

# Probability on Graphs

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May 11, 2023

## Contents

<b>1</b>	<b>Basics of graph theory</b>	<b>2</b>
1.1	Random walks on networks . . . . .	3
1.2	Currents and flows . . . . .	5
<b>2</b>	<b>Chapter two</b>	<b>6</b>
<b>3</b>	<b>Chapter three</b>	<b>6</b>
<b>4</b>	<b>Chapter four</b>	<b>6</b>
<b>5</b>	<b>Chapter five</b>	<b>6</b>
<b>6</b>	<b>Chapter six</b>	<b>6</b>
<b>A</b>	<b>Measure theory</b>	<b>7</b>
A.1	Convergence . . . . .	7
<b>B</b>	<b>Probability theory</b>	<b>7</b>
B.1	Calculus of probability . . . . .	7
B.2	Conditional expectation . . . . .	8
B.3	Radon-Nikodym theorem . . . . .	8
B.4	Stochastic processes . . . . .	8
B.4.1	Stopping times . . . . .	8
<b>C</b>	<b>Markov chains</b>	<b>8</b>

# 1 Basics of graph theory

**Definition 1** (Graph).

A graph  $G = (V, E)$  is a consists of

1.  $V \neq \emptyset$  and
2.  $E \subseteq \{\{u, v\} \mid u, v \in V\}$

We call elements of  $V$  vertices or nodes and elements of  $E$  edges or bonds. We write  $v \sim u$  if  $\{u, v\} \in E$ . A graph  $G = (V, E)$  is called network if for  $e = \{u, v\} \in E$ , we assign a weight  $c(u, v) > 0$ . For  $v \in V$ , we set  $c(v) = \sum_{u \sim v} c(u, v)$ . We further define

- A vertex  $v$  is called incident to an edge  $e$  if  $v \in e$
- The degree of a vertex  $v$  is the number of edges incident to it:  $\deg v = |\{e \in E \mid v \in e\}|$ .
- The graph  $G$  is called locally finite if for all  $v \in V$ ,  $\deg v < \infty$ .
- For  $u, v \in V$ ,  $\pi = (x_1, \dots, x_N)$  is called a path from  $u$  to  $v$  if  $u = x_1$ ,  $x_N = v$  and  $\{x_{n-1}, x_n\} \in E$ .
- A path from  $u$  to  $u$  is called a cycle.
- A graph  $G$  is called connected if for any  $u, v \in V$  there is a finite path from  $u$  to  $v$ .

ede

**Definition 2** (Product of graphs).

Let  $G_1, G_2$  be graphs. We define

$$G_1 \boxtimes G_2 := (V_1 \times V_2, \{((x_1, y_1), (x_2, y_2)) \mid \text{either } (x_1 = x_2, (y_1, y_2) \in E_2) \text{ or } (y_1 = y_2, (x_1, x_2) \in E_1)\})$$

as the product of  $G_1$  and  $G_2$ .

**Definition 3** (Vertex simple and edge simple paths).

Let  $G$  be a graph. A path is a (possibly infinite) sequence of vertices  $v_1, v_2, \dots$  such that  $(v_n, v_{n+1}) \in E$ .

1. If a path does not visit any vertex more than once, it is called a vertex simple path.
2. If a path does not visit any edge more than once, it is called an edge simple path.

**Definition 4** (Network).

A network is a graph  $G$  combined with a function  $c : E \rightarrow [0, \infty)$  with  $c(u, v) = 0$  if  $(v, u) \notin E$ . We call a network connected if  $(V, \{e \in E \mid c(e) > 0\})$  is connected. A network is locally finite if for any  $v \in V$ , we have  $c(v) = \sum_{u \sim v} c(u, v) < \infty$ .

**Lemma 1** (Example).

$V = \mathbb{Z}$ ,  $E = \{(v, u) \mid u \neq v \in V\}$  with  $c(v, u) = \frac{1}{|u-v|^2}$ .

**Definition 5** (Cycle).

A cycle is a path starting and ending in the same point. A cycle is simple if the only vertex appearing more than once is the first (and last) vertex.

**Definition 6** (Induced graphs and networks).

Let  $G = (V, E)$  be a graph and let  $K \subseteq V$ . The induced graph is the graph  $G_K = (K, \{e \in E \mid e \subseteq K\})$ . The induced network is defined similarly.

