Most of the things in these notes can be found in the book *Random Walks and Electric Networks*, by Peter Doyle and Laurie Snell. I highly recommend this excellent book. These notes cover some of the main points in the book, but they do not always do things as they are in the book.

## 1 Harmonic Functions

Let $G$ be a graph. The function $f : G \to \mathbf{R}$ (defined on the vertex set of $G$) is called *harmonic* at a vertex $v$ if

$$f(v) = \frac{1}{k} \sum_{i=1}^{k} f(w_i).$$

Here $k$ is the degree of $v$ and $w_1, ..., w_k$ are the vertices incident to $v$. Notice the similarity between this equation and Equation 12.

Suppose that the disjoint vertex sets $A$ and $B$ have been fixed. Suppose that $f$ is some function on $A \cup B$. We call the function $F : G \to \mathbf{R}$ a *harmonic extension* of $f$ if $F = f$ on $A \cup B$ and $F$ is harmonic on $G - A - B$. We will show that each $f$ has a unique harmonic extension.

**Lemma 1.1** If $F_1$ and $F_2$ are two harmonic extensions of $f$ then $F_1 = F_2$.

**Proof:** Let $g = F_1 - F_2$. Note that $g$ is a harmonic extension of the 0 function on $A \cup B$. There must be some vertex $v$ where $g$ achieves its maximum. But $g(v)$ is the average of the values of $g$ at the vertices incident to $v$. This is only possible if $g$ also takes its max at all the vertices incident to $v$. Continuing outward from $v$, we see that $g$ must take its max everywhere. But then this common value must be 0. ♠
Lemma 1.2  Every function \( f \) on \( A \cup B \) has a harmonic extension.

Proof: Let \( V \) be the vector space of functions defined on \( G - A - B \). Let \( \Delta_f : V \to V \) be the map

\[
\Delta_f g(v) = v - \frac{1}{k} \sum_{i} g(w_i).
\]  

As usual \( k \) is the degree of \( v \) and \( w_1, ..., w_k \) are the vertices incident to \( v \). The map \( \Delta_f \) is an affine transformation from \( V \) into \( V \). (It is matrix multiplication followed by translation which depends on the function \( f \).)

Suppose that \( \Delta_f(F_1) = \Delta_f(F_2) \). We extend \( g \) to that \( g = 0 \) on \( A \cup B \). Consider \( g = F_1 - F_2 \). Then, at each vertex \( v \in G - A - B \), the value \( g(v) \) is the average of its neighbors. But then the same argument as above shows that \( g \) cannot have a nonzero maximum or a nonzero minimum. Hence \( g \) is identically 0. (This step uses the fact that \( A \cup B \) is nonempty, so that \( g = 0 \) at some vertex.)

We have shown that \( \Delta_f \) is one to one. But then \( \Delta \) must be onto. In particular, the 0 function on \( G - A - B \) is in the image of \( \Delta_f \). That is, there exists \( F \in V \) such that \( \Delta_f(F) \) is the 0 function. By definition \( F \) is a harmonic extension of \( F \). ♣

Electric Flow: We keep the same notation as above. We imagine \( G \) as an electric network made of wires which all have the same resistance. We think of \( A \) as a set of sources and \( B \) as a set of sinks. Imagine using some kind of battery to keep all the vertices of \( A \) at voltage 0 and all the vertices of \( B \) at voltage 1. Electric current will then flow through the network.

Let \( V \) be the harmonic extension of the function that is equal to some constant \( V_a \) on \( A \) and equal to 0 on \( B \). The current \( i_{vw} \) that flows from vertex \( v \) to vertex \( w \) if \( V(v) - V(w) \). This definition obeys the usual laws one learns about in physics. First,

\[
\delta V = iR,
\]

where \( R \) is the resistance and \( \delta V \) denotes the change in voltage. Here we are setting \( R = 1 \) for every edge. Second, the flow of current into any vertex in \( G - A - B \) is the same as the total flow out.

