


Local Access to Huge Random Objects through Partial Sampling

Amartya Shankha Biswas 

CSAIL, MIT

asbiswas@mit.edu

Ronitt Rubinfeld

CSAIL, MIT

ronitt@csail.mit.edu

Anak Yodpinyanee 

CSAIL, MIT

anak@csail.mit.edu

Abstract

Consider an algorithm performing a computation on a *huge random object* (for example a random graph or a “long” random walk). Is it necessary to generate the entire object prior to the computation, or is it possible to provide query access to the object and sample it incrementally “on-the-fly” (as requested by the algorithm)? Such an *implementation* should emulate the random object by answering queries in a manner consistent with an instance of the random object sampled from the true distribution (or close to it). This paradigm is useful when the algorithm is sub-linear and thus, requiring the algorithm to sample the entire object up front would ruin its efficiency.

Our first set of results focus on undirected graphs with independent edge probabilities, i.e. each edge is chosen as an independent Bernoulli random variable. We provide a general implementation for this model under certain assumptions. Then, we use this to obtain the first efficient local implementations for the Erdős-Rényi $G(n, p)$ model, and the Stochastic Block model. As in previous local-access implementations for random graphs, we support VERTEX-PAIR and NEXT-NEIGHBOR queries. In addition, we introduce a new RANDOM-NEIGHBOR query. We also give the first local-access generation procedure for ALL-NEIGHBORS queries in the (sparse and directed) Kleinberg’s Small-World model. **Note that, in the sparse case, an ALL-NEIGHBORS query can be used to simulate the other types of queries efficiently.** Our implementations require no pre-processing time, and answer each query using $O(\text{poly}(\log n))$ time, random bits, and additional space.

We next show how to implement random Catalan objects, specifically focusing on Dyck paths (balanced random walks that are always positive). Here, we support HEIGHT queries to find the location of the walk, and FIRST-RETURN queries to find the time when the walk returns to a specified location. This in turn can be used to implement NEXT-NEIGHBOR queries on random rooted and binary trees, and MATCHING-BRACKET queries on random well bracketed expressions (the Dyck language).

Finally, we study random q -colorings of graphs with maximum degree Δ . This is a more difficult setting where the random object also has a “huge” description (the underlying graph) that can be accessed through adjacency list queries. **This setting is similar to Local Computation Algorithms [RTVX11, ARVX12]** with the added restriction that the output must follow a specific distribution in addition to being legal. We show how to sample the color of a single node in sub-linear time when $q > \alpha\Delta$ where α is a small constant.

2012 ACM Subject Classification Author: Please fill in 1 or more \ccsdsc macro

Keywords and phrases Dummy keyword

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Funding *Amartya Shankha Biswas*: funding

Ronitt Rubinfeld: funding

Anak Yodpinyanee: funding

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1 Introduction

Consider an algorithm performing a computation on a *huge random object* (for example a random graph or a “long” random walk). Is it necessary to generate the entire object prior to the computation, or is it possible to provide query access to the object and sample it incrementally “on-the-fly” (as requested by the algorithm)? Such an *implementation* would emulate the random object by answering appropriate queries in a consistent manner. Specifically, all responses to queries must be consistent with an instance of the random object sampled from the true distribution (or close to it). This paradigm is useful when the algorithm is sub-linear and thus, requiring the algorithm to sample the entire object up front would ruin its efficiency. The problem of sampling partial information about huge random objects was pioneered in [GGN03, GGN10]. Further work in [NN07, ELMR17] considers the generation of different random graph models.

1.1 Random Graphs

In Section 3, we implement queries to both the adjacency matrix and adjacency list representation for the generic class of *undirected graphs* with *independent edge probabilities* $\{p_{uv}\}_{u,v \in V}$, where p_{uv} denotes the probability that there is an edge between u and v . Throughout, we identify our vertices via their unique IDs from 1 to n , namely $V = [n]$. We implement **VERTEX-PAIR**, **NEXT-NEIGHBOR**, and **RANDOM-NEIGHBOR**¹ queries. Under reasonable assumptions on the ability to compute certain values pertaining to consecutive edge probabilities, our implementations support all three types of queries using $\mathcal{O}(\text{poly}(\log n))$ time, space, and random bits. In particular, our construction yields local-access implementations for the Erdős-Rényi $G(n, p)$ model (for *all* values of p), and the Stochastic Block model with random community assignment. As in [ELMR17] (and unlike the implementations in [GGN03, GGN10, NN07]), our techniques allow unlimited queries.

While **VERTEX-PAIR** and **NEXT-NEIGHBOR** queries, as well as **ALL-NEIGHBORS** queries for sparse graphs, have been considered in the prior works of [ELMR17, GGN03, GGN10, NN07], we provide the first implementation (to the best of our knowledge) of **RANDOM-NEIGHBOR** queries, which do not follow trivially from the **ALL-NEIGHBORS** queries in *non-sparse graphs*. Such queries are useful, for instance, for sub-linear algorithms that employ random walk processes. **RANDOM-NEIGHBOR** queries present particularly interesting challenges that are outlined below.

Directed Random Graphs: The Small World Model

We then consider local-access implementations for directed graphs in Kleinberg’s Small World model. In this case, the probabilities are based on distances in a 2-dimensional grid. Using a modified version of our previous sampling procedure, we implement **ALL-NEIGHBORS** queries using $\mathcal{O}(\text{poly}(\log n))$ time, space and random bits (since such graphs are sparse, the other queries follow directly).

1.2 Catalan Objects

We also consider the problem of sampling of very long ($2n$ step) one dimensional random walks. One obvious query of interest is **HEIGHT**(t) which returns the position of the walk at time t . **HEIGHT** queries for the simple unconstrained random walk follow trivially from the implementation of interval

¹**VERTEX-PAIR**(u, v) returns whether u and v are adjacent, **NEXT-NEIGHBOR**(v) returns a new neighbor of v each time it is invoked (until none is left), and **RANDOM-NEIGHBOR**(v) returns a uniform random neighbor of v (if v is not isolated).

summable functions presented in [GGN10]. Instead, we focus on an important generalization by considering balanced random walks (equal number of up and down steps) that are constrained to be always positive (commonly known as Dyck Paths). The added constraint introduces complicated non-local dependencies on the distribution of positions. However, we are able to support both queries using $\mathcal{O}(\text{poly}(\log n))$ resources.

Dyck paths are one type of Catalan object, and they have natural bijections to other Catalan objects such as bracketed expressions, random rooted trees and binary trees. Thus, we can use our Dyck Path implementation to obtain useful implementations of other random Catalan objects. For instance, **HEIGHT** queries correspond to **DEPTH** queries on rooted trees and bracketed expressions (Section 6.1).

However, we might want to support more interesting queries; for example, finding the children of a node in a random tree or finding the matching bracket in a random bracketed expression. To achieve this, we will also support **FIRST-RETURN** queries where **FIRST-RETURN**(t) returns the first time when the random walk returns to the same level as it was at time t . In Section 6.1, we will see that **FIRST-RETURN** queries correspond to **NEXT-NEIGHBOR** queries on trees and **MATCHING-BRACKET** queries on bracketed expressions.

1.3 Random Coloring of Graphs

Finally, we introduce a new model for implementating huge random objects with *huge description size*; that is, the distribution is specified as a uniformly random solution to a huge combinatorial problem. In this model, we implement query access to random q -colorings of a given huge graph G with maximum degree Δ . A random coloring is sampled by proposing $\mathcal{O}(n \log n)$ color updates and accepting the ones that do not create a conflict (Glauber dynamics). This is an inherently sequential process with the acceptance of a particular proposal depending on all preceding neighboring proposals. Moreover, unlike the previously considered random objects, this one has no succinct representation, and we can only uncover the proper distribution by probing the graph (in the manner of *local computation algorithms* [RTVX11]). Unlike LCAs which have to return *some* valid solution, we also have to make sure that we return a solution from the correct distribution. We are able to construct an efficient oracle that returns the final color of a vertex using only a sub-linear number of probes when $q \geq 7\Delta$.

For additional related work, see Section E.

2 Our Contributions and Techniques

The problem of computing local information of huge random objects was pioneered in [GGN03, GGN10]. Further work of [NN07] considers the generation of sparse random $G(n, p)$ graphs from the Erdős-Rényi model [ER60], with $p = O(\text{poly}(\log n)/n)$, which answers $\text{poly}(\log n)$ **ALL-NEIGHBORS** queries, listing the neighbors of queried vertices. While these implementations use polylogarithmic resources over their entire execution, they generate graphs that are only guaranteed to *appear random* to algorithms that inspect a *limited portion* of the generated graph. For example, the greedy routing algorithm on Kleinberg’s small world networks [Kle00] only uses $\mathcal{O}(\log^2 n)$ probes. Using our implementation, one can execute this algorithm on a random small world instance in $\mathcal{O}(\text{poly}(\log n))$ time without incurring the $\mathcal{O}(n)$ prior-sampling overhead.

In [ELMR17], the authors construct an oracle for the generation of recursive trees, and BA preferential attachment graphs. Unlike [NN07], their implementation allows for an arbitrary number of queries. This result is particularly interesting – although the graphs in this model are generated

Why are first returns difficult?

Dependencies from past queries

via a sequential process, the oracle is able to locally generate arbitrary portions of it and answer queries in polylogarithmic time. Though preferential attachment graphs are sparse, they contain vertices of high degree, thus [ELMR17] provides access to the adjacency list through **NEXT-NEIGHBOR** queries.

2.1 Local-Access Implementations

We begin by formalizing the model of *local-access implementations* (truthful implementation from [GGN10]?). Our work provides local-access implementations for various random objects described below.

► **Definition 1.** Given a distribution X over a set of huge random objects \mathbb{X} , a local access implementation of a family of query functions $\langle F_1, F_2, \dots \rangle$ where $F_i : \mathbb{X} \rightarrow \{0, 1\}$, provides an oracle that returns the value $F_i(X)$ for $X \sim \mathbb{X}$ and a given query F_i , while satisfying the following:

- **Consistency:** All the values $F_i(X)$ returned by the local-access implementation throughout the entire execution must be consistent with a single $X \in \mathbb{X}$.
- **Distribution equivalence:** The random object $X \in \mathbb{X}$ consistent with the responses $\{F_i(X)\}$ must be sampled from some distribution \mathbb{X}' that is ϵ -close to the desired distribution \mathbb{X} in L_1 -distance. In this work we focus on supporting $\epsilon = n^{-c}$ for any desired constant $c > 0$.
- **Performance:** The computation time, additional random bits, and additional space required to answer a single query must be sub-linear, and preferably $\text{poly}(\log n)$ with high probability.

In particular, we allow queries to be made adversarially and non-deterministically. The adversary has full knowledge of the algorithm's behavior and its past random bits.

2.2 Basic Tools for Efficient Sampling

This section is incomplete.

► **Lemma 2.** Let $\{p_i\}$ and $\{q_i\}$ be distributions satisfying the following conditions

1. There is a poly-time algorithm to approximate p_i and q_i up to $\pm n^{-2}$
2. Generating an index i according to q_i is closely implementable.
3. There exists a $\text{poly}(\log n)$ -time recognizable set B such that
 - $1 - \sum_{i \in B} p_i$ is negligible
 - There exists a constant c such that for every i , it holds that $p_i \leq \log^{O(1)} n \cdot q_i$

Then, generating an index i according to the distribution $\{p_i\}$ is closely-implementable.

CDF Based Sampling

Consider a probability distribution \mathbb{X} over $O(n)$ consecutive integers, whose cumulative distribution function (CDF) for can be computed with at most n^{-c} additive error for constant c . Using $O(\log n)$ CDF evaluations, one can sample from a distribution that is $\frac{1}{\text{poly}(n)}$ -close to \mathbb{X} in L_1 -distance.
2

²Generate a random N -bit number r , and binary-search for the smallest domain element x where $\mathbb{P}[X \leq x] \geq r$.

2.3 Undirected Graphs

Next-Neighbor Queries

The next neighbor of a vertex can be found trivially by generating consecutive entries of the adjacency matrix, but for small edge probabilities $p_{uv} = o(1)$ this implementation can be inefficient. As in [ELMR17], we speed this up by sampling the number of “non-neighbors” preceding the next neighbor. To do this, we assume that we can estimate the “skip” probabilities $F(v, a, b) = \prod_{u=a}^b (1 - p_{vu})$, where $F(v, a, b)$ is the probability that v has no neighbors in the range $[a, b]$. We later show that it is possible to compute this quantity efficiently for the $G(n, p)$ and Stochastic block models.

A main difficulty as compared to [ELMR17], arises from the fact that our graph is undirected, and thus we must “inform” all (potentially $\Theta(n)$) non-neighbors once we decide on the query vertex’s next neighbor. More concretely, if u' is sampled as the next neighbor of v after its previous neighbor u , we must maintain consistency in subsequent steps by ensuring that none of the vertices in the range (u, u') return v as a neighbor. This update will become even more complicated as we handle **RANDOM-NEIGHBOR** queries, where we may generate non-neighbors at random locations.

In Section 3.1, we present a very simple randomized implementation (Algorithm 1) that supports **NEXT-NEIGHBOR** queries efficiently, albeit the analysis of its performance is rather complicated. We remark that this approach may be extended to support **VERTEX-PAIR** queries with superior performance (given that we do not to support **RANDOM-NEIGHBOR** queries) and to provide deterministic resource usage guarantee – the full analysis can be found in Section C and D, respectively.

Random-Neighbor Queries

We provide **RANDOM-NEIGHBOR** queries (Section 3.2) using $\text{poly}(\log n)$ resources. The ability to do so is surprising since: (1) Sampling the degree of the query vertex, we suspect, is not viable for *sub-linear* implementations, because this quantity alone imposes dependence on the existence of *all* of its potential incident edges and on the rest of the graph (Why?). Therefore, our implementation needs to return a random neighbor, with probability reciprocal to the query vertex’s degree, without resorting to “knowing” its degree. (2) Even without committing to the degrees, answers to **RANDOM-NEIGHBOR** queries affect the conditional probabilities of the remaining adjacencies in a global and non-trivial manner.³

We formulate a *bucketing approach* (Section 3.2) which samples multiple consecutive edges at once, in such a way that the conditional probabilities of the unsampled edges remain independent and “well-behaved” during subsequent queries. For each vertex v , we divide the potential neighbors of v into consecutive ranges $\{B_v^{(i)}\}$ (buckets), so that each $B_v^{(i)}$ contains, in expectation, $\Theta(1)$ neighbors (i.e. $\sum_{u \in B_v^{(i)}} p_{vu} = \Theta(1)$). The subroutine of **NEXT-NEIGHBOR** is applied to sample the neighbors within a bucket in expected $\tilde{O}(1)$ time. We can now obtain a neighbor of v by picking a random neighbor from a random bucket, but this introduces a bias because all buckets may not have the same number of neighbors. We remove this bias by rejecting samples from bucket $B_v^{(i)}$ with probability proportional to the number of neighbors in $B_v^{(i)}$. **VERTEX-PAIR** queries are implemented by sampling the relevant bucket.

³Consider a $G(n, p)$ graph with small p , say $p = 1/\sqrt{n}$, such that vertices will have $\tilde{O}(\sqrt{n})$ neighbors with high probability. After $\tilde{O}(\sqrt{n})$ **RANDOM-NEIGHBOR** queries, we will have uncovered all the neighbors (w.h.p.), so that the conditional probability of the remaining $\Theta(n)$ edges should now be close to zero.

2.3.1 Applications to Random Graph Models

We now consider the application of our construction above to actual random graph models, where we must realize the assumption that $\prod_{u=a}^b (1 - p_{vu})$ and $\sum_{u=a}^b p_{vu}$ can be computed efficiently. This holds trivially for the $G(n, p)$ model via closed-form formulas, but requires an additional data structure for the Stochastic Block model.

