. doi.org/10.1016/j.tics.2011.03.006. **Caption Source 1:** Johns Hopkins Medicine. *Brain anatomy and how the brain works.* Johns Hopkins Medicine. https://www.hopkinsmedicine.org/health/conditions-and-diseases/anatomy-of-the-brain. **Caption Source 2:** Kocevar, G., L. Suprano, C. Stamile, S. Hannoun, P. Founrneret, O. Revol, F. Nusbaum, and D. Sappry-Marinier. (2019). Brain structural connectivity correlates with fluid intelligence in children: A DTI graph analysis. *Intelligent.* 72:67-95. https://doi.org/10.1016/j.intell.2018.12.003 **Caption Source 3:** Telesford, Q.K., S.L. Simpson, J.H. Burdette, et al. (2011). The brain as a complex system: Using network science as a tool for understanding the brain. *Brain Connectivity 1*(4), 295–308. Doi.org/10.1089/brain.2011.0055

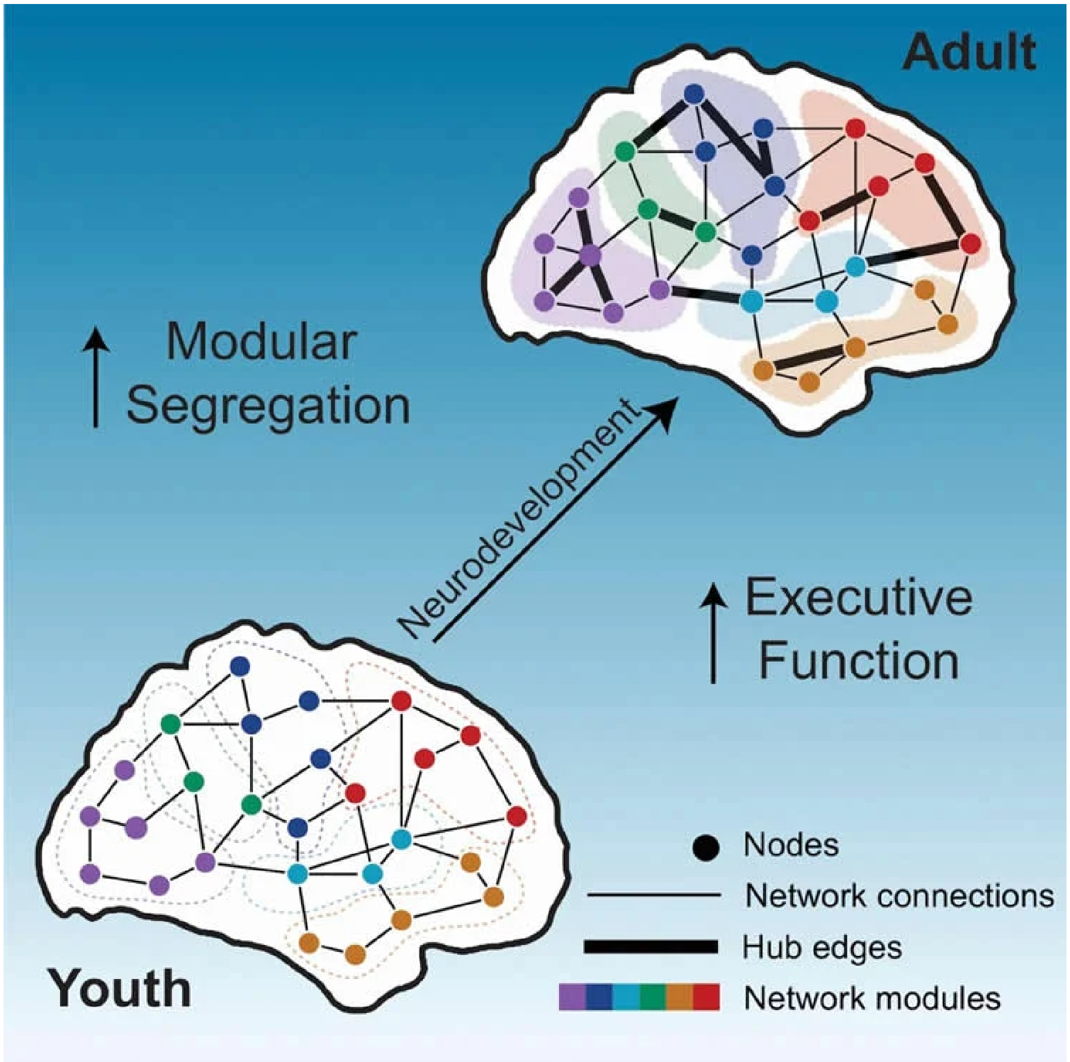


Brain Network Graph 2

The figure shows three views of the brain (left, right, and top) depicting five subnetworks (also known as modules) that make up the different parts of the brain. The **nodes** in the network represent brain neurons, and the **links** represent physical connections between neurons that allow electrical charges to flow through the brain. Networks with high modularity have dense connections between the nodes within modules but sparse connections between nodes in different modules.

Why map human brain networks? These images are from a research study that used network maps of the brains of children to identify differences in the kinds of connections in brains of children with and without epilepsy. Epilepsy is a seizure disorder, and people who have epilepsy experience sudden, uncontrolled bursts of electrical activity in the brain. Understanding epilepsy is important for preventing seizure-related injury and for supporting people with epilepsy in caring for their health and wellbeing.

Source: Besseling et al. (2014). Delayed convergence between brain network structure and function in rolandic epilepsy. *Front. Hum. Neurosci.* 8. https://www.frontiersin.org/articles/10.3389/fnhum.2014.00704/full



Brain Network Graph 3

The brain matters for human's ability to control impulses, stay organized, and make decisions—generally referred to as "executive function." As people grow up, their brains change in ways that help most people have more control over their behaviors. The image above shows a network map of a youth brain and an adult brain. In both networks, the colored **nodes** represent neurons in the brain, and the **edges** show the connections between neurons. The colors of the nodes correspond to different parts of the brain, also known as modules. Researchers found that in youth the brain is divided into modules, parts of the brain network that have lots of connections among their nodes and fewer connections to nodes in other modules. As youth grow into adults, the modules grow and add more connections, and the different modules become more strongly connected with each other. In other words, the brain becomes less modular when people grow up.

