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FACULTY OF SCIENCE

The Critical Value of the Contact Process

BACHELOR THESIS IN MATHEMATICS

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Preface

This thesis is the result of a semester of work, during which I investigated the contact process on the lattice. The goal of this investigation was to try and derive bounds on the critical value myself. This endeavour has been mostly successful. I managed to find a lower bound through a coupling with Galton-Watson trees. Additionally, with input from Henk, I generalised a result that compares upper bounds in different dimensions. Finally, I found a coupling with oriented percolation to get an upper bound on the critical value from an upper bound on the critical probability of oriented percolation. Throughout this process, various other interesting results and questions arose, which I also outlined in this thesis. I found the challenges in this project to be very interesting. The kind of creative and interesting proofs that one finds when working on couplings are exactly the ones that make me eager to work on mathematics.

What you will realise when reading this thesis, is that I am a strong believer of the phrase; “a picture can speak a thousand words”. Wherever it made sense, I made sure to include a picture to clarify proofs or definitions. To add to that, I have also made sure that a slightly shorter and less technical version of my thesis presentation is available online. This video serves as an introduction to this thesis, and in particular to Theorem 4.4.

If you are reading this, it is likely you are either my supervisor, the second reader or student in mathematics yourself. In this case, you are in luck, because I have taken great care to try and make that this text is complete and comprehensible for anyone with the knowledge of a bachelors student in mathematics. If however, at any point in the future, you run into questions while reading this thesis, I am sure I will be more than happy to answer your questions by e-mail or otherwise.

Before we get into this thesis, I would like to take a few sentences for some acknowledgements. I would like to thank Henk for his insights and contributions to this thesis. Moreover, I would like to thank all my friends for enduring my complaints whenever things were not working out. With that being said, I would finally like to thank you, the reader, for your interest in this thesis.

Introduction

In 1974, a mathematician called Ted Harris introduced the contact process on a lattice. This process can be understood as a model for the spread of an infection. We consider points of the lattice, which can either be healthy or infected. Any infected site spreads the infection to its direct neighbours at a certain infection rate. Additionally, infected points randomly recover at a constant rate. One realisation of this process can be found in Figure 1. In this thesis we will study this process. We will look at varying rates of infection and ask ourselves the question, is there a rate for which the infection has a positive chance of surviving?

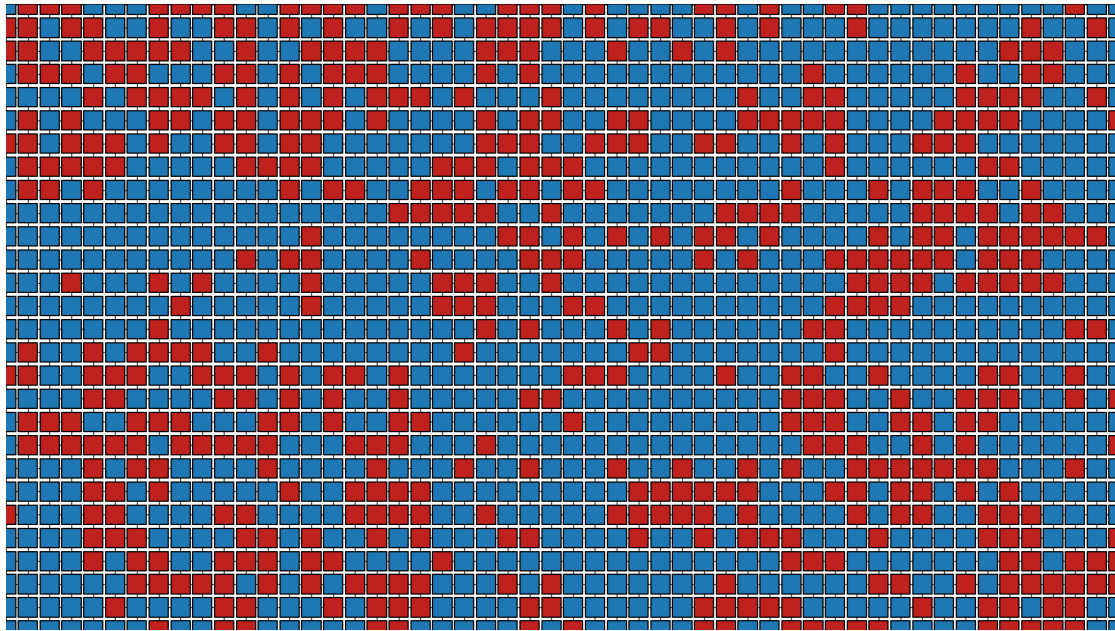


Figure 1: A realisation of the contact process on the square lattice. Red nodes are infected, blue ones are healthy.

There will turn out to be a specific rate at which this probability becomes strictly positive, starting from a single infection. This specific rate, called the critical value, will be the primary object of study throughout this thesis. We will determine bounds on this value on the lattices \mathbb{Z}^d .

To do so we will first study some necessary prerequisites in Section 1. Next we introduce the contact process in Section 2. These first two sections give all the information you need to read the next three sections, which are largely independent of each other. In the third Section 3 we will do a short study of the contact process on finite graphs. The fourth section 4 provides bounds on the critical value of the contact process. Finally, the fifth Section 5 provides numerical estimates of this critical value.

1 Prerequisites

In this first chapter we will be introducing the prerequisites needed to read this thesis. As a baseline the reader should be familiar with undergraduate probability theory and real analysis. A small portion of this thesis benefits from knowledge about measure theory, but this is by no means necessary.

Throughout this thesis, we will be making connections to a variety of stochastic processes. To keep the text around my own results compact, I have collected all definitions and notation for these processes in this first section. To start, we need to establish what a stochastic process is. Any process that evolves randomly over time, is considered a stochastic process.

Definition 1.1. A stochastic process is a collection of random variables $\{X_t\}_{t \in A}$. The process is called discrete-time if A is a finite or countable set and continuous-time if A is uncountable.

In the remainder of this chapter we will introduce various stochastic processes that we will use to study the contact process, as well as some results from probability theory.

1.2 Results from probability theory

We will sporadically use results from probability theory that might require a refresher. All these results have been collected in this subsection. First we recall what a memoryless distribution is.

Definition 1.3. We say that a random variable X is memoryless if

$$\mathbb{P}[X > t + a \mid X > a] = \mathbb{P}[X > t].$$

Example 1.4. Suppose that $X \sim \text{Exp}(\lambda)$, then X is memoryless, since

$$\mathbb{P}[X > t + a \mid X > a] = \int_a^{t+a} \frac{\lambda e^{-\lambda x}}{e^{-\lambda a}} dx = \int_a^{t+a} \lambda e^{-\lambda(x-a)} dx = \int_0^t \lambda e^{-\lambda x} dx = \mathbb{P}[X > t].$$

One useful result is that every (continuous-time) memoryless distribution is exponentially distributed. As outlined in [8, p. 68], this is a direct consequence of the fact that the only real-valued function that satisfies $f(s+t) = f(s)f(t)$ is the exponential function.

Theorem 1.5. *If a continuous-time random variable X is memoryless then there exists a $\lambda \in \mathbb{R}$ such that $X \sim \text{Exp}(\lambda)$.*

We need one more result of exponential random variables. By the nature of the contact process, it is often useful to compare two exponentially distributed random variables. This motivates the following lemma.

Lemma 1.6. *If $X_1 \sim \text{Exp}(\lambda_1)$ and $X_2 \sim \text{Exp}(\lambda_2)$ then $\mathbb{P}[X_1 \geq X_2] = \frac{\lambda_1}{\lambda_1 + \lambda_2}$.*

One way to prove this entails integrating the joint distribution, which is the product of the individual distributions by independence, over all values where $X_1 \geq X_2$. For the complete proof the reader can refer to [11, p. 292]. Another elementary tool from probability theory that will prove useful is the union bound.

Lemma 1.7. *(Union bound) For events A_1, \dots, A_n ,*

$$\mathbb{P}\left[\bigcup_{i=1}^n A_i\right] \leq \sum_{i=1}^n \mathbb{P}[A_i].$$

Finally, we will define the probability generating function. We will need this later in this chapter to prove an important result.

Definition 1.8. The probability generating function $G_X(s)$ of an integer valued random variable X is

$$G_X(s) = \mathbb{E}[s^X].$$

By the choice of this function $G_X(s)$ we can find the probabilities that $X = n$ by differentiating the probability generating function

$$\mathbb{P}[X = n] = \frac{G_X^{(n)}(0)}{n!}.$$

Note that the first derivative of this function evaluated in 1, corresponds to the expectation of X . Additionally, we know that this function is continuous for $s \in [0, 1]$. The probability generating function has many more useful properties. One can read more about these in [5, p. 148].

1.9 Solving systems of ODEs

Later in this thesis we will introduce something called the Kolmogorov forwards equations. This is a way to describe a specific type of stochastic process in terms of a system of ODEs. The steps required to solve such a systems are quite involved. Consequently, we will look at a short summary of the theory for solving systems of ODEs with constant coefficients. One can find these results in [4, p. 268].

Theorem 1.10. Suppose we have a system of ODEs with constant coefficients given by

$$\begin{aligned} u_1'(t) &= a_{11}u_1(t) + \cdots + a_{n1}u_n(t), \\ &\vdots \\ u_n'(t) &= a_{1n}u_1(t) + \cdots + a_{nn}u_n(t). \end{aligned}$$

If we write this equation in matrix form $u'(t) = Au(t)$ with $A = (a_{ij})_{1 \leq i, j \leq n}$ and $u = (u_i)_{1 \leq i \leq n}^T$, then the solution of the initial value problem with $u(t_0) = u_0$ is given by $u(t) = e^{At}u_0$.

That means, that in order to find the solution of such a system, we need to compute a matrix exponential. When the system is nice enough, we can do so by diagonalising the matrix. For our purposes the following statement suffices.

Theorem 1.11. If $A = PDP^{-1}$ with $D = \text{Diag}(\lambda_1, \dots, \lambda_n)$ then,

$$e^{At} = P \text{Diag}(e^{\lambda_1 t}, \dots, e^{\lambda_n t}) P^{-1}.$$

With these two results, we have covered all we need to know about ODEs for this thesis.

1.12 The Galton-Watson branching process

One of the stochastic processes we will consider in this thesis is the Galton-Watson branching process.

Definition 1.13. The Galton-Watson process is a stochastic process $\{X_n\}_{n \in \mathbb{N}}$ with $X_n: \mathbb{N} \mapsto \mathbb{N}$ i.i.d. random variables. We maintain a list of nodes, starting with v_0 . While the length of the list of nodes is greater or equal to n nodes, the random variable X_n determines the number of children of the n th node, these children get added to the end of the list of nodes.

The nodes as generated by the Galton-Watson process described above generate a tree by drawing edges between the children of each node. This tree is called a Galton-Watson tree.

Example 1.14. An example of a Galton-Watson process with the discrete uniform offspring distribution $X_n \sim \text{Unif}\{1, 2, 3\}$ i.i.d. is illustrated in Figure 2. We start with v_0 , and generate children according to X_0 . This adds two children, v_1 and v_2 . We go down the list to the next node, v_1 , which generates children its according to X_1 . This continues either indefinitely, or until all nodes in the list have generated children.

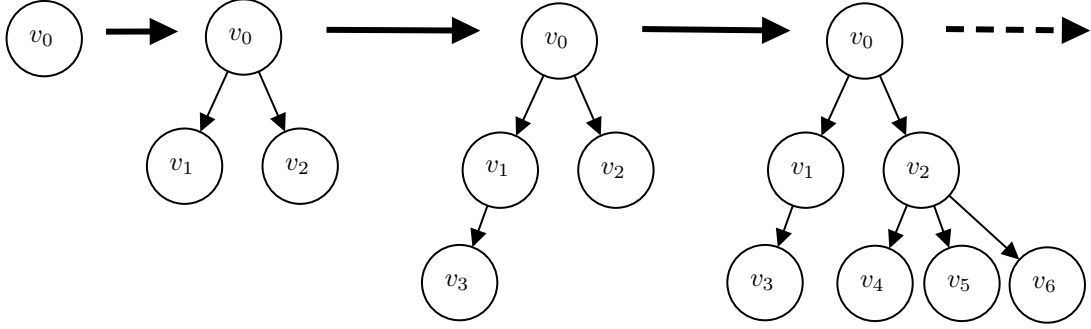


Figure 2: Example of a Galton-Watson process

Note that in this example, the process is bound to continue indefinitely, since we always generate at least one node. In this case we say that the process survives. Similarly, if we take X_n to be zero with probability 1, the first node will not have any child, so that the length of the list of nodes is less than 2, so that the process stops. In this case we say the process dies out. It turns out that there is a very general result about the survival of this process. To get to these results, we first define the distance between two edges.

Definition 1.15. If $G = (V_G, E_G)$ is a graph, and $e_1, e_2 \in E_G$ then the distance between e_1 and e_2 is the number of edges of the shortest path starting with e_1 and ending in e_2 , minus 1. Similarly, the distance between $v_1, v_2 \in V_G$ is the number of nodes of the shortest path starting in v_1 and ending in v_2 , minus 1. If there is no path between two edges or nodes, we say the distance is infinite.

When talking about Galton-Watson tree it makes sense to think in terms of generations. We will define a generation as the class of nodes Z_n that is a fixed distance n away from the first node v_0 . In particular, we will denote the probability of extinction η by $\mathbb{P}[\lim_{n \rightarrow \infty} Z_n = \emptyset]$.

Definition 1.16. The n th generation of the Galton-Watson tree, denoted by Z_n , is the set of nodes that are distance n away from initial node v_0 .

Next, we want to know whether or not the process goes extinct, that is, whether or not there exists an $N \in \mathbb{Z}_{\geq 0}$ such that $Z_N = \emptyset$. This is neatly summarised in the following theorem.

Theorem 1.17. For a branching process with i.i.d. offspring distribution X , denote the extinction probability by η . Then, $\eta = 1$ when $\mathbb{E}[X] \leq 1$ and $\mathbb{P}[X = 1] < 1$, while $\eta < 1$ if $\mathbb{E}[X] > 1$ or $\mathbb{P}[X = 1] = 1$. The extinction probability is the smallest solution in $[0, 1]$ of $G_X(s)$.

We will follow the proof in [13, p. 86]. The number of children in a generation is some sum of copies of X . The probability distribution of such a sum is given by the convolution of copies of the probability distribution of X . It turns out that these convolutions are much easier to work with through their probability generating functions.

Proof. We start by showing that $\eta = G_X(\eta)$. We consider $\eta_n = \mathbb{P}[Z_n = 0]$, this is increasing in n and bounded by η so that $\eta_n \uparrow \eta$. Consider $G_n(s) = \mathbb{E}[s^{Z_n}]$, the generating function of the nodes in the n th generation. Then, $G_n(0) = \eta_n$.

We condition on the first generation, so that for $n \geq 2$,

$$G_n(s) = \mathbb{E}[s^{Z_n}] = \sum_{i=0}^{\infty} \mathbb{P}[X = i] \mathbb{E}[s^{Z_n} \mid Z_1 = i] = \sum_{i=0}^{\infty} \mathbb{P}[X = i] G_{n-1}(s)^i$$

Where in the last step we used the fact that all the i individuals after the first generation produce offspring for another $n - 1$ generations in an independent and identical way, so that

$$\mathbb{E}[s^{Z_n} \mid Z_1 = i] = \mathbb{E}\left[s^{\sum_{k=1}^i Z_{n-1}}\right] = G_{n-1}(s)^i.$$

We now write $G_X(s)$ for the generating function of X , which gives that

$$G_n(s) = G_X(G_{n-1}(s)).$$

Substituting $s = 0$, we obtain $\eta_n = G_X(\eta_{n-1})$. As $n \rightarrow \infty$ we get $\eta_n \uparrow \eta$ so that, by the continuity of $s \mapsto G_X(s)$,

$$\eta = G_X(\eta).$$

Next we show that η is the smallest solution of $s = G_X(s)$. Suppose that $\psi \in [0, 1]$ satisfies $\psi = G_X(\psi)$. We prove that $\eta_n \leq \psi$ for all n by induction. Clearly the base case, $\eta_0 = 0 \leq \psi$ holds. Next we assume that $\eta_n \leq \psi$. Since $G_X(s)$ is increasing on $[0, 1]$ this implies that

$$\eta_{n+1} = G_X(\eta_n) \leq G_X(\psi) = \psi.$$

Which completes the inductive step. Since $\eta_n \uparrow \eta$ we can conclude that $\eta \leq \psi$, meaning that η is the smallest solution of $s = G_X(s)$. To complete the proof we will now distinguish three cases.

Case 1: If $\mathbb{P}[X = 1] = 1$, then $\mathbb{P}[Z_n = 1]$ for all n , so its clear that $\eta = 0 < 1$. One can also note that $G_X(s) = s$ for all $s \in [0, 1]$ in this case.

Case 2: If $\mathbb{P}[X \leq 1] = 1$ and $p = \mathbb{P}[X = 0] > 0$, then $\mathbb{P}[Z_n = 0] = 1 - (1 - p)^n \rightarrow 1$, so that $\eta = 1$.