Erdős-Rényi

In Section 4.1, we apply our construction to random $G(n, p)$ graphs for arbitrary p , and obtain VERTEX-PAIR, NEXT-NEIGHBOR, and RANDOM-NEIGHBOR queries, using polylogarithmic resources (time, space and random bits) per query. We remark that, while $\Omega(n + m) = \Omega(pn^2)$ time and space is clearly necessary to generate and represent a full random graph, our implementation supports local-access via all three types of queries, and yet can generate a full graph in $\tilde{O}(n + m)$ time and space (Corollary 14), which is tight up to polylogarithmic factors.

Stochastic Block Model

We generalize our construction to the Stochastic Block Model. In this model, the vertex set is partitioned into r communities $\{C_1, \dots, C_r\}$. The probability that an edge exists between $u \in C_i$ and $v \in C_j$ is p_{ij} . As communities in the observed data are generally unknown a priori, and significant research has been devoted to designing efficient algorithms for community detection and recovery, these studies generally consider the *random community assignment* condition for the purpose of designing and analyzing algorithms (see e.g., [MNS15]). Thus, we aim to construct implementations where the community assignment of vertices are independently sampled from some given distribution R ⁴. The difficulty here is to obtain a uniformly sampled assignment of vertices to communities on-the-fly.

Our approach is, as before, to sample for the next neighbor or a random neighbor directly, although our result does not simply follow closed-form formulas, as the probabilities for the potential edges now depend on the communities of endpoints. To handle this issue, we observe that it is sufficient to efficiently count the number of vertices of each community in any range of contiguous vertex indices. We then design a data structure extending a construction of [GGN10], which maintain these counts for ranges of vertices, and “sample” the partition of their counts only on an as-needed basis. This extension results in an efficient technique to sample counts from the *multivariate hypergeometric distribution* (Section B) which may be of independent interest. For r communities, this yields an implementation with $\mathcal{O}(r \cdot \text{poly}(\log n))$ overhead in required resources for each operation.

2.4 Directed Graphs

Lastly, we consider Kleinberg’s Small World model ([Kle00, MN04]) in Section 5. While Small-World models are proposed to capture properties of observed data such as small shortest-path distances and large clustering coefficients [WS98], this important special case of Kleinberg’s model, defined on two-dimensional grids, demonstrates underlying geographical structures of networks.

In this model, each vertex is identified via its 2D coordinate $v = (v_x, v_y) \in [\sqrt{n}]^2$. Define the Manhattan distance as $\text{DIST}(u, v) = |u_x - v_x| + |u_y - v_y|$, and the probability that each directed edge (u, v) exists is $c/(\text{DIST}(u, v))^2$. A common choice for c is given by normalizing the distribution

⁴Our algorithm also supports the alternative specification where the community sizes $\langle |C_1|, \dots, |C_r| \rangle$ are given instead, where the assignment of vertices V into these communities is chosen uniformly at random.

such that the expected out-degree of each vertex is 1 ($c = \Theta(1/\log n)$). We can also support a range of values of $c = \log^{\pm\Theta(1)} n$. Since the degree of each vertex in this model is $\mathcal{O}(\log n)$ with high probability, we design implementations supporting **ALL-NEIGHBOR** queries. In contrast to our previous cases, this model imposes an underlying two-dimensional structure of the vertex set, which governs the distance function as well as complicates the individual edge probabilities.

2.5 Random Catalan Objects

We consider a one dimensional random walk with n up and n down steps starting from the origin, with a boundary constraint that the height after t steps is always non-negative. Alternately, we can view this as a random sequence (permutation) of n black (corresponding to $+1$) and n white balls (corresponding to -1), with the restriction that the number of black balls is always at least the number of white balls in any prefix of the sequence.

Over the course of the execution, our algorithm will sample the height of the walk at many different positions $\{x_1, x_2, \dots, x_m\}$ (with $x_i < x_{i+1}$) both directly as a result of user given **HEIGHT** queries, and indirectly through recursive calls to **HEIGHT**. These sampled positions divide the sequence into contiguous *intervals* $[x_i, x_{i+1}]$, where the height of the endpoints y_i, y_{i+1} have been sampled, but none of the intermediate heights are known. The important observation is that the section of the path within an *interval* is completely independent of all other *intervals*. So, each interval $[x_i, x_{i+1}]$ represents a generalized Dyck problem with U up steps, D down steps and the boundary constraint that for any prefix of the interval, the number of up steps can be at most x_i smaller than the number of down steps.

Another useful fact is that the *imbalance* (difference in number of up and down steps) in any contiguous sub-interval of size B is bounded by $\mathcal{O}(\sqrt{B \log n})$ with high probability.

Height Queries

We start by implementing a subroutine that given an *interval* $[x_i, x_{i+1}]$ of length of length $2B$ with $2U$ up and $2D$ down steps, samples the number of up steps $U + d$ to the first half of the *interval*, which effectively answers the query **HEIGHT**($x_i + B$). This is done by sampling the parameter d from a distribution $\{p_d\}$ with $p_d = S_{left}(d) \cdot S_{right}(d) / S_{total}$, where $S_{left}(d)$ (respectively $S_{right}(d)$) is the number of possible paths in the left (resp. right) half of the *interval* when $U + d$ up steps and $D - d$ down steps are assigned to the first half, and S_{total} is the number of possible paths in the original $2B$ -interval. General **HEIGHT**(x) queries can then be answered by recursively halving the *interval* containing x and performing binary search.

The problem of sampling the number of up steps in the first half of the *interval* was solved for the case where the sequence is fully random in [GGN10]. Adding the non-negativity constraint introduces further difficulties as the distribution over d has a CDF that is difficult to compute. We construct a different distribution $\{q_d\}$ that approximates $\{p_d\}$ pointwise to a factor of $\log n$ and has an efficiently computable CDF. This allows us to sample from $\{q_d\}$ and leverage the rejection sampling lemma (Lemma 2) to obtain samples from $\{p_d\}$.

First-Return Queries

FIRST-RETURN queries present an additional challenge because we don't know which *interval* contains the first return. Since there could be up to $\Theta(n)$ intervals, is it inefficient to iterate through all of them. To circumvent this problem, we allow each interval to sample its own boundary constraint $k > 0$ instead of using the global non-negativity constraint. A boundary constraint of k implies

that the path within the interval $[x_i, x_{i+1}]$ never reaches the height $y_i - k$ or lower. Additionally, we maintain an invariant that states that this boundary $x_i - k$ coincides with $\min(x_i, x_{i+1})$. If this constraint is satisfied, we can find the interval containing $\text{FIRST-RETURN}(x)$ by finding the smallest sampled position $x_i > x$ whose sampled height $y_i \leq \text{HEIGHT}(x)$, and considering the interval $[x_{i-1}, x_i]$ preceding x_i .

Every time the **HEIGHT** algorithm creates new intervals by sub-dividing an existing one, this invariant is potentially broken. We re-establish it by sampling a “mandatory boundary” (a y -coordinate that must be achieved within the interval $[x_i, x_{i+1}]$ but not exceeded), and then sampling a position x where $x_i < x < x_{i+1}$ and $\text{HEIGHT}(x) = y$. The first step of sampling the mandatory boundary is performed by binary searching on the possible boundary locations. To find a position that touches this boundary, we parameterize the position with d and find the distribution $\{p_d\}$ associated with these events. We then define a piecewise continuous PDF $\hat{q}(\delta)$ such that $\hat{q}(\delta)$ approximates $p_{\lfloor \delta \rfloor}$. We then use this to construct $q_d = \int_d^{d+1} \hat{q}(\delta)$, and use rejection sampling (Lemma 2) again to sample indirectly from $\{p_d\}$.

2.6 Random Coloring of a Graph

Finally, we introduce a new model for implementating huge random objects where the distribution is specified as a uniformly random solution to a huge combinatorial problem. In all the problems we have considered so far as well as the ones studied in prior work [GGN10, NN07, ELMR17], the description size of the random object is small (typically $\mathcal{O}(\log n)$ to represent the size of the instance and a constant number of parameters). In this new setting, we will implement local query access to random q -colorings of a given huge graph G of size n with maximum degree Δ . The distribution in this case is defined by the graph structure which has size $\mathcal{O}(n\Delta)$. We present the following definition for local access implementations in this setting.

► **Definition 3.** *Given a combinatorial problem on graphs, a local access implementation of a family of query functions $\langle F_1, F_2, \dots \rangle$, provides an oracle \mathcal{A} with the following properties. \mathcal{A} has query access to a graph G , and a tape of random bits \mathbf{R} . Assuming that the solution set of the combinatorial problem on G is \mathbb{X} , \mathcal{A} upon being queried with F_i , returns the value $F_i(X)$ for a specific solution $X \in \mathbb{X}$ where the choice of X depends only on \mathbf{R} and the distribution of X (over \mathbf{R}) is ϵ -close to the uniform distribution over \mathbb{X} . Two different instances of \mathcal{A} with the same graph oracle and the same random bits, must agree on the choice of X that is consistent with all answered queries regardless of what queries were actually asked.*

We can contrast this definition with the one for *Local Computation Algorithms* [RTVX11] which also allow query access to *some* valid solution and can read the input through local probes. An additional difficulty in our setting is that we also have to make sure that we return a solution from the correct distribution. Similarly to LCAs, we can have multiple independent instances of our algorithm answering different queries, but remaining consistent with one another.

Color queries

We are able to construct an efficient implementation for **COLOR**(v) that returns the final color of v in a uniformly random q coloring of G using only a sub-linear number of probes when $q \geq 9\Delta$. Usually, a random coloring of a graph is sampled by proposing a random color update for a random vertex, and accepting the update if it does not create a conflict and repeating this process $\mathcal{O}(n \log n)$ times. This is an inherently sequential process with the acceptance of a particular proposal depending on all preceding neighboring proposals.

To make the runtime analysis simpler, we define a modified version of Glauber Dynamics that proceeds in $\mathcal{O}(\log n)$ epochs. In each epoch, all the vertices propose a random color and update themselves if their proposals do not conflict with any of their neighbors. This Markov Chain is a special case of the one presented in [FG18] for distributed graph coloring and mixes in $\mathcal{O}(\log n)$ epochs when $q \geq 9\Delta$. While we do not have the same restrictions as the distributed computation setting, we choose to use this chain so as to avoid long analysis of mixing times. In order to implement $\text{COLOR}(v)$, it suffices to implement a query $\text{ACCEPTED}(v, t)$ that indicates whether the proposal for v was accepted in the t^{th} epoch. The answer to this question depends on the prior colors of the potentially Δ neighbors of v . Naively sampling the colors of all these neighbors would result in Δ recursive invocations on the previous epoch ($t - 1$), and stepping *backwards* through the epochs to find the last accepted proposal. This leads to a bound of Δ^t on the number of recursive invocations.

We can improve this somewhat by only considering neighbors w of v who had any proposal for the same color c . In this case the expected number of recursive calls is bounded by $t\Delta/q$ ($t\Delta$ proposals to consider and each one is c w.p. $1/q$). So, if $q > t\Delta = \mathcal{O}(\Delta \log n)$, this allows us to bound the total number of resulting invocations. The improvement to $q \geq 9\Delta$ comes from the observation that for $w \in \Gamma(v)$ such that w proposed color c at epoch t' , the recursive call for w can jump to epoch t' and then step *forwards* through the epochs to find the first accepted proposal. Since the expected value of t' is close to $t/2$, we dramatically reduce the sub-problem size in each recursion, and this allows us to bound the runtime by $\mathcal{O}(t\Delta n^{6.12\Delta/q})$ which is sub-linear for $q \geq 9\Delta$.

3 Local-Access Implementations for Random Undirected Graphs

In this section, we provide an efficient local access implementations for random undirected graphs when the probabilities $p_{uv} = \mathbb{P}[(u, v) \in E]$ are given, and we can efficiently approximate the following quantities: (1) the probability that there is no edge between a vertex u and a range of consecutive vertices $[a, b]$, namely $\prod_{u=a}^b (1 - p_{vu})$, and (2) the sum of the edge probabilities (i.e., the expected number of edges) between u and vertices from $[a, b]$, namely $\sum_{u=a}^b p_{vu}$. In Section 4, we provide subroutines for computing these values for the Erdős-Rényi model and the Stochastic Block model. We also begin by assuming perfect-precision arithmetic, which we relax in Section A.

First, consider the adjacency matrix \mathbf{A} of G where each entry $\mathbf{A}[u][v]$ can exist in three possible states: $\mathbf{A}[u][v] = 1$ or 0 if the generator has determined that $\{u, v\} \in E$ or $\{u, v\} \notin E$ respectively, and $\mathbf{A}[u][v] = \phi$ if the marginal probability of $\mathbb{P}[(u, v) \in E]$ conditioned on all prior samples is p_{uv} . Our generator also maintains the vector **last** (used in the same sense as [ELMR17]), where **last** $[v]$ records the neighbor of v returned in the last call $\text{NEXT-NEIGHBOR}(v)$, or **last** $[v] = 0$ if no such call has been invoked. All cells of \mathbf{A} and **last** are initialized to ϕ and 0 , respectively.

We use the Bernoulli random variable $X_{uv} \sim \text{Bern}(p_{uv})$ when sampling the value of $\mathbf{A}[u][v] = \phi$. For the sake of analysis, we will frequently consider the *entire* table of RVs X_{uv} being sampled *up-front* (i.e., flip all coins), and the algorithm simply “uncovers” these variables instead of making coin-flips. Thus, every cell $\mathbf{A}[u][v]$ is originally ϕ , but will eventually take the value X_{uv} once the graph generation is complete.

Obstacles for maintaining \mathbf{A}

First, consider a naive implementation that fills out the cells of \mathbf{A} one-by-one as required by each query. There are two problems with this approach. Firstly, the algorithm only finds a neighbor, for a RANDOM-NEIGHBOR or NEXT-NEIGHBOR query, with probability p_{uv} , which requires too many

iterations: for $G(n, p)$ this requires $1/p$ iterations, which is already infeasible for $p = o(1/\text{poly}(\log n))$. Secondly, the algorithm may generate a large number of non-neighbors in the process, possibly in random or arbitrary locations.

3.1 Next-Neighbor Queries via Run-of-0's Sampling

We implement $\text{NEXT-NEIGHBOR}(v)$ by sampling for the first index $u > \text{last}[v]$ such that $X_{vu} = 1$, from a sequence of Bernoulli RVs $\{X_{v,u}\}_{u > \text{last}[v]}$. To do so, we sample a consecutive “run” of 0's with probability $\prod_{u=\text{last}[v]+1}^{u'} (1 - p_{vu})$: this is the probability that there is no edge between a vertex v and any $u \in (\text{last}[v], u']$, which can be computed efficiently by our assumption. The problem is that, some entries $\mathbf{A}[v][u]$'s in this run may have already been determined (to be 1 or 0) by queries $\text{NEXT-NEIGHBOR}(u)$ for $u > \text{last}[v]$. To mitigate this issue, we give a succinct data structure that determines the value of $\mathbf{A}[v][u]$ for $u > \text{last}[v]$ and, more generally, captures the state \mathbf{A} , in Section 3.1.1. Using this data structure, we ensure that our sampled run does not skip over any 1. Next, for the sampled index u of the first occurrence of 1, we check against this data structure to see if $\mathbf{A}[v][u]$ is already assigned to 0, in which case we re-sample for a new candidate $u' > u$. Section 3.1.2 discusses the subtlety of this issue.