Below we will always make the choice of \( V_a \) so that the current flowing out of \( a \) equals 1. In this case, we call \( V_a \) the voltage function.
2 Effective Resistance

Let $V$ be the voltage function. Just to do things a bit more formally, we define

$$i_a = \sum_{x\leftrightarrow a} (V(a) - V(x)).$$

(3)

Again, $V_a$ is chosen so that $i_a = 1$.

**Lemma 2.1** $i_a + i_b = 0$.

**Proof:** This is a consequence of Kirkhoff’s law. Here’s the proof. Define $i_{xy} = V(x) - V(y)$ when $x$ and $y$ are connected by an edge and otherwise $i_{xy} = 0$. Setting

$$i_x = \sum_y i_{xy},$$

(4)

we have $i_x = 0$ unless $x = a$ or $x = b$. This is Kirkhoff’s law, and it follows from the fact that $V$ is harmonic on $G - a - b$. But then

$$i_a + i_b = \sum_x i_x = \sum_x \sum_y i_{xy} = 0$$

(5)

The last sum is 0 because $i_{xy} = -i_{yx}$ and we are summing over all pairs. ♠

Say that a *nice flow* is a function $j : G \times G \rightarrow \mathbb{R}$ such that

1. $j_{xy} = 0$ if $x$ and $y$ do not share an edge.
2. $j_{xy} = -j_{yx}$.
3. If $x \in G - a - b$ then $j_x = 0$. That is, the amount of current flowing into $x$ is the same as the amount flowing out. Here $j_x = \sum j_{xy}$.

If, additionally, $j_a = 1$, we call $j_a$ a *unit flow*.

**Example:** Notice that if we take $j = i$ then the axioms are satisfied. But, there are plenty of examples of unit flows other than the electric flow. Here is an example. Suppose that $G'$ is a graph obtained by adding some edges to $G$. Then the current $i$ defined relative to $(G, a, b)$ gives a unit flow relative to $(G', a, b)$ but this unit flow on $G'$ might not be the current defined relative to $(G', a, b)$. The extra wires might change the current.

Here is a key equation.
Lemma 2.2 Suppose that $j$ is a nice flow and $\phi : G \rightarrow \mathbb{R}$ is any function. Then

$$j_a(\phi(a) - \phi(b)) = \frac{1}{2} \sum_{xy} j_{xy}(\phi(x) - \phi(y)).$$

Proof: Both the left hand side and the right hand side are linear functions of $\phi$. So, to prove this equality it suffices to prove it on a basis in the vector space of such functions. Suppose that $\phi(a) = 1$ and $\phi(x) = 0$ otherwise. Then the two sides are equal just by definition. Suppose that $\phi(x) = 1$ for some $x \in G - a - b$. Then the left side is obviously 0, and the right side is given by

$$\sum_{i=1}^k i_{xy_i},$$

and this vanishes by Kirchhoff’s law. Here $y_1, ..., y_k$ are the vertices incident to $x$. Finally, consider the case when $\phi$ is identically 1. Then both sides vanish. We’ve established the identity on a basis, so we’re done. ♠

Now we come to the main point of the section. Define the energy dissipation

$$E(G, a, b) = \frac{1}{2} \sum_{xy} i_{xy}^2.$$  \hspace{1cm} (6)

The factor of $1/2$ is added because $i_{xy}^2 = i_{yx}^2$ and both terms appear in the sum.

Theorem 2.3 $R(G, a, b) = E(G, a, b)$.

Proof: Applying Lemma 2.2 to the case $j = i$ and $\phi = V$ (the voltage function) we have

$$E(G, a, b) = \frac{1}{2} \sum_{xy} i_{xy}^2 = \frac{1}{2} \sum_{xy} i_{xy}(V(x) - V(y)) = i_a(V_a - V_b) = V_a - V_b = R(G, a, b).$$

This completes the proof. ♠

4
3 A Variational Principle

Let \((G, a, b)\) and \(V\) and \(i_{xy}\) be as above. Here we explain a variational principle that characterizes the current \(i_{ix}\) as the one which minimizes the energy dissipation.