Case 3: If $\mathbb{P}[X \leq 1] < 1$, then we consider the second derivative of the generating function of X ,

$$\mathbb{E}[X(X - 1)s^{X-2}] \geq 0$$

This means that $G_X(s)$ is strictly increasing and strictly convex for $s > 0$. Consequently, there are at most two solutions of $s = G_X(s)$ in $[0, 1]$, one of which is necessarily $s = 1$, by definition of $G_X(s)$. Since $G_X(s)$ is strictly convex and $G_X(0) > 0$, we can find the number of solutions by looking at $G'_X(1)$, which is precisely the expectation of X . If $G'_X(1) < 1$ we have not yet passed through the line $f(s) = s$, and thus there is only one solution in $[0, 1]$ implying $\eta = 1$. Else if $G'_X(1) > 1$ we must have passed through the line $f(s) = s$, and thus there are two solutions in $[0, 1]$, showing that $\eta < 1$, which completes the proof. \square

The study of branching processes has many more interesting questions, but these are of not of relevance to this thesis. If you want to read more, you can refer to [13].

1.18 Percolation processes

Percolation models are stochastic processes which were devised to model the flow of a liquid through a porous medium. We will look at bond percolation, on a graph G . We write V_G and E_G for the sets of vertices and edges of the graph respectively. We will then decide whether or not the edges in this graph are “open”.

Definition 1.19. The (ordinary) percolation process on a graph $G = (V_G, E_G)$ is a collection of Bernoulli random variables with parameter p given by $(X_e)_{e \in E_G}$.

The interpretation of Definition 1.19 is that we get a new graph with the same nodes as G and all the edges where $X_e = 1$. After we have done this, we ask if there exists a certain path through which water can flow. In infinite graphs, we look for an infinitely long path, that is, for each distance d , we can find two vertices that are distance $d' > d$ apart. We call this event “percolation”. If we do this percolation process on an infinite graph G with an origin $\underline{0}$, we can define a so called critical probability.

Definition 1.20. The critical probability $p_c(G)$ for percolation on a connected infinite graph G with origin $\underline{0}$ is given by

$$p_c(G) = \inf \{ p \mid \mathbb{P}_p [\underline{0} \rightsquigarrow \infty] > 0 \}.$$

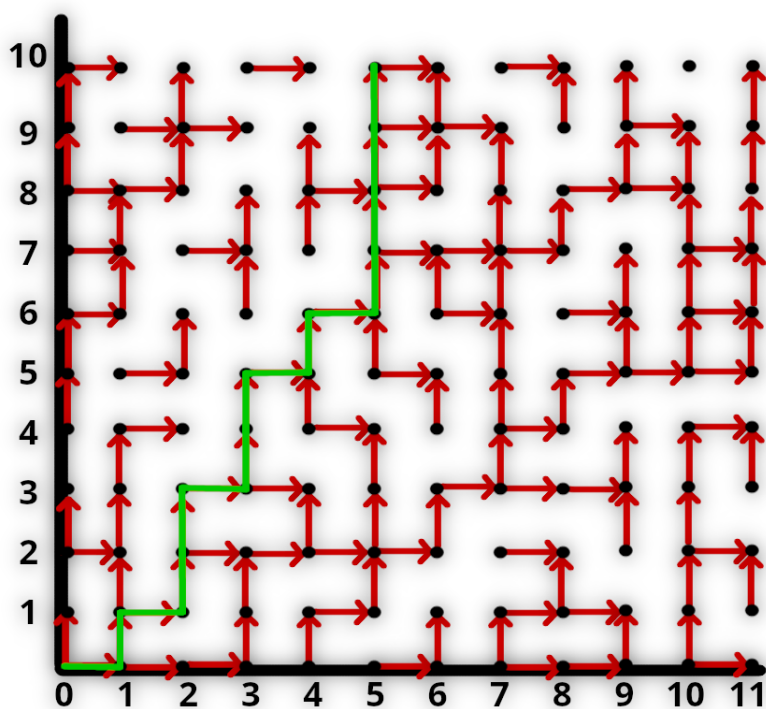


Figure 3: Path in oriented percolation

This probability is exactly the threshold for which an infinite path starting at the origin exists with positive probability in a connected graph. It turns out that this threshold is the same as

the threshold for any infinite path to exist with positive probability. One can see this as follows, if there is a positive probability of an infinite path starting from $\underline{0}$, there surely is a positive probability for any infinite path to exist. Conversely, if there is a positive probability for any infinite path to exist, there must be a finite distance between this infinite path and $\underline{0}$, so that there must be a positive probability that there is a connection from $\underline{0}$ to this infinite path. This gives that there must be a positive probability for an infinite path starting at $\underline{0}$.

One of the processes that we will be interested in is oriented bond percolation on $\mathbb{Z}_{\geq 0}^2$. This is the same percolation process as in Definition 1.19, but with positively oriented edges. That is, horizontal edges go from (i, j) to $(i + 1, j)$ and vertical edges go from (i, j) to $(i, j + 1)$. A part of the oriented percolation process on \mathbb{Z}^2 is illustrated in Figure 3. A path to the edge of the picture has been marked in green. Percolation implies that there is a strictly positive probability that there exists a green path like this which is infinitely long.

Not all percolation processes decide that edges are open with Bernoulli random variables. In this thesis we will require a special type of percolation. In particular, one where the event that an edge is open depends on the status of its neighbouring edges. This is called an n -independent percolation process.

Definition 1.21. An n -independent percolation process is a percolation process $(X_e)_{e \in E_G}$ such that the probability that X_{e_1} and X_{e_2} are independent if the distance between e_1 and e_2 is greater than n .

The study of percolation is one that is rich of interesting problems. However, for the purposes of this thesis, this short introduction suffices. If one wants to learn more about percolation, a good source is Geoffrey Grimmett's book [6].

2 Introduction to the contact process

In this section we introduce the subject of study in this thesis, the contact process. We start by discussing Markov processes in general. Next, we define the contact process and cover some important definitions and initial results. Finally, we will define couplings and discuss Harris' visual representation.

2.1 Markov processes

When modelling problems with stochastic processes we often deal with situations where the time you have to wait until the next event is memoryless. That is, regardless of how long you have been waiting, the probability of the event occurring within some fixed timespan remains constant. We can think of examples like the time until the next earthquake or until the failure of a machine.

This motivates the introduction of a special class of processes called Markov processes. In loose terms, a process is Markovian if the next state of the process does not depend on its history.

Definition 2.2. We say that a continuous-time stochastic process $\{X_t\}_{t \geq 0}$ with a countable state space S has the Markov property if

$$\mathbb{P}[X_t = x \mid X_r, 0 \leq r \leq s] = \mathbb{P}[X_t = x \mid X_s]$$

for $x \in S$ and $t \geq s \geq 0$.

In this thesis we will primarily consider Markov processes on graphs. Each node will have a state, and transitions to another state based on local rules. Another property we will come across is called time-homogeneity. In essence, time-homogeneity means that the transition probabilities do not depend on time.

Definition 2.3. We say that a continuous-time stochastic process $\{X_t\}_{t \geq 0}$ with state space S is time-homogenous if

$$\mathbb{P}[X_t = x \mid X_s = y] = \mathbb{P}[X_{t-s} = x \mid X_0 = y]$$

for $x, y \in S$ and $t \geq s \geq 0$.

One example of a Markov process is a continuous time Markov chain. This is a process with a discrete state space, where we describe the transitions from one state to the next. To ensure the Markov property, the transitions must be exponentially distributed due to Theorem 1.5. Hence, it suffices to give the parameter for each of the exponential distributions, which we call the transition rates.

Definition 2.4. A continuous-time Markov chain is a continuous-time Markov process $(X_t)_{t \geq 0}$ with $X_t \in V$. It has a countable state space S with transitions rates $(s_{i,j})_{i,j \in S}$ corresponding to the rate at which X_t is state v_i transitions to v_j .

The prime example of a Markov process is the Poisson process. This process is discussed in great detail in many texts on undergraduate probability, such as [8, p. 65] and [11, p. 292]. For completeness, one description of the Poisson process is included below.

Example 2.5. We look at a series of events where the times between occurrences are distributed by $T_i \sim \text{Exp}(\lambda)$. Let $N_t = \max \left[n : \sum_{i=0}^n T_i \leq t \right]$, this is what we call the Poisson process. We

claim that this is a Markov process, which is also time-homogenous. First recall from Example 1.5 that the transition times are memoryless. Using this, it is evident that this is a time-homogenous Markov process. The only thing that impacts the future probabilities is how many events there have been so far. It does not matter what time the previous event occurred at. The Poisson process can be thought of as a continuous-time Markov chain with state space \mathbb{N} and transition rates $n \rightarrow n + 1$ equal to λ .

The fact that the Poisson process has the Markov property and is homogenous in time will be used many times in this thesis. Currently, it is not clear how one would calculate the probabilities that we are in a certain state of a continuous-time Markov chain at time t . To do this we will introduce one more tool, called Kolmogorov's equations.

Theorem 2.6. (*Kolmogorov's equations*) *If we have a continuous-time Markov chain $(X_t)_{t \geq 0}$ with transition rates $(s_{i,j})_{1 \leq i,j \leq n}$. We define*

$$P_{i,j}(t) = \mathbb{P}[X(t+s) = j \mid X(s) = i] \text{ and } s_i = \sum_{j=1}^n s_{i,j}.$$

Then, the backwards equations state that

$$P'_{i,j}(t) = \sum_{k \neq i} s_{ik} P_{kj}(t) - s_i P_{ij}(t),$$

and the forwards equations state that,

$$P'_{i,j}(t) = \sum_{k \neq j} s_{kj} P_{ik}(t) - s_j P_{ij}(t).$$

These equations give a system of differential equations equations that we can solve to determine the exact probability that we are in a certain state. Often, we will just consider the probabilities $P_j(t) = \mathbb{P}[X(t) = j]$ starting the Markov chain from time 0, which slightly reduces the system. Details about these equations, including a proof, can be found in [11, p. 380-383]

2.7 The contact process

We start with the definition of the contact process. As explained in the introduction of this thesis, this is a model for the spread of an infection. We will keep track of a set of infected nodes, ξ_t , and specify the rates at which healthy nodes become infected and vice versa.

Definition 2.8. The contact process is a continuous-time Markov Process on the subsets of nodes of an undirected graph $G = (V, E)$ with a parameter λ , where the transitions are determined by

$$\begin{aligned} \text{for } x \in \xi_t, \quad \xi_t &\mapsto \xi_t \setminus \{x\} \text{ with rate } 1, \\ \text{for } x \notin \xi_t, \quad \xi_t &\mapsto \xi_t \cup \{x\} \text{ with rate } \lambda |\{y \in \xi_t : \{x, y\} \in E\}|. \end{aligned} \tag{2.1}$$

To fully define this process, we need to specify an initial occupancy. That is, we need to specify which nodes are infected at $t = 0$. To specify a contact process with initial occupancy $A \subset V$ we use $\{\xi_t^A\}_{t \geq 0}$.

Throughout this thesis we will be studying the contact process on the square lattice on \mathbb{Z}^d . This is a graph with nodes in \mathbb{Z}^d , and edges between any pair of points that has distance exactly 1 (as defined in Definition 1.15). We refer to this graph simply by \mathbb{Z}^d . We will concern ourselves

with the so-called critical infection rate $\lambda_c(\mathbb{Z}^d)$. This is the value of λ at which there occurs a fundamental change in the limiting behaviour of the stochastic process, analogous to critical probabilities in the study of random graphs. For the contact process this means it is the infimum over all the rates for which the set of infected nodes is eventually empty.

Definition 2.9. The critical infection rate on \mathbb{Z}^d , is defined by

$$\lambda_c(\mathbb{Z}^d) = \inf \left\{ \lambda : \lim_{t \rightarrow \infty} \xi_t^{\{0\}} = \emptyset \text{ a.s.} \right\}. \quad (2.2)$$

Often we will just write λ_c if it is clear which graph it concerns. Later we will prove in Lemma 2.17 that instead of initial occupancy $\{0\}$, we can take any finite selection of nodes. The critical value can be defined for a much broader class of graphs, however, to do this rigorously is beyond the scope of this thesis, so we stick with this simpler alternative.

When talking about the contact process we distinguish the so called subcritical and supercritical regions. These are the values of λ such $\lambda < \lambda_c(G)$ and $\lambda > \lambda_c(G)$ respectively. Qualitatively, when looking a finite portion of the process, we expect the share of infected sites to quickly tend towards 0 in the subcritical case, whereas in the supercritical case we expect the infection to converge to a certain non-zero (probabilistic) equilibrium. This illustrated below in Figure 4, which illustrates the expected behaviour of a portion of the graph \mathbb{Z} with 100 nodes where all nodes are infected at the start.

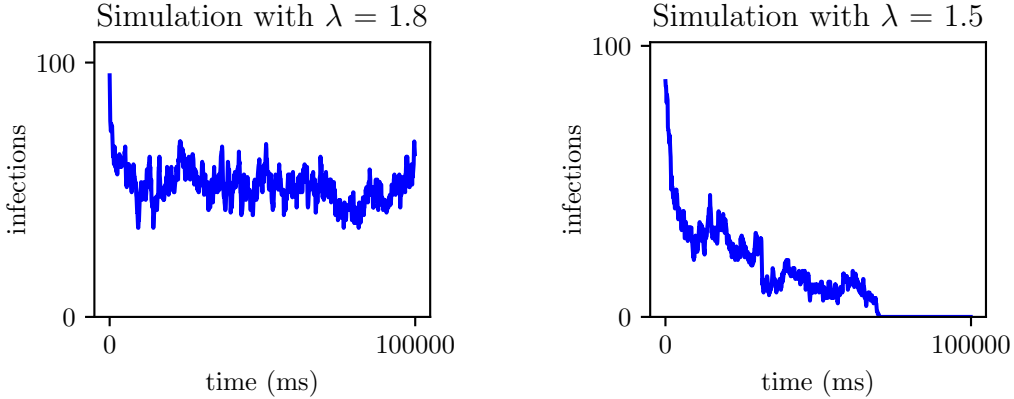


Figure 4: The contact process in the sub- and supercritical case

Let us now consider finite graphs, in this case the infection always dies out, so the critical value is trivially 0. Hence, it makes sense to look at another metric, namely the extinction time, which is defined as follows.

Definition 2.10. The extinction time of the contact process of a graph G with initial occupancy $A \subset G$ is given by

$$\tau_G^A = \inf \{ t : \xi_t^A = \emptyset \}. \quad (2.3)$$

In Section 3 we will make it plausible that a similar notion of sub- and supercritical exists for finite graphs. For the contact process we also define what is called the survival function. This function gives the probability of survival, given the parameter of the contact process.

Definition 2.11. The survival function $\psi : \mathbb{R}_{\geq 0} \mapsto [0, 1]$ maps a parameter λ of the contact process $\xi_t^{\{0\}}$ on \mathbb{Z}^d to $\mathbb{P} \left[\lim_{t \rightarrow \infty} \xi_t^{\{0\}} \neq \emptyset \right]$.

This survival function is often studied in literature regarding the contact process. In the final chapter we will develop methods for estimating the critical value, which also allow us to estimate this function. In Figure 5 the approximate shape of ψ is visualised.

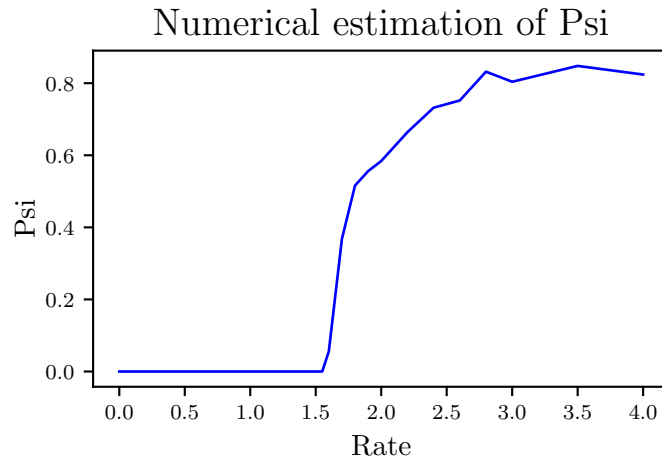


Figure 5: Numerical estimation of psi

2.12 Couplings

In this thesis we will greatly rely on the following two definitions. In order to study the contact process, it is often useful to make a comparison with a simpler process. We will often do so using a technique called coupling.

Definition 2.13. A coupling between two random variables $X_1 : \Omega_1 \mapsto \mathbb{R}$ and $X_2 : \Omega_2 \mapsto \mathbb{R}$ is a new probability space Ω' with two random variables $X'_1 : \Omega' \mapsto \mathbb{R}$ and $X'_2 : \Omega' \mapsto \mathbb{R}$ such that X'_1 and X'_2 are identically distributed to X_1 and X_2 respectively.

Most comparisons we will want to make are where one process dominates the other, that is, if an event happen in one process with a certain probability p , it also happens in the other with at least probability p . This motivates the following definition.