Source: Neuroscience News. (2017, May 25). *Researchers identify brian network organization changes.* Neuroscience News. https://neurosciencenews.com/organize-changes-network-6767/

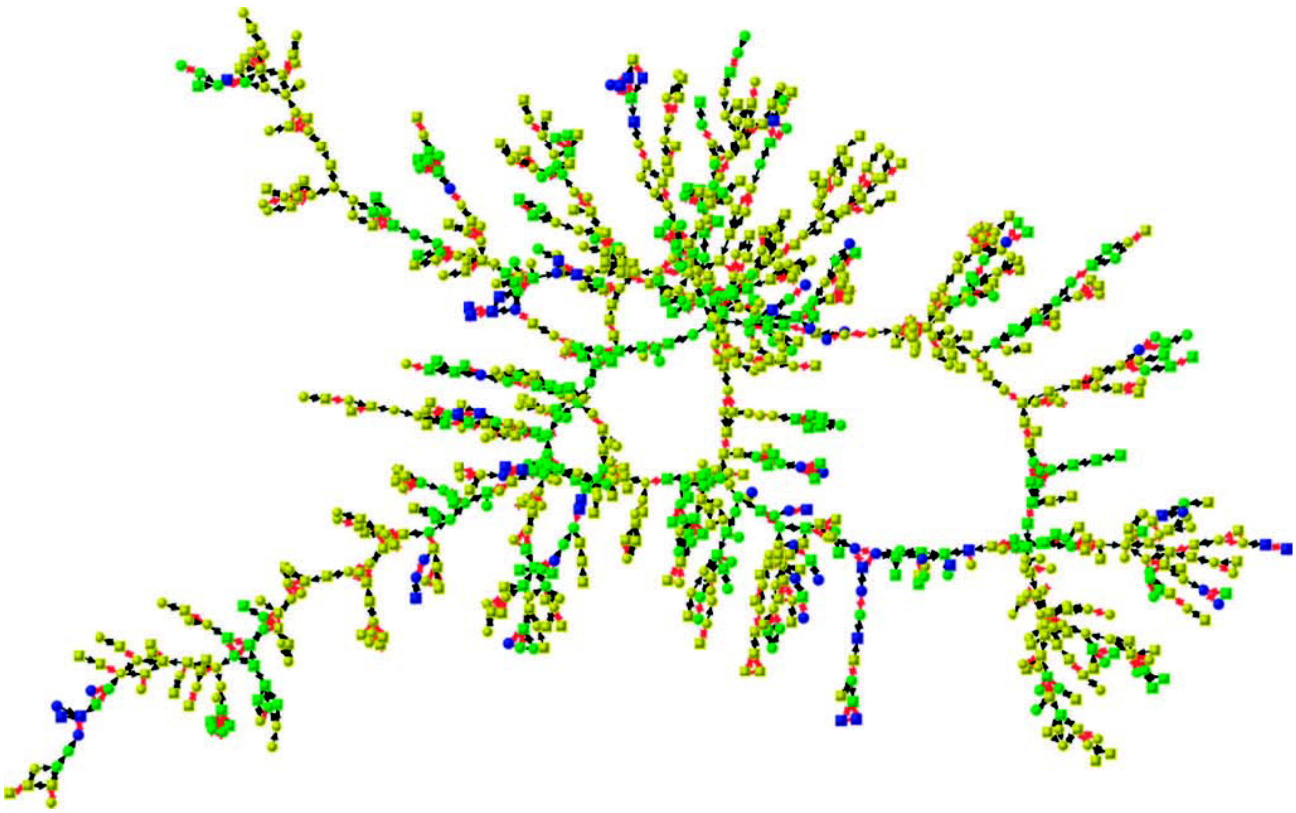
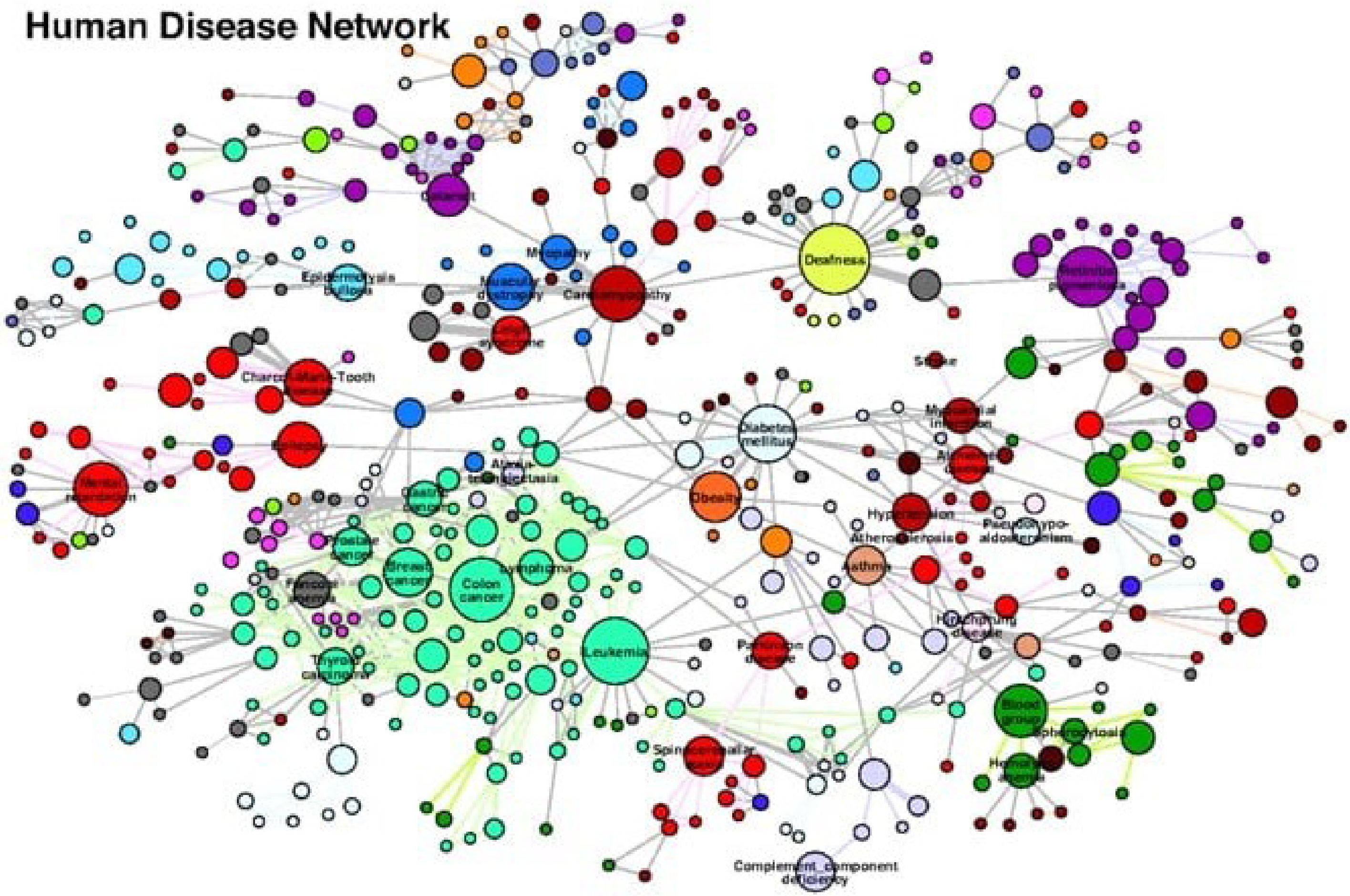


