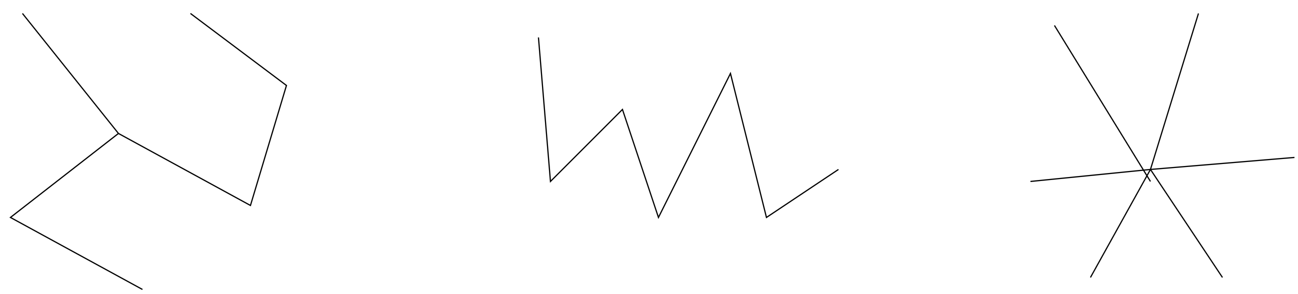
Trees



A *tree* is a graph which is

(a) Connected and

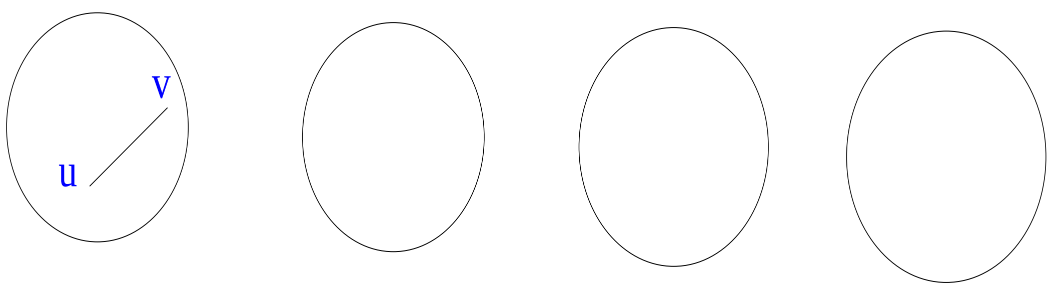
(b) has no cycles (*acyclic*).

Lemma 1 *Let the components of* G *be* $C_1, C_2, \ldots, C_r$, *Suppose* $e = (u, v) \notin E$, $u \in C_i$, $v \in C_j$.

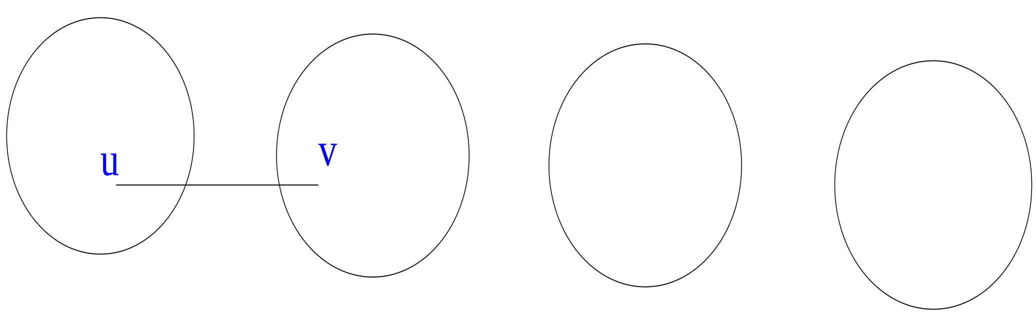
(a) $i = j \Rightarrow \omega(G + e) = \omega(G)$.

(b) $i \neq j \Rightarrow \omega(G + e) = \omega(G) - 1$.

(a)



(b)



Proof Every path P in $G+e$ which is not in G must contain e. Also,

$$\omega(G+e) \leq \omega(G).$$

Suppose

$$(x = u_0, u_1, \ldots, u_k = u, u_{k+1} = v, \ldots, u_\ell = y)$$

is a path in $G+e$ that uses e. Then clearly $x \in C_i$ and $y \in C_j$.

(a) follows as now no new relations $x \sim y$ are added.