Definition 2.14. A random variable $X : \Omega \mapsto \mathbb{R}$ is said to (stochastically) dominate $Y : \Omega \mapsto \mathbb{R}$ if

$$\mathbb{P}[X \geq x] \geq \mathbb{P}[Y \geq x], \text{ for all } x \in \mathbb{R}.$$

In this case, we write $X \geq_{st} Y$. If we have that

$$\mathbb{P}[X \geq x] > \mathbb{P}[Y \geq x], \text{ for all } x \in \mathbb{R},$$

we say that X strictly (stochastically) dominates Y , and we write $X >_{st} Y$

This in itself is not yet sufficient, as we will often we dealing with random variables that do not necessarily lie in the same probability space. The following result, shows that it is sufficient to find a suitable coupling.

Lemma 2.15. A random variable $X : \Omega_1 \mapsto \mathbb{R}$ is said to stochastically dominate $Y : \Omega_2 \mapsto \mathbb{R}$ if and only if there exists a coupling (X', Y') on Ω' such that $\mathbb{P}[X' \geq Y'] = 1$.

For the proof the reader can refer to [13, p. 64]. It might not immediately obvious why couplings are even worth studying, since we are just making copies of the random variables we already had. The trick will be to make these copies dependent, so that knowledge about one random variable tells us something about the other. Let us look at a simple example.

Example 2.16. Consider $X_1 \sim B(n, p)$ and $X_2 \sim B(m, p')$ with $n \geq m$ and $p \geq p'$. We will show that $X_1 \geq_{st} X_2$ through a suitable coupling. We will take samples x_0, \dots, x_{n-1} from $U(0, 1)$ and define

$$(X'_1, X'_2) = \left(\sum_{i=0}^n \mathbb{1}_{[0, p]}(x_i), \sum_{i=0}^m \mathbb{1}_{[0, p']}(x_i) \right).$$

Then we have that X_1 and X_2 are identically distributed to X'_1 and X'_2 since we are counting the number of successful Bernoulli experiments, and $\mathbb{P}[X'_1 \geq X'_2] = 1$ since any success in X_2 is also a success in X_1 . This shows $X_1 \geq_{st} X_2$ with Lemma 2.15.

Example 2.16 illustrates the power of couplings. Proving this inequality directly would be very cumbersome and computational. One very important result on the contact process is due to Harris. There exists a coupling between the contact process and a carefully selected set of Poisson processes. For each node in the graph we assign a rate 1 Poisson process, and a rate λ Poisson process for each outgoing edge. The first process determines the time when a site becomes healthy. The second processes determine when the process infects the corresponding neighbour, if they're infected themselves. For the contact process on \mathbb{Z} , an illustration can be found in Figure 6. In Figure 6 the blue crosses represent recoveries, and red arrows corresponds

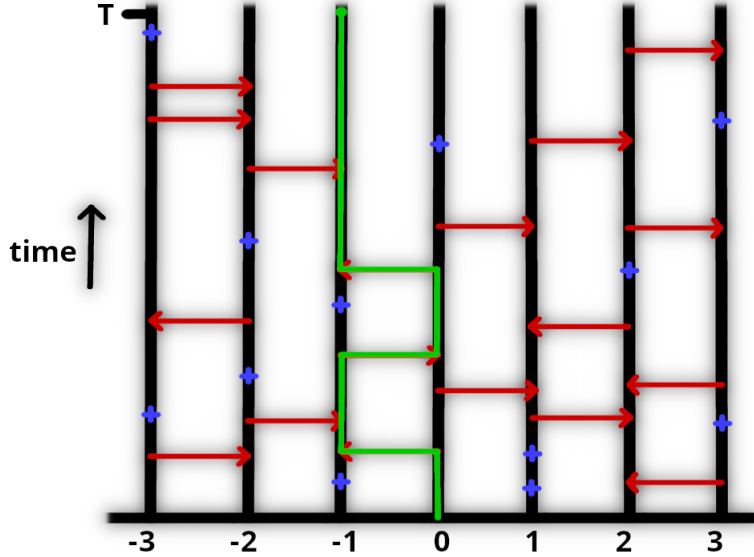


Figure 6: Harris' visual representation

to infections. In the figure we can see that the node -1 is infected at time T if node 0 is infected at time 0 , since we draw a path from 0 at time 0 to -1 at time T without any recoveries. We will mimic notation from percolation, writing $v_1 \rightsquigarrow \infty$ if there is an infinitely long infection path in

time starting in v_1 at time 0. By the coupling with Poisson processes it should be clear from Example 2.5 that the contact process is homogenous in time and has the Markov property.

Let us now return to the question after Definition 2.9. We can define the critical value as $\inf \left\{ \lambda : \lim_{t \rightarrow \infty} \xi_t^A = \emptyset \right\}$ for any finite initial configuration A , by the following lemma.

Lemma 2.17. *Considering a contact process $(\xi_t)_{t \geq 0}$ on a graph G . Then, the following are equivalent for any finite $A \subset \mathbb{Z}^d$,*

1. $\lambda > \lambda_c$,
2. $\psi(\lambda) > 0$,
3. $\lambda > \inf \left\{ \lambda : \lim_{t \rightarrow \infty} \xi_t^A = \emptyset \right\}$.

Proof. It follows directly from the definition of the critical value that (1) and (2) are equivalent. The implication (2) \implies (3) is trivial since $\{0\}$ is a possible choice of A . For the final implication (3) \implies (2), let us assume by contraposition that $\psi(\lambda) = 0$. Let Ξ be one realisation of Harris' visual representation. Then

$$\begin{aligned} \mathbb{P} \left[\lim_{t \rightarrow \infty} \xi_t^A = \emptyset \right] &= \mathbb{P} [A \not\rightsquigarrow \infty \text{ in } \Xi] \\ &\leq \sum_{i \in A} \mathbb{P} [i \not\rightsquigarrow \infty \text{ in } \Xi] \\ &= \sum_{i \in A} \mathbb{P} \left[\lim_{t \rightarrow \infty} \xi_t^{\{i\}} \neq \emptyset \right] = 0 \end{aligned}$$

using the union bound (Lemma 1.7). This shows that $\lambda \leq \inf \left\{ \lambda : \lim_{t \rightarrow \infty} \xi_t^A = \emptyset \right\}$, completing the proof. \square

One might wonder if we can prove any strict (stochastic) inequalities on the extinction time of more general classes of graphs. So to finish this we will first show a (non-strict) inequality for graph that are included in one another by defining a coupling between these two graphs.

Theorem 2.18. *If $G_1 \subset G_2$ are graphs, $A \subset G_2$ an initial occupancy and $A' = A \cap V_{G_1}$.*

- *If G_1 and G_2 are finite, then $\tau_{G_1}^{A'} \leq_{st} \tau_{G_2}^A$*
- *If G_1 and G_2 are infinite, then $\lambda_c(G_1) \leq \lambda_c(G_2)$.*

Proof. We prove this statement by defining a suitable coupling. Let $(\xi_t^A)_{t \geq 0}$ be a contact process on G_1 and $(\zeta_t^A)_{t \geq 0}$ a contact process on G_2 . At time $t = 0$ we will have that $\xi_0^{A'} \subset \zeta_0^A$. We couple in a way that preserves this inclusion. For sets A and B we will write

$$r(A, B) := \lambda |\{y \in A : \{x, y\} \in B\}|.$$

This is the rate of infection from infected points in A through edges in B . We will now couple in the, so that the contact processes coincide where G_1 and G_2 coincide.

$$\begin{aligned} \text{For } x \in \zeta_t, & & (\xi_t, \zeta_t) &\mapsto (\xi_t \setminus \{x\}, \zeta_t \setminus \{x\}) \text{ with rate } 1, \\ \text{for } x \in \xi_t \setminus \zeta_t, & & (\xi_t, \zeta_t) &\mapsto (\xi_t \setminus \{x\}, \zeta_t) \text{ with rate } 1, \\ \text{for } x \in \xi_t \text{ and } x \notin \zeta_t, & & (\xi_t, \zeta_t) &\mapsto (\xi_t, \zeta_t \cup \{x\}) \text{ with rate } r(\zeta_t, E_{G_1}) \\ \text{for } x \notin \xi_t \cap V_{G_1} \cap V_{G_2}, & & (\xi_t, \zeta_t) &\mapsto (\xi_t \cup \{x\}, \zeta_t \cup \{x\}) \text{ with rate } r(\xi_t \setminus \zeta_t, E_{G_1}) \\ \text{for } x \notin \xi_t \cap (V_{G_2} \setminus V_{G_1}), & & (\xi_t, \zeta_t) &\mapsto (\xi_t \cup \{x\}, \zeta_t) \text{ with rate } r(\xi_t \setminus \zeta_t, E_{G_2} \setminus E_{G_1}). \end{aligned}$$

This has been carefully constructed to exactly give us our two contact processes, whilst ensuring $\xi_t^{A'} \subset \zeta_t^A$ for all $t \geq 0$.

As a consequence of this coupling, it holds that $\mathbb{P}[|\xi_t| \geq |\zeta_t|] = 1$. This means that if the infection survives in G_1 , we then immediately know that it must also survive in G_2 , allowing us to apply Lemma 2.15 to conclude that the indicator of the event of survival in G_2 dominates that of G_1 . Consequently, we get that $\tau_{G_1}^A \leq_{st} \tau_{G_2}^A$ for all non-empty initial occupancies A in the finite case and hence that $\lambda_c(G_2) \leq \lambda_c(G_1)$ in the infinite case. \square

3 The contact process on finite graphs

In this first section we will look at the contact process on finite graphs. In particular, we will derive a way to find a crude upper and lower bound on the expected extinction time of the contact process on n -cyclic graphs. Additionally, we will take a look at general class of finite graphs, and prove strict inequalities on extinction time, for graphs that are strictly included in a another graph.

3.1 Expected extinction time on cyclic graphs

In this section we will derive a crude upper and lower bound on the expected extinction time of the contact process on n -cyclic graphs. We will do so by considering the probabilities that a certain number of nodes are infected at a set time. These probabilities are very hard to determine, but we are able to find an upper and lower bound. Let us first derive a few specific results on exponentially distributed random variables.

Lemma 3.2. *If X_1 and X_2 are independently exponentially distributed with parameters λ_1 and λ_2 respectively, then $\min(X_1, X_2) \sim \text{Exp}(\lambda_1 + \lambda_2)$.*

Proof. Since X_1 and X_2 are independent,

$$\mathbb{P}[\min(X_1, X_2) > a] = \mathbb{P}[X_1 > a, X_2 > a] = \mathbb{P}[X_1 > a] \mathbb{P}[X_2 > a] = e^{-\lambda_1 a - \lambda_2 a}.$$

Hence $\mathbb{P}[\min(X_1, X_2) \leq a] = 1 - e^{-\lambda_1 a - \lambda_2 a}$, and since this is precisely the cumulative distribution function of $\text{Exp}(\lambda_1 + \lambda_2)$, it must hold that $\min(X_1, X_2) \sim \text{Exp}(\lambda_1 + \lambda_2)$. \square

This now allows us to prove the following lemma, which will be useful for deriving the main result of this section.

Lemma 3.3. *Given that $X_1 \sim \text{Exp}(\lambda_1)$ and $X_2 \sim \text{Exp}(\lambda_2)$ independently*

$$\mathbb{E}[X_1 \mid X_1 < X_2] = \frac{1}{\lambda_1 + \lambda_2}.$$

Proof. We start by noting that the X_1 is equal to $\min(X_1, X_2)$ under the condition that $X_1 < X_2$, hence

$$\begin{aligned} \mathbb{E}[X_1 \mid X_1 < X_2] &= \mathbb{E}[\min(X_1, X_2)] \\ &= \frac{1}{\lambda_1 + \lambda_2} \end{aligned}$$

Using that $\min(X_1, X_2) \sim \text{Exp}(\lambda_1 + \lambda_2)$ as proven in Lemma 3.2. \square

Now that we have this tool we can formulate and prove the main results of this section. We will determine the lower and upper bound by comparing with a suitable continuous time Markov chain. Let us first determine a lower bound.

Theorem 3.4. *Let $\{\xi_t^A\}_{t \geq 0}$ denote the contact process on the n -cyclic graph $G = C_n$. Then a lower bound X_i of $\mathbb{E}[\tau_G^A \mid |A| = i]$ can be found for all $1 \leq i \leq n$ by solving the system*

$$\begin{cases} X_1 &= \frac{1}{(2\lambda+1)^2} + \frac{2\lambda}{2\lambda+1} \left(X_2 + \frac{1}{2\lambda+1} \right), \\ X_i &= \frac{i}{2\lambda+i} \left(X_{i-1} + \frac{1}{2\lambda+i} \right) + \frac{2\lambda}{2\lambda+i} \left(X_{i+1} + \frac{1}{2\lambda+i} \right), \quad 2 \leq i \leq n-1, \\ X_n &= X_{n-1} + \frac{1}{n}. \end{cases}$$

Proof. We want to find a lower bound on the number of infections. We establish an order on the edges and on the nodes of C_n , denoted by \geq_V and \geq_E respectively. Observe the total rate of new infections across the whole graph C_n , is at least 2λ if there is an healthy site. We will couple a continuous Markov chain in Figure 7 to the contact process on C_n so that if the contact process has gone extinct, the chain has as well. Denote the Markov chain by M_t . For every $t \geq 0$, let x_t^m be the first m infected nodes in \geq_V and E_t^{min} the two smallest edges in $\{y \in \xi_t : \{x, y\} \in E_{C_n}\}$ according to \geq_E at time t . Additionally, for sets A and B we will write

$$r(A, B) := \lambda |\{y \in A : \{x, y\} \in B\}|.$$

This is the rate of infection from infected points in A through edges in B . The coupling is defined as follows.

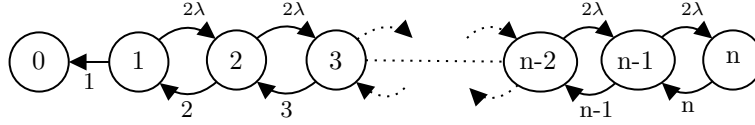


Figure 7: Lower bound Markov chain

$$\begin{aligned} \text{For } x \in \xi_t \text{ and } m = M_t, & \begin{cases} (\xi_t, M_t) \mapsto (\xi_t \setminus \{x\}, m-1) \text{ with rate } 1, \text{ if } \xi_t \in x_t^m, \\ (\xi_t, M_t) \mapsto (\xi_t \setminus \{x\}, m) \text{ with rate } 1, \text{ else.} \end{cases} \\ \text{For } x \notin \xi_t \text{ and } m = M_t, & \begin{cases} (\xi_t, M_t) \mapsto (\xi_t \cup \{x\}, m+1) \text{ with rate } r(\xi_t, E_t^{min}), \\ (\xi_t, M_t) \mapsto (\xi_t \cup \{x\}, m) \text{ with rate } r(\xi_t, E_{C_n} \setminus E_t^{min}). \end{cases} \end{aligned}$$

Any time step from i to $i-1$ in the Markov chain corresponds to a recovery in one of the first i infected nodes in the contact process. A step from i to $i+1$ in the Markov chain corresponds to an infection through one of the first two edges between a healthy and an infected site. Any other events in the contact process do not affect the Markov chain. By construction, the state of this Markov chain is certainly smaller or equal to the number of infections in the contact process, so the time until this Markov reaches 0 starting at $|A|$ is stochastically dominated by τ_G^A .

Now, we can derive a system of equations based on this Markov chain. Let $X \sim \exp(2\lambda)$ and $Y_i \sim \exp(i)$, then given that we are in state $2 \leq i \leq n-1$ we can find the expected time until extinction based on the neighbouring states. We let X_i be the time that this Markov chain goes extinct if we start in state i , then the expected value of X_i satisfies

$$\begin{cases} X_1 &= \mathbb{P}[Y_1 < X] \mathbb{E}[Y_1 \mid Y_1 < X] + \mathbb{P}[X < Y_1] (X_2 + \mathbb{E}[X \mid X < Y_1]), \\ X_i &= \mathbb{P}[Y_i < X] (X_{i-1} + \mathbb{E}[Y_i \mid Y_i < X]) + \\ &\quad \mathbb{P}[X < Y_i] (X_{i+1} + \mathbb{E}[X \mid X < Y_i]), \quad 2 \leq i \leq n-1 \\ X_n &= X_{n-1} + \mathbb{E}[Y_n]. \end{cases}$$

By Lemma 1.6 we get $\mathbb{P}[Y_i < X] = \frac{i}{2\lambda + i}$ and $\mathbb{P}[X < Y_i] = \frac{2\lambda}{2\lambda + i}$ and by Lemma 3.3 we find $\mathbb{E}[X \mid X < Y_i] = \mathbb{E}[Y_i \mid Y_i < X] = \frac{1}{2\lambda + i}$ to get the desired result. \square

Now, to find an upper bound we will analogously determine a Markov chain that gives an upper bound on the number of infections.