Figure 1. Loneliness clusters in the Framingham Social Network. This graph shows the largest component of friends, spouses, and siblings at Exam 7 (centered on the year 2000). There are 1,019 individuals shown. Each node represents a participant, and its shape denotes gender (circles are female, squares are male). Lines between nodes indicate relationship (red for siblings, black for friends and spouses). Node color denotes the mean number of days the focal participant and all directly connected (Distance 1) linked participants felt lonely in the past week, with yellow being 0–1 days, green being 2 days, and blue being greater than 3 days or more. The graph suggests clustering in loneliness and a relationship between being peripheral and feeling lonely, both of which are confirmed by statistical models discussed in the main text.

Loneliness Clusters in the Framingham Social Network graph

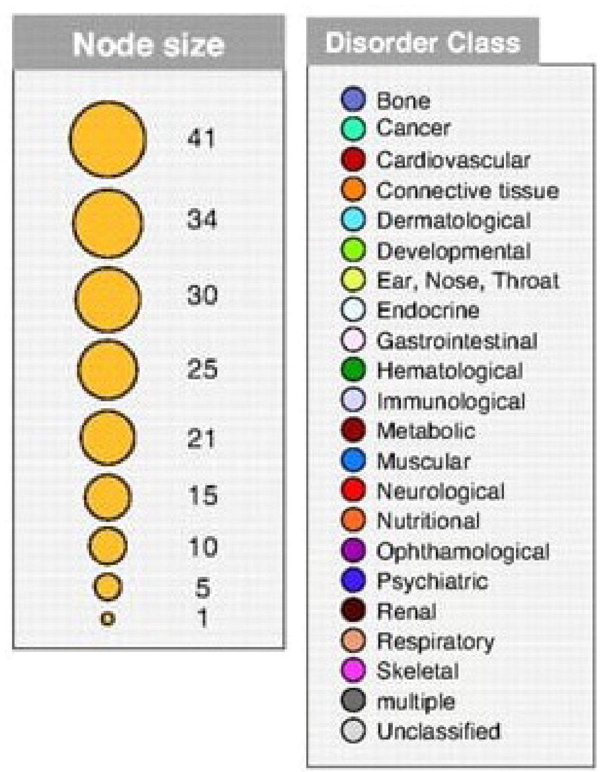
This graph shows participants in a study who lived in a town called Framingham in Massachusetts. They were interviewed and had data collected at a doctor's office every few years. **Lines** between nodes indicate relationships between the people in the study (**red** for siblings, **black** for friends and spouses). **Node shapes** represent individual gender (circles are female, squares are male). The **node color** relates to the number of days the people felt lonely (**yellow** 0-1 days, **green** 2 days, **blue** 3 or more days). The researchers want to know if people who are connected to each other are similar in their feelings of loneliness and if position in the network matters for being more or less lonely. It may seem strange to think of loneliness as a shared experience, yet this graph and the statistics measuring the associations suggest that it is.