We note that we do not yet try to handle other types of queries here yet. We also do not formally bound the number of re-sampling iterations of this approach here, because the argument is not needed by our final algorithm. Yet, we remark that $O(\log n)$ iterations suffice with high probability, even if the queries are adversarial. This method can be extended to support VERTEX-PAIR queries (but unfortunately not RANDOM-NEIGHBOR queries). See Section C for full details.

3.1.1 Data structure

From the definition of X_{uv} , $\text{NEXT-NEIGHBOR}(v)$ is given by $\min\{u > \text{last}[v] : X_{vu} = 1\}$ (or $n + 1$ if no satisfying u exists). Let $P_v = \{u : \mathbf{A}[v][u] = 1\}$ be the set of known neighbors of v , and $w_v = \min\{(P_v \cap (\text{last}[v], n]) \cup \{n + 1\}\}$ be its first known neighbor not yet reported by a $\text{NEXT-NEIGHBOR}(v)$ query, or equivalently, the next occurrence of 1 in v 's row on \mathbf{A} after $\text{last}[v]$. Note that $w_v = n + 1$ denotes that there is no known neighbor of v after $\text{last}[v]$. Consequently, $\mathbf{A}[v][u] \in \{\phi, 0\}$ for all $u \in (\text{last}[v], w_v)$, so $\text{NEXT-NEIGHBOR}(v)$ is either the index u of the first occurrence of $X_{vu} = 1$ in this range, or w_v if no such index exists.

We keep track of $\text{last}[v]$ in a dictionary, where the key-value pair $(v, \text{last}[v])$ is stored only when $\text{last}[v] \neq 0$: this removes any initialization overhead. Each P_v is maintained as an ordered set, which is also only instantiated when it becomes non-empty. We maintain P_v simply by adding u to v if a call $\text{NEXT-NEIGHBOR}(v)$ returns u , and vice versa. Clearly, $\mathbf{A}[v][u] = 1$ if and only if $u \in P_v$ by construction.

As discussed in the previous section, we cannot maintain \mathbf{A} explicitly, as updating it requires replacing up to $\Theta(n)$ ϕ 's to 0's for a single NEXT-NEIGHBOR query in the worst case. Instead, we argue that last and P_v 's provide a succinct representation of \mathbf{A} via the following observation. For simplicity, we say that X_{uv} is *decided* if $\mathbf{A}[u][v] \neq \phi$, and call it *undecided* otherwise.

► **Lemma 4.** *The data structures last and P_v 's together provide a succinct representation of \mathbf{A} when only NEXT-NEIGHBOR queries are allowed. In particular, $\mathbf{A}[v][u] = 1$ if and only if $u \in P_v$. Otherwise, $\mathbf{A}[v][u] = 0$ when $u < \text{last}[v]$ or $v < \text{last}[u]$. In all remaining cases, $\mathbf{A}[v][u] = \phi$.*

Proof. The condition for $\mathbf{A}[v][u] = 1$ clearly holds by construction. Otherwise, observe that $\mathbf{A}[v][u]$ becomes decided (that is, its value is changed from ϕ to 0) precisely during the first call of

NEXT-NEIGHBOR(v) that returns a value $u' > u$ which thereby sets $\mathbf{last}[v]$ to u' yielding $u < \mathbf{last}[v]$, or vice versa. \square

3.1.2 Queries and Updates

We now provide our generator (Algorithm 1), and discuss the correctness of its sampling process. The argument here is rather subtle and relies on viewing the random process as an “uncovering” process on the table of RVs X_{uv} ’s as previously introduced in Section ?? . Algorithm 1, considers the following experiment for sampling the next neighbor of v in the range $(\mathbf{last}[v], w_v)$. Suppose that we generate a sequence of $w_v - \mathbf{last}[v] - 1$ independent coin-tosses, where the i^{th} coin C_{vu} corresponding to $u = \mathbf{last}[v] + i$ has bias p_{vu} , regardless of whether X_{vu} ’s are decided or not. Then, we use the sequence $\langle C_{vu} \rangle$ to assign values to *undecided* random variable X_{vu} . The crucial observation here is that, the *decided* random variables $X_{vu} = 0$ do not need coin-flips, and the corresponding coin result C_{vu} can simply be discarded. Thus, we need to generate coin-flips up until we encounter some u satisfying both (i) $C_{vu} = 1$, and (ii) $\mathbf{A}[v][u] = \phi$.

Algorithm 1 Sampling **NEXT-NEIGHBOR**

```

1: procedure NEXT-NEIGHBOR( $v$ )
2:    $u \leftarrow \mathbf{last}[v]$ 
3:    $w_v \leftarrow \min\{(P_v \cap (u, n]) \cup \{n + 1\}\}$ 
4:   while  $u = w_v$  or  $\mathbf{last}[u] < v$ 
5:     sample  $F \sim F(v, u, w_v)$ 
6:      $u \leftarrow F$ 
7:   if  $u \neq w_v$ 
8:      $P_v \leftarrow P_v \cap \{u\}$ 
9:      $P_u \leftarrow P_u \cap \{v\}$ 
10:   $\mathbf{last}[v] \leftarrow u$ 
11:  return  $u$ 

```

Let $F(v, a, b)$ denote the probability distribution of the occurrence u of the first coin-flip $C_{vu} = 1$ among the neighbors in (a, b) . More specifically, $F \sim F(v, a, b)$ represents the event that $C_{v,a+1} = \dots = C_{v,F-1} = 0$ and $C_{v,F} = 1$, which happens with probability $\mathbb{P}[F = f] = \prod_{u=a+1}^{f-1} (1 - p_{vu}) \cdot p_{vf}$. For convenience, let $F = b$ denote the event where all $C_{vu} = 0$. Our algorithm samples $F_1 \sim F(v, \mathbf{last}[v], w_v)$ to find the first occurrence of $C_{v,F_1} = 1$, then samples $F_2 \sim F(v, F_1, w_v)$ to find the second occurrence $C_{v,F_2} = 1$, and so on. These values $\{F_i\}$ are iterated as u in Algorithm 1. As this process generates u satisfying (i) in the increasing order, we repeat until we find one that also satisfies (ii). Note that once the process terminates at some u , we make no implications on the results of any uninspected coin-flips after C_{vu} .

Obstacles for extending beyond Next-Neighbor queries

There are two main issues that prevent this method from supporting **RANDOM-NEIGHBOR** queries. Firstly, while one might consider applying **NEXT-NEIGHBOR** from some random location u to find the minimum $u' \geq u$ where $\mathbf{A}[v][u'] = 1$, the probability of choosing u' will depend on the probabilities p_{vu} ’s, and is generally not uniform. While a rejection sampling method may be applied to balance out the probabilities of choosing neighbors, these arbitrary p_{vu} ’s may distribute the neighbors rather unevenly: some small contiguous locations may contain so many neighbors that the rejection sampling approach requires too many iterations to obtain a single uniform neighbor.

Secondly, in developing Algorithm 1, we observe that $\mathbf{last}[v]$ and P_v together provide a succinct representation of $\mathbf{A}[v][u] = 0$ only for contiguous cells $\mathbf{A}[v][u]$ where $u \leq \mathbf{last}[v]$ or $v \leq \mathbf{last}[u]$: they cannot handle 0 anywhere else. Unfortunately, in order to extend our construction to support **RANDOM-NEIGHBOR** queries using the idea suggested in Algorithm ??, we must unavoidably assign $\mathbf{A}[v][u]$ to 0 in random locations beyond $\mathbf{last}[v]$ or $\mathbf{last}[u]$, which cannot be captured by the current data structure. Furthermore, unlike 1’s, we cannot record 0’s using a data structure similarly to

that of P_v . More specifically, to speed-up the sampling process for small p_{vu} 's, we must generate many random non-neighbors at once as suggested in Algorithm 1, but we cannot afford to spend time linear in the number of created 0's to update our data structure. We remedy these issues via the following bucketing approach.

3.2 Final Generator via the Bucketing Approach

We now resolve both of the above issues via the bucketing approach, allowing our generator to support all remaining types of queries. We begin this section by focusing first on **RANDOM-NEIGHBOR** queries, then extend the construction to the remaining ones. In order to handle **RANDOM-NEIGHBOR**(v), we divide the neighbors of v into *buckets* $B_v = \{B_v^{(1)}, B_v^{(2)}, \dots\}$, so that each bucket contains, in expectation, roughly the same number of neighbors of v . We may then implement **RANDOM-NEIGHBOR**(v) by randomly selecting a bucket $B_v^{(i)}$, fill in entries $\mathbf{A}[v][u]$ for $u \in B_v^{(i)}$ with 1's and 0's, then report a random neighbor from this bucket. As the bucket size may be too large when the probabilities are small, instead of using a linear scan, our **FILL** subroutine will be implemented with the **NEXT-NEIGHBOR** subroutine in Algorithm 1 previously developed in Section 3.1. Since the number of iterations required by this subroutine is roughly proportional to the number of neighbors, we choose to allocate a constant number of neighbors in expectation to each bucket: with constant probability the bucket contains some neighbors, and with high probability it has at most $O(\log n)$ neighbors.

Nonetheless, as the actual number of neighbors appearing in each bucket may be different, we balance out these discrepancies by performing *rejection sampling*, equalizing the probability of choosing any neighbor implicitly, again without the knowledge of $\deg(v)$ as previously done in Section ?? . Leveraging the fact that the maximum number of neighbors in any bucket is $\mathcal{O}(\log n)$, we show not only that the probability of success in the rejection sampling process is at least $1/\text{poly}(\log n)$, but the number of iterations required by **NEXT-NEIGHBOR** is also bounded by $\text{poly}(\log n)$, achieving the overall $\text{poly}(\log n)$ complexities. Here in this section, we will extensively rely on the assumption that the expected number of neighbors for consecutive vertices, $\sum_{u=a}^b p_{vu}$, can be computed efficiently.

3.2.1 Partitioning into buckets

More formally, we fix some sufficiently large constant L , and assign the vertex u to the $\lceil \sum_{i=1}^u p_{vi}/L \rceil^{\text{th}}$ bucket of v . Essentially, each bucket represents a contiguous range of vertices, where the expected number of neighbors of v in the bucket is (mostly) in the range $[L-1, L+1]$ (for example, for $G(n, p)$, each bucket contains roughly L/p vertices). Let us define $\Gamma^{(i)}(v) = \Gamma(v) \cap B_v^{(i)}$, the actual neighbors appearing in bucket $B_v^{(i)}$. Our construction ensures that $\mathbb{E}[|\Gamma^{(i)}(v)|] < L+1$ for every bucket, and $\mathbb{E} > L-1$ for every $i < |B_v|$ (i.e., the condition holds for all buckets but possibly the last one).

Now, we show that with high probability, all the bucket sizes $|\Gamma^{(i)}(v)| = \mathcal{O}(\log n)$, and at least a $1/3$ -fraction of the buckets are non-empty (i.e., $|\Gamma^{(i)}(v)| > 0$), via the following lemmas.

► **Lemma 5.** *With high probability, the number of neighbors in every bucket, $|\Gamma^{(i)}(v)|$, is at most $\mathcal{O}(\log n)$.*

Proof. Fix a bucket $B_v^{(i)}$, and consider the Bernoulli RVs $\{X_{vu}\}_{u \in B_v^{(i)}}$. The expected number of

neighbors in this bucket is $\mathbb{E}[|\Gamma^{(i)}(v)|] = \mathbb{E}\left[\sum_{u \in B_v^{(i)}} X_{vu}\right] < L + 1$. Via the Chernoff bound,

$$\mathbb{P}\left[|\Gamma^{(i)}(v)| > (1 + 3c \log n) \cdot L\right] \leq e^{-\frac{3c \log n \cdot L}{3}} = n^{-\Theta(c)}$$

for any constant $c > 0$. □

► **Lemma 6.** *With high probability, for every v such that $|B_v| = \Omega(\log n)$ (i.e., $\mathbb{E} = \Omega(\log n)$), at least a $1/3$ -fraction of the buckets $\{B_v^{(i)}\}_{i \in [|B_v|]}$ are non-empty.*

Proof. For $i < |B_v|$, since $\mathbb{E}[|\Gamma^{(i)}(v)|] = \mathbb{E}\left[\sum_{u \in B_v^{(i)}} X_{vu}\right] > L - 1$, we bound the probability that $B_v^{(i)}$ is empty:

$$\mathbb{P}[B_v^{(i)} \text{ is empty}] = \prod_{u \in B_v^{(i)}} (1 - p_{vu}) \leq e^{-\sum_{u \in B_v^{(i)}} p_{vu}} \leq e^{1-L} = c$$

for any arbitrary small constant c given sufficiently large constant L . Let T_i be the indicator for the event that $B_v^{(i)}$ is *not* empty, so $\mathbb{E}T_i = 1 - c$. By the Chernoff bound, the probability that less than $|B_v|/3$ buckets are non-empty is

$$\mathbb{P}\left[\sum_{i \in [|B_v|]} T_i < \frac{|B_v|}{3}\right] < \mathbb{P}\left[\sum_{i \in [|B_v|-1]} T_i < \frac{|B_v|-1}{2}\right] \leq e^{-\Theta(|B_v|-1)} = n^{-\Omega(1)}$$

as $|B_v| = \Omega(\log n)$ by assumption. □

3.2.2 Filling a bucket

We consider buckets to be in two possible states – filled or unfilled. Initially, all buckets are considered unfilled. In our algorithm we will maintain, for each bucket $B_v^{(i)}$, the set $P_v^{(i)}$ of known neighbors of u in bucket $B_v^{(i)}$; this is a refinement of the set P_v in Section 3.1. We define the behaviors of the procedure **FILL**(v, i) as follows. When invoked on an unfilled bucket $B_v^{(i)}$, **FILL**(v, i) performs the following tasks:

- decide whether each vertex $u \in B_v^{(i)}$ is a neighbor of v (implicitly setting $\mathbf{A}[v][u]$ to 1 or 0) unless X_{vu} is already decided; in other words, update $P_v^{(i)}$ to $\Gamma^{(i)}(v)$
- mark $B_v^{(i)}$ as filled.

For the sake of presentation, we postpone our description of the implementation of **FILL** to Section 3.3. For now, let us use **FILL** as a black-box operation.

3.2.3 Putting it all together: Random-Neighbor queries

Consider Algorithm 2 for generating a random neighbor via rejection sampling, in a rather similar overall framework as the simple implementation in Section ???. For simplicity, throughout the analysis, we assume $|B_v| = \Omega(\log n)$; otherwise, invoke **FILL**(v, i) for all $i \in [|B_v|]$ to obtain the entire neighbor list $\Gamma(v)$. This does not affect the analysis because we will soon bound the number of calls that Algorithm 2 makes to **FILL** by $O(\log n)$ (in expectation) for $|B_v| = \Omega(\log n)$.

To obtain a random neighbor, we first choose a bucket $B_v^{(i)}$ uniformly at random. If the bucket is not yet filled, we invoke **FILL**(v, i) and fill this bucket. Then, we *accept* the sampled bucket for generating our random neighbor with probability proportional to $|P_v^{(i)}|$. More specifically, let $M = \Theta(\log n)$ be the upper bound on the maximum number of neighbors in any bucket, as derived

in Lemma 5; we accept this bucket with probability $|P_v^{(i)}|/M$, which is well-defined (i.e., does not exceed 1) with high probability. (Note that if $P_v^{(i)} = \emptyset$, we remove i from the pool, then repeat as usual.) If we choose to accept this bucket, we return a random neighbor from $P_v^{(i)}$. Otherwise, *reject* this bucket and repeat the process again.

Since the returned value is always a member of $P_v^{(i)}$, a valid neighbor is always returned. Further, i is removed from R only if $B_v^{(i)}$ does not contain any neighbors. So, if v has any neighbor, **RANDOM-NEIGHBOR** does not return \perp . We now proceed to showing the correctness of the algorithm and bound the number of iterations required for the rejection sampling process.