Theorem 3.5. Let $\{\xi_t^A\}_{t \geq 0}$ denote the contact process be a contact process on the n -cyclic graph $G = C_n$. Then a lower bound X_i of $\mathbb{E}[\tau_G^A \mid |A| = i]$ can be found for all $1 \leq i \leq n$ by solving the system

$$\begin{cases} X_1 &= \frac{1}{(2\lambda+1)^2} + \frac{2\lambda}{2\lambda+1} \left(X_2 + \frac{1}{2\lambda+1} \right), \\ X_i &= \frac{i}{2i\lambda+i} \left(X_{i-1} + \frac{1}{2i\lambda+i} \right) + \frac{2i\lambda}{2i\lambda+i} \left(X_{i+1} + \frac{1}{2i\lambda+i} \right), \quad 2 \leq i \leq \lfloor \frac{n-1}{2} \rfloor, \\ X_i &= \frac{i}{2(n-i-1)\lambda+i} \left(X_{i-1} + \frac{1}{2(n-i-1)\lambda+i} \right) + \\ &\quad \frac{2(n-i-1)\lambda}{2(n-i-1)\lambda+i} \left(X_{i+1} + \frac{1}{2(n-i-1)\lambda+i} \right), \quad \lfloor \frac{n-1}{2} \rfloor < i \leq n-1, \\ X_n &= X_{n-1} + \frac{1}{n}. \end{cases}$$

Proof. We now consider a Markov chain which follows the upper bounds on the infection rates. The infection rate is maximal when there are as many healthy sites bordering infectious ones as possible. While the number of infections is strictly smaller than $\frac{n}{2}$, this means we have an infection rate of at most 2λ times the number of infected sites. Once the number of infections is larger or equal to $\frac{n}{2}$ we get a rate of at most 2λ times the number of healthy sites. We will use this fact to couple to the continuous-time Markov chain in Figure 8. Using the same notation as in Theorem 3.4, we will couple as follows.

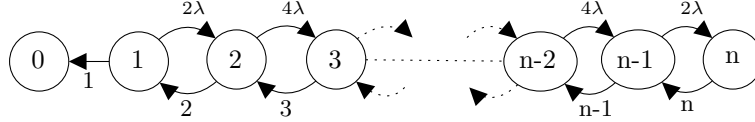


Figure 8: Upper bound Markov chain

For $x \in \xi_t$ and $m = M_t$, $(\xi_t, M_t) \mapsto (\xi_t \setminus \{x\}, m-1)$ with rate 1.

For $x \notin \xi_t$ and $m = M_t$, $\begin{cases} (\xi_t, M_t) \mapsto (\xi_t \cup \{x\}, m+1) \text{ with rate } r(\xi_t, E_{C_n}), \\ (\xi_t, M_t) \mapsto (\xi_t, m+1) \text{ with rate } 2\lambda \min(n-m, m) - r(\xi_t, E_{C_n}). \end{cases}$

Through this coupling we ensure that every recovery means we take a step from i to $i-1$ in the Markov chain, and for every infection we also take a step from i to $i+1$ in the chain. In addition to this we will also take steps from i to $i+1$ so that the total rate is always equal to the maximal rate we will ever have in the normal contact process.

By construction, the state of this Markov chain is certainly greater or equal to the number of infections in the contact process, so the time until this Markov reaches 0 starting at $|A|$ stochastically dominates τ_G^A . The rest of this proof of this theorem is analogous to that of Theorem 3.4, by again deriving a system of equations from the Markov chain. \square

For small values of n , you can write computer programs that are capable of solving these systems algebraically. We have done so to visualise the quality of these bounds, the scripts utilised can be found in Appendix A.1. If we specifically look at the extinction time given full occupancy, we get something that looks like Figure 9. We can see that as n increases, the difference between our upper and lower bound increases drastically. This pattern holds across all initial configurations, but gets slightly less drastic.

With the aid of the numeric solver an attempt has been made to derive an explicit solution for the systems in this chapter, but this was to no avail. We have seen in Figure 4, there is a

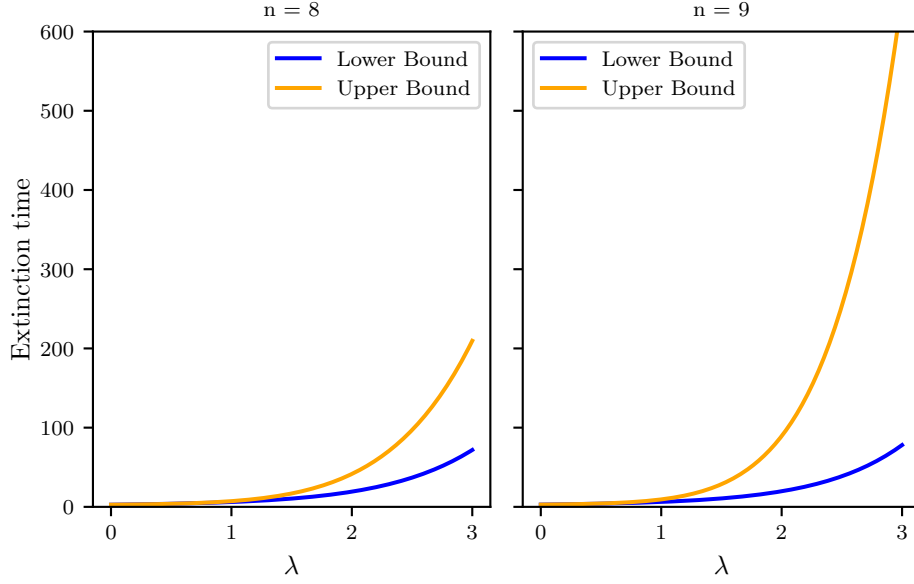


Figure 9: Upper and lower bound for $n = 8$ and $n = 9$

change in behaviour in infinite graphs around the critical value. Heuristically, one might think a similar change would occur in finite graphs. To investigate this, we will look at solutions of the system for fixed values of λ as n grows.

For most rates, the upper bound seemingly grows exponentially, whilst the lower bound appears to grow logarithmically. We can see this illustrated in Figure 10a where we plotted the bounds for rate 1. In this case, it is unclear how the expected extinction time behaves as n grows. However, if we now look at the graph with rate 0.25 in Figure 10b up until $n = 40$, we will see that both the upper and lower bound appear to grow logarithmically. Making the bound relatively tight for these smaller values of λ .

Additionally, if we take the rate greater than $\frac{n}{2}$, we see exponential growth until n in the lower bound. This is illustrated in Figure 10c, for rate 9 up until $n = 19$, to stay within the floating point range. This hints at the fact that a change in behaviour also occurs in these finite graphs. However, since the change does not occur in the lower bound for a fixed value of λ we cannot definitively say that it does in fact occur.

3.6 Strict inequality on extinction time

One might wonder if we can find any strict inequalities on extinction time. Given the inequality from Theorem 2.18, it suffices to show that the random variables $\tau_{G_1}^A$ and $\tau_{G_2}^A$ are different, for all A and $G_1 \subsetneq G_2$. To do so, we will identify a strictly positive probability, that G_1 goes extinct, while the infection is G_2 still non-extinct.

Theorem 3.7. *If $G_1 \subsetneq G_2$ are finite connected graphs, then $\tau_{G_1}^A <_{st} \tau_{G_2}^A$ for all non-empty initial occupancies.*

Proof. Since we have a finite graph, the total rate of infections and recoveries is always smaller or equal to $r = 2\lambda|E_{G_2}| + |V_{G_2}|$ where $|E_{G_2}|$ and $|V_{G_2}|$ denote the number of edges and vertices

of G_2 respectively. Throughout this proof, we utilise the same coupling as used in Theorem 2.18. Additionally, because of this same theorem, it suffices to prove $\tau_{G_1} \neq \tau_{G_2}$.

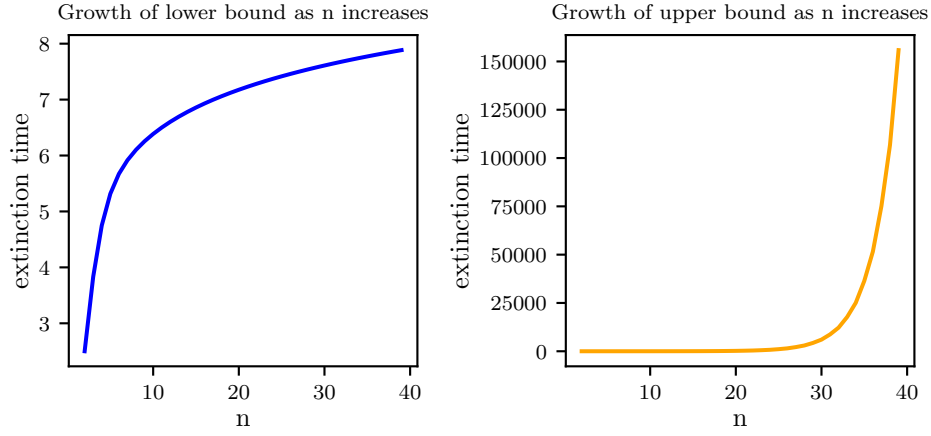
We first show that, without loss of generality, we can assume that the initial occupancy is full occupancy. We do this by showing that there is a positive probability to reach full occupancy, after which $\tau_{G_1} \neq \tau_{G_2}$ implies $\tau_{G_1}^A \neq \tau_{G_2}^A$ by the Markov property of the contact process. Connectedness of the graph implies that there is always a probability of infection greater or equal to $\frac{\lambda}{r}$ if there are uninfected sites. Let E denote the event that $(\xi_t^A)_{t \geq 0}$ reaches full occupancy starting from $t = 0$, then

$$\mathbb{P}[E] \geq \prod_{i=1}^{|V_{G_2} \setminus A|} \frac{\lambda}{r} > 0.$$

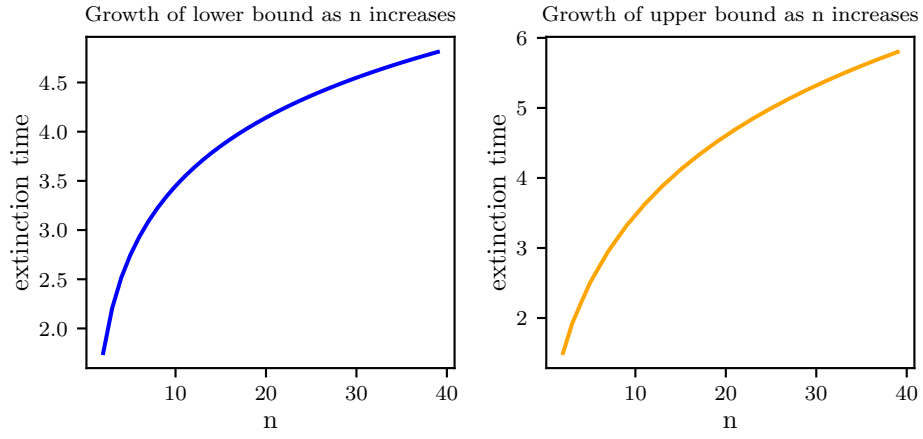
Now assuming full occupancy, we will use the same trick to show that there is a strictly positive probability that all sites of G_1 recover at a time smaller than T , whilst none of $G_2 \setminus G_1$ do, all the while there are no infections. The probability that a node recovers before any new infections is therefore greater or equal to $\frac{|\xi_t|}{r}$ by Lemma 1.6. This gives

$$\mathbb{P}[\tau_{G_1} < \tau_{G_2}] \geq \prod_{i=1}^{|V_{G_1}|} \frac{i}{r} > 0,$$

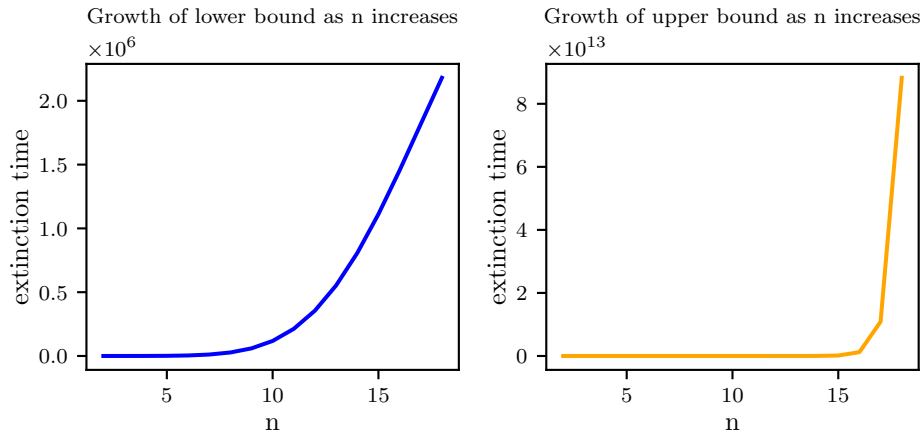
proving that $\tau_{G_1} \neq \tau_{G_2}$, completing the proof. \square



(a) Growth of upper and lower bound for rate 1



(b) Growth of upper and lower bound for rate 0.25



(c) Growth of upper and lower bound for rate 9

Figure 10: Growth of upper and lower bounds for various rates

4 Upper and lower bounds on the critical value

In this section we will derive upper and lower bounds for $\lambda_c(\mathbb{Z}^d)$. We will do so by making a comparison to the Galton-Watson branching process to establish a lower bound in Subsection 4.1. Next, in Subsection 4.8, we find an upper bound by comparing contact processes in different dimensions in a specific way. Finally we determine an upper bound for the critical value of the contact process in dimension 1.

4.1 Lower bound

We can obtain an asymptotic lower bound by making a coupling to Galton-Watson trees. We will explore the contact process until a certain number of the changes have occurred. To do so we define frontier events.

Definition 4.2. We say there is a frontier event at time t in the contact process anytime there is a recovery of an infected node, or an infection of a healthy node.

In order to couple with Galton-Watson trees we need to ensure the independence of the child distributions. We can use the time-homogeneity and the Markov property of the contact process to couple to a Galton-Watson tree. The child distribution will be determined by the number of infected sites after k frontier events. Doing this gives us the following lemma.

Lemma 4.3. *The contact process $\{\xi_t\}_{t \geq 0}^{\{0\}}$ on \mathbb{Z}^d dies out if the expected number of infected sites after the first $k \in \mathbb{Z}_{\geq 1}$ frontier events is less or equal to 1.*

Proof. We will show that we can generate a Galton-Watson tree from the contact process $\{\xi_t\}_{t \geq 0}^{\{0\}}$ on \mathbb{Z}^d such that extinction of the tree, implies extinction of the contact process. The Galton-Watson process we will construct will have the following child distribution X ,

$$X := \text{the total number of infected sites after the first } k \text{ frontier events.}$$

Let 0 correspond to the first node of the contact process, we will consider Harris' visual representation. We will do an exploration of the visual representation, such that we visit each node at most once.

We consider the first frontier event that can be reached from 0. If this is a recovery we are done. If it is an infection, we now look for the next frontier event that can be reached from the two infected sites. For this next event we again distinguish between recovery and infection. In the case of recovery, we continue considering with the one infected site left. If it is an infection, we continue with all the sites that have been infected. We repeat this until we have seen k frontier events. Doing this gives a sample X_1 of X that determines the children of the first node.

Next, for each of the children of the first node. We do the same exploration. However now, anytime we come across a node that we have already visited, we will determine future events for this node with new i.i.d. Poisson events for infections and recoveries. Any infections caused by this node, will also generate events independently from the contact process. After finishing the exploration, a node will continue according to our exploration procedure if and only if its infection has been caused by the contact process. The other nodes will just sample from X i.i.d. from this point onwards. The process we described is illustrated with $k = 2$ in figure 11 for the contact process with $d = 1$.

To complete the proof, we realise that, if the Galton-Watson tree dies out after n generations, that means that the contact process has died out before hitting kn frontier events. This is because we have considered all the frontier events. We can trivially see that $\mathbb{P}[X = 1] < 1$ for all

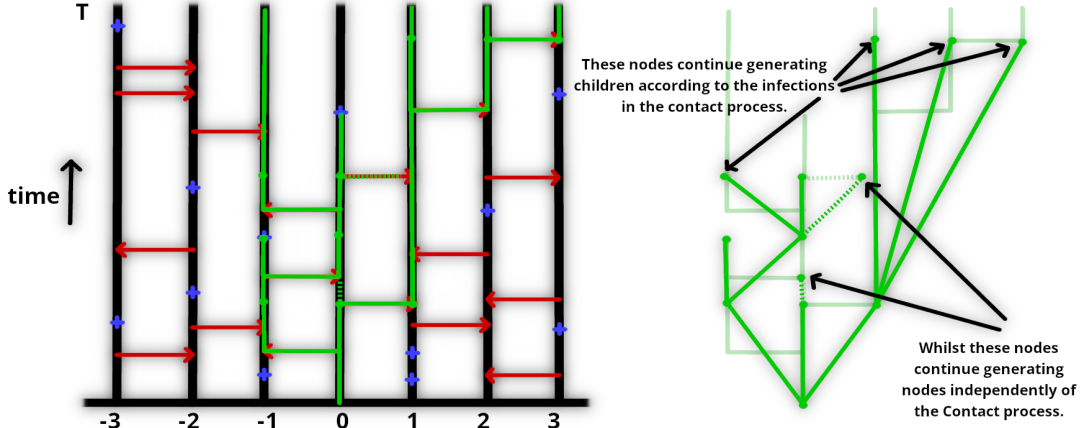


Figure 11: Coupling with Galton Watson trees in one dimension

possible $k \in \mathbb{Z}_{\geq 1}$, because there is always a chance that the first node recovers, equal to $\frac{1}{2\lambda+1}$, which means that the contact process dies out if $\mathbb{E}[X] \leq 1$ by Theorem 1.17. \square

For small values of k , it is possible to exactly determine the distribution of children. This allows us to establish an asymptotic lower bound.