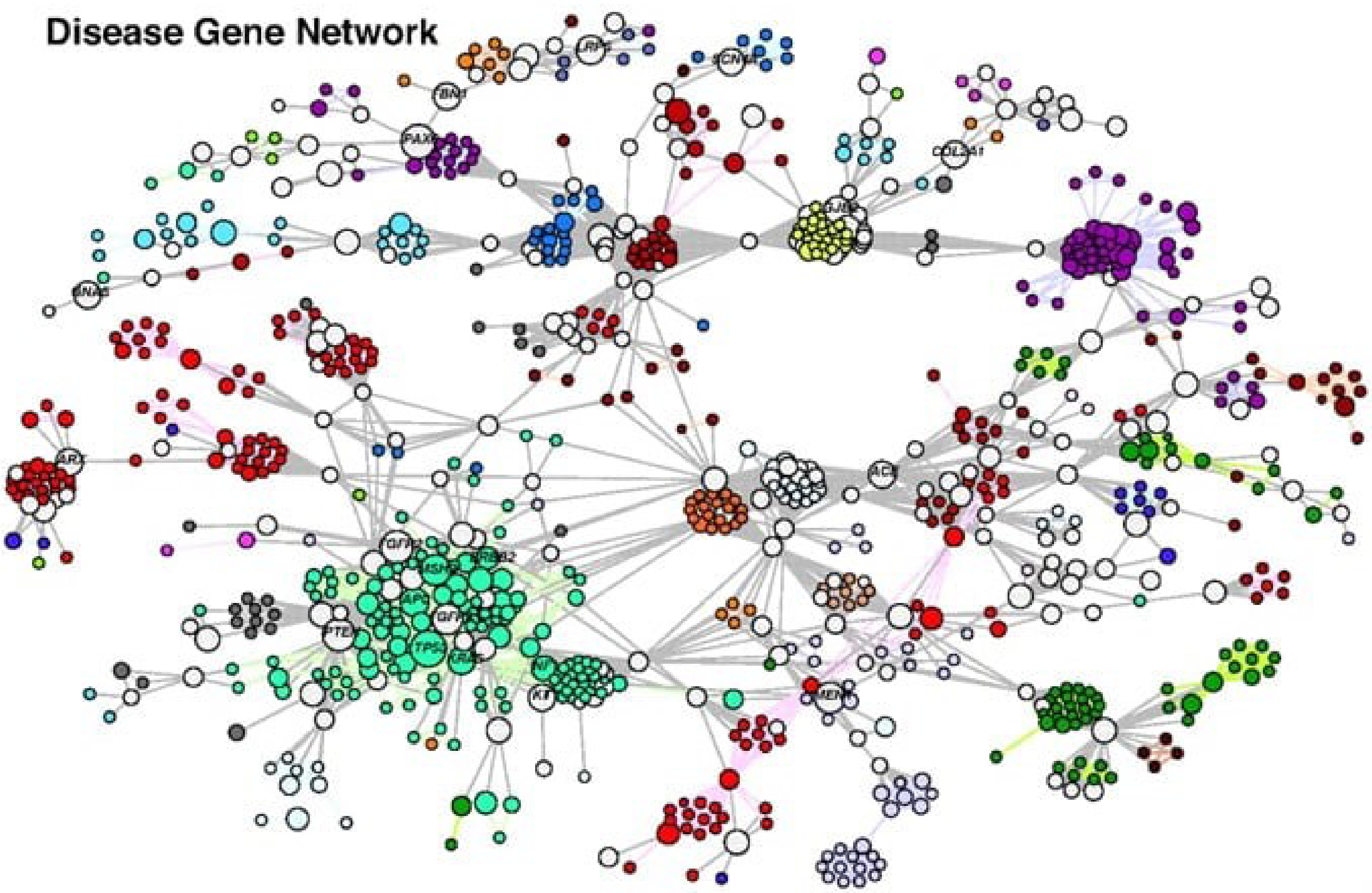
Source: Cacioppo, J.T., J.H. Fowler, N.A. Christakis. (2009). Alone in the crowd: The structure and spread of loneliness in a large social network. *J Pers Soc Psych 97*(6), 977-991. doi.org/10.1037/a0016076

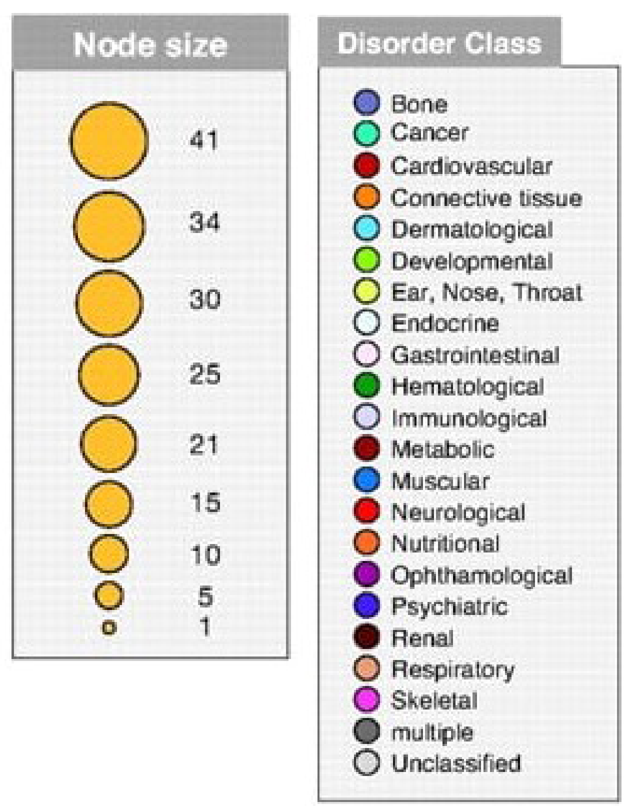


Human disease network graph
In the human disease network, each **node** represents a disorder, and the lines, or edges, connects disorders that share at least one gene. The size of each node represents the number of genes involved in the disorder. Colors correspond to disorder classes. Line thickness corresponds to the number of genes share by the connected disorders.

Source: Cacioppo, J.T., J.H. Fowler, N.A. Christakis. (2009). Alone in the crowd: The structure and spread of loneliness in a large social network. *J Pers Soc Psych 97*(6), 977-991. doi.org/10.1037/a0016076







Disease gene network graph

In the Disease Gene Network, each **node** represents a gene, with two genes connected if they are both involved in the same disorder. The size of each node represents the number of disorders in which the gene is involved. These graphs illustrate the common genetic origin of many diseases.

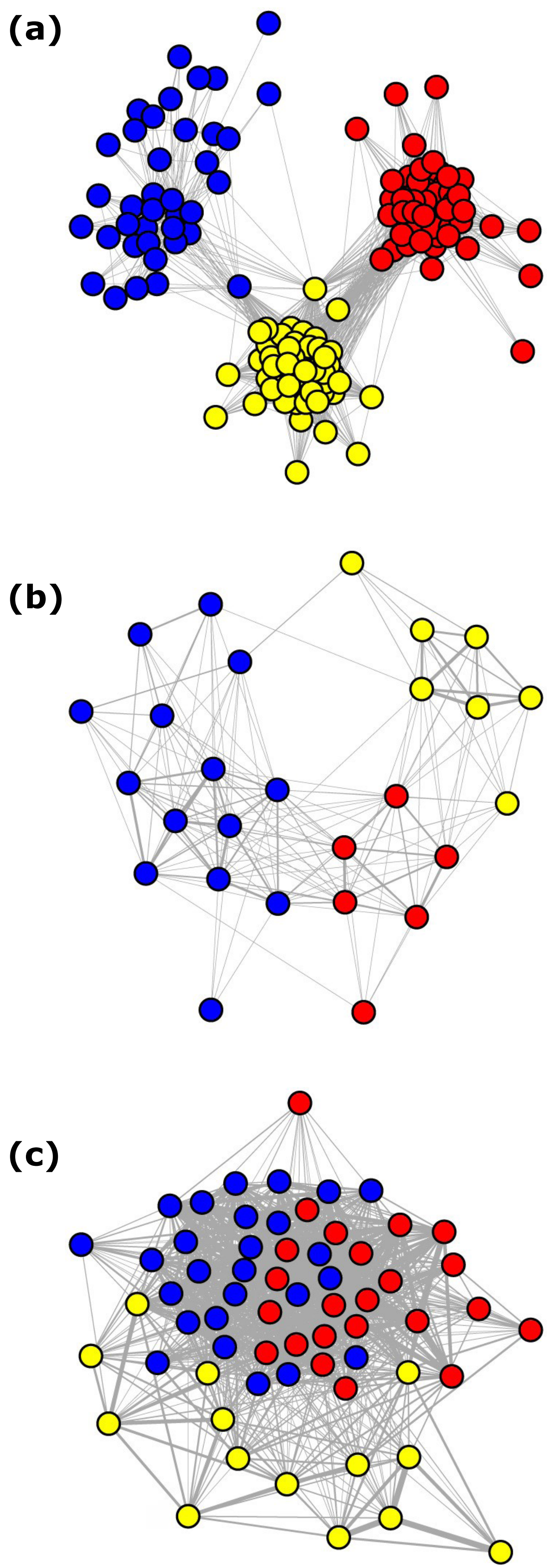
Source: Cacioppo, J.T., J.H. Fowler, N.A. Christakis. (2009). Alone in the crowd: The structure and spread of loneliness in a large social network. *J Pers Soc Psych 97*(6), 977-991. doi.org/10.1037/a0016076