► **Lemma 7.** *Algorithm 2 returns a uniformly random neighbor of vertex v .*

Proof. It suffices to show that the probability that any neighbor in $\Gamma(v)$ is returned with uniform positive probability, within the same iteration. Fix a single iteration and consider a vertex $u \in P_v^{(i)}$: we compute the probability that u is accepted. The probability that i is picked is $1/|R|$, the probability that $B_v^{(i)}$ is accepted is $|P_v^{(i)}|/M$, and the probability that u is chosen among $P_v^{(i)}$ is $1/|P_v^{(i)}|$. Hence, the overall probability of returning u in a single iteration of the loop is $1/(|R| \cdot M)$, which is positive and independent of u . Therefore, each vertex is returned with the same probability. \square

► **Lemma 8.** *Algorithm 2 terminates in $\mathcal{O}(\log n)$ iterations in expectation, or $\mathcal{O}(\log^2 n)$ iterations with high probability.*

Proof. Following the analysis above, the probability that some vertex from $P_v^{(i)}$ is accepted in an iteration is at least $1/(|R| \cdot M)$. From Lemma 6, a $(1/3)$ -fraction of the buckets are non-empty (with high probability), so the probability of choosing a non-empty bucket is at least $1/3$. Further, $M = \Theta(\log n)$ by Lemma 5. Hence, the success probability of each iteration is at least $1/(3M) = \Omega(1/\log n)$. Thus, with high probability, the number of iterations required is $\mathcal{O}(\log^2 n)$ with high probability. \square

3.3 Implementation of Fill

Lastly, we describe the implementation of the **FILL** procedure, employing the approach of skipping non-neighbors, as developed for Algorithm 1. We aim to simulate the following process: perform coin-tosses C_{vu} with probability p_{vu} for every $u \in B_v^{(i)}$ and update $\mathbf{A}[v][u]$'s according to these coin-flips unless they are decided (i.e., $\mathbf{A}[v][u] \neq \phi$). We directly generate a sequence of u 's where the coins $C_{vu} = 1$, then add u to P_v and vice versa if X_{vu} has not previously been decided. Thus, once $B_v^{(i)}$ is filled, we will obtain $P_v^{(i)} = \Gamma^{(i)}(v)$ as desired.

As discussed in Section 3.1, while we have recorded all occurrences of $\mathbf{A}[v][u] = 1$ in $P_v^{(i)}$, we need an efficient way of checking whether $\mathbf{A}[v][u] = 0$ or ϕ . In Algorithm 1, **last** serves this purpose by showing that $\mathbf{A}[v][u]$ for all $u \leq \mathbf{last}[v]$ are decided as shown in Lemma 4. Here

Algorithm 2 Bucketing Generator

```

procedure RANDOM-NEIGHBOR( $v$ )
   $R \leftarrow [|B_v|]$ 
  while  $R = \emptyset$ 
    sample  $i \in R$  u.a.r.
    if  $B_v^{(i)}$  is not filled
      FILL ( $v, i$ )
    if  $|P_v^{(i)}| > 0$ 
      with probability  $\frac{|P_v^{(i)}|}{M}$ 
        sample  $u \in P_v^{(i)}$  u.a.r
        return  $u$ 
    else
       $R \leftarrow R \setminus \{i\}$ 
  return  $\perp$ 

```

instead, with our bucket structure, we maintain a single bit marking whether each bucket is filled or unfilled: a filled bucket implies that $\mathbf{A}[v][u]$ for all $u \in B_v^{(i)}$ are decided. The bucket structure along with mark bits, unlike **last**, are capable of handling intermittent ranges of intervals, namely buckets, which is sufficient for our purpose, as shown in the following lemma. This yields the implementation Algorithm 3 for the **FILL** procedure fulfilling the requirement previously given in Section 3.2.2.

► **Lemma 9.** *The data structures $P_v^{(i)}$'s and the bucket marking bits together provide a succinct representation of \mathbf{A} as long as modifications to \mathbf{A} are performed solely by the **FILL** operation in Algorithm 3. In particular, let $u \in B_v^{(i)}$ and $v \in B_u^{(j)}$. Then, $\mathbf{A}[v][u] = 1$ if and only if $u \in P_v^{(i)}$. Otherwise, $\mathbf{A}[v][u] = 0$ when at least one of $B_v^{(i)}$ or $B_u^{(j)}$ is marked as filled. In all remaining cases, $\mathbf{A}[v][u] = \phi$.*

Proof. The condition for $\mathbf{A}[v][u] = 1$ still holds by construction. Otherwise, observe that $\mathbf{A}[v][u]$ becomes decided precisely during a **FILL**(v, i) or a **FILL**(u, j) operation, which thereby marks one of the corresponding buckets as filled. \square

Note that $P_v^{(i)}$'s, maintained by our generator, are initially empty but may not still be empty at the beginning of the **FILL** function call. These $P_v^{(i)}$'s are again instantiated and stored in a dictionary once they become non-empty. Further, observe that the coin-flips are simulated independently of the state of $P_v^{(i)}$, so the number of iterations of Algorithm 3 is the same as the number of coins $C_{vu} = 1$ which is, in expectation, a constant (namely $\sum_{u \in B_v^{(i)}} \mathbb{P}[C_{vu} = 1] = \sum_{u \in B_v^{(i)}} p_{vu} \leq L + 1$).

By tracking the resource required by Algorithm 3 we obtain the following lemma; note that “additional space” refers to the enduring memory that the generator must allocate and keep even after the execution, not its computation memory. The $\log n$ factors in our complexities are required to perform binary-search for the range of $B_v^{(i)}$, or for the value u from the CDF of $F(u, a, b)$, and to maintain the ordered sets $P_v^{(i)}$ and $P_u^{(j)}$.

■ **Algorithm 3** Sampling in a Bucket

```

procedure FILL( $v, i$ )
   $(a, b) \leftarrow B_j^{(i)}$ 
  while  $a \geq b$ 
    sample  $u \sim F(v, a, b)$ 
     $B_u^{(j)} \leftarrow$  bucket containing  $v$ 
    if  $B_u^{(j)}$  is not filled
       $P_v^{(i)} \leftarrow P_v^{(i)} \cup \{u\}$ 
       $P_u^{(j)} \leftarrow P_u^{(j)} \cup \{v\}$ 
     $a \leftarrow u$ 
  mark  $B_u^{(j)}$  as filled

```

► **Lemma 10.** *Each execution of Algorithm 3 (the **FILL** operation) on an unfilled bucket $B_v^{(i)}$, in expectation:*

- terminates within $\mathcal{O}(1)$ iterations (of its **repeat** loop);
- computes $\mathcal{O}(\log n)$ quantities of $\prod_{u \in [a, b]} (1 - p_{vu})$ and $\sum_{u \in [a, b]} p_{vu}$ each;
- aside from the above computations, uses $\mathcal{O}(\log n)$ time, $\mathcal{O}(1)$ random N -bit words, and $\mathcal{O}(1)$ additional space.

Observe that the number of iterations required by Algorithm 3 only depends on its random coin-flips and independent of the state of the algorithm. Combining with Lemma 8, we finally obtain polylogarithmic resource bound for our implementation of **RANDOM-NEIGHBOR**.

► **Corollary 11.** *Each execution of Algorithm 2 (the **RANDOM-NEIGHBOR** query), with high probability,*

- terminates within $\mathcal{O}(\log^2 n)$ iterations (of its **repeat** loop);

- computes $\mathcal{O}(\log^3 n)$ quantities of $\prod_{u \in [a,b]} (1 - p_{vu})$ and $\sum_{u \in [a,b]} p_{vu}$ each;
- aside from the above computations, uses $\mathcal{O}(\log^3 n)$ time, $\mathcal{O}(\log^2 n)$ random N -bit words, and $\mathcal{O}(\log^2 n)$ additional space.

Extension to other query types

We finally extend our algorithm to support other query types as follows.

- **VERTEX-PAIR**(u, v): We simply need to make sure that Lemma 9 holds, so we first apply **FILL**(u, j) on bucket $B_u^{(j)}$ containing v (if needed), then answer accordingly.
- **NEXT-NEIGHBOR**(v): We maintain **last**, and keep invoking **FILL** until we find a neighbor. Recall that by Lemma 6, the probability that a particular bucket is empty is a small constant. Then with high probability, there exists no $\omega(\log n)$ consecutive empty buckets $B_v^{(i)}$'s for any vertex v , and thus **NEXT-NEIGHBOR** only invokes up to $\mathcal{O}(\log n)$ calls to **FILL**.

We summarize the results so far with through the following theorem.

► **Theorem 12.** *Given a random graph model defined by the probability matrix $\{p_{uv}\}$ and assuming that we can compute the quantities $\prod_{u=a}^b (1 - p_{vu})$ and $\sum_{u=a}^b p_{vu}$ in polylogarithmic time, there exists a local-access implementation for this random graph model that supports **RANDOM-NEIGHBOR**, **VERTEX-PAIR** and **NEXT-NEIGHBOR** queries using polylogarithmic running time, additional space, and random words per query.*

We have also been implicitly assuming perfect-precision arithmetic and we relax this assumption in Section A. In the following Section 4, we show applications of Theorem 12 to the $G(n, p)$ model, and the Stochastic Block model under random community assignment, by providing formulas and by constructing data structures for computing the quantities specified in Theorem 12.

4 Applications to Erdős-Rényi Model and Stochastic Block Model

In this section we demonstrate the application of our techniques to two well known, and widely studied models of random graphs. That is, as required by Theorem 12, we must provide a method for computing the quantities $\prod_{u=a}^b (1 - p_{vu})$ and $\sum_{u=a}^b p_{vu}$ of the desired random graph families in logarithmic time, space and random bits. Our first implementation focuses on the well known Erdős-Rényi model – $G(n, p)$: in this case, $p_{vu} = p$ is uniform and our quantities admit closed-form formulas.

Next, we focus on the Stochastic Block model with randomly-assigned communities. Our implementation assigns each vertex to a community in $\{C_1, \dots, C_r\}$ identically and independently at random, according to some given distribution R over the communities. We formulate a method of sampling community assignments locally. This essentially allows us to sample from the *multivariate hypergeometric distribution*, using $\text{poly}(\log n)$ random bits, which may be of independent interest. We remark that, as our first step, we sample for the number of vertices of each community. That is, our construction can alternatively support the community assignment where the number of vertices of each community is given, under the assumption that the *partition* of the vertex set into communities is chosen uniformly at random.

4.1 Erdős-Rényi Model

As $p_{vu} = p$ for all edges $\{u, v\}$ in the Erdős-Rényi $G(n, p)$ model, we have the closed-form formulas $\prod_{u=a}^b (1 - p_{vu}) = (1 - p)^{b-a+1}$ and $\sum_{u=a}^b p_{vu} = (b - a + 1)p$, which can be computed in constant

time according to our assumption, yielding the following corollary.

► **Corollary 13.** *The final algorithm in Section 3 locally generates a random graph from the Erdős-Rényi $G(n, p)$ model using $\mathcal{O}(\log^3 n)$ time, $\mathcal{O}(\log^2 n)$ random N -bit words, and $\mathcal{O}(\log^2 n)$ additional space per query with high probability.*

We remark that there exists an alternative approach that picks $F \sim F(v, a, b)$ directly via a closed-form formula $a + \lceil \frac{\log U}{\log(1-p)} \rceil$ where U is drawn uniformly from $[0, 1)$, rather than binary-searching for U in its CDF. Such an approach may save some $\text{poly}(\log n)$ factors in the resources, given the perfect-precision arithmetic assumption. This usage of the log function requires $\Omega(n)$ -bit precision, which is not applicable to our computation model.

While we are able to generate our random graph on-the-fly supporting all three types of queries, our construction still only requires $\mathcal{O}(m + n)$ space (N -bit words) in total at any state; that is, we keep $\mathcal{O}(n)$ words for **last**, $\mathcal{O}(1)$ words per neighbor in P_v 's, and one marking bit for each bucket (where there can be up to $m + n$ buckets in total). Hence, our memory usage is nearly optimal for the $G(n, p)$ model:

► **Corollary 14.** *The final algorithm in Section 3 can generate a complete random graph from the Erdős-Rényi $G(n, p)$ model using overall $\tilde{\mathcal{O}}(n + m)$ time, random bits and space, which is $\tilde{\mathcal{O}}(pn^2)$ in expectation. This is optimal up to $\mathcal{O}(\text{poly}(\log n))$ factors.*

4.2 Stochastic Block model

For the Stochastic Block model, each vertex is assigned to some community C_i , $i \in [r]$. By partitioning the product by communities, we may rewrite the desired formulas, for $v \in C_i$, as $\prod_{u=a}^b (1 - p_{vu}) = \prod_{j=1}^r (1 - p_{ij})^{|[a, b] \cap C_j|}$ and $\sum_{u=a}^b p_{vu} = \sum_{j=1}^r |[a, b] \cap C_j| \cdot p_{ij}$. Thus, it is sufficient to design a data structure, or a *generator*, that draws a community assignment for the vertex set according to the given distribution R . This data structure should be able to efficiently count the number of occurrences of vertices of each community in any contiguous range, namely the value $|[a, b] \cap C_j|$ for each $j \in [r]$. To this end, we use the following lemma (proven in Section B), yielding an implementation for the Stochastic Block model using $\mathcal{O}(r \text{poly}(\log n))$ resources per query.

► **Theorem 15.** *There exists a data structure (generator) that samples a community for each vertex independently at random from R with $\frac{1}{\text{poly}(n)}$ error in the L_1 -distance, and supports queries that ask for the number of occurrences of vertices of each community in any contiguous range, using $\mathcal{O}(r \text{poly}(\log n))$ time, random N -bit words and additional space per query. Further, this data structure may be implemented in such a way that requires no overhead for initialization.*

► **Corollary 16.** *The final algorithm in Section 3 generates a random graph from the Stochastic Block model with randomly-assigned communities using $\mathcal{O}(r \text{poly}(\log n))$ time, random N -bit words, and additional space per query with high probability.*

We provide the full details of the construction in the following Section B. Our construction extends upon a similar generator in the work of [GGN10] which only supports $r = 2$. Our overall data structure is a balanced binary tree, where the root corresponds to the entire range of indices $\{1, \dots, n\}$, and the children of each vertex corresponds to each half of the parent's range. Each node⁵ holds the number of vertices of each community in its range. The tree initially contains only the root, with the number of vertices of each community sampled according to the multinomial

⁵For clarity, “vertex” is only used in the generated graph, and “node” is only used in the internal data structures of the generator.

distribution⁶ (for n samples (vertices) from the probability distribution R). The children are only generated top-down on an as-needed basis according to the given queries. The technical difficulties arise when generating the children, where one needs to sample "half" of the counts of the parent from the correct marginal distribution. To this end, we show how to sample such a count as described in the statement below. Namely, we provide an algorithm for sampling from the *multivariate hypergeometric distribution*.

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5 Local-Access Generators for Random Directed Graphs

In this section, we consider Kleinberg's Small-World model [Kle00, MN04] where the probability that a *directed* edge (u, v) exists is $\min\{c/(\text{DIST}(u, v))^2, 1\}$. Here, $\text{DIST}(u, v)$ is the Manhattan distance between u and v on a $\sqrt{n} \times \sqrt{n}$ grid. We begin with the case where $c = 1$, then generalize to different values of $c = \log^{\pm\Theta(1)}(n)$. We aim to support **ALL-NEIGHBORS** queries using $\text{poly}(\log n)$ resources. This returns the entire list of out-neighbors of v .