**Definition 7** (Connected component).

Let  $G$  be a graph or a network. A connected component is a set  $K$  of vertices such that  $G_K$  is connected, but for every  $K \subsetneq H$ ,  $G_H$  is not connected.

**Definition 8** (Contraction of graphs).

Let  $G = (V, E, c)$  be a graph (or network) and let  $K \subseteq V$ . The contracted graph (or network)  $G/K$  is the graph  $(V \setminus K \cup \{z\}, \{e \in E \mid e \subseteq V \setminus K\} \cup \{(v, z) \mid v \notin K, \exists u \in K : (v, u) \in E\})$ . For all  $u, v \notin K$ , take conductance  $c'(v, u) = c(v, u)$  for  $v \notin K$  take  $c(v, u) = \sum_{u \in K} c(v, u)$ .

**Definition 9** (Forest and tree).

A forest is a graph with no (simple) cycles. A tree is a connected forest.

**Remark.**

A contraction of an edge lets it "disappear" in a sense that the vertices are merged.

**Definition 10** (Homomorphisms).

Let  $G_1, G_2$  be graphs. A function  $\phi : V_1 \rightarrow V_2$  is called a homomorphism if

1. for all  $(u, v) \in E_1$ , we have that  $(\phi(u), \phi(v)) \in E_2$

$\phi$  is called isomorphism if  $\phi$  is bijective, and both  $\phi, \phi^{-1}$  are homomorphisms.  $G_1, G_2$  are called isomorphic if such an isomorphism exists. An isomorphism  $\phi$  is called an automorphism if  $G_1 = G_2$ .

**Definition 11** (Transitivity).

A graph  $G = (V, E)$  is called (vertex) transitive if for all  $v, u \in V$  there is an automorphism  $\phi$  such that  $\phi(v) = u$ .  $G$  is called edge transitive if for every  $e_1, e_2 \in E$  there is an automorphism  $\phi(e_1) = e_2$ .

**Remark.**

There are graphs that are vertex transitive but not edge transitive.

**Remark.**

Good source of example for transitive graphs: Let  $G$  be a graph, and let  $Y \subseteq G \setminus \{\text{unit}\}$ . Take the graph  $V = G$  and  $(u, v) \in E$  if there is  $y \in Y$  such that  $u = yv$  or  $v = yu$ .

## 1.1 Random walks on networks

**Definition 12** (Simple random walk on networks).

Let  $G = (V, E, c)$  be a network and assume that  $G$  is locally finite. The simple random walk on  $G$  is the (discrete time) Markov chain with transition matrix

$$\Pi(x, y) = \frac{c(x, y)}{\sum_z c(x, z)} \cdot \mathbb{1} \left[ \sum_z c(x, z) > 0 \right] + 1 \cdot \mathbb{1} \left[ \sum_z c(x, z) = 0 \right]$$

A random walk on a locally finite graph  $G = (V, E)$  is a random walk on the network  $(V, E, 1)$ .

**Remark.**

Question: Does  $\mathbb{Z}^d$  have a transient subgraph?

Answer: No, every subgraph of a recurrent graph is recurrent.

The main tool to provide the proof for the answer is based on the connection between the random walk and electrical networks.

**Lemma 2.**

Let  $G = (V, E, c)$  be a finite connected network. For every  $x \in V$ , let  $p^x$  be the distribution of the random walk on  $G$  started on  $x$ . Let  $a, z \in V$ . Let  $\tau_a$  ( $\tau_z$ ) be the first time hitting  $a$  ( $z$ ), and let  $\tau_{a,z}$  be first time hitting either of them. Then,  $\tau_a, \tau_z, \tau_{a,z} < \infty$ .

**Fact.**

Let  $G = (V, E, c)$  be a finite connected network. We consider the simple random walk defined as above. Then, every state  $x$  is recurrent. We have  $\mathbb{P}_x(\tau_a < \infty) = \mathbb{P}_x(\tau_z < \infty) = 1$ .