Define

\[ E(j) = \frac{1}{2} \sum_{xy} j_{xy}^2. \tag{7} \]

All we are assuming about \(j\) is that it is a nice flow. We call \(j\) a unit flow if \(j_a = 1\). We call \(j\) a null flow if \(j_a = 0\). We already know that \(R(G, a, b) = E(i)\). Here is the main result:

**Theorem 3.1** \(E(i) \leq E(j)\). In other words, \(R(G, a, b)\) is the min of all \(E(j)\) taken over all unit flows \(j\).

**Proof:** The nice flows form a vector space. Let \(V\) be this vector space. There is a canonical inner product on \(V\), namely

\[ \langle j, k \rangle = \frac{1}{2} \sum_{xy} j_{xy} k_{xy}. \tag{8} \]

With this formalism, we have \(E(j) = \langle j, j \rangle\). Suppose that \(k\) is a null flow. Then

\[ \langle k, i \rangle = \sum_{x,y} k_{xy} i_{xy} = \frac{1}{2} \sum_{x,y} k_{xy} (V(x) - V(y)) = k_a (V(a) - V(b)) = 0. \tag{9} \]

The starred equality is Lemma 2.2. Now let \(j\) be any unit flow. We can write \(j = i + k\) where \(k \in V\) is a null flow. But then

\[ E(j) = \langle i + k, i + k \rangle = E(i) + E(k) \geq E(i). \]

Here have used the fact that \(\langle i, k \rangle = 0\). ♠

This result has a geometric interpretation. The set of null flows is a hyperplane through the origin in \(V\) and and set of unit flows is a translation of this hyperplane by the electric flow. By essentially the Pythagorean theorem, the square distance from a unit flow to the origin is minimized by \(i\).
4 Rayleigh’s Theorem

Now we can prove the main technical result.

**Theorem 4.1** Let $G'$ be a graph obtained from $G$ by adding some edges. Then $R(G', a, b) \leq R(G, a, b)$.

**Proof:** We have $R(G, a, b) = E(G, a, b)$ and $R(G', a, b) = E(G', a, b)$. So, it suffices to prove that $E(G, a, b) \leq E(G', a, b)$. Let $i$ be the electric flow on $G$ relative to $a, b$. Let $i'$ be the electric flow on $G'$ relative to $a, b$. Note that $i$ is also a unit flow on $G'$. Hence

$$E(G', a, b) = E(i') \leq E(i) = E(G, a, b)$$

Each of the steps is one of the two theorems we proved above. ♠

If we have a graph $G$, and a finite number of vertices $S \subset V$, which is disjoint from $a \cup b$, we let $G/S$ denote the graph obtained by identifying all the points of $S$ to single vertices.

**Lemma 4.2** $R(G/S, a, b) \leq R(G, a, b)$.

**Proof:** All the theory above makes sense for graphs with multiple edges. So we let $G'$ denote the graph obtained by starting with $G$ and adding an edge from each vertex of $S$ to each other vertex of $S$. By Rayleigh’s Theorem, we have $R(G', a, b) \leq R(G, a, b)$.

Consider the graph map $\phi : G' \to G_S$ which maps each vertex to its equivalence class in $G_S$ and which maps edges to edges. If $v$ is a vertex not in $S$ then $\phi(v) = v$. If $v \in S$ then $\phi(v)$ is the new “big” vertex in $G$. By construction

$$V' = V_S \circ \phi,$$

where $f'$ is the voltage function on $G'$ and $V_S$ is the voltage function on $G_S$. The point is that all the vertices of $G'$ in $S$ have the same voltage because they are all connected to each other. But then the electric current on each edge of $G'$ is the same as the corresponding electric current on $G_S$. Hence $R(G', a, b) = R(G_S, a, b)$. ♠
5 Graphs in Parallel

Here is a short discussion about graphs which appear in parallel. Suppose that \( c \in G - a - b \) is a cut vertex of \( G \). Let \( G_a \) be the lobe of \( G \) which contains \( a \) and let \( G_b \) be the lobe of \( G \) which contains \( b \).