Bird community structure network graphs

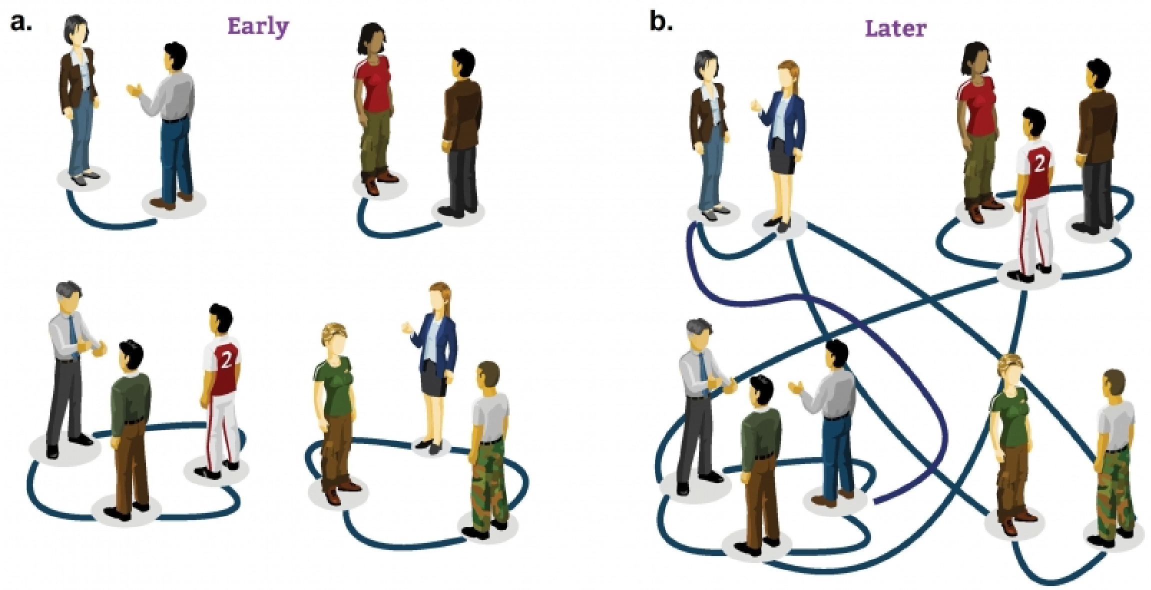
Data collected on bird social interaction is graphed to show community structure. The different colored **nodes** in each graph represent different social communities within one species of bird; the **edges** connect birds who interacted with each other. Three bird communities are shown in these three network graphs: (a) mixed species tits, (b) golden-crowned sparrows, (c) mixed species thornbills.

Researchers aimed to determine how the different populations of birds interacted with one another.

Why study bird community structure? Animals' (including humans') life experiences influence how they view their social environments. The social environment—including organization of social groups—sets the stage for how animals interact. Scientists consider both the context of an animal's lifetime and their social environment and their impacts on evolutionary processes such as coevolution (when closely associated species influence each other's evolution), speciation (the formation of new and distinct species), and evolution of societies.