*Proof.* For every  $x$ , let  $\gamma_x$  be a path from  $x$  to  $a$ . Let  $h_x$  be the probability that the random walk takes the path  $\gamma_x$  immediately starting in  $x$ . Let  $h = \min_{x \in V} h_x > 0$ . Let  $\mathcal{F}_n = \sigma(X_1, \dots, X_n)$ ,  $\mathcal{F} = \sigma(X_1, X_2, \dots)$ . Then,  $\{\tau_a < \infty\} \in \mathcal{F}$ . By Kolmogorov's 0-1-law,  $\mathbb{P}_x(\tau_a < \infty | \mathcal{F}) \in \{0, 1\}$ . We have  $\mathbb{P}_x(\tau_a < \infty | \mathcal{F}) = \lim_{n \rightarrow \infty} \mathbb{P}_x(\tau_a < \infty | \mathcal{F}_n)$ . We have  $\mathbb{P}_x(\tau_a < \infty | \mathcal{F}_n) \geq h$ . Thus,  $\mathbb{P}_x(\tau_a < \infty | \mathcal{F}) \geq h$ . It follows from the 0-1-law,  $\mathbb{P}_x(\tau_a < \infty | \mathcal{F}) = 1$  and thus  $\mathbb{P}_x(\tau_a < \infty) = \mathbb{E}[\mathbb{P}_x(\tau_a < \infty | \mathcal{F})]$ .  $\square$

**Definition 13** (Voltage function).

The voltage function is defined as  $v : V \rightarrow \mathbb{R}, x \mapsto v(x) := p^x(\tau_{a,z} = \tau_a)$ .

**Lemma 3** (Properties of the voltage function).

Let  $v : V \rightarrow \mathbb{R}, x \mapsto p^x(\tau_{a,z} = \tau_a)$  be the voltage function. Then, the following statements hold:

1.  $v(a) = 1$
2.  $v(z) = 0$
3. For  $x \neq a, z$ , we have  $v(x) = \sum_{y \in V} \mathbb{P}_x(X_1 = y)v(y) = \sum_{y \in V} \frac{c(x,y)}{\sum_{z \in V} c(x,z)} v(y) = \sum_{y \in V} c(x,y) \frac{v(y)}{c(x)}$   
(harmonicity)

*Proof.* To show the harmonicity, we use the Markov property. Since  $x \neq a, z$ ,  $p^x(\tau_a \geq 1) = 1$ . The Markov property implies

$$\begin{aligned} p^x(\tau_a \leq \tau_z) &= \mathbb{E}_x[p^x(\tau_a < \tau_z)] \\ &= \sum_y p^x(X_1 = y) \cdot p^y(\tau_a < \tau_z) \\ &= \sum_y p^x(X_1 = y) \cdot v(y) \end{aligned}$$

□

**Lemma 4** (Uniqueness of voltage function).

The voltage function  $v$  is the only function satisfying the properties above.

*Proof.* Assume  $v_1, v_2$  satisfy the properties of the voltage function. We show  $h \equiv v_1 - v_2 = 0$ .

1. By properties 1 and 2,  $h(a) = h(z) = 0$ .
2. For  $x \neq a, z$ , we have  $h(x) = \sum_y \frac{c(x,y)}{c(x)} h(y)$  ( $h(x)$  is a weighted average over its neighbors). Assume  $h(x) \neq 0$ . We assume  $\mathbb{E}h(x) > 0$ . Let  $M = \max\{h(x) \mid x \in V\} > 0$ . Let  $H = \{x \mid h(x) = M\}$ . Note that  $a, z \notin H$ . Let  $x$  be an element of  $H$  with a neighbor  $w$  outside of  $H$ . Then, the following are true

- (a)  $x \in H$ , thus  $h(x) = M$ .
- (b)

$$\begin{aligned} h(x) &= \sum_y \frac{c(x,y)}{c(x)} h(y) \\ &= \frac{c(x,w)}{c(x)} h(w) + \sum_{y \neq w} \frac{c(x,y)}{c(x)} h(y) \\ &\leq h(w) \frac{c(x,w)}{c(x)} + M \sum_{y \neq w} \frac{c(x,y)}{c(x)} \\ &= h(w) \frac{c(x,w)}{c(x)} + M \left(1 - \frac{c(x,w)}{c(x)}\right) \\ &= M + \underbrace{(h(w) - M)}_{<0} \cdot \underbrace{\frac{c(x,w)}{c(x)}}_{>0} < M \end{aligned}$$

This is a contradiction to  $h \neq 0$ .

□

**Remark.**

The proof is similar to the proof of uniqueness of the solution to the Dirichlet problem.