**Lemma 5.1 (Parallel)** \( R(G, a, b) = R(G_a, a, c) + R(G_b, c, b) \).

**Proof:** Let \( V \) be the voltage function for \( G \). Let \( V' \) be the restriction of \( V - V(c) \) to \( G_a \). By construction \( V' \) is harmonic on \( V_a \) and \( i'_a = 1 \). Hence

\[
R(G_a, a, c) = V(a) - V(c).
\]

A similar argument shows that

\[
R(G_b, b, c) = V(c) - V(b) = V(c).
\]

The point of this second equation is that \( i_b = -i_a \), so the function \( -(V - V(c)) \) is the voltage function for \( (G_b, b, c) \). Adding up these equations gives us the desired result. ♠

6 Four Examples

In this section we use the theory above to work out 4 examples. Before we give these examples, we mention that we can speak about effective resistance when \( a \) and \( b \) are replaced by disjoint subsets \( A \) and \( B \) of vertices. We define \( G^A,B \) to be the graph obtained by identifying all the vertices of \( A \) to a single vertex and all the vertices of \( B \) to a single vertex. We call these new vertices \( a \) and \( b \) and then we proceed as above. That is, we set \( R(G, A, B) = R(G^A,B, a, b) \).

**Paths:** Suppose that \( P_n \) is the path with \( n \) edges. Let \( v_0, \ldots, v_n \) be the vertices of \( G \). Let \( a = v_n \) and \( b = v_0 \). Let \( A = \{v_n\} \) and \( B = \{v_0\} \). We define \( V(v_j) = j \). Then \( V \) exactly the voltage function, because \( i_a = 1 \) and \( V(i + 1) - V(i) = 1 \) for all \( i \). Hence \( R(P_n, a, b) = 1/n \). Taking a limit as \( n \to \infty \), we could say that the effective resistance of the infinite path with \( a = 0 \) and \( b = \infty \) is 0.
**Rooted Binary Trees:** Let $G_n$ be $n$-generations of the rooted binary tree. So, the leaves of $G$ have distance $n$ from the root. The root vertex $a$ has degree 2 and all other non-leaves of $G$ have degree 3. Let $B_n$ be the set of leaves of $G_n$. Given a vertex $v$ we let

$$V_n(v) = 2^{-d} - 2^{-n}$$

where $d$ is the distance from $v$ to $a$. For instance $V(a) = 1 - 2^{-n}$, and $V = 1/2 - 2^{-n}$ on the two neighbors of $a$. The total current flowing out of $a$ is 1 and you can check that $V$ is harmonic at all vertices of $G$ except $a$. Also, $V$ takes the same value on all the leaves of $G_n$. So, $V$ gives rise to a harmonic function on $(G_n)_{a,B_n}$. Hence $E(G_n, a, B_n) = 1 - 2^{-n}$. Taking a limit, we would say that the effective resistance of the infinite binary tree (starting at the root) is 1.

**The Infinite Square Grid:** Let $G_\infty$ denote the usual infinite graphs of edges of the unit square tiling of the plane. Let $G_n$ be the subgraph of $G_\infty$ consisting of the edges of the $(2n) \times (2n)$ square grid centered at the origin. Let $a = \{0,0\}$ and let $B_n$ denote the outer cycle of $G_{2n}$.

Now we prove that

$$\lim_{n \to \infty} R(G_n, a, B_n) = \infty.$$  \hfill (10)

Consider the concentric cycles $B_1, B_2, ..., B_n$. These cycles are pairwise disjoint. Let $G'_n$ denote the graph obtained by collapsing each of these cycles to a point. The graph $G'_n$ looks like the right side of Figure 1. Figure 1 shows the case $n = 2$. Here we have replaced the multiple edges by a number which indicates the number of edges connecting each vertex to the next.