5.1 Generator for $c = 1$

Observe that since the graphs we consider here are directed, the answers to the **ALL-NEIGHBOR** queries are all independent: each vertex may determine its out-neighbors independently. Given a vertex v , we consider a partition of all the other vertices of the graph into sets $\{\Gamma_1^v, \Gamma_2^v, \dots\}$ by distance: $\Gamma_k^v = \{u : \text{DIST}(v, u) = k\}$ contains all vertices at a distance k from vertex v . Observe that $|\Gamma_k^v| \leq 4k = O(k)$. Then, the expected number of edges from v to vertices in Γ_k^v is therefore $|\Gamma_k^v| \cdot 1/k^2 = O(1/k)$. Hence, the expected degree of v is at most $\sum_{k=1}^{2(\sqrt{n}-1)} O(1/k) = O(\log n)$. It is straightforward to verify that this bound holds with high probability (use Hoeffding's inequality). Since the degree of v is small, in this model we can afford to perform **ALL-NEIGHBORS** queries instead of **NEXT-NEIGHBOR** queries using an additional $\text{poly}(\log n)$ resources.

Nonetheless, internally in our generator, we sample for our neighbors one-by-one similarly to how we process **NEXT-NEIGHBOR** queries. We perform our sampling in two phases. In the first phase, we sample a distance d , such that the next neighbor closest to v is at distance d . We maintain **last** $[v]$ to be the last sampled distance. In the second phase, we sample all neighbors of v at distance d , under the assumption that there must be at least one such neighbor. For simplicity, we sample these neighbors as if there are *full* $4d$ vertices at distance d from v : some sampled neighbors may lie outside our $\sqrt{n} \times \sqrt{n}$ grid, which are simply discarded. As the running time of our generator is proportional to the number of generated neighbors, then by the bound on the number of neighbors, this assumption does not asymptotically worsen the performance of the generator.

5.1.1 Phase 1: Sample the distance D

Let $a = \text{last}[v] + 1$, and let $D(a)$ to denote the probability distribution of the distance where the next closest neighbor of v is located, or \perp if there is no neighbor at distance at most $2(\sqrt{n} - 1)$. That is, if $D \sim D(a)$ is drawn, then we proceed to Phase 2 to sample all neighbors at distance D . We repeat the process by sampling the next distance from $D(a + D)$ and so on until we obtain \perp , at which point we return our answers and terminate.

To sample the next distance, we perform a binary search: we must evaluate the CDF of $D(a)$. The CDF is given by $\mathbb{P}[D \leq d]$ where $D \sim D(a)$, the probability that there is *some* neighbor at distance

⁶See e.g., section 3.4.1 of [Knu97]

at most d . As usual, we compute the probability of the negation: there is *no* neighbor at distance at most d . Recall that each distance i has exactly $|\Gamma_i^v| = 4i$ vertices, and the probability of a vertex $u \in \Gamma_i^v$ is not a neighbor is exactly $1 - 1/i^2$. So, the probability that there is no neighbor at distance i is $(1 - 1/i^2)^{4i}$. Thus, for $D \sim D(a)$ and $d \leq 2(\sqrt{n} - 1)$,

$$\mathbb{P}[D \leq d] = 1 - \prod_{i=a}^d \left(1 - \frac{1}{i^2}\right) = 1 - \prod_{i=a}^d \left(\frac{(i-1)(i+1)}{i^2}\right)^{4i} = 1 - \left(\frac{(a-1)^a}{a^{a-1}} \cdot \frac{(d+1)^d}{d^{d+1}}\right)^4$$

where the product enjoys telescoping as the denominator $(i^2)^{4i}$ cancels with $(i^2)^{4(i-1)}$ and $(i^2)^{4(i+1)}$ in the numerators of the previous and the next term, respectively. This gives us a closed form for the CDF, which we can compute with 2^{-N} additive error in constant time (by our computation model assumption). Thus, we may sample for the distance $D \sim D(a)$ with $O(\log n)$ time and one random N -bit word.

5.1.2 Phase 2: Sampling neighbors at distance D

After sampling a distance D , we now have to sample all the neighbors at distance D . We label the vertices in Γ_D^v with unique indices in $\{1, \dots, 4D\}$. Note that now each of the $4D$ vertices in Γ_D^v is a neighbor with probability $1/D^2$. However, by Phase 1, this is conditioned on the fact that there is at least one neighbor among the vertices in Γ_D^v , which may be difficult to sample when $1/D^2$ is very small. We can emulate this naively by repeatedly sampling a “block”, composing of the $4D$ vertices in Γ_D^v , by deciding whether each vertex is a neighbor of v with uniform probability $1/D^2$ (i.e., $4D$ identical independent Bernoulli trials), and then discarding the entire block if it contains no neighbor. We repeat this process until we finally sample one block that contains at least one neighbor, and use this block as our output.

For the purpose of making the sampling process more efficient, we view this process differently. Let us imagine that we are given an infinite sequence of independent Bernoulli variables, each with bias $1/D^2$. We then divide the sequence into contiguous blocks of length $4D$ each. Our task is to find the *first* occurrence of success (a neighbor), then report the whole block hosting this variable.

This first occurrence of a successful Bernoulli trial is given by sampling from the geometric distribution, $X \sim \text{Geo}(1/D^2)$. Since the vertices in each block are labeled by $1, \dots, 4D$, then this first occurrence has label $X' = X \bmod 4D$. By sampling $X \sim \text{Geo}(1/D^2)$, the first X' Bernoulli variables of this block is also implicitly determined. Namely, the vertices of labels $1, \dots, X' - 1$ are non-neighbors, and that of label X' is a neighbor. The sampling for the remaining $4D - X'$ vertices can then be performed in the same fashion we sample for next neighbors in the $G(n, p)$ case: repeatedly find the next neighbor by sampling from $\text{Geo}(1/D^2)$, until the index of the next neighbor falls beyond this block.

Thus at this point, we have sampled all neighbors in Γ_D^v . We can then update $\mathbf{last}[v] \leftarrow D$ and continue the process of larger distances. Sampling each neighbor takes $O(\log n)$ time and one random N -bit word; the resources spent sampling the distances is also bounded by that of the neighbors. As there are $O(\log n)$ neighbors with high probability, we obtain the following theorem.

► **Theorem 17.** *There exists an algorithm that generates a random graph from Kleinberg’s Small World model, where probability of including each directed edge (u, v) in the graph is $1/(\mathbf{DIST}(u, v))^2$ where \mathbf{DIST} denote the Manhattan distance, using $O(\log^2 n)$ time and random N -bit words per ALL-NEIGHBORS query with high probability.*

5.2 Generator for $c \neq 1$

Observe that to support different values of c in the probability function $c/(\text{DIST}(u, v))^2$, we do not have a closed-form formula for computing the CDF for Phase 1, whereas the process for Phase 2 remains unchanged. To handle the change in the probability distribution Phase 1, we consider the following, more general problem. Suppose that we have a process P that, one-by-one, provide occurrences of successes from the sequence of independent Bernoulli trials with success probabilities $\langle p_1, p_2, \dots \rangle$. We show how to construct a process \mathcal{P}^c that provide occurrences of successes from Bernoulli trials with success probabilities $\langle c \cdot p_1, c \cdot p_2, \dots \rangle$ (truncated down to 1 as needed). For our application, we assume that c is given in N -bit precision, there are $O(n)$ Bernoulli trials, and we aim for an error of $\frac{1}{\text{poly}(n)}$ in the L_1 -distance.

5.2.1 Case $c < 1$

We use rejection sampling in order to construct a new Bernoulli process.

► **Lemma 18.** *Given a process \mathcal{P} outputting the indices of successful Bernoulli trials with bias $\langle p_i \rangle$, there exists a process \mathcal{P}^c outputting the indices of successful Bernoulli trials with bias $\langle c \cdot p_i \rangle$ where $c < 1$, using one additional N -bit word overhead for each answer of \mathcal{P} .*

Proof. Consider the following rejection sampling process to generating the Bernoulli trials. In addition to each Bernoulli variable X_i with bias p_i , we sample another coin-flip C_i with bias c . Set $Y_i = X_i \cdot C_i$, then $\mathbb{P}[Y_i = 1] = \mathbb{P}[X_i = 1] \cdot \mathbb{P}[C_i] = c \cdot p_i$, as desired. That is, we keep a success of a Bernoulli trial with probability c , or reject it with probability $1 - c$.

Now, we are already given the process \mathcal{P} that “handles” X_i ’s, generating a sequence of indices i with $X_i = 1$. The new process \mathcal{P}^c then only needs to handle the C_i ’s. Namely, for each i reported as success by \mathcal{P} , \mathcal{P}^c flips a coin C_i to see if it should also report i , or discard it. As a result, \mathcal{P}^c can generate the indices of successful Bernoulli trials using only one random N -bit word overhead for each answer from \mathcal{P} . \square

Applying this reduction to the distance sampling in Phase 1, we obtain the following corollary.

► **Corollary 19.** *There exists an algorithm that generates a random graph from Kleinberg’s Small World model with edge probabilities $c/(\text{DIST}(u, v))^2$ where $c < 1$, using $O(\log^2 n)$ time and random N -bit words per ALL-NEIGHBORS query with high probability.*

5.2.2 Case $c > 1$

Since we aim to sample with larger probabilities, we instead consider making $k \cdot c$ independent copies of each process \mathcal{P} , where $k > 1$ is a positive integer. Intuitively, we hope that the probability that one of these process returns an index i will be at least $c \cdot p_i$, so that we may perform rejection sampling to decide whether to keep i or not. Unfortunately such a process cannot handle the case where $c \cdot p_i$ is large, notably when $c \cdot p_i > 1$ is truncated down to 1, while there is always a possibility that none of the processes return i .

► **Lemma 20.** *Let $k > 1$ be a constant integer. Given a process \mathcal{P} outputting the indices of successful Bernoulli trials with bias $\langle p_i \rangle$, there exists a process \mathcal{P}^c outputting the indices of successful Bernoulli trials with bias $\langle \min\{c \cdot p_i, 1\} \rangle$ where $c > 1$ and $c \cdot p_i \leq 1 - \frac{1}{k}$ for every i , using one additional N -bit word overhead for each answer of $k \cdot c$ independent copies of \mathcal{P} .*

Proof. By applying the following form of Bernoulli's inequality, we have

$$(1 - p_i)^{k \cdot c} \leq 1 - \frac{k \cdot c \cdot p_i}{1 + (k \cdot c - 1) \cdot p_i} = 1 - \frac{k \cdot c \cdot p_i}{1 + k \cdot c \cdot p_i - p_i} \leq 1 - \frac{k \cdot c \cdot p_i}{1 + (k - 1)} = 1 - c \cdot p_i$$

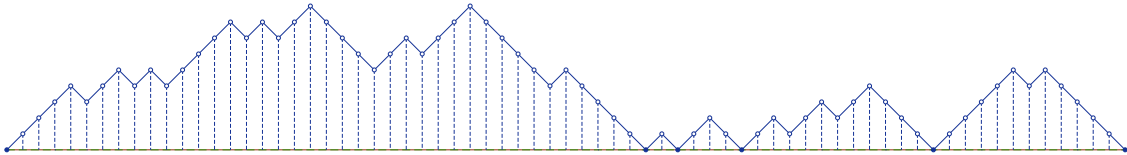
That is, the probability that at least one of the generators report an index i is $1 - (1 - p_i)^{k \cdot c} \geq c \cdot p_i$, as required. Then, the process \mathcal{P}^c simply reports i with probability $(c \cdot p_i) / (1 - (1 - p_i)^{k \cdot c})$ or discard i otherwise. Again, we only require N -bit of precision for each computation, and thus one random N -bit word suffices. \square

In Phase 1, we may apply this reduction only when the condition $c \cdot p_i \leq 1 - \frac{1}{k}$ is satisfied. For lower value of $p_i = 1/D^2$, namely for distance $D < \sqrt{c/(1 - 1/k)} = O(\sqrt{c})$, we may afford to sample the Bernoulli trials one-by-one as c is $\text{poly}(\log n)$. We also note that the degree of each vertex is clearly bounded by $O(\log n)$ with high probability, as its expectation is scaled up by at most a factor of c . Thus, we obtain the following corollary.

► **Corollary 21.** *There exists an algorithm that generates a random graph from Kleinberg's Small World model with edge probabilities $c/(\text{DIST}(u, v))^2$ where $c = \text{poly}(\log n)$, using $O(\log^2 n)$ time and random N -bit words per ALL-NEIGHBORS query with high probability.*

6 Sampling Random Catalan Objects

Earlier, we were interested in querying the following random object. In a random permutation of n white marbles and n black marbles, how many white marbles are present in the first k positions. As we have seen before, [GGN10] gives us a method of sampling from this (hypergeometric) distribution. In constructing a generator for the Stochastic Block model, we generalized this by adding more colors (multivariate hypergeometric distribution). We also took this to the extreme where all marbles are distinguishable (i.e. a random permutation), and saw that this could also be implemented efficiently. Now we focus on a more challenging variant of this question with more complicated conditional dependences among the placement of the marbles.



■ **Figure 4** Simple Dyck path with $n = 35$.

Important extension of interval summable queries.

We consider a sequence of n white and n black marbles such that every prefix of the sequence has at least as many white marbles as black ones. This can be interpreted as a Dyck path; a $2n$ step *balanced* one-dimensional walk with exactly n up and down steps. In Figure 4, each step moves one unit along the positive x -axis (time) and one unit up or down the positive y -axis (position). The prefix constraint implies that the y -coordinate of any point on the walk is ≥ 0 i.e. the walk never crosses the x -axis. The number of possible Dyck paths (see Theorem 56) is the n^{th} Catalan number $C_n = \frac{1}{n+1} \cdot \binom{2n}{n}$. Many important combinatorial objects occur in Catalan families of which these are an example.

Our goal will be to support queries to a uniformly random instance of a Dyck path, which will in turn allow us to sample other random Catalan objects such as rooted trees, and bracketed expressions. Specifically, we will want to answer the following queries:

- **HEIGHT**(i): Returns the position of the path after i steps
- **FIRST-RETURN**(i): Returns an index $j > i$ such that **HEIGHT**(j) = **HEIGHT**(i) and for any k between i and j , **HEIGHT**(k) is strictly greater than **HEIGHT**(i).

6.1 Bijections to other Catalan objects

The **HEIGHT** query is natural for Dyck paths, but the **FIRST-RETURN** query is important in exploring other Catalan objects. For instance, consider a random well bracketed expression; equivalently an uniform distribution over the Dyck language. One can construct a trivial bijection between Dyck paths and words in this language by replacing up and down steps with opening and closing brackets respectively. The **HEIGHT** query corresponds to asking for the nesting depth at a certain position in the word, and **FIRST-RETURN**(i) returns the position of the matching bracket for position i .

figure

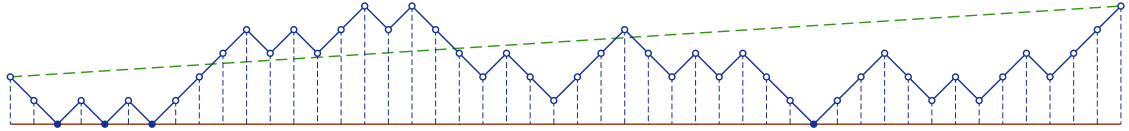
Starting with the root, for each “up-step” we move to a new child of the current node, and for each “down-step”, we backtrack towards the root. Here, the **HEIGHT** query returns the depth of a node and the **FIRST-RETURN** query can be used to find the *next child* of a node.

Moving forwards, we will focus on Dyck paths for the sake of simplicity.

Figure? Degree queries by repeated application.