Theorem 4.4. *For all $d \in \mathbb{Z}_{\geq 1}$ we have that $\lambda_c(\mathbb{Z}^d) \geq \frac{1}{8} + \frac{\sqrt{18d-1}}{8d\sqrt{2d-1}}$.*

Proof. We will determine the number of children after 2 frontier events, starting with 1 infection. Denote this by X . The probability that the infection remains after 1 frontier event is $\frac{2d\lambda}{2d\lambda+1}$, in which case there will be two infected sites. Either one of these sites infect another site, with probability $\frac{2(2d-1)\lambda}{2(2d-1)\lambda+2}$ or one of them recovers with probability $\frac{2}{2(2d-1)\lambda+2}$. Here we use that a cluster of two infected sites has $2(2d-1)$ uninfected neighbours. Next, we calculate the expected number children;

$$\begin{aligned} \mathbb{E}[X] &= \frac{2d\lambda}{2d\lambda+1} \left(\frac{2}{2(2d-1)\lambda+2} + 3 \frac{2(2d-1)\lambda}{2(2d-1)\lambda+2} \right) \\ &= \frac{2d\lambda}{2d\lambda+1} \frac{6(2d-1)\lambda+2}{2(2d-1)\lambda+2} \\ &= \frac{12d(2d-1)\lambda^2+4d\lambda}{4d(2d-1)\lambda^2+2(2d-1)\lambda+4d\lambda+2}. \end{aligned}$$

Now we need to solve $\mathbb{E}[X] \leq 1$, expanding gives

$$\begin{aligned} 12d(2d-1)\lambda^2+4d\lambda &\leq 4d(2d-1)\lambda^2+2(2d-1)\lambda+4d\lambda+2 \\ 4d(d-1)\lambda^2-(2d-1)\lambda-1 &\leq 0. \end{aligned}$$

Now, by solving this quadratic equation we find that the infection survives if

$$\begin{aligned}
\lambda &\geq \frac{2d-1 + \sqrt{(2d-1)^2 + 16d(2d-1)}}{8d(2d-1)} \\
&= \frac{2d-1 + \sqrt{36d^2 - 20d + 1}}{8d(2d-1)} \\
&= \frac{1}{8} + \frac{\sqrt{(2d-1)(18d-1)}}{8d(2d-1)} \\
&= \frac{1}{8} + \frac{\sqrt{18d-1}}{8d\sqrt{2d-1}}.
\end{aligned}$$

Which finally allows us to conclude using Lemma 4.3 that $\lambda_c(\mathbb{Z}^d) \geq \frac{1}{8} + \frac{\sqrt{18d-1}}{8d\sqrt{2d-1}}$. \square

Note that Theorem 4.4 can be improved further by increasing the number of frontier events we consider. Doing so will result in polynomials of increasingly higher degrees. In Subsection 5.2 we will do some numerical experiments to see how far we can go in dimension 1. For the remainder of this subsection, we will consider $(X_n)_{n \in \mathbb{Z}_{\geq 0}}$, where X_n denote the number of infections after n frontier events. If for any realisation of the contact process, the number of infection is finite, X_n will be zero for all m after the infection has died out. We would like to show that the method to obtain lower bounds from this chapter allows us to find arbitrarily good lower bounds, as the number of frontier events approaches infinity. Ultimately, we will be unsuccessful, but the following results takes some steps towards this goal, and shows that it is plausible that this is in fact true.

The primary obstacle to show this result is the case, is showing that $\mathbb{E}[X_n]$ converges to 0 in the subcritical case. One might think to try and apply Lebesgue's dominated convergence theorem, since $X_n \rightarrow 0$. However, it proves to be very difficult to find a random variable with finite first moment to bound X_n . Instead we will use some results on exponential decay. The proofs of these results are way beyond the scope of this thesis, and together they would probably be a suitable topic for a thesis on their own. For this reason we will just state these results, without the proof.

First we start with a bound on the expected number of infected sites after some time. The following can be found in [10, p. 60].

Theorem 4.5. *There exists a constant c independent of t such that*

$$\mathbb{E} \left[|\xi_t^{\{0\}}| \right] \leq c(1+t^d) \sqrt{\mathbb{P}[\xi_t^0 \neq \emptyset]}.$$

Next we will state a result due to Carol Bezuidenhout and Geoffrey Grimmett in 1990[3], which is often referred to as exponential decay in the subcritical regime. It is also worth mentioning David Griffeath who proved exponential decay for \mathbb{Z} in 1981. We use the version stated in [10, p. 67].

Theorem 4.6. *(C. Bezuidenhout, Geoffrey Grimmett, 1990) Suppose $\lambda < \lambda_c(\mathbb{Z}^d)$, then there are positive constants $\varepsilon(\lambda) > 0$ such that*

$$\mathbb{P} \left[\xi_t^{\{0\}} \neq \emptyset \right] \leq e^{-\varepsilon(\lambda)t}$$

Finally, we can combine these two theorems to show $\mathbb{E} \left[|\xi_t^{\{0\}}| \right]$ converges to 0 in the subcritical case.

Theorem 4.7. *Consider the contact process on \mathbb{Z}^d , then*

1. *if $\lambda > \lambda_c$, $\mathbb{E} \left[|\xi_t^{\{0\}}| \right] \rightarrow \infty$.*

2. *if $\lambda < \lambda_c$, $\mathbb{E} \left[|\xi_t^{\{0\}}| \right] \rightarrow 0$,*

Proof. If $\lambda > \lambda_c$, X_n diverges to infinity with positive probability, so $\mathbb{E} \left[|\xi_t^{\{0\}}| \right] \rightarrow \infty$.

If $\lambda < \lambda_c$, we use Theorem 4.5 and Theorem 4.6. Then, since $\lim_{n \rightarrow \infty} \frac{t^d}{e^t} = 0$,

$$\mathbb{E} \left[|\xi_t^{\{0\}}| \right] \leq c(1 + t^d) \sqrt{\mathbb{P}[\xi_t^{\{0\}} \neq \emptyset]} \leq c(1 + t^d) e^{-\frac{1}{2}\varepsilon(\lambda)t} \rightarrow 0.$$

□

Theorem 4.7 shows that as time goes to infinite, the expectation $\mathbb{E} \left[|\xi_t^{\{0\}}| \right]$ behaves in the way that we want $\mathbb{E}[X_n]$ to behave. It might seem like the same convergence for $\mathbb{E}[X_n]$ should then immediately follow from this theorem, but when one writes out the details we find many technical challenges. If one would further research the results from this thesis, completing this proof would be a good place to start.

In Subsection 5.2 we will compute $\mathbb{E}[X_n]$ for increasing value of n to get numerical lower bounds. In this section we will see that the lower bound increases rather slowly as n increases.

4.8 Upper bound

From Theorem 2.18 we can immediately conclude the following statement.

Corollary 4.9. *For all $d \in \mathbb{N}$ we have that $\lambda_c(\mathbb{Z}^{d+1}) \leq \lambda_c(\mathbb{Z}^d)$*

This implies that an upper bound of the contact process on \mathbb{Z} gives an upper bound for all \mathbb{Z}^d . We can do much better however. The following is a result by Richard Holley and Thomas Liggett which one can find in [9, p.307]. We state and prove a slightly more generalised version than the one there, which allows to compare \mathbb{Z}^{nd} with \mathbb{Z}^n for all n , instead of just the case $n = 1$.

Theorem 4.10. *(R. Holley, T. M. Liggett, 1978) Let $\{\xi_t\}_{t \geq 0}$ be the contact process on \mathbb{Z}^{nd} with parameter λ and $\{\zeta_t\}_{t \geq 0}$ the contact process on \mathbb{Z}^n with parameter λd . Then,*

- 1.

$$\mathbb{P}[\xi_t^{\{0\}} \neq \emptyset] \leq \mathbb{P}[\zeta_t^{\{0\}} \neq \emptyset]$$

for all $t \geq 0$.

2. $d\lambda_c(\mathbb{Z}^{nd}) \leq \lambda_c(\mathbb{Z}^n)$

Proof. The implication 1 \implies 2 follows by Lemma 2.17 and the definition of the critical value. To proof the first point we define a function $\pi_{n,d}: \mathbb{Z}^{dn} \mapsto \mathbb{Z}^n$. Note that we are referring to the sets \mathbb{Z}^d . The function is defined as follows,

$$\pi_{n,d}(x_1, \dots, x_{nd}) = \left(\sum_{i=1}^d x_i, \sum_{i=d+1}^{2d} x_i, \dots, \sum_{i=(n-1)d+1}^{dn} x_i \right). \quad (4.1)$$

and for any finite set A ,

$$\pi_d(A) = \{\pi_{n,d}(x) \mid x \in A\}.$$

We will now make a coupling between $\{\xi_t\}_{t \geq 0}$ and $\{\zeta_t\}_{t \geq 0}$ that ensures that

$$\zeta_t \subset \pi_{n,d}(\xi_t). \quad (4.2)$$

If we have found this coupling, it is clear that 1 holds. First note that at $t = 0$, (4.2) is satisfied. For each $y \in \zeta_t$, there must at least one x_y such that $\pi_{n,d}(x_y) = y$. For each t we let $X_t = \{x_y | y \in \zeta_t\}$ be the set that contain exactly one x_y dependent of t for each $y \in \zeta_t$. If we consider (4.1) we can see that for every neighbour in \mathbb{Z} there are d neighbours in \mathbb{Z}^{nd} since we can disturb d different coordinates in the same way to get the same output of $\pi_{n,d}$. Let us now write down the exact coupling.

$$\begin{aligned} \text{For } x_y \in X_t, \quad & (\zeta_t, \xi_t) \mapsto (\zeta_t \setminus \{\pi_{n,d}(x_y)\}, \xi_t \setminus \{x_y\}) \text{ with rate } 1, \\ \text{For } x \in \xi_t \setminus X_t, \quad & (\zeta_t, \xi_t) \mapsto (\zeta_t, \xi_t \setminus \{x\}) \text{ with rate } 1, \\ \text{For } x \notin \xi_t, \quad & (\zeta_t, \xi_t) \mapsto (\zeta_t \cup \{\pi_{n,d}(x)\}, \xi_t \cup \{x\}) \text{ with rate } \lambda |\{x_y \in X_t : \{x, x_y\} \in E\}|, \\ \text{For } x \notin \xi_t, \quad & (\zeta_t, \xi_t) \mapsto (\zeta_t, \xi_t \cup \{x\}) \text{ with rate } \lambda |\{y \in \xi_t \setminus X_t : \{x, y\} \in E\}|. \end{aligned}$$

With this coupling, for a recovery in ζ_t , we will there is a recovery in ξ_t . If $y - 1$ is not in B , we say there is a infection in $y - 1$ due to the presence of y if any of the neighbours of x_y with $\pi_{n,d}(x_y) = y - 1$ get infected due to the presence of x_y , even if this neighbour was already infected in ξ_t . The construction is analogous for $y + 1$. This coupling ensures that the infection rate of $\{\zeta_t\}_{t \geq 0}$ will be d times the infection rate of $\{\xi_t\}_{t \geq 0}$ since sites in ζ_t get infected anytime one of the $2d$ neighbours get infected by x_y in ξ_t . Any points in $\{\zeta_t\}_{t \geq 0}$ that are not used will evolve independently of $\{\xi_t\}_{t \geq 0}$ according to the normal contact process. Finally, using this construction, it is clear that 4.2 remains satisfied, since if for $x \in \mathbb{Z}^n$ the final point in $\pi_{n,d}^{-1}(x)$ recovers, x must also recover, and if there is an infection to $x \in \mathbb{Z}^n$, it is ensured that there is at least one node is infected in $\pi_{n,d}^{-1}(x)$. We have now constructed a coupling with all desired properties, which completes the proof. \square

In order to derive an upper bound on $\lambda_c(\mathbb{Z})$, we will make a comparison with another stochastic process, called oriented percolation. We will find that a realisation of a certain oriented percolation process is contained within the visual representation of the contact process. Utilising results on the survival of percolation process, we can then show an upper bound. To make this coupling between the percolation process and the contact process, we first have to look at the following lemma.

Lemma 4.11. *Let $\{\xi_t\}_{t \geq 0}$ be the contact process on K_2 , the complete graph on two points, 0 and 1. If the initial occupancy is equal to $\{0\}$, then the probability $p(T)$ that 1 is infected at time T is given by*

$$p(T) = \frac{1}{2} e^{\frac{-(3+\lambda)T}{2}} \left(\cosh \frac{RT}{2} + \frac{1+3\lambda}{R} \sinh \frac{RT}{2} \right) - \frac{1}{2} e^{-(1+\lambda)T},$$

where $R = \sqrt{\lambda^2 + 6\lambda + 1}$. Additionally, the probability that 0 is infected at time T is given by

$$q(T) = \frac{1}{2} e^{\frac{-(3+\lambda)T}{2}} \left(\cosh \frac{RT}{2} + \frac{1+3\lambda}{R} \sinh \frac{RT}{2} \right) - \frac{1}{2} e^{-(1+\lambda)T}.$$

Proof. In order to derive this probability we will set up a system of differential equations with the probabilities that our contact process in a certain state. The continuous-time Markov chain we are dealing with is illustrated in Figure 12.

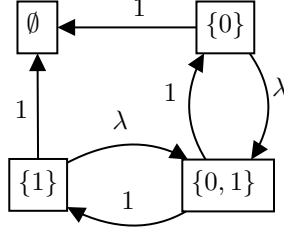


Figure 12: The continuous-time Markov chain for the contact process on K_2

If we let $p_\emptyset(t)$, $p_0(t)$, $p_1(t)$ and $p_{01}(t)$ be the probabilities that the Markov chain is in the respective state, then using the forwards Kolmogorov equations from Theorem 2.6 gives us the following system of differential equations,

$$\begin{aligned} p'_\emptyset(t) &= p_1(t) + p_0(t), \\ p'_0(t) &= -(\lambda + 1)p_0(t) + p_{01}(t), \\ p'_1(t) &= -(\lambda + 1)p_1(t) + p_{01}(t), \\ p'_{01}(t) &= -2p_{01}(t) + \lambda p_0(t) + \lambda p_1(t). \end{aligned}$$

Note that our desired probability $p(t)$ is equal to $p_1(t) + p_{01}(t)$, so we will solve for $p_1(t)$ and $p_{01}(t)$. We can simplify this system by letting $D(t) = p_0(t) - p_1(t)$ and $S(t) = p_0(t) + p_1(t)$. If we subtract the respective equations for $p_0(t)$ and $p_1(t)$, we get an ODE for $D(t)$, given by

$$D'(t) = -(\lambda + 1)D(t).$$

Utilising the initial conditions $p_0(0) = 1$ and $p_1(0) = 0$, we then see that $D(t) = e^{-(\lambda+1)t}$.