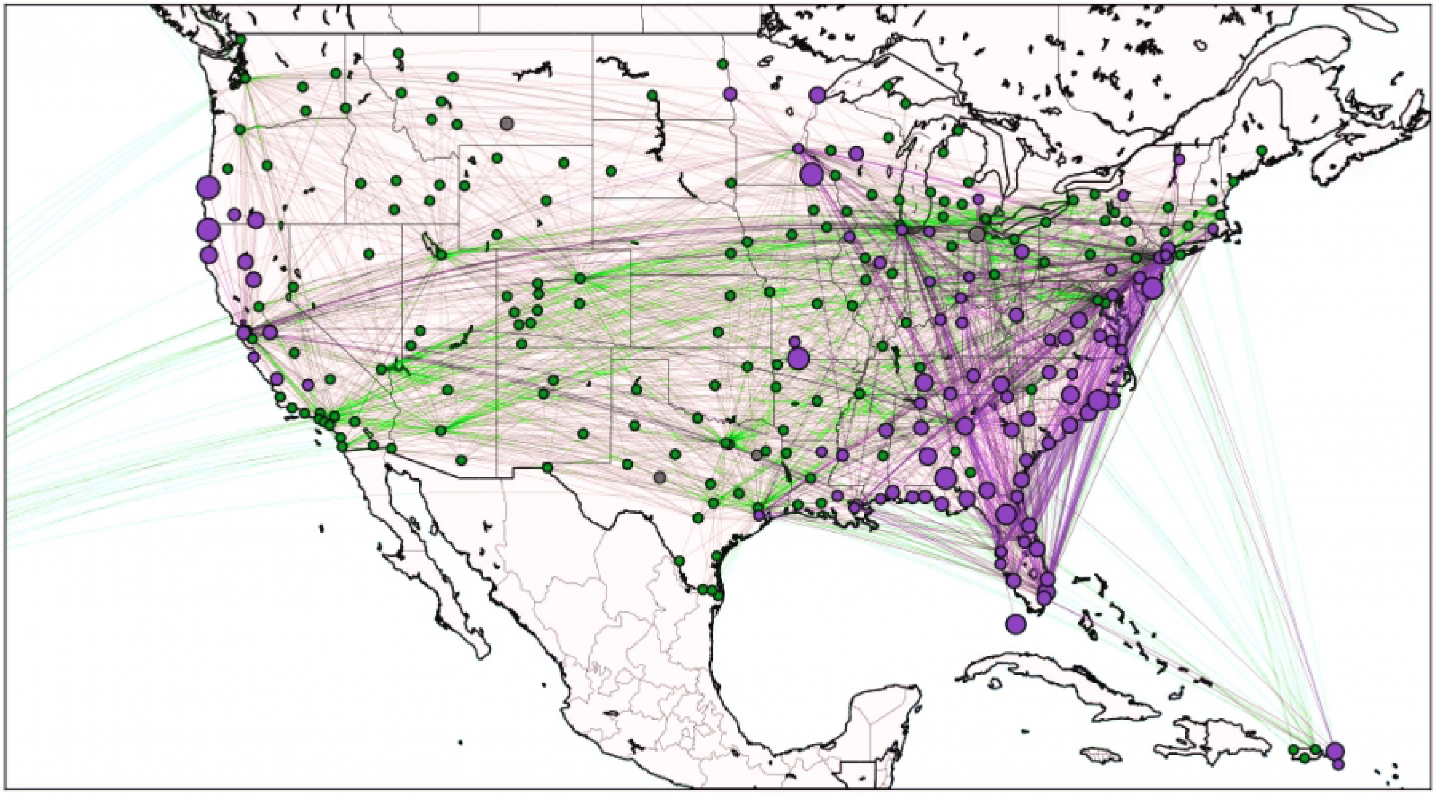
Source: Shizuka, D., and D.R. Farine. (2016). Measuring the robustness of network community structure using assortativity. *Anim. Behav. 112*(Feb-2016), 237-246. https://doi.org/10.1016/j.anbehav.2015.12.007



Cocktail party social network graph

The **nodes** in these networks represent people at a fictional party and the **lines/ edges** represent interactions between people. The graph shows that more people have connections by the end of the party.

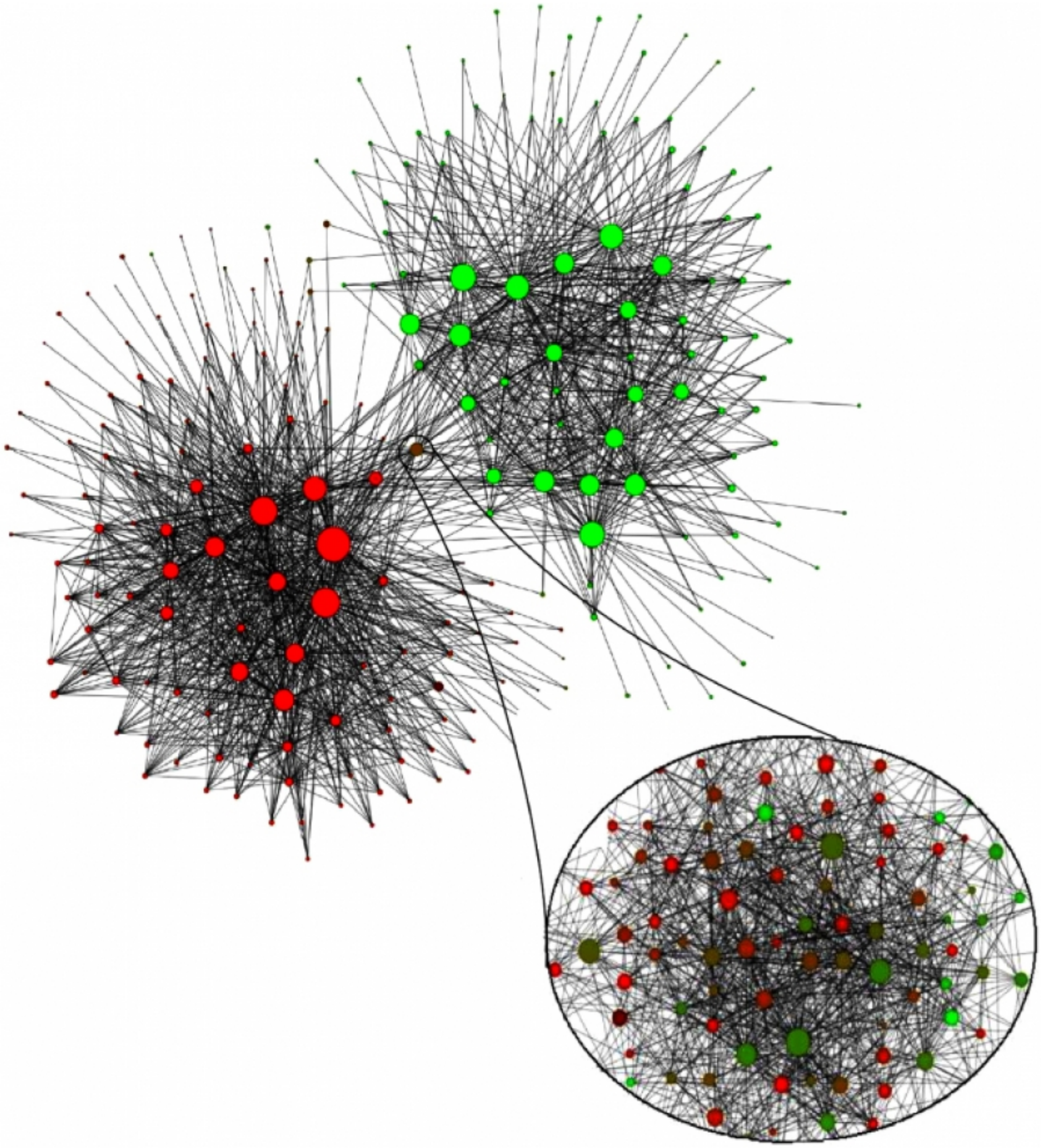
Source: Barabási, A. (2016). *Network Science*. Cambridge University Press: Cambridge, UK. http://networksciencebook.org



Clusters of congested airports network graph

This aviation (airplane) map of the United States of America shows congested airports as **purple nodes**, while those with normal traffic as **green nodes**. The **links** represent flights from one airport to another. The clustering of congested airports indicates that the delays are dependent on each other—when one airport has delays, it can delay planes at other airports, causing a cascade through the airport network.