6.2 Catalan Trapezoids and Generalized Dyck Paths

In order to sample Dyck paths locally, we will need to analyze more general Catalan objects. Specifically, we consider a sequence of U up-steps and D down-steps, such that the sum of any initial sub-string is not less than $1 - k$. This means that we start our Dyck path at a height of $k - 1$, and we are never allowed to cross below zero (Figure 5).



■ **Figure 5** Complex Dyck path with $U = 25$, $D = 22$ and $k = 3$. Notice that the boundary is shifted.

We will denote the set of such *generalized Dyck paths* as $\mathbb{C}_k(U, D)$ and the number of paths as $C_k(U, D) = |\mathbb{C}_k(U, D)|$, which is an entry in the *Catalan Trapezoid* of order k (presented in [Reu14]). We also use $\mathbb{C}_k(U, D)$ to denote the uniform distribution over $\mathbb{C}_k(n, m)$. Now, we state a result from [Reu14] without proof

$$C_k(U, D) = \begin{cases} \binom{U+D}{D} & 0 \leq D < k \\ \binom{U+D}{D} - \binom{U+D}{D-k} & k \leq D \leq U + k - 1 \\ 0 & D > U + k - 1 \end{cases} \quad (1)$$

For $k = 1$ and $n = m$, these represent the vanilla Catalan numbers i.e. $C_n = C_1(n, n)$ (number of simple Dyck paths). Our goal is to sample from the distribution $\mathbb{C}_1(n, n)$.

Consider the situation after sampling the height of the Dyck path at various locations $\langle x_1, x_2, \dots, x_m \rangle$. The revealed locations partition the path into disjoint *intervals* $[x_i, x_{i+1}]$ where the heights of the endpoints have been sampled. We define $y_i = \text{HEIGHT}(x_i)$ and notice that these intervals are independent of each other. Specifically, the path in the interval $[x_i, x_{i+1}]$ will be sampled from $\mathbb{C}_k(U, D)$, where $k-1 = y_i$, $U+D = x_{i+1} - x_i$, and $U-D = y_{i+1} - y_i$, and this happens independent

of any samples outside the interval. Next, we will show how one can sample heights within such an interval, and in Section 6.4 we will move on to the more complicated **FIRST-RETURN** queries.

Is this necessary?

We also maintain a threshold $\mathcal{T} = \Theta(\log^4 n)$. If a query lands in an interval that has length less than \mathcal{T} , then we brute force sample the entire interval one step at a time. Assuming that the probabilities of these events can be approximated efficiently (Lemma 61, this takes $\text{poly}(\log n)$ time).

6.3 Sampling the Height

We will implement $\text{HEIGHT}(t)$ by showing how to (efficiently) sample the position of the path in the midpoint of an existing interval. We can then extend this to arbitrary positions by running a binary search on the appropriate interval using the midpoint samples. If the interval in question has odd length, we sample one step on the boundary and proceed with a shortened interval.

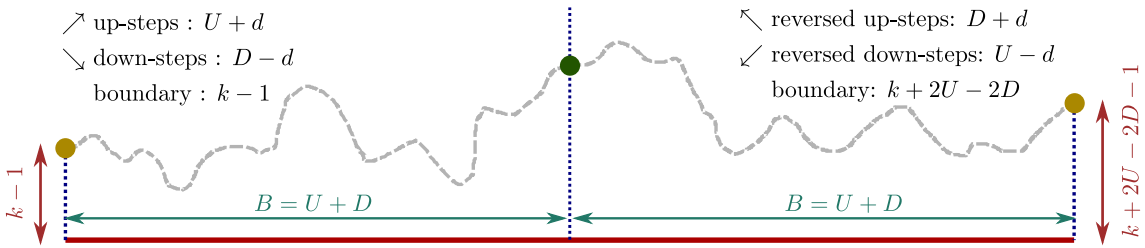


Figure 6 The $2B$ -interval is split into two equal parts resulting in two separate Dyck problems. The green node (center) is the sampled height of the midpoint corresponding to a specific value of d . The path considered in both sub-intervals starts at a yellow node (left and right edges) and ends at the green node. From this perspective, the path on the right is reversed with up and down steps being swapped. A possible path is shown in gray.

Our general recursive step is as follows. We consider an interval of length $2B$ comprising of $2U$ up-steps and $2D$ down-steps where the sum of any prefix cannot be less than $k - 1$ i.e. this interval should be sampled from $C_k(2U, 2D)$ (the factor of two makes the analysis cleaner). Without loss of generality, we assume that $2D \leq B$; if this were not the case, we could simply flip the sequence and negate the elements. This essentially means that the overall path in the interval is non-decreasing in height.

We will sample the height of the path $B = U + D$ steps into the interval at the midpoint (see Figure 6). This is equivalent to sampling the number of up or down steps that get assigned to the first half of the interval. We parameterize the possibilities by d and define p_d to be the probability that exactly $U + d$ up-steps and $D - d$ down steps get assigned to the first half, and therefore the second half gets exactly $U - d$ up steps and $D + d$ down steps.

$$p_d = \frac{S_{\text{left}}(d) \cdot S_{\text{right}}(d)}{S_{\text{total}}(d)}$$

Here, $S_{\text{left}}(d)$ denotes the number of possible paths in the first half (using $U + d$ up steps) and $S_{\text{right}}(d)$ denotes the number of possible paths in the second half (using $U - d$ up steps). Note that all of these paths have to respect the k -boundary constraint (cannot dip more than $k - 1$ units below the starting height). Moving forwards, we will drop the d when referring to the path counts. We (conceptually) flip the second half of the interval, such that the corresponding path begins from the end of the $2B$ -interval and terminates at the midpoint (Figure 6). This results in a different starting point, and the boundary constraint will also be different. Hence, we define

$k' = k + 2U - 2D$ to represent the new boundary constraint (since the final height of the $2B$ -interval is $k' - 1$). Finally, S_{total} is the total number of possible paths in the interval (of length $2B$).

We will use the rejection sampling lemma (Lemma 2 from [GGN10]). An important point to note is that in order to apply this lemma, we must be able to compute the p_d values at least approximately. For now, we will assume that we have access to an oracle that will compute the value for us. Lemma 61 shows how to construct such an oracle. We also use the following lemma to bound the deviation of the path.

► **Lemma 22.** *Consider a contiguous sub-path of a simple Dyck path of length $2n$ where the sub-path is of length $2B$ comprising of U up-steps and D down-steps (with $U + D = 2B$). Then there exists a constant c such that the quantities $|B - U|$, $|B - D|$, and $|U - D|$ are all $< c\sqrt{B \log n}$ with probability at least $1 - 1/n^2$ for every possible sub-path.*

6.3.1 The Simple Case: Far Boundary

► **Lemma 23.** *Given a Dyck path sampling problem of length B with U up and D down steps with a boundary at k , there exists a constant c such that if $k > c\sqrt{B \log n}$, then the distribution of paths sampled without a boundary $C_\infty(U, D)$ (hypergeometric sampling) is statistically $\mathcal{O}(1/n^2)$ -close in L_1 distance to the distribution of Dyck paths $C_k(U + D)$.*

unconstrained random walks will not dip below $1 - k$ threshold whp

By Lemma 23, the problem of sampling from $C_k(2U, 2D)$ reduces to sampling from the hypergeometric distribution $C_\infty(2U, 2D)$ when $k > \mathcal{O}(\sqrt{B \log n})$ i.e. the probabilities p_d can be approximated by:

$$q_d = \frac{\binom{B}{D-d} \cdot \binom{B}{D+d}}{\binom{2B}{2D}}$$

This problem of sampling from the hypergeometric distribution is equivalent to the interval summable functions implemented in [GGN10] (using $\mathcal{O}(\text{poly}(\log n))$ resources).

6.3.2 Path Segments Close to Zero

A difficult case is when $k = \mathcal{O}(\sqrt{B \log n})$ and we need to compute the actual probability p_d . For the definitions in Section F.4, we see that:

$$S_{left} = C_k(U + d, D - d) \quad S_{right} = C_{k'}(U - d, D + d) \quad S_{total} = C_k(2U, 2D) \quad (2)$$

Here, $k' = k + 2U - 2D$, and so $k' = \mathcal{O}(\sqrt{B \log n})$ (using Lemma 22). The distribution $C_k(2U, 2D)$ we wish to sample from has probabilities $p_d = S_{left} \cdot S_{right} / S_{total}$. We will use rejection sampling (Lemma 2) by constructing a different distribution q_d that approximates p_d up to logarithmic factors over the vast majority of its support (we ignore all $|d| > \Theta(\sqrt{B \log n})$ since the associated probability mass is negligible by Lemma 22). To invoke the rejection sampling lemma, we present a method to approximate the probabilities p_d in Lemma 61. The only thing left to do is to find an appropriate q_d that also has an *efficiently computable CDF*. Surprisingly, as in Section 6.3.1, we will be able to use the hypergeometric distribution for q_d ,

$$q_d = \frac{\binom{B}{D-d} \cdot \binom{B}{D+d}}{\binom{2B}{2D}} = \frac{\binom{B}{D-d} \cdot \binom{B}{U-d}}{\binom{2B}{2D}}$$

However, the argument for why this q_d is a good approximation to p_d is far less straightforward.

First, we consider the case where $k \cdot k' \leq 2U + 1$. In this case, we use loose bounds for $S_{left} < \binom{B}{D-d}$ and $S_{right} < \binom{B}{U-d}$ along with the following lemma (proven in Section F).

► **Lemma 24.** *When $kk' > 2U + 1$, $S_{total} > \frac{1}{2} \cdot \binom{2B}{2D}$.*

Combining the three bounds we obtain $p_d < \frac{1}{2}q_d$. Intuitively, in this case the Dyck boundary is far away, and therefore the number of possible paths is only a constant factor away from the number of unconstrained paths (see Section 6.3.1). The case where the boundaries are closer (i.e. $k \cdot k' \leq 2U + 1$) is trickier, since the individual counts need not be close to the corresponding binomial counts. However, in this case we can still ensure that the sampling probability is within poly-logarithmic factors of the binomial sampling probability. We use the following lemmas (proven in Section F).

► **Lemma 25.** $S_{left} \leq c_1 \frac{k \cdot \sqrt{\log n}}{\sqrt{B}} \cdot \binom{B}{D-d}$ for some constant c_1 .

► **Lemma 26.** $S_{right} < c_2 \frac{k' \cdot \sqrt{\log n}}{\sqrt{B}} \cdot \binom{B}{U-d}$ for some constant c_2 .

► **Lemma 27.** *When $kk' \leq 2U + 1$, $S_{total} < c_3 \frac{k \cdot k'}{B} \cdot \binom{2B}{2D}$ for some constant c_3 .*

We can now put these lemmas together to show that $p_d/q_d \leq \Theta(\log n)$ and invoke Lemma 2 to sample the value of d . This gives us the height of the Dyck path at the midpoint of the two given points.

► **Theorem 28.** *Given two positions a and b (and the associated heights) in a Dyck path of length $2n$ with the guarantee that no position between a and b has been sampled yet, there is an algorithm that returns the height of the path halfway between a and b . Moreover, this algorithm only uses $\mathcal{O}(\text{poly}(\log n))$ resources.*

Proof. If $b - a$ is even, we can set $B = (b - a)/2$. Otherwise, we first sample a single step from a to $a + 1$, and then set $B = (b - a - 1)/2$. Since there are only two possibilities for a single step, we can explicitly approximate the probabilities, and then sample accordingly. This allows us to apply the rejection sampling from Lemma 2 using $\{q_d\}$ to obtain samples from $\{p_d\}$ as defined above. \square

► **Theorem 29.** *There is an algorithm that provides sample access to a Dyck path of length $2n$, by answering queries of the form $\text{HEIGHT}(x)$ with the correctly sampled height of the Dyck path at position x using only $\mathcal{O}(\text{poly}(\log n))$ resources per query.*

Proof. The algorithm maintains a successor-predecessor data structure (e.g. Van Emde Boas tree) to store all positions x that have already been sampled. Each newly sampled position is added to this structure. Given a query $\text{HEIGHT}(x)$, the algorithm first finds the successor and predecessor (say a and b) of x among the already queried positions. This provides us the guarantee required to apply Theorem 28, which allows us to query the height at the midpoint of a and b . We then binary search by updating either the successor or predecessor of x and repeat until we sample the height of position x . \square

6.4 Supporting “First Return” Queries

We also support more complex queries to a Dyck path. Specifically, in addition to querying the height after t steps, we introduce a **FIRST-RETURN** query that allows the user to query the next time the path returns to that height (if at all i.e. only if the step from x to $x + 1$ is an up-step).

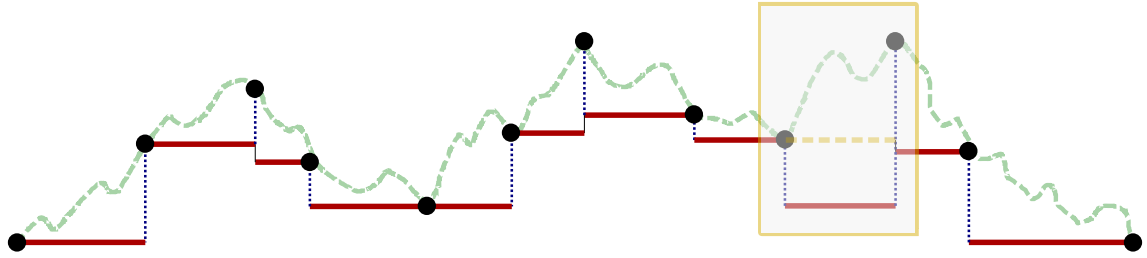
The utility of this kind of query can be seen in other interpretations of Catalan objects. For instance, if we interpret it as a well bracketed expression, $\text{FIRST-RETURN}(x)$ returns the position of the bracket matching the one started at x . If we consider a uniformly random rooted tree, the function effectively returns the next child of a vertex (see Section 6.1).

6.4.1 Maintaining a Boundary Invariant

Notice that over a sequence of HEIGHT queries $\langle x_1, x_2, \dots, x_m \rangle$ to the Dyck path, many different positions are revealed (possibly in adversarial locations). This partitions the path into at most $m + 1$ disjoint and independent *intervals* with set boundary conditions. The first step towards finding the FIRST-RETURN from position t would be to locate the *interval* where the return occurs. Even if we had an efficient technique to filter intervals, we would want to avoid considering all $\Theta(m)$ intervals to find the correct one. In addition the inefficiency, the fact that a specific interval *does not* contain the first return causes dependencies for all subsequent samples.

We resolve this issue by maintaining the following invariant. Consider all positions that have been queried already $\langle x_1, x_2, \dots, x_m \rangle$ (in increasing order) along with their corresponding heights $\langle y_1, y_2, \dots, y_m \rangle$.

► **Invariant 30.** *For any interval $[x_i, x_{i+1}]$ where the heights of the endpoints have been sampled to be y_i and y_{i+1} , and no other position in the interval has yet been sampled, the section of the Dyck path between positions x_i and x_{i+1} is constrained to lie above $\min(y_i, y_{i+1})$.*



■ **Figure 7** Error in third segment.

It's not even clear that it is always possible to maintain such an invariant. After sampling the height of a particular position x_i as y_i (with $x_{i-1} < x_i < x_{i+1}$), the invariant is potentially broken on either side of x_i . We will re-establish the invariant by sampling an additional point on either side. This proceeds as follows for the interval between x_i and x_{i+1} (see error in Figure 7):

1. Sample the lowest height h achieved by the walk between x_i and x_{i+1} .
2. Sample a position x such that $x_i < x < x_{i+1}$ and $\text{HEIGHT}(x) = h$.