By adding the respective equations for $p_0(t)$ and $p_1(t)$, we get a system of ODEs for $S(t)$ and $p_{01}(t)$,

$$\begin{aligned} S'(t) &= -(\lambda + 1)S(t) + 2p_{01}(t), \\ p'_{01}(t) &= \lambda S(t) - 2p_{01}(t). \end{aligned}$$

We can write this in the following matrix form,

$$\begin{pmatrix} S'(t) \\ p'_{01}(t) \end{pmatrix} = A \begin{pmatrix} S(t) \\ p_{01}(t) \end{pmatrix} = \begin{pmatrix} -\lambda - 1 & 2 \\ \lambda & -2 \end{pmatrix} \begin{pmatrix} S(t) \\ p_{01}(t) \end{pmatrix}.$$

Then, by utilising the initial conditions $S(0) = 1$ and $p_{01}(0) = 0$ and Theorem 1.10, the solution is given by

$$\begin{pmatrix} S(t) \\ p_{01}(t) \end{pmatrix} = e^{At} \begin{pmatrix} 1 \\ 0 \end{pmatrix}.$$

In order to find this solution, we need to diagonalise A in order to compute the matrix exponential, we write $R = \sqrt{\lambda^2 + 6\lambda + 1}$, so that with Theorem 1.11

$$\begin{aligned} A &= \frac{1}{R} \begin{pmatrix} \frac{-\lambda-R+1}{2\lambda} & \frac{-\lambda+R+1}{2\lambda} \\ 1 & 1 \end{pmatrix} \begin{pmatrix} \frac{1}{2}(-R-\lambda-3) & 0 \\ 0 & \frac{1}{2}(R-\lambda-3) \end{pmatrix} \begin{pmatrix} -\lambda & \frac{1}{2}(R-\lambda+1) \\ \lambda & \frac{1}{2}(R+\lambda-1) \end{pmatrix}, \\ e^{At} &= \frac{1}{R} \begin{pmatrix} \frac{-\lambda-R+1}{2\lambda} & \frac{-\lambda+R+1}{2\lambda} \\ 1 & 1 \end{pmatrix} \begin{pmatrix} e^{\frac{1}{2}(-R-\lambda-3)t} & 0 \\ 0 & e^{\frac{1}{2}(R-\lambda-3)t} \end{pmatrix} \begin{pmatrix} -\lambda & \frac{1}{2}(R-\lambda+1) \\ \lambda & \frac{1}{2}(R+\lambda-1) \end{pmatrix}. \end{aligned}$$

So that we can finally calculate the solution,

$$\begin{aligned}
e^{At} \begin{pmatrix} 1 \\ 0 \end{pmatrix} &= \frac{1}{R} \begin{pmatrix} \frac{-\lambda-R+1}{2\lambda} & \frac{-\lambda+R+1}{2\lambda} \\ 1 & 1 \end{pmatrix} \begin{pmatrix} e^{\frac{1}{2}(-R-\lambda-3)t} & 0 \\ 0 & e^{\frac{1}{2}(R-\lambda-3)t} \end{pmatrix} \begin{pmatrix} -\lambda & \frac{1}{2}(R-\lambda+1) \\ \lambda & \frac{1}{2}(R+\lambda-1) \end{pmatrix} \begin{pmatrix} 1 \\ 0 \end{pmatrix} \\
&= \frac{1}{R} \begin{pmatrix} \frac{-\lambda-R+1}{2\lambda} e^{\frac{1}{2}(-R-\lambda-3)t} & \frac{-\lambda+R+1}{2\lambda} e^{\frac{1}{2}(R-\lambda-3)t} \\ e^{\frac{1}{2}(-R-\lambda-3)t} & e^{\frac{1}{2}(R-\lambda-3)t} \end{pmatrix} \begin{pmatrix} -\lambda \\ \lambda \end{pmatrix} \\
&= \begin{pmatrix} \frac{\lambda+R-1}{2R} e^{\frac{1}{2}(-R-\lambda-3)t} + \frac{-\lambda+R+1}{2R} e^{\frac{1}{2}(R-\lambda-3)t} \\ \frac{\lambda}{R} \left(e^{\frac{1}{2}(R-\lambda-3)t} - e^{\frac{1}{2}(-R-\lambda-3)t} \right) \end{pmatrix} \\
&= \begin{pmatrix} e^{\frac{1}{2}(-\lambda-3)t} \left(\cosh\left(\frac{Rt}{2}\right) - \frac{\lambda-1}{R} \sinh\left(\frac{Rt}{2}\right) \right) \\ \frac{2\lambda}{R} e^{\frac{1}{2}(-\lambda-3)t} \sinh\left(\frac{Rt}{2}\right) \end{pmatrix}
\end{aligned}$$

We can combine all of these results to find $p(t)$. If we realise that $p_1(t) = -\frac{1}{2}(D(t) - S(t))$ we can see that

$$\begin{aligned}
p(t) &= p_{01}(t) - \frac{1}{2}(D(t) - S(t)) \\
&= \frac{2\lambda}{R} e^{\frac{1}{2}(-\lambda-3)t} \sinh\left(\frac{Rt}{2}\right) - \frac{1}{2} \left(e^{-(\lambda+1)t} - \left(e^{\frac{1}{2}(-\lambda-3)t} \left(\cosh\left(\frac{Rt}{2}\right) - \frac{\lambda-1}{R} \sinh\left(\frac{Rt}{2}\right) \right) \right) \right) \\
&= \frac{1}{2} e^{\frac{-(3+\lambda)t}{2}} \left(\cosh\left(\frac{Rt}{2}\right) + \frac{1+3\lambda}{R} \sinh\left(\frac{Rt}{2}\right) \right) - \frac{1}{2} e^{-(1+\lambda)t}.
\end{aligned}$$

This gives us the desired quantity for $p(T)$. We can easily derive $q(t)$ using that $p_0(t) = \frac{1}{2}(S(t) + D(t))$.

$$\begin{aligned}
q(t) &= p_{01}(t) + \frac{1}{2}(S(t) + D(t)) \\
&= \frac{2\lambda}{R} e^{\frac{1}{2}(-\lambda-3)t} \sinh\left(\frac{Rt}{2}\right) + \frac{1}{2} \left(e^{\frac{1}{2}(-\lambda-3)t} \left(\cosh\left(\frac{Rt}{2}\right) - \frac{\lambda-1}{R} \sinh\left(\frac{Rt}{2}\right) \right) + e^{-(\lambda+1)t} \right) \\
&= \frac{1}{2} e^{\frac{-(3+\lambda)t}{2}} \left(\cosh\left(\frac{Rt}{2}\right) + \frac{1+3\lambda}{R} \sinh\left(\frac{Rt}{2}\right) \right) + \frac{1}{2} e^{-(1+\lambda)t}
\end{aligned}$$

This gives us $q(T)$, completing the proof. \square

We will now make the coupling to oriented percolation that we described. In this percolation we will use the event that there is a path in K_2 from 0 at time 0 to 1 at time T .

Theorem 4.12. *The process $\{\xi_t\}_{t \geq 0}$ survives if there exists a $T \in \mathbb{R}_{\geq 0}$ such that,*

$$\frac{1}{2} e^{\frac{-(3+\lambda)t}{2}} \left(\cosh\left(\frac{Rt}{2}\right) + \frac{1+3\lambda}{R} \sinh\left(\frac{Rt}{2}\right) \right) - \frac{1}{2} e^{-(1+\lambda)t} > p_c$$

where $R = \sqrt{\lambda^2 + 6\lambda + 1}$ and p_c denotes the critical probability for a certain type of 1-independent oriented percolation.

Proof. We will use Harris' visual representation of the contact process on the graph $\mathbb{Z}_{\geq 0}$, and make a partition in time with time steps T . We will define an 1-independent oriented percolation process based on this visual representation. We let points in $(z_1, z_2) \in \mathbb{Z}_{\geq 0} \times \mathbb{Z}_{\geq 0}$ correspond to z_1 at time step $(z_1 + z_2)T$ in Harris's visual representation. We will separately define conditions for the horizontal and vertical edges to be open.

- We say that the edge between (z_1, z_2) and $(z_1 + 1, z_2)$ is open if there is a path of infections only passing through z_1 and $z_1 + 1$ from z_1 at time $(z_1 + z_2)T$ to $z_1 + 1$ at time $(z_1 + z_2 + 1)T$. If we denote this event using E , we see that because of Lemma 4.11,

$$\mathbb{P}[E] = \frac{1}{2}e^{-\frac{(3+\lambda)t}{2}} \left(\cosh \frac{Rt}{2} + \frac{1+3\lambda}{R} \sinh \frac{Rt}{2} \right) - \frac{1}{2}e^{-(1+\lambda)t}.$$

- We say that the edge between (z_1, z_2) and $(z_1, z_2 + 1)$ is open if there is a path of infections only passing through z_1 and $z_1 + 1$ from z_1 at time $(z_1 + z_2)T$ to z_1 at time $(z_1 + z_2 + 1)T$. If F is the event that such a path exists then by Lemma 4.11,

$$\mathbb{P}[F] = \frac{1}{2}e^{-\frac{(3+\lambda)t}{2}} \left(\cosh \left(\frac{Rt}{2} \right) + \frac{1+3\lambda}{R} \sinh \left(\frac{Rt}{2} \right) \right) + \frac{1}{2}e^{-(1+\lambda)t}.$$

In Figure 13 some examples and counterexamples are provided for the event E and F . Note

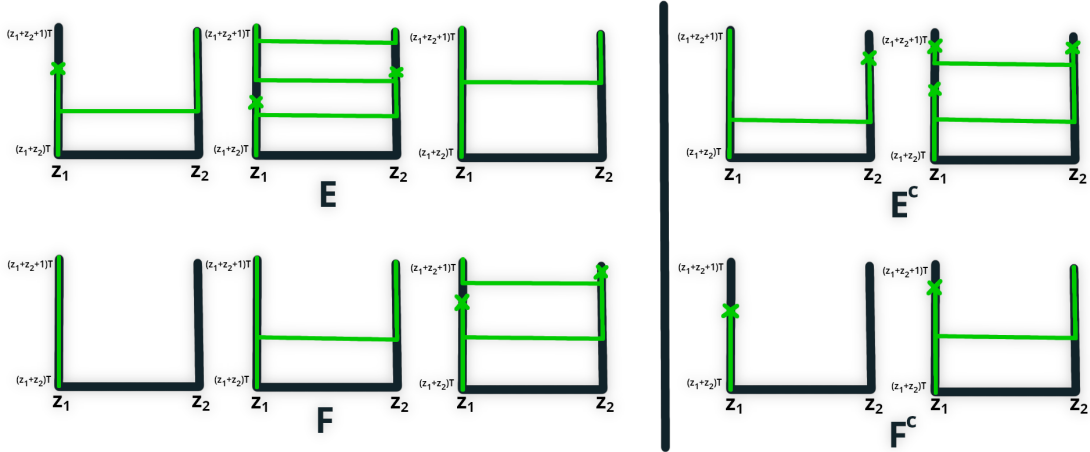


Figure 13: Coupling with Oriented percolation

that due to the Markov property of the contact process, these probabilities are always the same, regardless of what node we are looking at. How paths in the contact process are related to paths in oriented percolation is visualised in Figure 14. The probabilities are also 1-independent, since the probabilities of an edge being open only depend on whether or not the neighbouring edges are open.

This final part of the proof is showing that the event of an infinite path in the oriented percolation process is a subset of the event of an infinite path in the visual representation, which implies that the infection survives.

Let us consider an infinite path in the oriented percolation process, which starts at $(0, 0)$ without loss of generality. By construction if an edge starting from $(0, 0)$ is open it means there

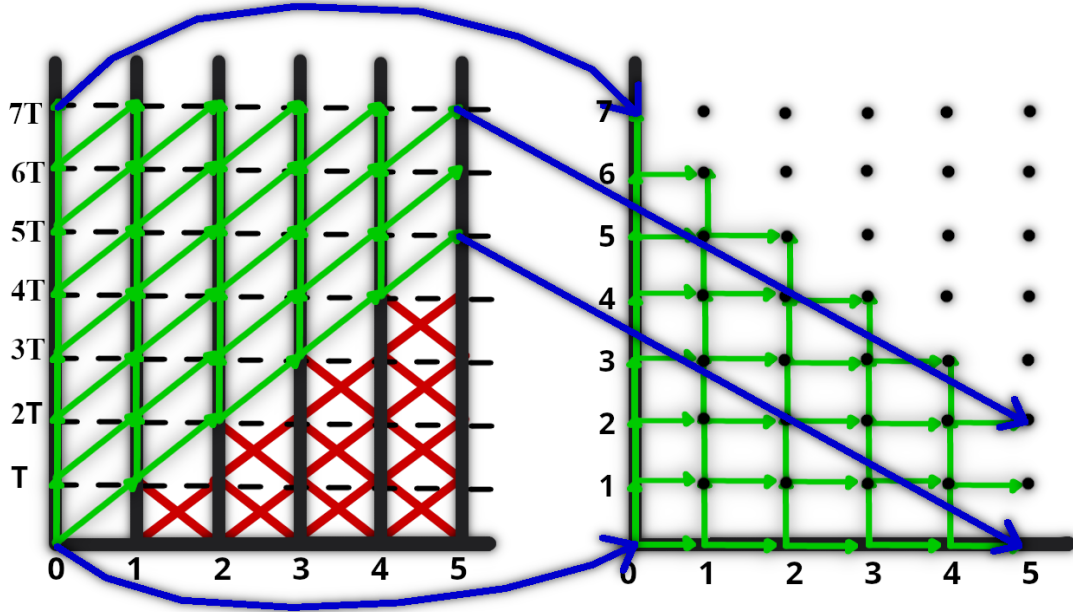


Figure 14: Coupling with Oriented percolation

is a path corresponding to this edge in the contact process. This argument holds for all edges in the path in the percolation process, which means that there is also an infinite path in the visual representation of the contact process, meaning that the contact process survives. Utilising that $\mathbb{P}[E] < \mathbb{P}[F]$ we see that $\mathbb{P}[E] > p_c$ is a sufficient condition for survival. \square

The event that neighbouring edges are open is positively correlated in the 1-independent percolation model above. This fact suggests that the critical probability of the model is smaller than that of normal oriented percolation.

Lemma 4.13. *The critical value of the 1-independent percolation model described in Theorem 4.12 is smaller or equal to $p_c(\mathbb{Z}^2)_{\text{oriented}}$.*

Proof. The proof consists of two steps, we first relate the critical percolation of the 1-independent model to that of another 1-independent percolation model such that the probability of an edge being open, in the absence of other information, is the same for all edges. Secondly, we show that the critical probability of this second model is smaller than that of ordinary oriented percolation.

To do the first step of the proof, note that we can always get a 1-independent percolation model where all edges are open with the same probability by resampling edges. We will use the events E and F as in Theorem 4.12.

We will randomly close vertical edges, so that the new probability that a vertical edges is open is equal to $\mathbb{P}[F]$. We see that difference between $\mathbb{P}[E]$ and $\mathbb{P}[F]$ is equal $e^{-(1+\lambda)T}$, so we will close vertical edges uniformly with probability $e^{-(1+\lambda)T}$, which gives us the correct resampled probability. Doing this only increases the critical probability, since more edges get closed. Denote this new model by $1OP$

Now note that if an edge is open, it never decreases the probability that the a neighbouring edge is open in the dependent oriented percolation process. Knowing that a vertical edge is open, increase the probability that the necessary path exists for the horizontal edge to be open.

Similarly, if we know that a path exists such that the horizontal edge is open, it increases the chances that there are no recoveries in the time interval, and therefore can only increase the chances that the vertical edges is open. Thus, if $p = e_1, e_2, \dots, e_n$ is a path of length n in oriented percolation,

$$\begin{aligned}\mathbb{P}[p \text{ open in } 1OP] &= \mathbb{P}[e_1 \text{ open in } 1OP] \mathbb{P}[e_2 \text{ open in } 1OP \mid e_1 \text{ open in } 1OP] \dots \\ &\quad \mathbb{P}[e_n \text{ open in } 1OP \mid e_{n-1} \text{ open in } 1OP] \\ &\geq \mathbb{P}[e_1 \text{ open in } OP] \mathbb{P}[e_2 \text{ open in } OP] \dots \mathbb{P}[e_n \text{ open in } OP] \\ &= \mathbb{P}[p \text{ open in } OP]\end{aligned}$$

Let Λ_n denote the box with radius n surrounding the origin. Then we get,

$$\begin{aligned}\mathbb{P}[\underline{0} \rightsquigarrow \delta\Lambda_n \text{ in } 1\text{-independent model}] &= \mathbb{P}\left[\bigcup_{p \text{ path from } \underline{0} \text{ to } \delta\Lambda_n} p \text{ open in } 1\text{-independent}\right] \\ &\geq \mathbb{P}\left[\bigcup_{p \text{ path from } \underline{0} \text{ to } \delta\Lambda_n} p \text{ open in ordinary } OP\right] \\ &= \mathbb{P}[\underline{0} \rightsquigarrow \delta\Lambda_n \text{ in ordinary } OP.]\end{aligned}$$

Taking the limit in the inequality above then proves the desired result. \square

To complete the upper bound, we need to determine an upper bound of the critical value of oriented edge percolation. To get an upper bound that is as good as possible, we will refer to one result from literature on oriented percolation. The following result is proven in [1].

Theorem 4.14. (*P. Ballister, B. Bollobás, A. Stacey, 1993*) *The following inequality holds on critical value of oriented edge percolation $p_c^{\text{oriented}} \leq 0.6863$.*

Finally we can combine all these results to find an upper bound on the critical value of the contact process on \mathbb{Z} , by finding an optimal value of T .

Corollary 4.15. *The value $\lambda_c(\mathbb{Z})$ is smaller than 5.6318.*

Proof. We have to minimise λ under the constraint that

$$\frac{1}{2}e^{-\frac{(3+\lambda)t}{2}} \left(\cosh \frac{Rt}{2} + \frac{1+3\lambda}{R} \sinh \frac{Rt}{2} \right) - \frac{1}{2}e^{-(1+\lambda)t} > 0.6863.$$

Then, Theorem 4.12, Lemma 4.13 and Theorem 4.14 allows us to conclude that for this value of λ it holds that $\lambda_c(\mathbb{Z}) < \lambda$. The problem is illustrated in Figure 15. There exists no nice algebraic expression for this, but numerically we can get $T \approx 0.4902$, yielding $\lambda_c < 5.6318$. \square

It is worth noting that connections have already been made between the contact process and oriented percolation. The connections have been very impactful to the study of the contact process and can be read about in the 1990 paper by Carol Bezuidenhout and Geoffrey Grimmett [2].