(b) Only possible new relations $x \sim y$ are for $x \in C_i$ and $y \in C_j$. But $u \sim v$ in $G+e$ and so $C_i \cup C_j$ becomes (only) new component. □

Lemma 2 $G = (V, E)$ *is acyclic (*forest*) with (tree) components* $C_1, C_2, \ldots, C_k$. $|V| = n$. $e = (u, v) \notin E$, $u \in C_i$, $v \in C_j$.

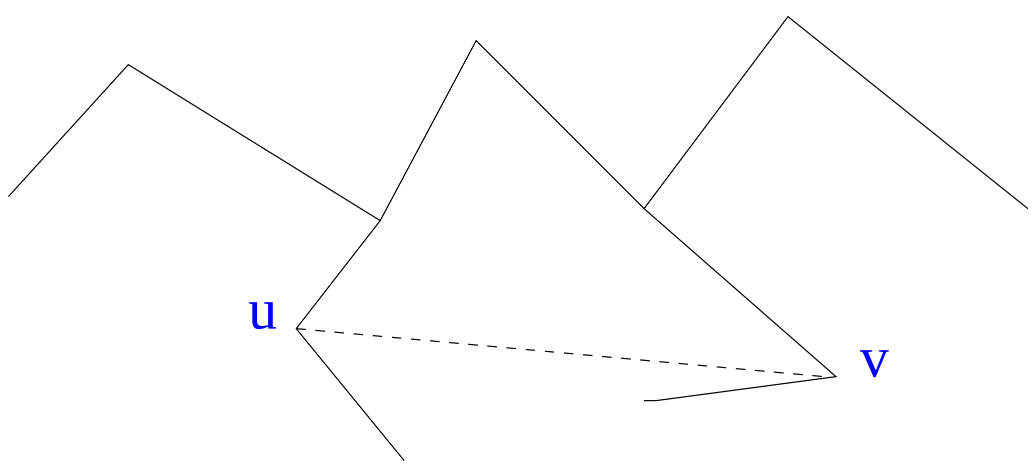
(a) $i = j \Rightarrow G + e$ *contains a cycle.*

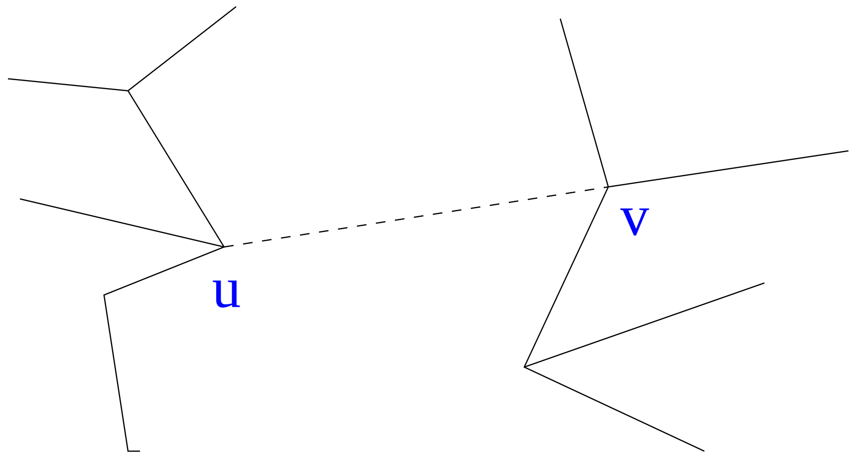
(b) $i \neq j \Rightarrow G + e$ *is acyclic and has one less component.*

(c) G *has* $n - k$ *edges.*

(a) $u, v \in C_i$ implies there exists a path $(u = u_0, u_1, \ldots, u_\ell = v)$ in G.

So $G + e$ contains the cycle $u_0, u_1, \ldots, u_\ell, u_0$.

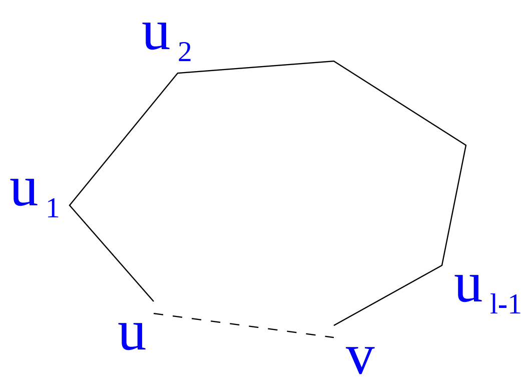




(b) Suppose $G + e$ contains the cycle C. $e \in C$ else C is a cycle of G.

$$C = (u = u_0, u_1, \ldots, u_\ell = v, u_0).$$

But then G contains the path $(u_0, u_1, \ldots, u_\ell)$ from u to v – contradiction.