Figure 1: Collapsing the cycles
The collapse of $G_n$ is just a path of length $n$ whose effective resistances are $1/(4 \times 1)$, $1/(4 \times 3)$, $1/(4 \times 5)$, etc. These graphs all appear in parallel. So, by Rayleigh’s Theorem, the total effective resistance is

$$R(G_n, A, B_n) \geq \frac{1}{4} \times \left( \frac{1}{1} + \frac{1}{3} + \ldots + \frac{1}{2n+1} \right)$$

(11)

This series is closely related to the harmonic series, and is easily seen to diverge. This completes the proof. One could say that the resistance to $\infty$ if the infinite square grid is infinite.

**The Infinite Cubical Grid:** Now let $G_\infty$ denote the infinite cubical graph in $\mathbb{R}^3$. Now we will prove that the resistance from the origin to $\infty$ is finite in $G_\infty$. To avoid quite a tedious argument we will not bother making the intermediate finite graph constructions. We’re just going to go right to the limit, with the understanding that (with some care) the process could be truncated and we could take an honest limit as in previous cases. Alternatively, it is better to just define effective resistance for infinite graphs.

We are going to build an infinite tree $T_\infty \subset G_\infty$ in layers. By Rayleigh’s Theorem, we have

$$R(G_\infty, a, \infty) \leq R(T_\infty, a, \infty).$$

Here $\infty$ essentially denotes the limit of the (presumed) shells $B_n$ in the finite approximations.

We will build $T_\infty$ in layers. For each $k = 0, \ldots, n$, define

$$\Phi_k = \{(100i, 100j, 1000 \times 2^k) | i, j \in \{1, \ldots, 2^k\}\}$$

The slope of any line segment joining a point of $\Phi_{k-1}$ to a point of $\Phi_k$ is at most 1. So, we can join each point in $\Phi_{k-1}$ to 4 points (making a square) in $\Phi_k$ by paths of length at most $C \times 2^k$. So, the point $p_{ij}$ in $\Phi_{k-1}$ gets joined to the points in square $ij$ in $\Phi_k$.

This is our tree, but the paths we have used are somewhat irregular. We lengthen some of the paths in $T_\infty$ by adding extra vertices so that between $\Phi_{k-1}$ and $\Phi_k$, all edges have length $10000 \times 2^k$. This process only increases the resistance, by Rayleigh’s Theorem. (You have to think a bit about how Rayleigh’s Theorem applies in this case.) The new tree $T'_\infty$ is no longer a subgraph of $G_{\text{infty}}$ but we don’t care. What we know is that

$$R(T_\infty, a, \infty) \leq R(T'_\infty, a, \infty).$$
We just have to bound this latter quantity.

Why did we add these edges. Well, by symmetry the voltage function on \( T' \) takes the same value on all vertices that are the same distance from the initial node! So, we can collapse all the vertices at the same distance from the initial node and we get a graph with the same resistance. The collapsed graph is just a “path” consisting of \( 4^k \) paths, each having length \( 10000 \times 2^k \). The effective resistance of this “path” is

\[
\frac{10000 \times 2^k}{4^k} = 10000 \times 2^{-k}.
\]

Summing this, we see that the effective resistance to \( \infty \) is at most \( 20000 \times 2^{-k} \). This completes the proof.

So far we have been talking entirely about electric networks, but now we turn to the subject of random walks. In a certain sense, our analysis of the resistance of the square grid and the cubical grid gives a proof of Polya’s famous theorems about recurrence of the standard random walk in \( \mathbb{Z}^2 \) and the transience of the standard random walk on \( \mathbb{Z}^3 \). What remains to do is to relate what we have done above to the theory of random walks, and then interpret our resistance results in terms of probability.