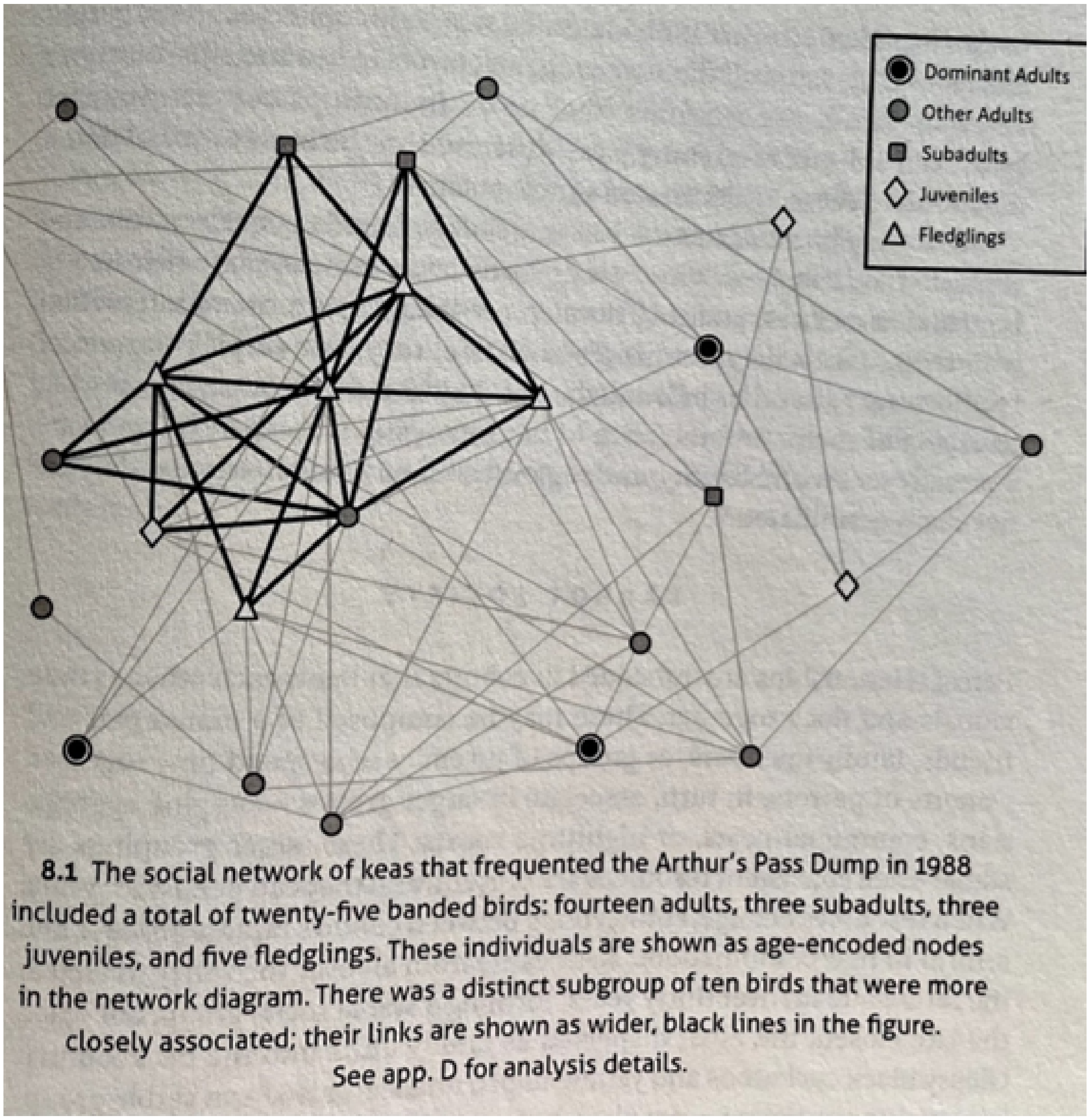
Source: Barabási, A. (2016). *Network Science*. Cambridge University Press: Cambridge, UK. http://networksciencebook.org



Communities in Belgium mobile phone network graphs

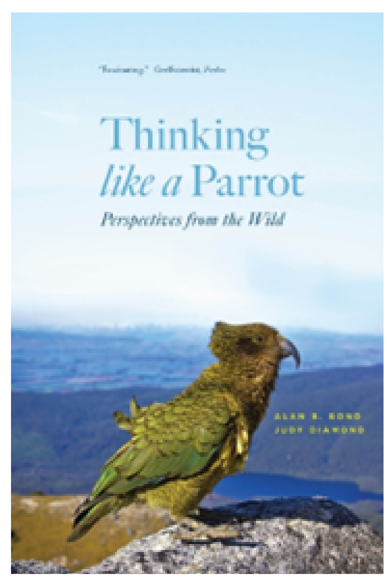
This graph shows communities of at least 100 people (represented as **nodes**) and the phone calls between people in those communities. The data comes from a Belgium mobile phone network. The **red nodes** show communities of people who speak French, and the **green nodes** show communities where people speak Dutch. Phone calls from one community to another are indicated by **links**. Node size is proportional to the number of individuals in the corresponding community. The community that connects the two main clusters contains several smaller communities (less than 100 people each) that make up the capital city Brussels where both languages are spoken. The blowout depicts the nodes representing smaller communities within the node in the larger graph.