The drop in the number of components follows from Lemma 1.

The rest follows from

(c) Suppose $E = \{e_1, e_2, \dots, e_r\}$ and $G_i = (V, \{e_1, e_2, \dots, e_i\})$ for $0 \leq i \leq r$.

Claim: G_i has $n - i$ components.

Induction on i.

$i = 0$: G_0 has no edges.

$i > 0$: G_{i-1} is acyclic and so is G_i. It follows from part (a) that e_i joins vertices in distinct components of G_{i-1}. It follows from (b) that G_i has one less component than G_{i-1}.

End of proof of claim

Thus $r = n - k$ (we assumed G had k components).

$\square$

Corollary 1 *If a tree T has n vertices then*

(a) *It has $n - 1$ edges.*

(b) *It has at least 2 vertices of degree 1, ($n \geq 2$).*

Proof (a) is part (c) of previous lemma. $k = 1$ since T is connnected.

(b) Let s be the number of vertices of degree 1 in T. There are no vertices of degree 0 – these would form separate components. Thus

$$2n - 2 = \sum_{v \in V} d_T(v) \geq 2(n - s) + s.$$

So $s \geq 2$. □

Theorem 1 *Suppose* $|V| = n$ *and* $|E| = n - 1$*. The following three statements become equivalent.*

(a) G *is connected.*

(b) G *is acyclic.*

(c) G *is a tree.*

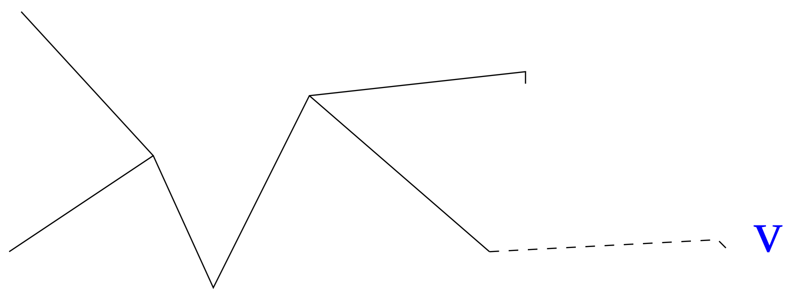
Let $E = \{e_1, e_2, \ldots, e_{n-1}\}$ and
$G_i = (V, \{e_1, e_2, \ldots, e_i\})$ for $0 \leq i \leq n - 1$.

$(a) \Rightarrow (b)$: G_0 has n components and G_{n-1} has 1 component. Addition of each edge e_i must reduce the number of components by 1 – Lemma 2(b). Thus G_{i-1} acyclic implies G_i is acyclic. (b) follows as G_0 is acyclic.

$(b) \Rightarrow (c)$: We need to show that G is connected. Since G_{n-1} is acyclic, $\omega(G_i) = \omega(G_{i-1}) - 1$ for each i – Lemma 2(b). Thus $\omega(G_{n-1}) = 1$.

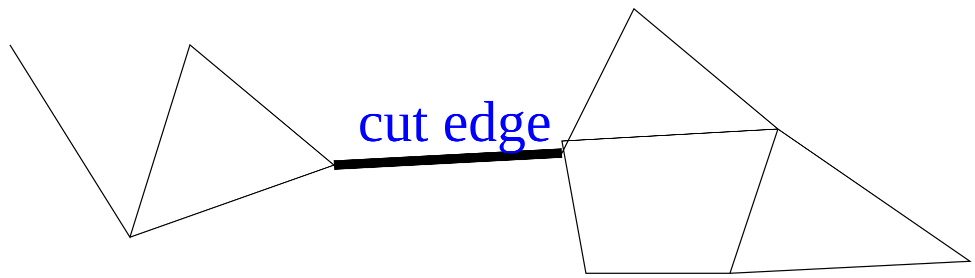
$(c) \Rightarrow (a)$: trivial.