### 7 Random Walks on Graphs

Let \( G \) be a graph in which every vertex has finite degree. We usually take \( G \) to be a finite graph, but sometimes we will consider countable graphs. Suppose that we have given a linear ordering to the edges incident to each vertex of \( G \). A random walk on \( G \), starting from the vertex \( v \in G \), is a sequence of fair coin flips \( b_1, b_2, b_3, \ldots \) where the \( (j) \)th coin has as many aides as the degree of the vertex \( v_j \). The value of \( b_1 \) selects the vertex \( v_2 \) adjacent to \( v \), the value of \( b_2 \) selects the vertex \( v_3 \) adjacent to \( v_2 \), and so on. Here we have set \( v_1 = v \). One funny thing about this process is that the number of sides of the coin can vary from vertex to vertex. If you prefer, one can consider random walks on regular graphs, and then one can use the same coin all the time.

Suppose that \( A \) and \( B \) are two disjoint subsets of vertices. We define \( P(v, A, B) \) to be the probability that a random walk starting from \( v \) reaches \( A \) before it reaches \( B \). Some of you might be satisfied that this notion of
probability makes intuitive sense. In this case, just skip the next section. Otherwise, you can read a quick sketch of how this probability is defined in terms of measure theory.

In any case, we are really only going to use a few basic properties of the above function. Suppose that \( w_1, \ldots, w_k \) are the vertices incident to \( v \) and \( v \in G - A - B \). Then the basic property is

\[
P(v, A, B) = \frac{1}{k} \sum_{i=1}^{k} P(w_i, A, B).
\] (12)

In other words, we have an equal chance of going from \( v \) to each \( w_i \), and then we can compute the probability of hitting \( B \) before \( A \) and just average these probabilities.

Let us relate random walks to electric networks. We have seen already that every function on \( A \cup B \) has a unique harmonic extension. Suppose that we set \( f = 1 \) on \( A \) and \( f = 0 \) on \( B \). Let’s define

\[
F(v) = P(v, A, B).
\] (13)

Note that \( F = f \) on \( A \cup B \). Equation 12 tells us that \( F \) is harmonic for all \( v \in G - A - B \). In other words, the probability function \( v \to P(v, A, B) \) we have been considering in previous sections is the unique harmonic extension of the function which is 1 on \( A \) and 0 on \( B \).

## 8 Polya’s Theorems

Let \( G_\infty \) be the infinite square grid. Now we explain why a random walk on \( G_\infty \), starting at the origin \( a \), returns to the origin with probability 1. Let \( G_n \) be the graph made from \( n \) consecutive layers of \( G_\infty \). Let \( B_n \) denote the outermost layer of \( G_n \). Let \( P_n \) denote the probability that a random walk starting at the origin \( a \) returns to the origin before hitting \( B_n \). The probability that a random walker returns to the origin in \( G_\infty \) is at least as big as the probability that a random walker on \( G_n \) hits \( B_n \) before returning to \( a \), because in the latter case the process stops and in the former case the process continues and the walker has more changes to return home.

Think about it this way. Suppose we lived in a crazy country where the police throw you in prison if you wander more than 10 miles from your house. Your chances of returning home are increased if the police just disappear. The
boundary $B_n$ is basically the prison that you land in if you wander too far from home.

Now we estimate the probability that a random walk starting at $a$ hits $B_n$ before returning to $a$. Since every random walk starting at $a$ must hit a neighbor of $a$, the probability that a random walk starting at $a$ returns to the origin is the average of the probabilities that a random walk starting at each of the neighbors of $a$ hits $a$ before hitting $B_n$. Let $b$ be such a neighbor. The probability in question is $F_n(b)$, where $F_n$ is the harmonic extension on $G_n$ of the function which is 1 on $a$ and 0 on $B_n$.

Here

$$F_n = \frac{V_n}{R_n}, \quad R_n = R(G_n, a, B_n),$$

where $V_n$ is the voltage function. Since the total current flowing out of $G_n$ with respect to the potential $V_n$ is at most 1, we have

$$V_n(b) \geq R_n - 1.$$ 

But then

$$F_n(b) \geq \frac{R_n - 1}{R_n}.$$

Since $R_n \to \infty$ as $n \to \infty$ we see that $F_n(b) \to 1$. This completes the proof.