Since h is the minimum height along this interval, sampling the point x suffices to preserve the invariant. Lemma 37 shows how this invariant can be used to efficiently find the interval containing the first return.

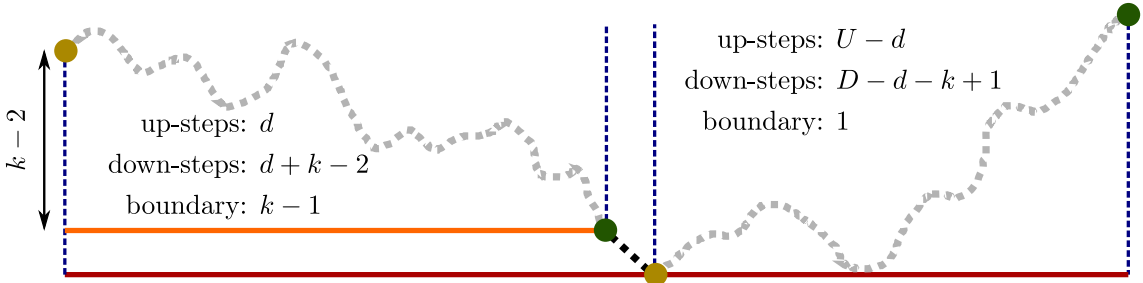
6.4.2 Sampling the Lowest Achievable Height in an Interval

For the first step, we need to sample the lowest height h of the walk between x_i and x_{i+1} (with $x_i < x_{i+1}$). Say that this interval defines a generalized Dyck problem with U up steps and D down steps with a boundary that is $k - 1$ units below y_i .

Given any two boundaries k_{lower} and k_{upper} on the same interval (with $k_{lower} < k_{upper}$, we can count the number of possible generalized Dyck paths that violate the k_{upper} boundary but *not* the k_{lower} boundary as $P(k_{lower}, k_{upper}) = C_{k_{lower}}(U, D) - C_{k_{upper}}(U, D)$. We set $k_{low} = k, k_{up} = 0$, and $k_{mid} = (k_{low} + k_{up})/2$. Since we can compute $P(k_{low}, k_{up})$, $P(k_{low}, k_{mid})$, and $P(k_{mid}, k_{up})$, we can sample a single bit to decide if the “lower boundary” should move up or if the “upper boundary” should move down. We then repeat this binary search until we find $k' = k_{low} = k_{up} - 1$ and k' becomes the “mandatory boundary” (i.e. the walk reaches the height exactly $k' - 1$ units below y_i but no lower.

6.4.3 Sampling First Position that Touches the “Mandatory Boundary”

Now that we have a “mandatory boundary” k , we just need to sample a position x with height $h = x_i - k + 1$. In fact, we will do something stronger by sampling the *first* time the walk touches the boundary after x_i . As before, we assume that this interval contains U up steps and D down steps.



■ **Figure 8** Zooming into the error in Figure 7

We will parameterize the position x the number of up-steps d between x_i and x (See Figure 8), implying that $x = x_i + 2d + k - 1$. Given a specific d , we want to compute the number of valid paths that result in d up-steps before the first approach to the boundary. We will calculate this quantity by counting the total number of paths to the left and right of the first approach and multiplying them together.

Since we only care about getting a asymptotic (up to $\text{poly}(\log n)$ factors) estimate of the probabilities, it suffices to estimate the number of paths asymptotically as well. As in Section 6.3.2, we define S_{left} to be the number of paths in the sub-interval before the first approach (left side of Figure 8), S_{right} to be the number of paths following the first approach, and S_{total} to be the total number of paths that touch the “mandatory boundary” at k :

$$S_{left} = C_k(d, d + k - 2) \quad S_{right} = C_1(U - d, D - d - k + 1) \quad S_{total} = C_k(U, D) - C_{k-1}(U, D)$$

Our goal is to sample d from the distribution $\{p_d\}$ where $p_d = S_{left} \cdot S_{right} / S_{total}$. Using Equation 1, we obtain the following approximations for S_{left} and S_{right} .

► **Lemma 31.** *If $d > \log^4 n$, then $S_{left}(d) = \Theta\left(\frac{2^{2d+k}}{\sqrt{d}} e^{-r_{left}(d)} \cdot \frac{k-1}{d+k-1}\right)$ where $r_{left}(d) = \frac{(k-2)^2}{2(2d+k-2)}$. Furthermore, $r_{left}(d) = \mathcal{O}(\log^2 n)$.*

► **Lemma 32.** *If $U + D - 2d - k > \log^4 n$, then $S_{right}(d) = \Theta\left(\frac{2^{U+D-2d-k}}{\sqrt{U+d-2d-k}} e^{-r_{right}(d)} \cdot \frac{U-D+k}{U-d+1}\right)$ where $r_{right}(d) = \frac{(U-D-k-1)^2}{4(U+D-2d-k+1)}$. Furthermore, $r_{right}(d) = \mathcal{O}(\log^2 n)$.*

Deal with
other values
of d

We now consider the values of d that are outside the range of the two preceding lemmas. These values are the ones where $d < \log^4 n$ or $2d > U + D - k - \log^4 n$. Since d is the number of up steps (in the left sub-interval), $d \geq 0$ and since the length of the right sub-interval must be non-negative, we get $U + D - 2d - k + 1 \geq 0$. Thus, we define the set

$$\mathcal{R} = \{d \mid 0 \leq d < \log^4 n \text{ or } -1 < 2d - U - D + k < \log^4 n\} \quad (3)$$

Clearly, we can bound the size of this set as $|\mathcal{R}| = \mathcal{O}(\log^4 n)$. An immediate consequence of Lemma 31 and Lemma 32 is the following.

► **Corollary 33.** When $d \notin \mathcal{R}$, $S_{left}(d) \cdot S_{right}(d) = \Theta \left(\frac{2^{U+D}}{\sqrt{d(U+D-2d-k)}} \cdot e^{-r(d)} \cdot \frac{k-1}{d+k-1} \cdot \frac{U-D+k}{U-d+1} \right)$ where $r(d) = \mathcal{O}(\log^2 n)$.

6.4.4 Estimating the CDF

We will now use these observations to construct a suitable $\{q_d\}$ that can be used to invoke the rejection sampling lemma. In addition to being a good approximation to $\{p_d\}$, $\{q_d\}$ must be of a form that allows us to compute its CDF efficiently. First, we rewrite the approximate probability as $p_d = \Theta(\mathcal{K} \cdot f(d) \cdot e^{-r(d)})$ where:

$$\mathcal{K} = \frac{2^{U+D}}{S_{total}} = \frac{2^{U+D}}{C_k(U, D) - C_{k-1}(U, D)} \quad f(d) = \frac{(k-1)(U-D+k)}{\sqrt{d(U+D-2d-k)}(d+k-1)(U-d+1)}$$

Notice that \mathcal{K} is a constant and $f(d)$ is a function whose integral has a closed form. Using the fact that $r(d) = \mathcal{O}(\log^2 n)$ (from Corollary 33), we obtain the following lemma:

► **Lemma 34.** Given the piecewise continuous function

$$\hat{q}(\delta) = \begin{cases} p_{\lfloor \delta \rfloor} & \text{if } \lfloor \delta \rfloor \in \mathcal{R} \\ \mathcal{K} \cdot f(\delta) \cdot \exp(\lfloor r(\lfloor \delta \rfloor) \rfloor) & \text{if } \lfloor \delta \rfloor \notin \mathcal{R} \end{cases} \implies p_d = \Theta \left(\int_d^{d+1} \hat{q}(\delta) \right)$$

Furthermore, $\hat{q}(\delta)$ has $\mathcal{O}(\log^4 n)$ continuous pieces.

Proof. For $d \in \mathcal{R}$, the integral trivially evaluates to exactly p_d . For $d \notin \mathcal{R}$, it suffices to show that $p_d = \Theta(\hat{q}(\delta))$ for all $\delta \in [d, d+1)$. We already know that $p_d = \Theta(\mathcal{K} \cdot f(d) \cdot e^{-r(d)})$. Moreover, for any $\delta \in [d, d+1)$, the exponential term in $\hat{q}(\delta)$ is within a factor of e of the original $e^{-r(d)}$ term.

For all $\mathcal{O}(\log^4 n)$ values $d \in \mathcal{R}$, $\hat{q}(\delta)$ is constant on the interval $[d, d+1]$. □

Now, we have everything in place to define the distribution $\{q_d\}$ that we will be sampling from. Specifically, we will define q_d and its CDF Q_d as follows:

$$q_d = \frac{\int_d^{d+1} \hat{q}(\delta)}{\mathcal{N}} \quad Q_d = \frac{\int_0^{d+1} \hat{q}(\delta)}{\mathcal{N}} \quad (4)$$

Here the normalizing factor \mathcal{N} is $\int_0^{d_{max}+1} \hat{q}(\delta)$. To show that these can be computed efficiently, it suffices to show that any integral of \hat{q}_d can be efficiently evaluated.

► **Lemma 35.** *Given the function \hat{q}_d defined in Lemma 34, it is possible to compute the integral $\int_{d_1}^{d_2+1} \hat{q}(\delta)$ in $\text{poly}(\log n)$ time for any valid d_1, d_2 (i.e. the bounds must be such that $d_i \geq 0$ and $U + D - 2d - k + 1 \geq 0$).*

Proof. As noted in Lemma 34, $\hat{q}(\delta)$ is piecewise continuous function with $\mathcal{O}(\log^4 n)$ pieces. For all $\mathcal{O}(\log^4 n)$ values $d \in \mathcal{R}$, $\hat{q}(\delta)$ is constant on the interval $[d, d + 1]$. Now consider values We claim that the number of continuous segments in the *valid* range is $\mathcal{O}(\log^4 n)$. \square

► **Theorem 36.** *Kinesthetics*

6.4.5 Finding the Correct Interval: First-Return Query

As before, consider all positions that have been queried already $\langle x_1, x_2, \dots, x_m \rangle$ (in increasing order) along with their corresponding heights $\langle y_1, y_2, \dots, y_m \rangle$.

► **Lemma 37.** *For any position x_i , assuming that Invariant 30 holds, we can find the interval $(x_{k-1}, x_k]$ that contains $\text{FIRST-RETURN}(x_i)$ We do this by setting k to be either the smallest index $f > i$ such that $y_f \leq y_i$ or setting $k = i + 1$.*

Proof. We assume the contrary i.e. there exists some $k \neq f$ and $k \neq i + 1$ such that the correct interval is $(x_{k-1}, x_k]$. Since $y_f < y_i$, the position of first return to y_i happens in the range $(x_i, x_f]$. So, the only possibility is $i + 1 < k \leq f - 1$. By the definition of y_f , we know that both y_k and y_{k-1} are strictly larger than y_i . Invariant 30 implies that the boundary for this interval $(y_{k-1}, y_k]$ is at $\min(y_{k-1}, y_k) > y_i$. So, it is not possible for the first return to be in this interval. \square

The good news is that there are only two intervals that we need to worry about. Now the challenge is to find the smallest index $f > i$ such that $y_f \leq y_i$. One solution is to maintain an interval tree over the range $[2n]$ storing the position of the boundary. Specifically, we have a balanced binary tree with $2n$ leaves with the i^{th} leaf storing the boundary at position i . Each internal node stores the minimum value amongst all the leaves in its sub-tree. In this setting, we can binary search for f by guessing a bound f' and performing a *range minimum query* over the interval $(x_i, x_{f'}]$. Overall, this requires $\mathcal{O}(\log n)$ range queries each of which makes $\mathcal{O}(\log n)$ probes to the binary tree.

However, we cannot explicitly maintain or even construct this tree, and updates can be as expensive as $\Theta(n)$. To mitigate this, we start with just a root node (indicating that the initial boundary is 1 everywhere) and build the tree dynamically as needed. We perform updates using *lazy propagation* by only propagating updates down to the children (creating children if necessary) when needed. So, at any given time, some nodes in the tree may not hold the correct value, but the correct value must be present on the path to the root.

► **Theorem 38.** *There is an algorithm using $\mathcal{O}(\text{poly}(\log n))$ resources per query that provides sample access to a Dyck path of length $2n$ by answering queries of the form $\text{FIRST-RETURN}(x_i)$ with the correctly sampled position y ; where $y > x_i$ is the position where the Dyck path first returns to $\text{HEIGHT}(x_i)$ after position x_i .*

Proof. We first query the interval $(x_i, x_{i+1}]$ to find a first return using Theorem 36. If a return is not found, we calculate f using . Since $x_{f-1} < x_i \leq x_f$ by definition, the interval $(x_{f-1}, x_f]$ must contain a position at height y_i . We sample a point in the middle of this interval and fix the boundary invariant by sampling another point, essentially breaking it up into $\mathcal{O}(1)$ sub-intervals

Needs a theorem

cite

cite

This probably needs more explanation

what?

each at most half the size of the original. Based on the new samples, we find the sub-interval containing the first return in $\mathcal{O}(1)$ time. We repeat up to $\mathcal{O}(\log n)$ times until the current interval size drops below the threshold \mathcal{T} . Then we spend $\tilde{\mathcal{O}}(\mathcal{T})$ time to brute force sample this interval and find the first return position (if it wasn't revealed in previous steps). \square

7 Random Coloring of a Graph

Query access

We wish to locally sample an uniformly random coloring of a graph. A q -coloring of a graph $G = (V, E)$ is a function $\sigma : V \rightarrow [q]$, such that for all $(u, v) \in E$, $\sigma_u \neq \sigma_v$. We will consider only bounded degree graphs, i.e. graphs with max degree $\leq \Delta$. Otherwise, the coloring problem becomes NP-hard.

cite

Using the technique of path-coupling, Vigoda showed that for $q > 2\Delta$, one can sample an uniformly random coloring by using a MCMC algorithm.

cite

The Markov Chain proceeds in T steps. The state of the chain at time t is given by $\mathbf{X}^t \in [q]^{|V|}$. Specifically, the color of vertex v at step t is \mathbf{X}_v^t .

In each step of the Markov process, a pair $(v, c) \in V \times [q]$ is sampled uniformly at random. Subsequently, if the recoloring of vertex v with color c does not result in a conflict with v 's neighbors, i.e. $c \notin \{X_u^t : u \in \Gamma(v)\}$, then the vertex is recolored i.e. $X_v^{t+1} \leftarrow c$.

After running the MC for $T = \mathcal{O}(n \log n)$ steps we reach the stationary distribution (ϵ close), and the coloring is an uniformly random one.

Exact Bound: $t_{mix}(\epsilon) \leq \left(\frac{q-\Delta}{q-2\Delta}\right) n (\log n + \log(1/\epsilon))$

cite book
(Peres, Lyons)

7.1 Modified Glauber Dynamics

Now we define a modified Markov Chain as a special case of the *Local Glauber Dynamics* presented in [FG18]. The modified Markov chain proceeds in epochs. We denote the initial coloring of the graph by \mathbf{X}^0 and the state of the coloring after the k^{th} epoch by \mathbf{X}^k . In the k^{th} epoch \mathcal{E}_k :

- Sample $|V|$ colors $\langle c_1, c_2, \dots, c_n \rangle$ from $[q]$, where c_v is the proposed color for vertex v .
- For each vertex v , we set \mathbf{X}_v^k to c_v if for all neighbors w of v , $\mathbf{X}_w^k \neq c_v$ and $\mathbf{X}_w^{k-1} \neq c_v$.

This procedure is a special case of the *Local Glauber Dynamics* presented in [FG18]. The goal in [FG18] is to find a simultaneous update rule that causes few conflicts among neighbors (and converges to the correct distribution). Notice that we *can* have adjacent nodes update in the same epoch. However for the sake of succinctness we use their update rule and avoid a tedious path coupling argument.