Corollary 2 *If v is a vertex of degree 1 in a tree T then $T - v$ is also a tree.*



Proof Suppose T has n vertices and $n-1$ edges. Then $T - v$ has $n - 1$ vertices and $n - 2$ edges. It acyclic and so must be a tree. $\square$

Cut edges

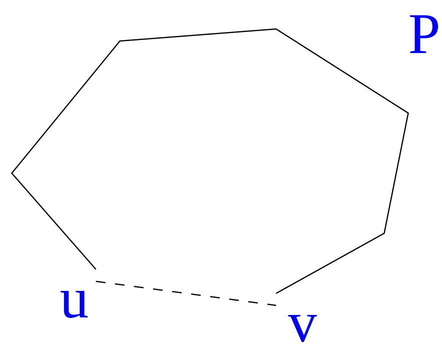


e is a *cut edge* of G if $\omega(G - e) > \omega(G)$.

Theorem 2 *$e = (u, v)$ is a cut edge iff e is not on any cycle of G.*

Proof ω increases iff there exist $x \sim y \in V$ such that all walks from x to y use e.

Suppose there is a cycle (u, P, v, u) containing e. Then if $W = x, W_1, u, v, W_2, y$ is a walk from x to y using e, x, W_1, P, W_2, y is a walk from x to y that doesn't use e. Thus e is not a cut edge.



If e is not a cut edge then $G - e$ contains a path P from u to v ($u \sim v$ in G and relations are maintained after deletion of e). So (v, u, P, v) is a cycle containing e.

$\square$

Corollary 3 *A connected graph is a tree iff every edge is a cut edge.*

Corollary 4 *Every finite connected graph G contains a spanning tree.*

Proof Consider the following process: starting with G,

1. If there are no cycles – **stop**.

2. If there is a cycle, delete an edge of a cycle.

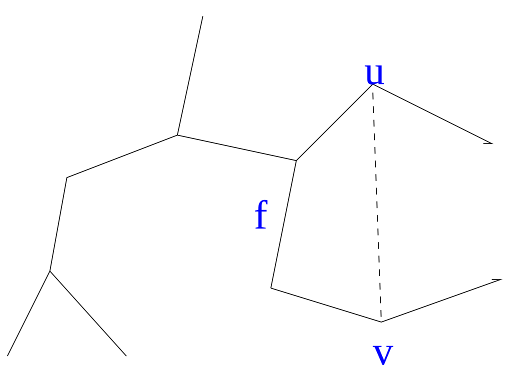
Observe that (i) the graph remains connected – we delete edges of cycles. (ii) the process must terminate as the number of edges is assumed finite.

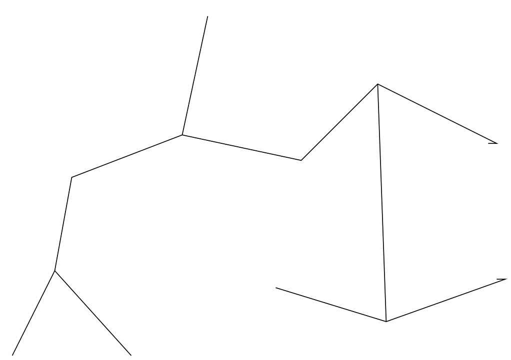
On termination there are no cycles and so we have a connected acyclic spanning subgraph i.e. we have a spanning tree. □

Theorem 3 *Let* T *be a spanning tree of* $G = (V, E)$, $|V| = n$. *Suppose* $e = (u, v) \in E \setminus T$.

(a) $T + e$ *contains a* unique *cycle* $C(e)$.

(b) $f \in C(e)$ *implies that* $T + e - f$ *is a spanning tree of* G.





Proof (a) Lemma 2(a) implies that $T + e$ has a cycle C. Suppose that $T + e$ contains another cycle $C' \neq C$. Let edge $g \in C' \setminus C$. $T' = T + e - g$ is connected, has $n - 1$ edges. But T' contains a cycle C, contradictng Lemma 2(b).