**Remark.**

In the theory of electrical networks, the (physical) voltage function satisfies the same three properties (up to normalization of the boundary conditions). Therefore, everything that is known about physical electrical networks has the potential of being useful in the understanding of random walks on networks.

**Definition 14** (Resistance).

For an edge  $e$ , we define its resistance as

$$r(e) = \frac{1}{e}$$

## 1.2 Currents and flows

**Definition 15** (Current).

Let  $e = (x, y) \in E$ . For every  $x, y$  we define the current as

$$I(x, y) = \frac{v(x) - v(y)}{r(x, y)} = (v(x) - v(y)) c(x, y)$$

**Lemma 5** (Properties of the current).

Let  $I$  be the current. Then, the following statements hold:

1.  $I(x, y) = -I(y, x)$  (Antisymmetry)
2. For  $x \neq a, z$ ,  $\sum_{y \neq x} I(x, y) = 0$  (Kirchhof's node law)
3. For a cycle  $x_0, \dots, x_N = x_0$ , then  $\sum_{n=1}^N I(x_{n-1}, x_n) r(x_{n-1}, x_n) = 0$  (Kirchhof's circuit law)

*Proof.*

1. follows from  $c(x, y) = c(y, x)$ .
2. Notice that

$$\begin{aligned} \sum_{y \neq x} I(x, y) &= \sum_{y \neq x} c(x, y) (v(x) - v(y)) \\ &= v(x) \sum_{y \neq x} c(x, y) - \sum_{y \neq x} c(x, y) v(y) \\ &= v(x) c(x) - c(x) \sum_{y \neq x} \frac{c(x, y)}{c(x)} v(y) \\ &= 0 \end{aligned}$$

where we used the harmonicity of  $v$ .

3. By definition of  $I$ , we have  $(I \cdot r)(x, y) = v(x) - v(y)$ . Thus, we have

$$\sum_{n=1}^N I(x_{n-1}, x_n) r(x_{n-1}, x_n) = \sum_{n=1}^N v(x_{n-1}) - v(x_n) = 0$$

□

**Definition 16** (Flow).

A flow is a function  $F : V^2 \rightarrow \mathbb{R}$ , such that

1.  $F(x, y) = -F(y, x)$
2. If  $x \approx y$ , then  $F(x, y) = 0$
3. For all  $x \neq a, z$ , we have  $\sum_{y \neq x} F(x, y) = 0$  (Kirchhof's node law)

**Definition 17** (Total current).

The total current in a network is defined as

$$\sum_{x \neq a} I(a, x) = \sum_{x \neq z} I(x, z)$$

*Proof.* We prove equality for the two descriptions of total current.

$$\begin{aligned} \sum_{x \neq a} I(a, x) - \sum_{x \neq z} I(x, z) &= \sum_{x \neq a} I(a, x) + \sum_{x \neq z} I(z, x) + \underbrace{\sum_{y \neq a, z} \sum_{x \neq y} I(y, x)}_{=0} \\ &\stackrel{(I)}{=} \sum_y \sum_{x \neq y} I(y, x) \\ &= \sum_{\{x, y\} \subseteq V} I(x, y) + I(y, x) \\ &= 0 \end{aligned}$$

□

**Definition 18** (Effective resistance).

The effective resistance in a network is defined as

$$R_{\text{eff}}(a, z) = \frac{1}{\text{total current}}$$

Similarly, we denote

$$c_{\text{eff}}(a, z) = \text{total current}$$

**Notation** (Stopping times).

We use the following notation for stopping times

$$\begin{aligned}\tau_x &= \inf\{t \geq 0 \mid X_t = x\} \\ \sigma_x &= \inf\{t \geq 0 \mid X_t \neq x\} \\ \eta_x^0 &= 0 \\ \eta_x &= \inf\{t > 0 \mid X_t = x\} \\ \eta_x^{n+1} &= \inf\{t > \eta_x^n \mid X_t = x\}\end{aligned}$$

Notice that  $\tau_x \neq \eta_x$  under  $\mathbb{P}_x$  and  $\tau_x = \eta_x$  under  $\mathbb{P}_y$  for  $y \neq x$ .

