## 1.1 Real-world Graphs

A graph is a mathematic structure of discrete entities (**vertices**) and the interactions between them (**edges**). Pretty much anything that exists can be described in the notation of graphs. Or, as I like to say, **everything is a graph**.

"Real-world graphs" are graphs that arise in biology, technology, social science, etc. Commonly studied graphs include road networks, social networks, protein interaction networks, the brain, the Internet, among many many others. Better understanding these real-world graphs has been a strong driver of the field of graph theory. A number of these graphs have several common and inter-related properties:

**Sparsity**: Most vertices are only connected to a small fraction of total vertices in the graph.
*Example*: How many people are you friends with on Facebook (social relationship graph) out of the 2+ billion that use it?
**Degree skew**: A large difference between maximum and minimum degree for all vertices. A few vertices have a large degree while most vertices have a much smaller degree.
*Example*: How celebrities on Twitter (social follower graph) might have millions of followers, whereas you or I might have hundreds.
**Hubs**: The large degree vertices serve as central hubs, connecting disparate parts of the graph.
*Example*: Search engines or other link aggregators on the Internet (information graph).
**Irregularity**: There is not necessarily a fixed structure based on geometric limitations or similar restrictions.
*Example*: Your friends on Facebook can be from any geographic location on the globe.
**Small-world**: Due to these hubs and irregularity, the vertices in the graph are all quickly accessible from one another.
*Example*: How many clicks does it take for you to get from one Wikipedia page to any other? Ever hear of "Six degrees of Kevin Bacon"?

However, a lot of the graphs that we'll consider in this class don't fully represent these real-world properties. This is generally done for ease of proofs and understanding. But I think it's still useful to recognize the above for the occasional example of real-world data that we'll use.

## 1.2 Basic Definitions

Below are some basic (and more formalized) definitions and terminology that will be used throughout the course. As mentioned, graphs and aspects of graph theory appears within a wide variety of fields (computer science, math, network science, social sciences, physics, biology, many more), and all of these fields tend to use different notation and terminology. I'll try and keep things as consistent as possible for all of our sake. Additional terms and definitions will be introduced as we come across them.

A **graph** $G$ is a tuple consisting of a set $V(G)$ of elements called **vertices**, a set $E(G)$ of pair of vertices called **edges**, and the **endpoint** relations of edges that associate each edge with two vertices. Additionally, each vertex and edge can have some non-zero number of *weights* associated with it (remember minimum spanning trees?). We consider **undirected graphs** for now, in which each edge is a non-directional pairwise relation.

If $e = (v, u)$ is an edge in $G$, then
$e$ **joins** $u$ and $v$; $e$ is **incident** with $u$ and $v$;
$u$ and $v$ are **incident** with $e$;
$u$ and $v$ are **endpoints** of $e$;
$u$ and $v$ are **adjacent** to each other;
$u$ and $v$ are in each others' **neighborhood**.
The **degree** of $v$ is the number of $u \subseteq V(G)$ that are adjacent to $v$.

The **order** of a graph $G(V, E)$ is $|V|$; the **size** of $G(V, E)$ is $|E|$. If both $|V|$ and $|E|$ are finite, $G$ is called **finite**. A graph of order $p$ and size $q$ is called a $(p, q)$-graph.

**Multiple edges** or **multi-edges** are edges which have the same pair of endpoints. **Loops** are edges in which the endpoints are the same vertex.

A **simple graph** has no multiple edges or loops
A **null graph** is a graph with $V = E = \emptyset$
A **trivial graph** is a graph with $E = \emptyset$ and $|V| = 1$
An **empty graph** is a graph with $E = \emptyset$ and $|V| \geq 1$

A **path** is a simple graph whose vertices can be listed such that any two vertices are adjacent iff (if and only if) they are consecutive in the list. A **cycle** is a simple graph with an equal number of vertices and edges whose vertices can be placed around a circle and two vertices are adjacent iff they are appear consecutively along the circle. A **tree** is a simple connected graph with no cycles.

A **bipartite graph** is a graph which is the union of two disjoint independent sets.
A **complete graph**, or **clique**, is a graph where any two vertices in the graph are adjacent. We denote a clique of size $n$ by $K_n$.
A **complete bipartite graph** or **biclique** with independent sets of sizes $n$ and $m$ we denote as $K_{n,m}$

A **subgraph** of a graph $G$ is a graph $H$ that is entirely **contained** in $G$ ($H \subseteq G$), or that $V(H) \subseteq V(G)$ and $E(H) \subseteq E(G)$ with all endpoint assignment being the same.

A bulk of this class will be diving deeper into proofs, algorithms, and interesting properties for each of the above various graph types (and more!). Some of the terminology used we haven't explicitly defined yet, but we will in due time as necessary.

## 1.3 Graph Representation

There are multiple ways to represent a graph. Below are a few examples.

An **adjacency matrix** $A(G)$ is an $n \times n$ (where $n = |V|$) matrix where a (positive) nonzero value in each $a_{i,j}$ indicates that many edges with endpoints from $v_i$ to $v_j$. The sum of nonzeros in a row $i$ is equal to the degree of $v_i$. For a simple graph with no loops, the diagonal will be zeros and the only nonzero appearing with be 1. For undirected graphs, the adjacency matrix will be symmetric.

An **incidence matrix** $M(G)$ is an $n \times m$ (where $n = |V|$ and $m = |E|$) in which a value of 1 in $m_{i,j}$ indicates that $v_i$ is incident on edge $e_j$. Again the sum of nonzeros in a row $i$ is the degree of $v_i$.

For memory efficiency with most real-world graphs, adjacency/incidence matrices are rarely used in computation. Recall, most real-world graphs are extremely sparse. One of the easiest graph representations commonly utilized is to simply store for each vertex its degree and adjacencies (**adjacency format**). Another common representation is the **compressed sparse row** (CSR) format. It uses two arrays: the first array $L$ of length $2|E|$ lists in order adjacencies of $v_1$ then $v_2$ then $\ldots$ $v_n$. The second array $O$ of length $|V| + 1$ lists offsets for each $v_i$ to where their adjacencies begin in the first array. The degree for any $v_i$ can be calculated as $O[i+1] - O[i]$. For iterative computations, a CSR format can have a slight locality/cache benefit over the degree-adjacency representation.