(b) $T + e - f$ is connected and has $n - 1$ edges. Therefore it is a tree. $\square$

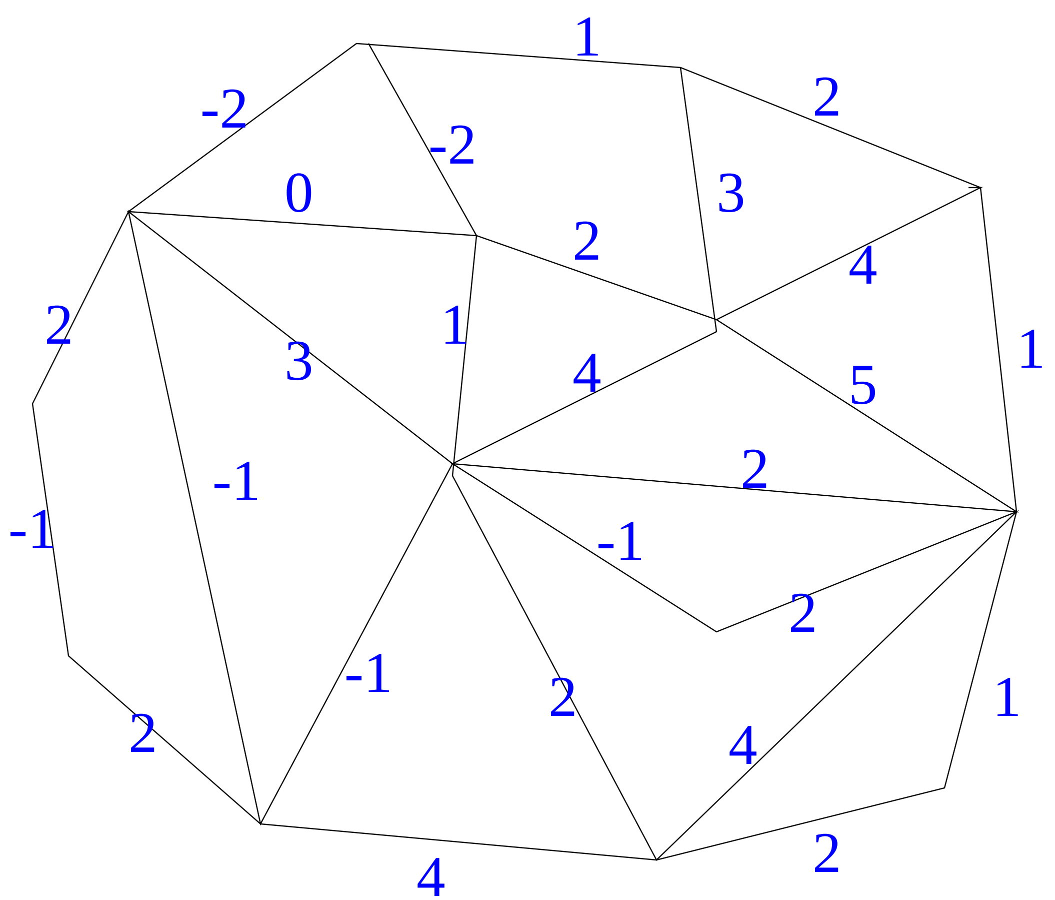
Maximum weight trees

$G = (V, E)$ is a connected graph.

$w : E \to \boldsymbol{R}$. $w(e)$ is the *weight* of edge e.

For spanning tree T, $w(T) = \sum_{e \in T} w(e)$.

Problem: find a spanning tree of maximum weight.



Greedy Algorithm

Sort edges so that $E = \{e_1, e_2, \ldots, e_m\}$ where

$$w(e_1) \geq w(e_2) \geq \cdots \geq w(e_m).$$

begin

  $T := \emptyset$

  for $i = 1, 2, \ldots, m$ **do**

  begin

    if $T + e_i$ does not contain a cycle

    then $T \leftarrow T + e_i$

  end

Output T

end

Greedy always adds the maximum weight edge which does not make a cycle with previously chosen edges.

Theorem 4 *The tree constructed by GREEDY has maximum weight.*

Proof Let the edges of the *greedy tree* be $e_1^\star, e_2^\star, \ldots, e_{n-1}^\star$, in order of choice. Note that $w(e_i^\star) \geq w(e_{i+1}^\star)$ since neither makes a cycle with $e_1^\star, e_2^\star, \ldots, e_{i-1}^\star$.

Let $f_1, f_2, \ldots, f_{n-1}$ be the edges of any other tree where $w(f_1) \geq w(f_2) \geq \cdots w(f_{n-1})$.