**Lemma 6** ( $n$ -th return time of Markov chains).

Notice that if  $X$  is a Markov chain, then we have

$$\eta_x^{n+1} = (\tau_x \circ \theta_{\sigma_x} + \sigma_x) \circ \theta_{\eta_x^n} + \eta_x^n$$

**Theorem 1.**

We have that

$$\mathbb{P}_a(\tau_z < \eta_a) = \frac{c_{\text{eff}}(a, z)}{c(a)}$$

**Theorem 2** (Commute time formula).

We have that

$$\mathbb{E}_a[\tau_z] + \mathbb{E}_z[\tau_a] = 2R_{\text{eff}}(a, z) + \sum_{e \in E} c(e)$$

**Exercise.**

We have that

$$\mathbb{P}_x(\tau_a < \tau_z) \leq \frac{c_{\text{eff}}(x, a)}{c_{\text{eff}}(x, z)}$$

**2 Chapter two**

**3 Chapter three**

**4 Chapter four**

**5 Chapter five**

**6 Chapter six**

## A Measure theory

**Theorem 3** (Layer-cake representation).

Let  $f : \Omega \rightarrow \mathbb{R}$  such that  $f \geq 0, f' \geq 0$ . Then

$$\mathbb{E}[f(X)] = \int_0^\infty \mathbb{P}(f(X) > t) dt = \int_{f^{-1}(0)}^{f^{-1}(\infty)} \mathbb{P}(X > t) f'(t) dt$$

### A.1 Convergence

**Theorem 4** (Fatou's lemma).

Let  $(X_n)_n$  consist of non-negative random variables. Then,

$$\mathbb{E}[\liminf_{n \rightarrow \infty} X_n] \leq \liminf_{n \rightarrow \infty} \mathbb{E}[X_n]$$

**Theorem 5** (Monotone convergence theorem).

Let  $(X_n)_n$  consist of non-negative increasing random variables. Then,

$$\mathbb{E}[\lim_{n \rightarrow \infty} X_n] = \lim_{n \rightarrow \infty} \mathbb{E}[X_n]$$

**Theorem 6** (Dominated convergence theorem).

Let  $(X_n)_n$  consist of converging random variables that are absolutely dominated by  $Y \in L^1(\Omega, \mathbb{P})$ . Then,

$$\mathbb{E}[\lim_{n \rightarrow \infty} X_n] = \lim_{n \rightarrow \infty} \mathbb{E}[X_n]$$

## B Probability theory

### B.1 Calculus of probability

**Theorem 7** (Chebychev's inequality).

Let  $\phi : \mathbb{R} \rightarrow [0, \infty)$  be increasing. Then

$$\mathbb{P}(X \geq \lambda) \leq \frac{\mathbb{E}[\phi(X)]}{\phi(\lambda)}$$

**Remark.**

Chebychev's inequality can be used to find sharp estimations by considering parametrized functions such as  $\phi(\xi) = \exp(t\xi)$  or  $\phi(\xi) = (\xi + t)^2$  and optimizing  $t$ .

**Definition 19** (Limit of events).

We define

$$\begin{aligned} \overline{\lim}_{n \rightarrow \infty} A_n &= \bigcap_{n=1}^{\infty} \bigcup_{k=n}^{\infty} A_k \\ \lim_{n \rightarrow \infty} A_n &= \bigcup_{n=1}^{\infty} \bigcap_{k=n}^{\infty} A_k \end{aligned}$$

**Theorem 8** (Calculus of probability).

**Theorem 9** (Borel-Cantelli).

Let  $A_n \Omega$ . Then

1. If  $\sum_{n=1}^{\infty} \mathbb{P}(A_n) < \infty$ , then  $\mathbb{P}(\overline{\lim}_{n \rightarrow \infty} A_n) = 0$  ( $A_n$  happens finitely).
2. If  $\sum_{n=1}^{\infty} \mathbb{P}(A_n) = \infty$  and  $(A_n)_n$  are independent, then  $\mathbb{P}(\overline{\lim}_{n \rightarrow \infty} A_n) = 1$

## B.2 Conditional expectation

**Definition 20** (Conditional expectation).

$Y$  is called  $\mathcal{G}$ -conditional expectation of  $X$  if

1.  $Y$  is  $\mathcal{G}$ -measurable
2. for each  $A \in \mathcal{G}$ ,  $\mathbb{E}[Y \mathbb{1}_A] = \mathbb{E}[X \mathbb{1}_A]$

We write  $Y = \mathbb{E}[X|\mathcal{G}]$ .