To end this chapter we combine all the results on the critical value of the contact process obtained so far.

Corollary 4.16. *The following bounds on the critical value of \mathbb{Z}^d hold.*

$$\frac{1}{8} + \frac{\sqrt{18d-1}}{8d\sqrt{2d-1}} \leq \lambda_c(\mathbb{Z}^d) < \frac{5.6318}{d}$$

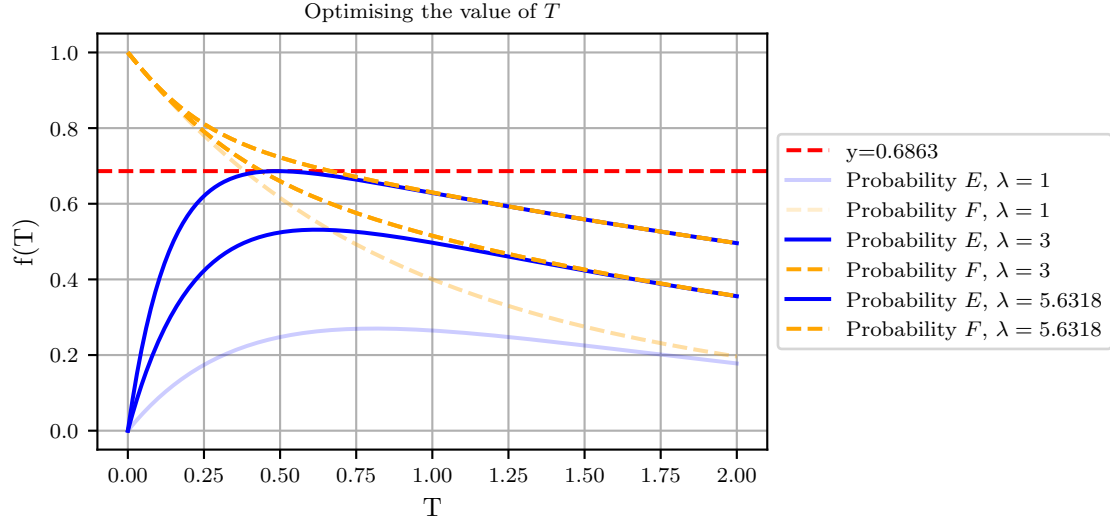


Figure 15: Finding the minimal value of lambda that fits the constraints.

Proof. Combine Theorem 4.4, Theorem 4.10 and Corollary 4.15. □

These estimates, especially the upper bound, are not particularly tight. The coupling with oriented percolation requires strong results on the critical value of oriented percolation, which makes it a rather weak result. Much tighter bound are available in the literature, namely it is known that [9, p. 308]

$$\frac{1}{2d-1} \leq \lambda_c(\mathbb{Z}^d) < \frac{2}{d}. \quad (4.3)$$

5 Numerical methods

While working on this thesis, extensive use has been made of computational methods. In this final chapter, I have compiled the most interesting results. Full scripts are provided in the appendix, together with a link to a GitHub repository with minimal working examples.

5.1 Visualisation

One useful tool to help understand a complex stochastic process, like the contact process, is a visualisation. Being able to see how the process behaves could give insights that are not obvious from the mathematical definition. In Appendix A.2 one can find a script for a simulation of the contact process on a small part of \mathbb{Z}^2 , plotting how it evolves in real-time. It includes controls for adjust the rate in real time with the scroll wheel, toggling full-screen with F11 and toggling a graph with the total number of infections using the left mouse button.

The heart of the simulation is the `contact_process` function. We generate Poisson events for all recoveries and infections in the time interval. The final state of the node is then updated in global list `inf` according to the most recent event. This sort of simulation is sometimes called tau-leaping, and is not entirely exact. One can imagine a situation where a node is healthy, get infected and infects one of its neighbours within one timestep. This infection of its neighbour would not be registered by this simulation.

However the big advantage of this technique is that the time required to simulate it does not grow as fast when a large number of nodes is infected. This makes it ideal for visualisation, as drawing the picture already takes up a large amount of the computing resources. The visualisation has been used in introduction to generate Figure 1.

We also focused on visualisations for the final presentation. To do so we used the mathematics animation Python package `manim`, specifically using the branch `manim-slides`[7] which is an adaptation of `manim` for presentations. The slides for the presentation, as well as the code used to generate it, are available on the GitHub page. Note that no efforts have been made to make this script more readable.

5.2 Improved lower bound

In Lemma 4.3 we derived a result which allows us to find a lower bound on the critical value of the contact process. We have done so for 2 frontier events in Theorem 4.4. It is interesting to ask ourselves how far we can go. In the subsection we will first numerically prove a stronger lower bound in one dimension, using the computer algebra package `sympy`. Finally, we will numerically calculate the expected value for $\lambda = 1.05$ to show that this value is a lower bound of the critical value $\lambda_c(\mathbb{Z})$.

Let us first look at the algebraic solver. We will consider what the contact process looks like, with an equivalence up to horizontal shifts. That means that in our program we will consider $\xi_t = \{-1, 1, 2\}$ to be the same as $\xi_t = \{2, 4, 5\}$. This will drastically reduce the number of steps our algorithm takes as we consider larger numbers of frontier events.

In our program we will start with a dictionary containing the state string `xox` and associated probability 1. This state string represents the class of states where one site is infected. Now, to calculate the distribution of frontiers after the next frontier event, we loop through every state string. For this state string we will consider all possible events and the probability that they occur. We track of these states and probabilities in a new dictionary, which can then be used for the next iteration of the loop.

A full implementation can be found in Appendix A.3. Using this implementation we now find the next lower bound.

Theorem 5.3. *The following lower bound holds*

$$\lambda_c(\mathbb{Z}) \geq 0.8958876.$$

Proof. Using the script in Appendix 4.3 until $d = 11$ together with Lemma 4.4 yields that $\lambda_c(\mathbb{Z}) \geq 0.8958876$. \square

However we can go further still. If we fix the value of λ and omit the symbolic expressions, the script can be sped up significantly, allowing us to go to greater depths than $d = 11$. We see that for $\lambda = 1$ the expected value dips below 1 after $d = 24$. However, not unsurprisingly, once we increase the value to $\lambda = 1.1$, by $d = 24$ the expected value is still approximately 1.29.

Theorem 5.4. *The following lower bound holds,*

$$\lambda_c(\mathbb{Z}) \geq 1.05.$$

Proof. Using the adapted script found in Appendix A.3 we see that with rate 1.05, for $d = 34$ the expected number of children after d frontier events is approximately 0.999052027980148 and hence with great certainty smaller than 1. Allowing us to conclude the lower bound with Lemma 4.4 \square

For both of the previous theorems, results were obtained after less than an hour of computation time. The amount of possible states after d frontier events scales roughly like 2^d , so the complexity of the algorithm is exponential. Given this fact, its unlikely that more computing time will lead to drastically better results.

One avenue of possible improvement we came across while working on these results comes from the following observation. If we let X_n denote the number of infections after n frontier events, it seems that in the supercritical case $\mathbb{E}[X_n]$ is strictly increasing. If this is indeed true, in order to show $\lambda \leq \lambda_c$ it suffices to show that $\mathbb{E}[X_n] - \mathbb{E}[X_{n+1}] \geq 0$ for some value of n . This is obviously much less difficult than showing that $\mathbb{E}[X_n] \leq 1$ for some n . A bit of time was spent trying to prove this fact, but it seems rather difficult to do so. Nonetheless, this could be an avenue of further research.

5.5 Numerical estimation of the critical value

Finally, we want to see if we can numerically determine the critical value of the contact process on \mathbb{Z} . We will use the bisection method to find the right most zero of the survival function ψ as defined in Definition 2.11. To do so, we will employ a suitable Monte Carlo method. We will simulate all the events in a contact process, starting with just the origin infected, for some number of attempts. If in any of these attempts, we exceed some threshold, we will conclude that this value is right of the rightmost zero. Otherwise we assume it to be left of the rightmost zero.

The simulation stores the contact process in a dictionary with tuples as keys storing node class objects. This node class contains a boolean to indicate whether the node is infected, and a count of all the uninfected neighbours of this node. Indexing our dictionary with tuples allows us to write the algorithm for arbitrary dimensions.

To generate the next event, we uniformly sample in $[0, 1]$ and then pick whether or not this event is a recovery or an infection by checking if our sampled value is smaller than the total infection rate divided by the total infection and recovery rate, then we uniformly sample over all the possible options. This is a valid approach by Lemma 1.6, and is much faster than simulating Poisson processes.

An implementation of this method is included in Appendix A.4. Some steps have been taken to optimise this script, for example, we are using the `operator.add` function to utilise c language speeds for checking all neighbouring tuples. Additionally, we use the `loky` library to allow for multiprocessing, yielding practical speed-up of about 4 to 8 times.

Using a threshold of 1000 infections, with 25 attempts, we tried estimating the critical value of the contact process for dimensions 1 to 20, starting from the bounds by Liggett (4.3). The threshold was too low to obtain any meaningful results for dimension 11 to 20, but for dimension 1 to 10 we got the results in Table 1 after several hours of computing.

Dimension	1	2	3	4	5	6	7	8	9	10
Estimate	1.646	0.413	0.219	0.153	0.114	0.099	0.079	0.072	0.060	0.054

Table 1: Estimates of the critical value for dimension 1 to 10

One might wonder how good these estimates are. However, we can compare them to other numerical estimates, like the ones by Munir Sabag and Mário de Oliveira [12], who did estimations up to dimension 5 for the conserved contact process back in 2002. It is noted by the authors that these values seems to agree with those of the ordinary contact process, which suffices for our purposes. Their estimations, corrected to undo normalisation, are shown in Table 2.

Dimension	1	2	3	4	5
Estimate	1.6489	0.41218	0.21947	0.14938	0.11384

Table 2: Estimates of the critical value for dimension 1 to 5 by Sabad and de Oliveira

Comparing these values with our estimations, we see that for these first 5 dimensions, we have a deviation of at most 0.005.

We can also employ this method to estimate how our survival function ψ from Definition 2.11 develops by counting the number of times we exceed the threshold in our total amount of attempts. Since this requires us to do many more attempts, we have to use a lower threshold to stay within a reasonable amount of computing time. One of these estimations is shown in Figure 5. This was generated with 250 attempts and a threshold of 100, requiring about 2 hours of computing. We calculated an empirical probability for several values, increasing the density as we approach the critical value, to compensate for the larger slope.

6 References

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- [12] Munir M. S. Sabag and Mário J. de Oliveira. Conserved contact process in one to five dimensions. *Phys. Rev. E*, 66:036115, Sep 2002.
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A Python scripts

All scripts have been confirmed to work with Python version 3.13.2, with exception of the script for the final presentation, which runs on Python version 3.10.11 due to some outdated dependencies. In the table below you can find all packages used, with the specific version.

Package	Version	Available at
numpy	2.1.3	https://pypi.org/project/numpy/2.1.3/
matplotlib	3.10.1	https://pypi.org/project/matplotlib/3.10.1/
scipy	1.15.2	https://pypi.org/project/scipy/1.15.2/
networkx	3.4.2	https://pypi.org/project/networkx/3.4.2/
loky	3.5.2	https://pypi.org/project/loky/3.5.2/
psutil	7.0.0	https://pypi.org/project/psutil/7.0.0/
manim	0.19.0	https://pypi.org/project/manim/0.19.0/
manim-slides	5.5.1	https://pypi.org/project/manim-slides/5.5.1/

The code in the chapter has been reduced to a minimal working example, wherever that makes sense. This means that all code that is not relevant to solving the problem at hand, such as plot labels, has been removed. All scripts are accessible at this [GitHub page](#).

A.1 Expected extinction time on cyclic graphs

In subsection 3.1 we derived a system of equation to find a lower and upper bound on the expected extinction time of the contact process on a cyclic graph given different initial configurations. We used a symbolic solver to derive Figure 9. This appendix contains the scripts to solve these systems. First, we have a script to solve the system for the lower bound algebraically.

```

1 from sympy import symbols, Rational
2 import sympy.plotting as spp
3 from sympy.matrices import Matrix
4 import math
5 '''
6 We define a sympy symbol, specify the dimension of the system, and initialise the
7 ↪ matrix and vector.
8 '''
9 l = symbols("l")
10 n = 5
11 b = [1/(2*l + i + 1) for i in range(n - 1)] + [Rational(1, n)]
12 A = []
13 for i in range(n - 1):
14     A.append([- (i + 1)/(2*l + i + 1) if i == j + 1 else 1 if i == j else - (2 *
15 ↪ 1)/(2*l + i + 1) if i == j - 1 else 0 for j in range(n)])
16 A.append([0 for _ in range(n-2)] + [-1, 1])
17 '''
18 We solve the system, and plot the result.
19 '''
20 r = Matrix(A).LUsolve(Matrix(b))
21 p1 = spp.plot(r[-1], (l, 0, 3), show=False)
22 p1.show()

```

We can easily adapt this script to solve the upper bound system, by replacing line 10 to line 14 with the following code snippet.

```

1 b = [1 / (2 * i * l + i + 1) if i <= math.floor((n - 1) / 2) else 1 / (2 * (n - i -
  ↳ 1) * l + i + 1) for i in range(n - 1)] + [Rational(1,n)]
2 A = []
3 for i in range(n - 1):
4     A.append([
5         -(i + 1) / (2 * min(i, n - i - 1) * l + i + 1) if i == j + 1 else 1 if i ==
  ↳ j else
6         -(2 * min(i, n - i - 1) * l) / (2 * min(i, n - i - 1) * l + i + 1) if i ==
  ↳ j - 1 else 0 for j in range(n)
7     ])
8 A.append([0 for _ in range(n-2)] + [-1, 1])

```

We also studied the behaviour of the bounds for fixed lambda, as n grows. To solve these larger systems, we use a sparse matrix implementation. This can solve the systems at a fraction of the time required compared to the regular solver. These scripts have been used to generate the plots in Figure 10.

```

1 from scipy.sparse import diags
2 from scipy.sparse.linalg import spsolve
3 import math
4 import numpy as np
5 import matplotlib.pyplot as plt
6 '''
7 We define a rate, specify the range of dimension for which we solve the system, and
  ↳ initialise the matrix and vector.
8 '''
9 l = 0.25
10 n_values = range(2, 40) # Range of n values to observe growth
11 solutions = []
12 '''
13 Solve the system and plot the solution
14 '''
15 for n in n_values:
16     b = np.array([1 / (2 * l + i + 1) for i in range(n - 1)] + [1 / n])
17     diagonals = [
18         [-(i + 1) / (2 * l + i + 1) for i in range(1, n)], # Sub-diagonal
19         [1] * n, # Main diagonal
20         [-(2 * l) / (2 * l + i + 1) for i in range(n - 1)] # Super-diagonal
21     ]
22     A = diags(diagonals, offsets=[-1, 0, 1], shape=(n, n)).toarray()
23     A[-1, -2:] = [-1, 1]
24     r = spsolve(A, b)
25     solutions.append(r[-1])
26 plt.plot(n_values, solutions)
27 plt.show()

```

Where again the script can easily be adapt to work for the upper bound by replacing line 15 to 19 by the next snippet.

```

1 b = np.array([1 / (2 * i * l + i + 1) if i <= math.floor((n - 1) / 2) else 1 / (2 *
  ↳ (n - i - 1) * l + i + 1) for i in range(n - 1)] + [1 / n])
2 diagonals = [

```



```

3      [-(i + 1) / (2 * min(i, n - i - 1) * l + i + 1) for i in range(1, n)],
      ↪ # Sub-diagonal
4      [1] * n,
      ↪ # Main diagonal
5      [-(2 * min(i, n - i - 1) * l) / (2 * min(i, n - i - 1) * l + i + 1) for i in
      ↪ range(n - 1)] # Super-diagonal
6  ]

```

A.2 Visualisation

The following script does an estimation of the contact process as described in subsection 5.1. As a reminder, it includes controls to adjust the rate in real time with the scroll wheel, toggle full screen with F11 and toggle a graph with the total number of infections using the left mouse button.

```

1  import matplotlib.pyplot as plt
2  from matplotlib.backends.backend_tkagg import FigureCanvasTkAgg
3  import tkinter as tk
4  from tkinter import *
5  import psutil
6  import numpy as np
7  import networkx as nx
8
9  '''
10 We configure a Tkinter window, and the associated objects required to draw the
   ↪ network and graph.
11 '''
12 root = Tk()
13 defaultFont = tk.font.nametofont('TkDefaultFont')
14 frame= Frame(root).pack(fill= BOTH, padx= 0, pady=0)
15 root.title("Contact process")
16 screen_width = root.winfo_screenwidth()
17 screen_height = root.winfo_screenheight()
18 fig = plt.figure(frameon=True, figsize=(screen_width/100,screen_height/100),
   ↪ dpi=102)
19 canvas = FigureCanvasTkAgg(fig, root)
20
21 '''
22 Keybinds:
23 button_0      :   Display a graph that shows the number of infection over time.
24 scroll         :   Increase/decrease the rate of infection.
25 F11           :   Toggle fullscreen.
26 '''
27 root.bind("<F11>", lambda e: root.attributes("-fullscreen", not
   ↪ root.attributes("-fullscreen")))
28 root.bind("<Button-1>", lambda event: globals().__setitem__('display_infections',
   ↪ not display_infections))
29 root.bind("<MouseWheel>", lambda event: globals().__setitem__('r', max(0, r + 0.1
   ↪ if event.delta > 0 else r - 0.1)))
30
31 '''
32 Main variables:

```

```

33 G : The graph on which we run the contact process.
34 dt : The timestep in ms at which we update the graph.
35 T : The final time in ms the simulation
36 r : The initial infection rate per second
37 display_infection : Bool that determines whether or not a graph is displayed
↪ that shows recent infections.
38 inf : A list of infected nodes
39 inf_count : Stores the number of infected nodes at each timestep
40 '''
41 scale = 35
42 G = nx.grid_2d_graph((int)(screen_height/scale), (int)(screen_width/scale))
43 dt, T, r = 500, 1000000, 0.5
44 global display_infections; display_infections = False
45 inf = {list(G)[i] : 1 for i in range(len(list(G)))}
46 pos = {(x,y):(y,-x) for x,y in G.nodes()}
47 inf_count = []
48
49 def generate_poisson_events(rate, time_duration):
50     '''
51     rate : The rate of the Poisson process
52     time_duration : The time interval in which to generate events.
53     Runs the poisson process and returns the time of the last hit. If not hits
↪ occur, returns -1.
54     '''
55     num_events = np.random.poisson(rate * time_duration)
56     event_times = np.sort(np.random.uniform(0, time_duration, num_events))
57     if num_events > 0:
58         return np.max(event_times)
59     return -1
60
61 def contact_process(graph, dt, rate):
62     '''
63     graph : The graph on which we do the contact process
64     dt : The simulation timestep
65     rate : The rate of the contact process
66     Updates the inf array to represent the contact process and append the number of
↪ infection at this time to inf_count
67     '''
68     for i in graph.nodes():
69         recov_time = generate_poisson_events(1/1000, dt)
70         inf_time = -1
71         for j in nx.all_neighbors(graph, i):
72             if inf[j] == 1:
73                 inf_time = max(inf_time, generate_poisson_events(rate/1000, dt))
74             if inf_time >= 0 or recov_time >= 0:
75                 inf[i] = 0 if recov_time > inf_time else 1
76         inf_count.append(sum(1 for value in inf.values() if value == 1))
77
78     '''Generates colours for networkx to draw infected nodes red, and healthy ones
↪ blue'''
79 def generate_colour_map(inf):
80     return ['#BF211E' if value == 1 else '#1f77b4' for value in inf.values()]
81

```

```

82
83 def timeStep(current_time):
84     '''
85     current_time    :    The time at which we want to display the contact process
86     This function clears the previous figure does the following three things
87     1. Draw a label that show the current rate
88     2. Draw G
89     3. If display_infections is true, draw a graph that shows the number of
      ↪ infections
90     '''
91     plt.clf()
92     r_label = Label(root, text=f"Rate (1): {r:.2f}", font=("Open Sans", 36),
      ↪ fg="black", bg="white", bd=5, relief="solid")
93     r_label.place(relx=0.5, rely=0.03, anchor="n")
94     r_label.config(text=f"Rate (1): {r:.2f}")
95
96     col = generate_colour_map(inf)
97     ax = plt.gca()
98     ax.set_xlim([min(x for x, y in pos.values()) + 1, max(x for x, y in
      ↪ pos.values()) - 1])
99     ax.set_ylim([min(y for x, y in pos.values()) + 1, max(y for x, y in
      ↪ pos.values()) - 1])
100    ax.set_axis_off()
101    nx.draw(G, pos, ax=ax, node_size=screen_width/(0.1*scale), node_color=col,
      ↪ with_labels=False, edgecolors='black', linewidths=1.5, node_shape='s')
102    plt.subplots_adjust(left=0, right=1, top=1, bottom=0)
103
104    if(display_infections):
105        plt.subplot(1, 2, 1, facecolor=(1, 1, 1, 0.8))
106        plt.plot(inf_count[max(0, len(inf_count) - 100): len(inf_count) -
      ↪ 1],linewidth=5)
107        plt.ylim(0, len(G.nodes()))
108        plt.xlabel("time (ms)", labelpad=-35, loc='center', fontsize=18),
      ↪ plt.ylabel("infections", labelpad=-35, loc='center', fontsize=18)
109        plt.title("Infected sites over time", pad=-20, loc='center', y=0.95,
      ↪ fontsize=36)
110        plt.gca().tick_params(labelsize=0)
111        for spine in plt.gca().spines.values():
112            spine.set_edgecolor('black')
113            spine.set_linewidth(5)
114
115    canvas.draw()
116    canvas.get_tk_widget().pack(side=TOP, fill=BOTH, expand=True)
117
118    '''
119    Main loop:
120    Runs the contact and visualises the contact process until time T.
121    '''
122    for i in range((int)(T/dt)):
123        if not (1 in inf.values()):
124            break
125        root.update_idletasks()
126        root.update()

```

```

127     contact_process(G, dt, r)
128     root.after(0, timeStep(i*dt))
129     root.mainloop()

```

The code used for generating the final presentation is also available on the GitHub. The file name is `FinalPresentation.py`. Note that no efforts have been made to make this script more readable.

A.3 Improved lower bound

This is the script associated with the algebraic solver in subsection 5.2.

```

1  import sympy as sp
2  '''
3  First initialise key variables. The variable initial is a dictionary that has all
4  ↪ frontiers in a step,
5  with the associated probability. In this dictionary, zeroes denote infected sites,
6  ↪ crosses healthy ones.
7  The max number of iterations the program will run is stored in d. For the sympy
8  ↪ algebra we define a
9  symbol lambda.
10 '''
11
12 initial = { "xox" : 1}
13 d = 10
14 l = sp.Symbol('l')
15 '''
16
17 state : String that represents a frontier state.
18 Finds total rate of events that change the frontier.
19 '''
20
21 def getTotalRate(state):
22     rate = 2*l
23     for i in range(1, len(state) - 1):
24         rate += 1 if state[i] == 'o' else 1 * (int(state[i - 1] == 'o') +
25         ↪ int(state[i + 1] == 'o'))
26     return rate
27 '''
28
29 string : String to change
30 insert : The value to insert into string
31 position : Position at which we will insert string
32 Returns string with insert inserted at position.
33 '''
34
35 def stringReplace(string, insert, position):
36     return string[:position] + insert + string[position + 1:]
37 '''
38
39 heal : A bool that indicates whether or not the event is a recovery
40 i : The current index in state
41 totalRate : The total rate of infection/healing in state
42 state : A string that indicates current state of the frontier
43 probability : The probability of reaching state
44 next : The dictionary of possible states with probabilities after one more
45 ↪ event
46 Returns updated next with the events at i accounted for.
47 '''

```

```

37 def event(heal, i, totalRate, state, probability, next):
38     if(heal):
39         st = stringReplace(state, 'x', i)
40         while st[1] == 'x' and st != 'xx':
41             st = st[1:]
42         while st[len(st) - 2] == 'x' and st != 'xx':
43             st = st[:len(st) - 1]
44         prob = probability * 1/totalRate
45     else:
46         st = stringReplace(state, 'xo' if i == 0 else 'ox' if i == len(state) - 1
47             ↪ else 'o', i)
48         prob = probability * 1/totalRate * 1
49         next[st] = next.get(st, 0) + prob
50     return next
51 '''
52 state_dict : Dictionary with frontier states and associated probabilities
53 Returns the expected number of children with the frontier distribution state_dict.
54 '''
55 def expectation(state_dict):
56     return sum(prob * state.count('o') for state, prob in state_dict.items())
57 '''
58 Using the event function, this snippet of code determine and prints the expect
59 ↪ number
60 of infections after d frontier events. We loop through all states, and to all
61 ↪ nodes
62 in these states, appending the result of every possible event with the associated
63 probability to next.
64 '''
65 next_state = initial
66 for index in range(d+1):
67     next = {}
68     for state in next_state:
69         probability = next_state[state]
70         totalRate = getTotalRate(state)
71         if(state == "xx" ):
72             if (state in next):
73                 next[state] += probability
74             else:
75                 next.update({ state : probability} )
76         elif(state != "xx" ):
77             next = event(False, 0, totalRate, state, probability, next)
78             next = event(False, len(state) - 1, totalRate, state, probability,
79                 ↪ next)
80             for i in range(1, len(state) - 1):
81                 if state[i] == 'o':
82                     next = event(True, i, totalRate, state, probability, next)
83                 else:
84                     if state[i - 1] == 'o':
85                         next = event(False, i, totalRate, state, probability, next)
86                     if state[i + 1] == 'o':
87                         next = event(False, i, totalRate, state, probability, next)
88     next_state = next

```

```

86     print(f"iteration {index}: l = {sp.nsolve(expectation(next_state) - 1, 1, 1)}")
87     '''
88     We finally plot the solution to show how the expected value develops.
89     '''
90     p1 = sp.plot(expectation(next_state), xlim = (0, 3), ylim = (0,2), show=False)
91     p1.show()

```

We can do some slight adaptations to the script to do numerical approximations of the lower bound. By changing 1 in line 10 to a fixed value and then replacing line 61 to 96 with the following snippet we get the expected value for a fixed value of λ .

```

1     '''
2     Using the event function, this snippet of code determine and prints the expect
   ↪ number
3     of infections after d frontier events. We loop through all states, and to all
   ↪ nodes
4     in these states, appending the result of every possible event with the associated
5     probability to next.
6     '''
7     next_state = initial
8     for index in range(d):
9         next = {}
10        for state in next_state:
11            probability = next_state[state]
12            totalRate = getTotalRate(state)
13
14            if(state == "xx"):
15                if (state in next):
16                    next[state] += probability
17            else:
18                next.update({ state : probability} )
19
20        elif(state != "xx"):
21            next = event(False, 0, totalRate, state, probability, next)
22            next = event(False, len(state) - 1, totalRate, state, probability,
   ↪ next)
23
24        for i in range(1, len(state) - 1):
25            if state[i] == 'x':
26                if state[i - 1] == 'o':
27                    next = event(False, i, totalRate, state, probability, next)
28                if state[i + 1] == 'o':
29                    next = event(False, i, totalRate, state, probability, next)
30            elif state[i] == 'o':
31                next = event(True, i, totalRate, state, probability, next)
32        next_state = next
33        print("expected children at depth " + str(index) + " = " +
   ↪ str(expectation(next_state)))

```

A.4 Numerical estimation of the critical value

This final script numerically estimates the critical value of the contact process for the dimensions 1 to 20. The script can easily be modified to exclusively generate estimates for dimension 1 or

to estimate the survival functions ψ .

```

1 import numpy as np
2 import loky
3 from loky import as_completed
4 import random
5 import operator
6 '''
7 attempts      :      The total number of contact processes that are tried.
8 thres         :      The total number of infections required to declare survival
9 max_dimension  :      The largest dimension for which we will determine the
    ↪ critical probability.
10 '''
11
12 attempts = 25
13 thres = 500
14 max_dimension = 20
15 max_steps = np.inf
16 neighbour_offset = []
17 '''
18 Node object to represent each node in the contact process
19 Each node has an infected status and a count of uninfected neighbours
20 '''
21 class Node:
22     def __init__(self, infected = True, uninfected_neighbours=2):
23         self.infected = infected
24         self.uninfected_neighbours = uninfected_neighbours
25     def __repr__(self):
26         return f"Node(infected={self.infected},
27             ↪ uninfected_neighbours={self.uninfected_neighbours})"
28 '''
29 Runs one timestep of the contact process
30 total_infections      :      Total number of infections in the system
31 total_rate            :      Total rate of infection in the system
32 key_list              :      List of keys representing the current state of the system
33 contact_process       :      Dictionary representing the current state of the system
34 rate                 :      The rate of infection
35 Returns the updated list of keys, contact process, total infections, and total
36 ↪ rate
37 '''
38 def time_step(total_infections, total_rate, key_list, contact_process, rate):
39     infection = np.random.uniform(0, 1) < total_rate / (total_infections +
40     ↪ total_rate)
41     if(not infection):
42         index = np.random.randint(0, len(key_list))
43         toheal = key_list[index]
44         contact_process[toheal].infected = False
45         total_rate -= contact_process[key_list[index]].uninfected_neighbours * rate
46         total_infections -= 1
47         for offset in neighbour_offset:
48             neighbour_key = tuple(map(operator.add, key_list[index], offset))
49             contact_process[neighbour_key].uninfected_neighbours += 1
50             if contact_process[neighbour_key].infected:
51                 total_rate += rate

```

```

49     key_list[index] = key_list[-1]
50     key_list.pop()
51     elif(infection):
52         options = []
53         infect = random.choices(key_list,
54             ↪ weights=[contact_process[key].uninfected_neighbours for key in
55             ↪ key_list], k=1)[0]
56         for offset in neighbour_offset:
57             neighbour_key = tuple(map(operator.add, infect, offset))
58             if neighbour_key in contact_process and not
59                 ↪ contact_process[neighbour_key].infected:
60                 options.append(neighbour_key)
61
62         new = np.random.randint(0, len(options))
63         contact_process[options[new]].infected = True
64         total_rate += contact_process[options[new]].uninfected_neighbours * rate
65         total_infections += 1
66         key_list.append(options[new])
67         for offset in neighbour_offset:
68             neighbour_key = tuple(map(operator.add, options[new], offset))
69             if neighbour_key not in contact_process:
70                 contact_process[neighbour_key] = Node(False, 2*dimension - 1)
71             else:
72                 contact_process[neighbour_key].uninfected_neighbours -= 1
73                 if contact_process[neighbour_key].infected:
74                     total_rate -= rate
75         return total_infections, total_rate, key_list, contact_process
76
77     '''
78     Threshold : The threshold for the number of infections
79     dimension : Dimension of the graph  $Z^d$ 
80     Run one iteration of the contact process until the number of infections is greater
81     ↪ than 100 or smaller or equal to 0
82     Returns True if the number of infections is greater than or equal to the threshold,
83     ↪ False otherwise
84     '''
85     ti = 0
86     tr = 0
87     def run_contact_process(rate, dimension):
88         akeys_lst = []
89         akeys_lst.append(tuple((0 for _ in range(dimension))))
90         cprocess = {tuple([0 for _ in range(dimension)]): Node(True, 2*dimension)}
91         for i in range(dimension):
92             for offset in [1, -1]:
93                 neighbour_key = tuple(tuple((0 for _ in range(dimension)))[j] + (offset
94                     ↪ if j == i else 0) for j in range(dimension))
95                 cprocess[neighbour_key] = Node(False, 2*dimension - 1)
96
97     ti = 1
98     tr = 2 * rate * dimension
99     steps = 0
100     while ti < thres and ti > 0 and steps < max_steps:
101         steps += 1
102         ti, tr, akeys_lst, cprocess = time_step(ti, tr, akeys_lst, cprocess, rate)

```



```

96     if ti >= thres:
97         return True
98     return False
99
100     """
101     low          :    The lower bound for the critical value
102     high         :    The upper bound for the critical value
103     attempts     :    The number of attempts to run the contact process
104     epsilon      :    The tolerance for the bisection method
105     dimension     :    Dimension of the graph  $Z^d$ 
106     Given a lower and upper bound, estimate the critical value using bisection method.
107     Returns lower and upper estimate for the critical value
108     """
109     def crit_value_bisection(low, high, attempts, epsilon, dimension):
110         with loky.get_reusable_executor(max_workers=14) as executor:
111             while high - low > epsilon:
112                 found_true = False
113                 tasks_completed = 0
114                 mid = (low + high) / 2
115                 futures = set()
116                 for _ in range(attempts):
117                     future = executor.submit(run_contact_process, mid, dimension)
118                     futures.add(future)
119                 for future in as_completed(futures):
120                     tasks_completed += 1
121                     result = future.result()
122                     if result:
123                         found_true = True
124                     if found_true:
125                         break
126                 if found_true:
127                     high = mid
128                 else:
129                     low = mid
130                 print(f"The critical value is likely between {low:.6f} and
131                     ↪ {high:.6f}.")
132             return high, low
133
134     """
135     Determine the critical value in for various dimensions.
136     """
137     for dimension in range(1, max_dimension + 1):
138         neighbour_offset = []
139         for i in range(dimension):
140             for offset in [1, -1]:
141                 neighbour_offset.append([offset if j == i else 0 for j in
142                     ↪ range(dimension)])
143         rate_low = 1/(2*dimension - 1)
144         rate_high = 2/(dimension)
145         rate_high, rate_low = crit_value_bisection(rate_low, rate_high, attempts,
146             ↪ 0.001, dimension)
147         print(f"The critical value in dimension {dimension} is likely between
148             ↪ {rate_low:.6f} and {rate_high:.6f}.")

```