We show that

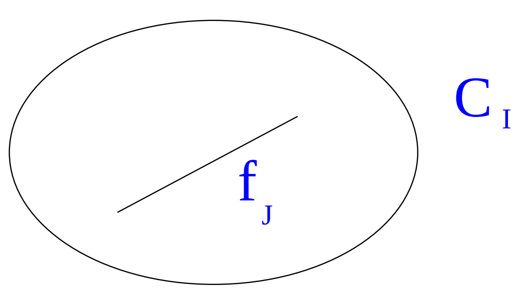
$$w(e_i^\star) \geq w(f_i) \qquad 1 \leq i \leq n-1. \qquad (1)$$

Suppose (1) is false. There exists $k > 0$ such that

$$w(e_i^\star) \geq w(f_i),\ 1 \leq i < k \text{ and } w(e_k^\star) < w(f_k).$$

Each of $f_i,\ 1 \leq i \leq k$ is either a member of $\{e_1^\star, e_2^\star, \ldots, e_{k-1}^\star\}$ or makes a cycle with $\{e_1^\star, e_2^\star, \ldots, e_{k-1}^\star\}$. Otherwise one of them would have been chosen in preference to $e_k^\star$.

Let the components of the forest $(V, \{e_1^\star, e_2^\star, \ldots, e_{k-1}^\star\})$ be $C_1, C_2, \ldots, C_{n-k+1}$. Each $f_i,\ 1 \leq i \leq k$ has both of its endpoints in the same component.



Let μ_i be the number of f_j which have both endpoints in C_i and let ν_i be the number of vertices of C_i. Then

$$\mu_1 + \mu_2 + \cdots \mu_{n-k+1} = k \tag{2}$$
$$\nu_1 + \nu_2 + \cdots \nu_{n-k+1} = n \tag{3}$$