## B.3 Radon-Nikodym theorem

**Theorem 10** (Radon-Nikodym).

## B.4 Stochastic processes

**Definition 21** (Martingale).

**Theorem 11** (Doob's maximal inequality).

### B.4.1 Stopping times

**Theorem 12** (Optional stopping).

## C Markov chains

**Definition 22** (Discrete-time Markov chain).

A discrete-time Markov chain is a sequence  $X = (X_n)_n$  of random variables with

1.  $\mathbb{P}(X_{n+1} = y \mid X_1 = x_1, \dots, X_n = x_n) = \mathbb{P}(X_{n+1} = y \mid X_n = x_n)$

One might also use the following characterization which extends more easily to  $X = (X_t)_{t \geq 0}$ :

1.  $\mathbb{E}_x[g \circ \theta_s \mid \mathcal{F}_s] = \mathbb{E}_{X_s}[g]$  for all measurable and bounded  $g$

where  $\mathbb{P}_x(X_0 = x) = 1$ .

**Definition 23** (Time-homogeneity).

A Markov chain  $X$  is called time-homogeneous if

$$\mathbb{P}(X_{n+1} = y \mid X_n = x) = \mathbb{P}(X_1 = y \mid X_0 = x)$$

**Definition 24** (Stationarity).

A Markov chain  $X$  is called stationary if

$$\mathbb{P}(X_k = x_0, \dots, X_{n+k} = x_n) = \mathbb{P}(X_0 = x_0, \dots, X_n = x_n)$$

**Definition 25** (Standard stopping times).

For a (right-continuous) family of random variables  $X = (X_t)_{t \in \mathcal{T}}$ , where we allow  $\mathcal{T} = \mathbb{R}, \mathbb{N}$ , we write

1.  $\tau_x = \inf \{t > 0 \mid X_t = x\}$
2.  $\sigma_x = \inf \{t > 0 \mid X_t \neq x\}$
3.  $R_x^n = 0$ ,  $R_x^{n+1} = (\tau_x \circ \theta_{\sigma_x} + \sigma_x) \circ \theta_{R_x^n} + R_x^n$

Notice that a process  $X$  is a Markov chain if  $(R_x^{n+1} - R_x^n) =_d R_x^1$  and  $(R_x^{n+1} - R_x^n)_n$  forms independent and identically distributed random variables. (So called recurrence times)



**Remark.**

The standard approach to prove statements about probabilities of Markov chains is as follows: . . . .

**Definition 26** (Invariant measure).

A measure  $\pi$  is called invariant for the Markov chain  $X$  if  $\pi\Pi = \pi$

$$1. \pi(y) = \sum_x \pi(x)p(x, y)$$

**Definition 27** (Reversible measure).

A measure  $\pi$  is called reversible for the Markov chain  $X$  if

$$1. \pi(x)p(x, y) = \pi(y)p(y, x)$$

**Definition 28** (Irreducible Markov chain).

A Markov chain  $X$  is called irreducible if for all  $x, y$  there is  $n \geq 1$  such that  $\mathbb{P}_x(X_n = y) > 0$ .

**Remark.**

Irreducibility means there is the probability that a chain starting in  $x$  might reach  $y$ . It does not have to occur, though.

**Definition 29** (Recurrence and transience).

$x$  is called recurrent if  $\mathbb{P}_x(R_x^1 < \infty) = 1$ , otherwise transient.

**Theorem 13** (Invariant distribution implies recurrence).

An irreducible Markov chain with an invariant distribution is recurrent.

**Theorem 14** (Existence of an invariant measure).

An irreducible and recurrent Markov chain has an invariant distribution which is unique and strictly positive.

**Theorem 15** (Characterization of invariant distribution).

Let  $X$  be a Markov chain with an invariant distribution  $\pi$ . Then

$$\pi(y) = \lim_{n \rightarrow \infty} \mathbb{P}_x(X_n = y)$$

regardless of the choice for  $x$ .

**Theorem 16** (Cycle characterization of reversibility).

A discrete-time Markov chain  $X$  is reversible if and only if for all states  $x_1, \dots, x_N$  with  $x_1 = x_N$ , we have

$$\prod_{n=1}^N p(x_n, x_{n+1}) = \prod_{n=1}^N p(x_{N-n+1}, x_{N-n})$$

*Proof.*

□