Now let’s consider the situation for the cubical grid $G_\infty$. This time the resistance out to infinity is finite. So, there is a nonzero harmonic extension of the function which is 1 on $a$ and tends to 0 as one tends to $\infty$ in $G_\infty$. So, interpreting this fact probabilistically, we see that the probability that a random walk starts at $a$ and returns to $a$ is less than 1. Hence there is a positive probability that the random walk starts at $a$ and never returns.

9 Measure Theoretic Aside

Here is the way the probability $P(v, A, B)$ is treated from the standpoint of measure theory. Again, if you are happy with the definition already, just skip this part of the notes.

In general, the set of all possible coin flips is the subset $S(G, v)$ of infinite allowable integer sequences. A sequence is allowable if, for all $j$, the $j$th digit $b_j$ does not exceed the degree of the vertex $v_j$ selected by the previous terms.
For regular graphs of degree $d$, the set $S(G, v_0)$ is just the set of all infinite sequences involving $d$ digits.

We let

$$S = S(G, v)$$

(14)

Supposing that we have chosen initial allowable sequence $\beta = (b_1, ..., b_n)$, the cylinder set $C_\beta$ is the set of all allowable infinite sequences which have start with $\beta$. The probability that a finite random walk of length $n$ starting at $v$ will produce $\beta$ is

$$|C_\beta| = \frac{1}{d_1...d_n},$$

(15)

where $d_j$ is the degree of $v_j$.

In general, one defines the outer measure of a subset $E \subset S$ as follows.

$$\mu^*(E) = \inf \sum_{C \in \mathcal{C}} |C|.$$  

(16)

Here $\mathcal{C}$ is a covering of $S$ by cylinder sets and $|C|$ denotes the probability that $C$ occurs, as above. What we are doing is taking the infimum over all possible coverings.

A subset $E$ is called measurable if

$$\mu^*(X - E) + \mu^*(X \cap E) = \mu^*(X)$$

(17)

for all other subsets $X \subset S$. In this case, we define $\mu(E) = \mu^*(E)$. This definition looks insane, because it is something we would have to test for all other subsets. However, one can check several basic properties:

- Cylinder sets themselves are measurable. This is pretty easy. If we have a covering of $X$ we get coverings of $X \cap E$ just by intersecting the cover with $E$ and we get a covering of $X - E$ by intersecting our covering with $S - E$, which is a finite union of cylinder sets.

- If $E$ is measurable so is $S - E$. This just follows straight from the definition.

- The countable union of measurable sets is again measurable. This is a bit more work, but not too bad.
A set is called a Borel set if it is obtained by starting with cylinder sets and taking complements and countable unions finitely many times. From the three properties above, Borel sets are measurable.

The function $\mu$ is called a Borel measure. The pair $(S, \mu)$ is called a probability space. Subsets of $S$ are often called events. When $E$ is a Borel event, $\mu(E)$ is the probability that $E$ occurs. The measure $\mu$ is countably additive: If $E_1, E_2, E_3, \ldots$ is any countable collection of pairwise disjoint measurable subsets of $S$, then

$$\mu(\bigcup E_j) = \sum \mu(E_j).$$

(18)

The set $E(v, A, B)$ of random walks which start at $v$ and hit $A$ before $B$ is one of these Borel sets. We define

$$P(v, A, B) = \mu(E(v, A, B)).$$

(19)

Let us sketch the derivation of Equation 12. Let $E = E(v, A, B)$ and also define $E_j = E(w_j, A, B)$. Note that $E_j$ is a subset of the space $S(w_j, A, B)$. Finally let $E'_j \subset S$ denote the set of random walks which first go to $w_j$ and then lie in $E_j$. We have

$$\mu(E_j) = (1/k) \mu_j(E'_j)$$

(20)

Here $\mu_j$ is the measure on $S(G, w_j)$. Also, from Equation 18 (in the finite case) we have $\mu(E) = \sum_j \mu(E_j)$. Putting these two facts together gives Equation 12.