It follows from (2) and (3) that there exists t such that

$$\mu_t \geq \nu_t. \tag{4}$$

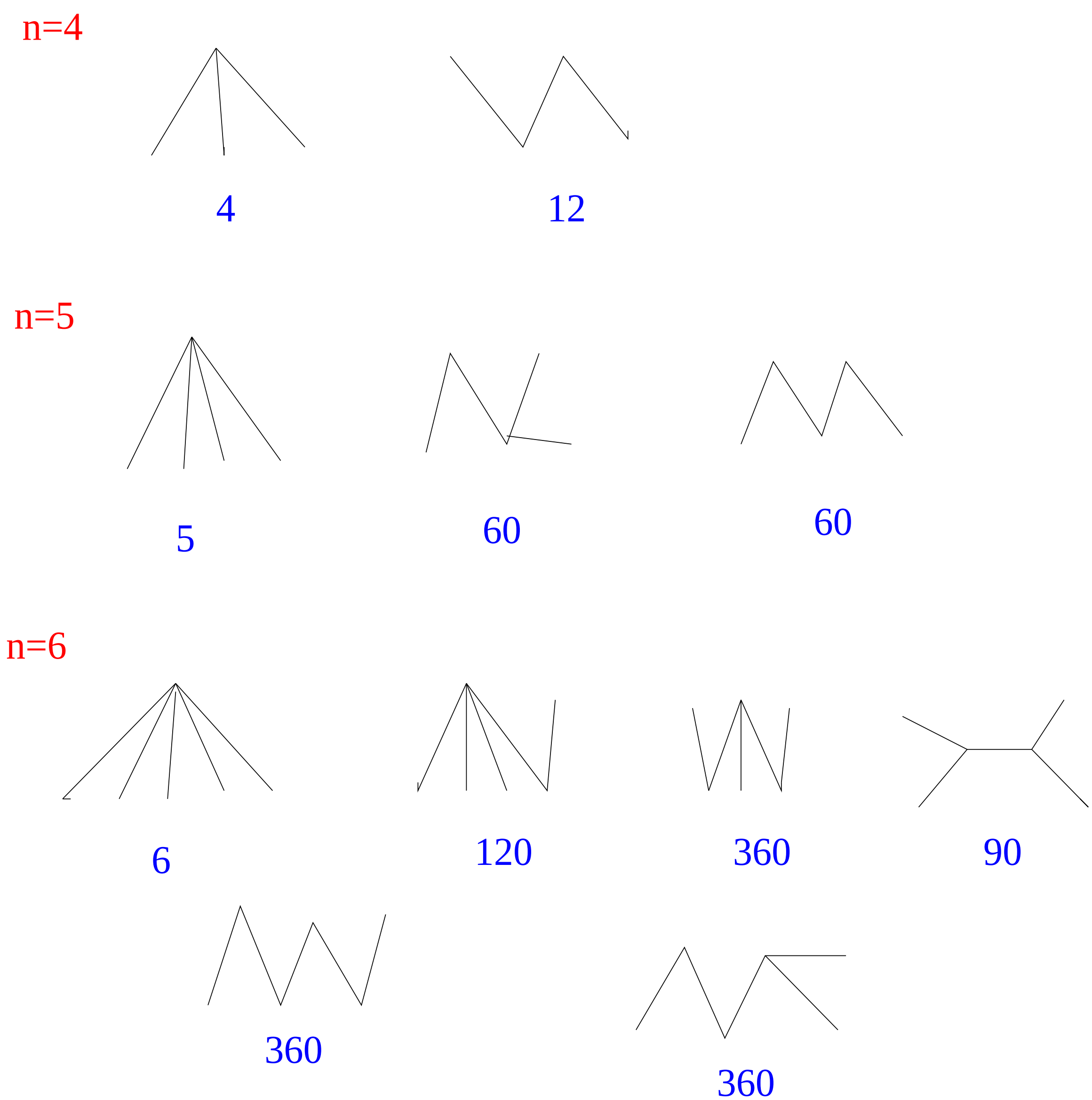
[Otherwise

$$\begin{aligned}\sum_{i=1}^{n-k+1} \mu_i &\leq \sum_{i=1}^{n-k+1} (\nu_i - 1) \\ &= \sum_{i=1}^{n-k+1} \nu_i - (n-k+1) \\ &= k-1.\end{aligned}$$

]

But (4) implies that the edges f_j such that $f_j \subseteq C_t$ contain a cycle. □

How many trees? – Cayley's Formula



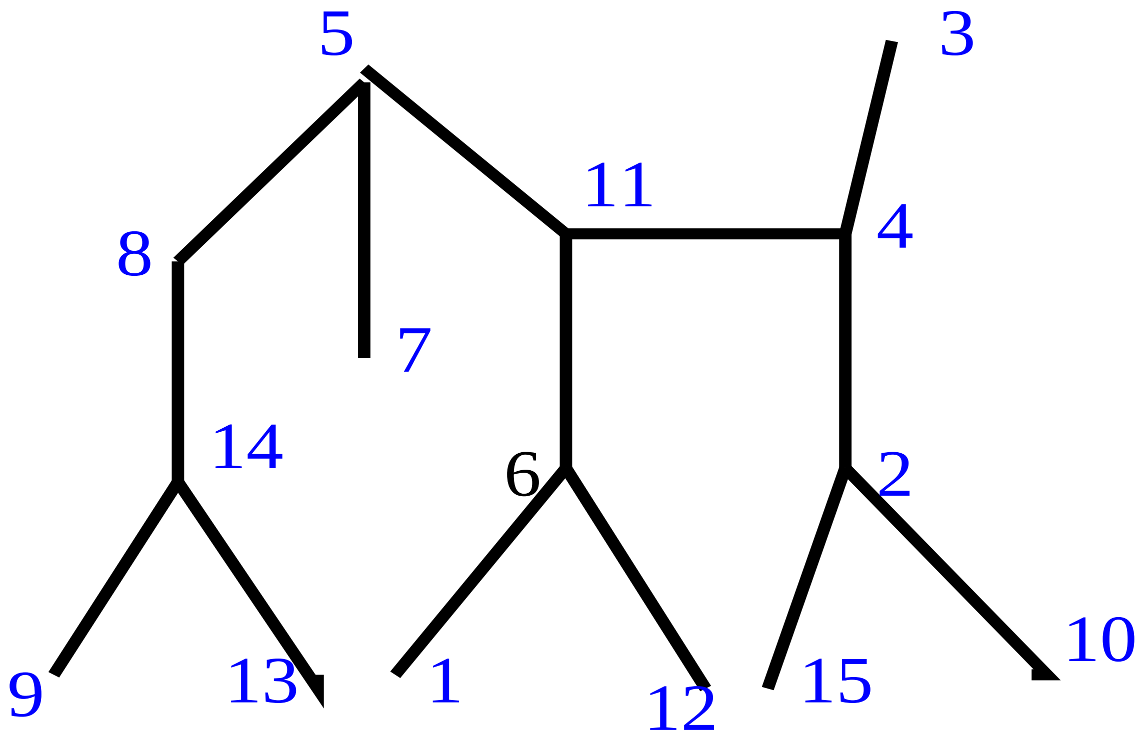
Prüfer's Correspondence

There is a 1-1 correspondence ϕ_V between spanning trees of K_V (the complete graph with vertex set V) and sequences V^{n-2}. Thus for $n \geq 2$

$$\tau(K_n) = n^{n-2} \qquad \text{Cayley's Formula.}$$

Assume some arbitrary ordering $V = \{v_1 < v_2 < \cdots < v_n\}$.