Source: Barabási, A. (2016). *Network Science*. Cambridge University Press: Cambridge, UK. http://networksciencebook.org

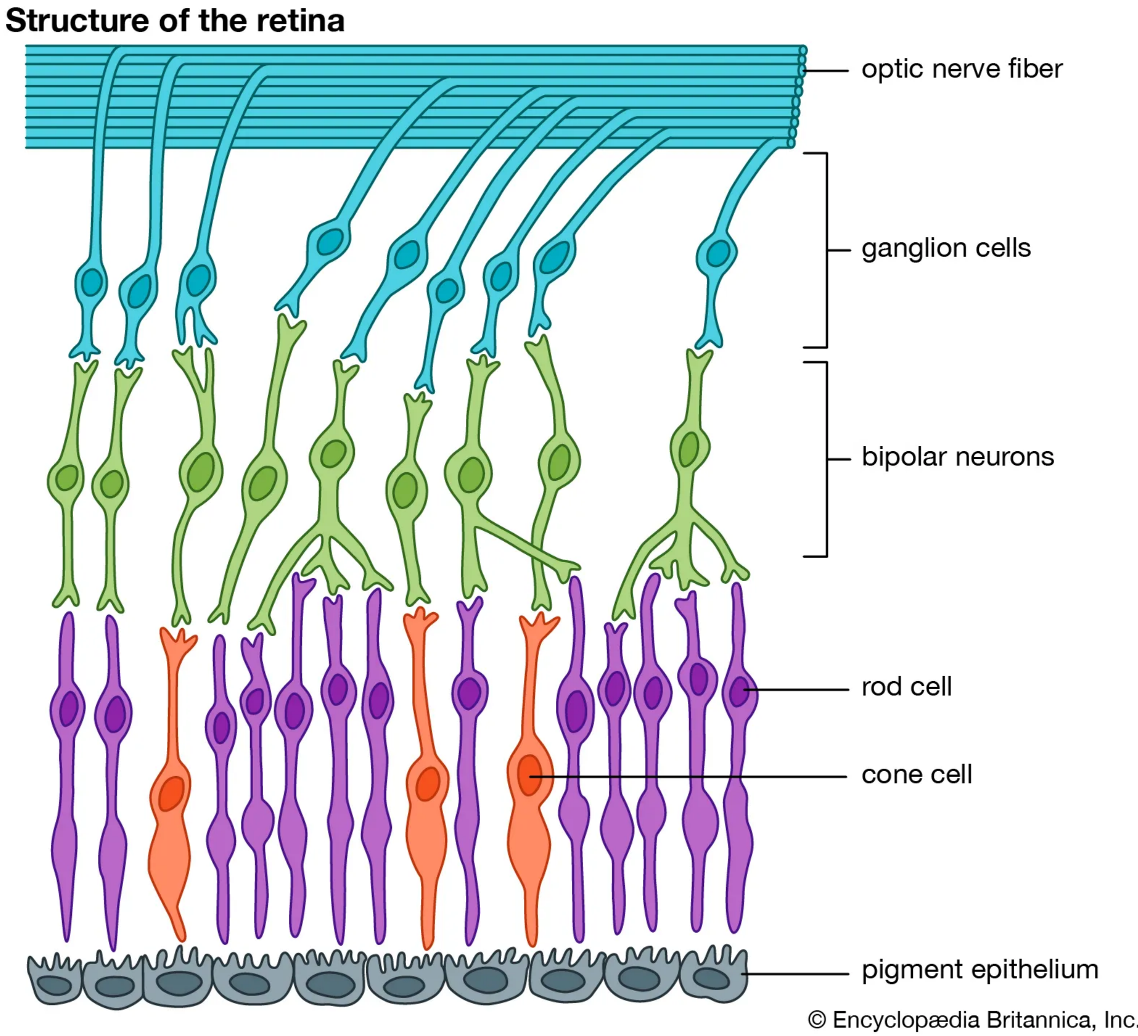


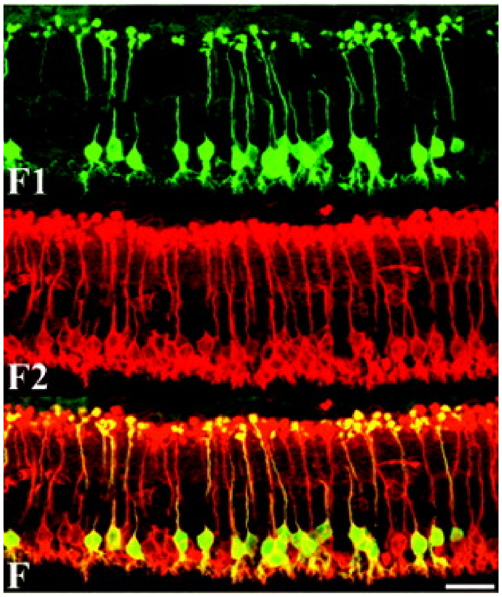
***Thinking Like a Parrot* network graph**

This graph shows a social network of keas (large parrots that live in New Zealand). Parrots group together in areas where resources such as food are available, and they form relationships by protecting each other from predators. In the graph, the **nodes** represent the keas, and the **links** connect parrots who have relationships with one another. The black circle nodes represent dominant adult parrots; the gray circles are other adults; the squares are subadults; the diamonds are juveniles; and the triangles are fledglings. (Subadults are not youth and not yet adults.) The wider, black links represent the relationships between a distinct subgroup of ten birds who are closer with each other than with the rest.



Source: Bond, A.B., and J.Diamond. (2019). *Thinking Like a Parrot: Perspectives from the Wild*. Chicago, IL: The University of Chicago Press.





Human retina model

The human retina, located at the back of the eye, serves as a neuronal network as it takes in light and turns it into an electrical signal. Then that signal is sent to the brain, where the optic nerve makes sense of the signal. The cells and neurons are the **nodes** in the network, and the connections between them are the **links.** Any damage to the network, such as loss of connection between a rod cell and a bipolar neuron, will cause vision loss in that region of the eye.

Source 1: Davson, H., E.S. Perkins, A. Augustyn, et al. (2022). Human eye. *Encycolpaedia Britannica*. https://www.britannica.com/science/human-eye/The-retinal-image **Source 2:** Zhang, X., B. Chen, A.H. Ng, J. Tanner, D. Tay, K. So, R.A. Rachel, N. Copeland, N. Jenkins, and J. Huang. (2005). Transgenic mice expressing cre-recombinase specifically in retinal rod bipolar neurons. *IOVS* 46, 3515-20. https://doi.org/10.1167/iovs.04-1201