$\phi_V(T)$:
begin
  $T_1 := T$;
  for $i = 1$ **to** $n-2$ **do**
  begin
    $s_i :=$ neighbour of least leaf ℓ_i of T_i.
    $T_{i+1} = T_i - \ell_i$.
  end $\quad \phi_V(T) = s_1 s_2 \ldots s_{n-2}$
end



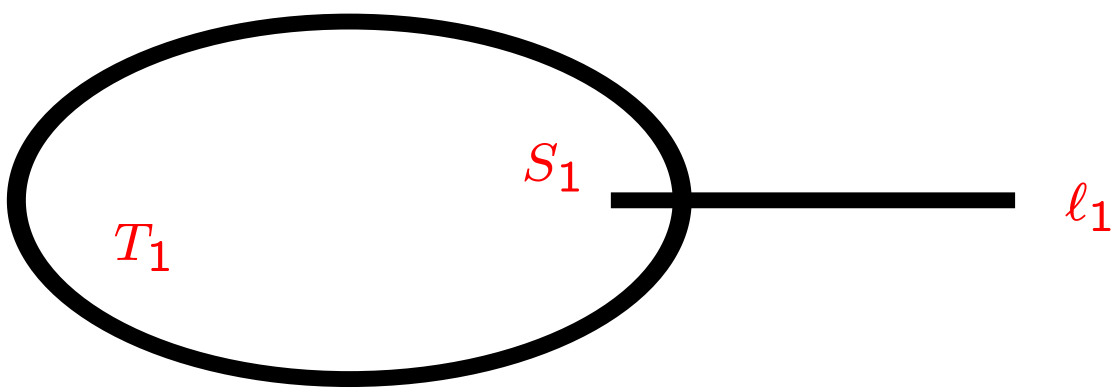
6,4,5,14,2,6,11,14,8,5,11,4,2

Lemma 3 *$v \in V(T)$ appears exactly $d_T(v) - 1$ times in $\phi_V(T)$.*

Proof Assume $n = |V(T)| \geq 2$. By induction on n.

$n = 2$: $\phi_V(T) = \Lambda$ = empty string.

Assume $n \geq 3$:



$\phi_V(T) = s_1 \phi_{V_1}(T_1)$ where $V_1 = V - \{s_1\}$.

s_1 appears $d_{T_1}(s_1) - 1 + 1 = d_T(s_1) - 1$ times – induction.

$v \neq s_1$ appears $d_{T_1}(v) - 1 = d_T(v) - 1$ times – induction. □

Construction of ϕ_V^{-1}

Inductively assume that for all $|X| < n$ there is an inverse function ϕ_X^{-1}. (True for $n = 2$).
Now define ϕ_V^{-1} by

$$\phi_V^{-1}(s_1 s_2 \ldots s_{n-2}) = \phi_{V_1}^{-1}(s_2 \ldots s_{n-2}) \text{ plus edge } s_1 \ell_1,$$

where $\ell_1 = \min\{s : s \notin s_1, s_2, \ldots s_{n-2}\}$ and $V_1 = V - \{\ell_1\}$. Then

$$\begin{aligned} \phi_V(\phi_V^{-1}(s_1 s_2 \ldots s_{n-2})) &= s_1 \phi_{V_1}(\phi_{V_1}^{-1}(s_2 \ldots s_{n-2})) \\ &= s_1 s_2 \ldots s_{n-2}. \end{aligned}$$

Thus ϕ_V has an inverse and the correspondence is established.

Number of trees with a given degree sequence

Corollary 5 *If* $d_1 + d_2 + \cdots + d_n = 2n - 2$ *then the number of spanning trees of* K_n *with degree sequence* $d_1, d_2, \ldots, d_n$ *is*

$$\binom{n-2}{d_1-1, d_2-1, \ldots, d_n-1} = \frac{(n-2)!}{(d_1-1)!(d_2-1)!\cdots(d_n-1)!}.$$

Proof From Prüfer's correspondence and Lemma 3 this is the number of sequences of length $n-2$ in which 1 appears $d_1 - 1$ times, 2 appears $d_2 - 1$ times and so on. □