Cite Path
Coupling

We can directly use the path coupling argument from [FG18] which be briefly describe below. Given two colorings \mathbf{X} and \mathbf{Y} , we define $d(\mathbf{X}, \mathbf{Y})$ as the number of vertices v such that $\mathbf{X}_v \neq \mathbf{Y}_v$. We define the coupling $(\mathbf{X}, \mathbf{Y}) \rightarrow (\mathbf{X}', \mathbf{Y}')$ where \mathbf{X} and \mathbf{Y} differ only at a single vertex v such that $\mathbf{X}_v = c_X$ and $\mathbf{Y}_v = c_Y$. Now, we pick a random permutation of the vertices along with uniformly sampled colors:

$$\langle (v_1, c_1), (v_2, c_2), \dots, (v_n, c_n) \rangle = \langle (\pi_1, c_1), (\pi_2, c_2), \dots, (\pi_n, c_n) \rangle$$

Now, for each (v_i, c_i) in order, we update the coloring of X and Y as follows:

- If the current color of v_i as well as c_i are both in $\{c_X, c_Y\}$, then the \mathbf{X} chain picks the color c_i and the \mathbf{Y} chain picks the other color.

■ Otherwise, both chains pick the same color c_i for the vertex v_i .

We use the following result from [FG18] that bounds the coupled distance.

► **Lemma 39.** *If $q = 2\alpha\Delta$ and $d(\mathbf{X}, \mathbf{Y}) = 1$, then $\mathbb{E}[d(\mathbf{X}', \mathbf{Y}')] \leq 1 - \left(1 - \frac{1}{2\alpha}\right) e^{-3/\alpha} + \frac{1/2\alpha}{1-1/\alpha}$*

► **Corollary 40.** *If $q \geq 9\Delta$ and $d(\mathbf{X}, \mathbf{Y}) = 1$, then $\mathbb{E}[d(\mathbf{X}', \mathbf{Y}')] < \frac{1}{e^{1/3}}$*

► **Theorem 41.** *If $q \geq 9\Delta$, then the chain is mixed after $\tau_{\text{mix}}(\epsilon) = 3 \left(\ln n + \ln\left(\frac{1}{\epsilon}\right)\right)$ epochs.*

Proof. Starting for a maximum distance of n , the distance decreases to 1 after at most $3 \ln n$ epochs, and it takes a further $3 \ln\left(\frac{1}{\epsilon}\right)$ to reduce the distance to ϵ . \square

7.2 Local Coloring Algorithm

Given query access to the adjacency matrix of a graph G with maximum degree Δ and a vertex v , the algorithm has to output the color of v after running $t = \mathcal{O}(\ln n)$ epochs of *Modified Glauber Dynamics*. We will define the number of colors as $q = 2\alpha\Delta$ where $\alpha > 1$.

The proposals at each epoch are a vector of color samples $\mathbf{C}^t \sim_{\mathcal{U}} [q]^n$. Note that these values are fully independent and as such any \mathbf{C}_v^t can be sampled trivially. We also use \mathbf{X}^t to denote the final vector of vertex colors at the end of the t^{th} epoch. Finally, we define indicator variables χ_v^t to denote if the color for vertex v was accepted at the t^{th} epoch; $\chi_v^t = 1$ if and only if for all neighbors $w \in \Gamma(v)$, we satisfy the condition $\mathbf{C}_v^t \neq \mathbf{X}_w^{t-1}$ and $\mathbf{C}_v^t \neq \mathbf{C}_w^t$. So, the color of a vertex v after the t^{th} epoch \mathbf{X}_v^t is set to be \mathbf{C}_v^i where $i \leq t$ is the largest index such that $\chi_v^i = 1$. While the proposals \mathbf{C}_v^t are easy to sample, it is much less clear how we can sample the χ_v^t values. Note that we can compute \mathbf{X}_v^t quite easily if we know the values χ_v^i for all $i \leq t$. So, we focus our attention on the query $\text{ACCEPTED}(v, t)$ that returns χ_v^t .

7.2.1 Naive Coloring Implementations

The general strategy to implement this is to iterate over all neighbors w of v , and for each of them check if they conflict with v 's proposed color. Given a neighbor w , one naive way to do this is to iterate backwards from epoch t querying to find if w 's proposal was accepted until the first accepted proposal (from the latest epoch $t' < t$) is found. At this point, if $\mathbf{C}_w^{t'} = \mathbf{C}_v^t$, then the current color of w conflicts with v 's proposal. Otherwise there is no conflict and we can proceed to the next neighbor. This process however makes Δ recursive calls to a sub-problem that is only slightly smaller i.e. $T(t) \leq \Delta \cdot T(t-1)$. This leads to a running time upper bound of Δ^t which is superlinear for the desired $t = \Omega(\log n)$.

We can prune the number of recursive calls by only processing the neighbors w which actually proposed the color \mathbf{C}_v^t during *some* epoch. In this case, the expected number of neighbors that have to be probed recursively is $\leq t\Delta/q$ (since the total number of neighbor proposals over t epochs is at most $t\Delta$). So, the overall runtime is upper bounded by $(t\Delta/q)^t$. For this algorithm, if we allow $q > t\Delta = \Omega(\Delta \log n)$ colors, the runtime becomes sublinear. This lower bound on q is however asymptotically worse than the sequential requirement $q > 2\Delta = \mathcal{O}(\Delta)$.

■ Algorithm 9 Generator

```

1: procedure ACCEPTED( $v, t$ )
2:    $c \leftarrow \mathbf{C}_v^t$ 
3:   for  $w \leftarrow \Gamma(v)$ 
4:     if  $\mathbf{C}_w^t = c$ 
5:       return 0
6:   for  $t' \leftarrow [t, t-1, t-2, \dots, 1]$ 
7:     if  $\mathbf{C}_w^{t'} = c$  and ACCEPTED( $w, t'$ )
8:        $flag \leftarrow 1$ 
9:       while  $t' < t-1$ 
10:         $t' \leftarrow t' + 1$ 
11:        if ACCEPTED( $w, t'$ )
12:           $flag \leftarrow 0$ 
13:        break
14:   if  $flag = 1$ 
15:     return 0
16:   break
17: return 1

```

7.2.2 Jumping Back to Past Epochs

The expected number of neighbors that need to be checked can always be $t\Delta$ in the worst case. The crucial observation is that even though these recursive calls seem unavoidable, we can aim to reduce the size of the recursive subproblem and thus bound the number of levels of recursion. Because of the more complex structure of this epoch jumping process, the main challenge is to analyze the runtime.

Algorithm 9 shows our final procedure for sampling χ_v^t where $c = C_v^t$ is the color proposed by v in epoch t . As before, we iterate through all neighbors w of v . The condition $c \neq C_w^t$ can easily be checked by sampling C_w^t in the current epoch. If no conflict is seen, the next step is to check whether $c \neq X_w^{t-1}$.

To achieve this, we iterate through all the epochs in reverse order (without making recursive calls) to check whether the color c was ever proposed for vertex w . If not, we can ignore w , and otherwise let's say that the last proposal for c was at epoch t' i.e. $C_w^{t'} = c$. Now, we directly “jump” to the t'^{th} epoch and recursively check if this proposal was accepted. If the proposal $C_w^{t'}$ was not accepted, we keep iterating back until we find another candidate proposal for color c or we run out of epochs. Otherwise if $\chi_w^{t'} = 1$ (proposal accepted), we move to epoch $t' + 1$ to see if w 's color was replaced. If not, we check epoch $t' + 2$, $t' + 3$, and so on until we reach epoch $t - 1$. At this point we have seen that $\chi_w^{t'} = 1$ (color c was accepted) and every subsequent proposal until the current epoch was rejected i.e. $X_w^{t-1} = c$ and this leads to a conflict with v 's current proposal for color c and hence $\chi_v^t = 0$. If at any of the iterations, we see that a different proposal was accepted, then w does not cause a conflict and we can move on to the next neighbor. If we exhaust all the neighbors and don't find any conflicts then $\chi_v^t = 1$.

Now we analyze the runtime of **ACCEPTED** by constructing and solving a recurrence relation. We will use the following lemma to evaluate the expectation of products of relevant random variables.

► **Lemma 42.** *The probability that any given proposal is rejected $\mathbb{P}[\chi_v^t = 0]$ is at most $1/\alpha$. Moreover, this upper bound holds even if we condition on all the values in \mathbf{C} except C_v^t .*

Proof. A rejection can occur due to a conflict with at most 2Δ possible values in $\{C_w^t, X_w^{t-1} | w \in \Gamma(v)\}$. Since there are $2\alpha\Delta$ colors, the rejection probability is at most $1/\alpha$. \square

► **Definition 43.** *We define T_t to be a random variable indicating the number of recursive calls performed during the execution of **ACCEPTED**(v, t) while sampling a single χ_v^t .*

What probes?

So, the number of probes required to check whether a color c (assigned at epoch t') was overwritten at some epoch before t is:

$$\left[T_{t'+1} + \mathcal{B}\left(\frac{1}{\alpha}\right) \cdot T_{t'+2} + \mathcal{B}\left(\frac{1}{\alpha^2}\right) \cdot T_{t'+3} + \cdots + \mathcal{B}\left(\frac{1}{\alpha^{t-t'-2}}\right) \cdot T_{t-1} \right] \quad (5)$$

► **Lemma 44.** *For $\alpha > 4.5$, the expected number of calls to the procedure **ACCEPTED** while sampling a single χ_v^t is $\mathbb{E}[T_t] = \mathcal{O}(e^{1.02t/\alpha})$.*

What probes?
Given graph
G and q col-
ors ...

Proof. We start with the recurrence for the expected number of probes to $\{\chi^{t'}\}_{t' \in [t]}$ (equivalently calls to **ACCEPTED**) used by the algorithm. We will use $\mathcal{B}(p)$ to refer to the Bernoulli random

variable with bias p . When checking a single neighbor w , the algorithm iterates through all the epochs t' such that $C_w^{t'} = c$ (in reality, only the last occurrence matters, but we are looking for an upper bound). If such a t' is found (this happens with probability $1/q$ independently for each trial), there is one recursive call to $T_{t'}$. Regardless of what happens, let's say the algorithm queries $T_{t'+1}, T_{t'+2}, \dots, T_{t-1}$ until an **ACCEPTED** proposal is found. Adding an extra $T_{t'}$ term to Equation 5 and summing up over all neighbors and epochs we get the following:

$$T_t \leq \Delta \cdot \sum_{t'=1}^t \mathbb{P}[C_w^{t'} = c] \cdot \left[T_{t'} + T_{t'+1} + \mathcal{B}\left(\frac{1}{\alpha}\right) \cdot T_{t'+2} + \mathcal{B}\left(\frac{1}{\alpha^2}\right) \cdot T_{t'+3} + \dots \right. \quad (6)$$

$$\left. \dots + \mathcal{B}\left(\frac{1}{\alpha^{t-t'-2}}\right) \cdot T_{t-1} \right] \quad (7)$$

$$\leq \Delta \cdot \mathcal{B}\left(\frac{1}{q}\right) \left[\sum_{t'=1}^{t-1} T_{t'} + \sum_{t'=1}^{t-1} T_{t'} \cdot \left(1 + \mathcal{B}\left(\frac{1}{\alpha}\right) + \mathcal{B}\left(\frac{1}{\alpha^2}\right) + \dots \right) \right] \quad (8)$$

In the second step, we just group all the terms from the same epoch together. Using Lemma 42 and the fact that $\mathbb{P}[C_w^{t'} = c]$ is independent of all other events, we can write a recurrence for the expected number of probes.

$$\mathbb{E}[T_t] \leq \Delta \cdot \frac{1}{2\alpha\Delta} \left[\sum_{t'=1}^{t-1} T_{t'} + \sum_{t'=1}^{t-1} T_{t'} \cdot \left(1 + \frac{1}{\alpha} + \frac{1}{\alpha^2} + \dots \right) \right] \leq \frac{1}{2\alpha} \cdot \sum_{t'=1}^{t-1} T_{t'} \cdot \left[1 + \frac{\alpha}{\alpha-1} \right] \quad (9)$$

Now, we make the assumption that $\mathbb{E}[T_{t'}] \leq e^{kt/\alpha}$, and show that this satisfies the expectation recurrence for the desired value of k . First, we sum the geometric series:

$$\sum_{t'=1}^{t-1} \mathbb{E}[T_{t'}] = \sum_{t'=1}^{t-1} e^{kt'/\alpha} < \frac{e^{kt/\alpha} - 1}{e^{k/\alpha} - 1} < \frac{e^{kt/\alpha}}{e^{k/\alpha} - 1}$$

The expectation recurrence to be satisfied then becomes:

$$\mathbb{E}[T_t] \leq \frac{1}{2\alpha} \cdot \frac{e^{kt/\alpha}}{e^{k/\alpha} - 1} \cdot \left[1 + \frac{\alpha}{\alpha-1} \right] = e^{kt/\alpha} \cdot \frac{2\alpha-1}{2\alpha(\alpha-1)(e^{k/\alpha}-1)} = e^{kt/\alpha} \cdot f(\alpha, k)$$

We notice that for $k = 1.02$ and $\alpha > 4.5$, $f(\alpha) < 1$. This can easily be verified by checking that $f(\alpha, 1.02)$ decreases monotonically with α in the range $\alpha > 4.5$. Thus, our recurrence is satisfied for $k = 1.02$, and therefore the expected number of calls is $\mathcal{O}(e^{1.02t/\alpha})$.

Finally, we note that each probe potentially takes time $\mathcal{O}(t\Delta)$ to iterate through all the neighbors in all epochs resulting in a total runtime of $\mathcal{O}(t\Delta e^{kt/\alpha})$. \square

► **Theorem 45.** *Given adjacency list query access to a graph with n nodes, maximum degree Δ , and $q = 2\alpha\Delta \geq 9\Delta$ colors, we can sample the color of any given node in an $(1/n)$ -approximate uniformly random coloring of the graph in a consistent manner using only $\mathcal{O}(n^{6.12/\alpha} \Delta \log n)$ time space and random bits. This is sublinear for $\alpha > 6.12$ and the sampled coloring is $1/n$ -close to the uniform distribution in L_1 distance.*

Proof. We compute the mixing time from Theorem 41 to obtain $\tau_{mix}(1/n) = 6 \ln n$ (this is valid since $q > 9\Delta$). Since $\alpha > 4.5$, we can invoke Lemma 44 to conclude that the number of calls to **ACCEPTED** is $\mathcal{O}(n^{6.12/\alpha} \Delta \log n)$ which is sublinear for $\alpha > 6.12$. Each call to **ACCEPTED**(v, t) potentially spends $t\Delta$ time looking for neighbors in each epoch before t . Since $t \leq 6 \ln n$, the overall runtime becomes $\mathcal{O}(n^{6.12/\alpha} \Delta \log n)$. \square

8 Open Problems

- Degree queries for undirected random graphs?
- Faster implementation of coloring $\mathcal{O}(\text{poly}(\log n))$?
- Reduce the required value of α ?
- Random walks on other networks? Ideally, any network.

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A

 Removing the Perfect-Precision Arithmetic Assumption

In this section we remove the perfect-precision arithmetic assumption. Instead, we only assume that it is possible to compute $\prod_{u=a}^b (1 - p_{vu})$ and $\sum_{u=a}^b p_{vu}$ to N -bit precision, as well as drawing a random N -bit word, using polylogarithmic resources. Here we will focus on proving that the family of the random graph we generate via our procedures is statistically close to that of the desired distribution. The main technicality of this lemma arises from the fact that, not only the generator is randomized, but the agent interacting with the generator may choose his queries arbitrarily (or adversarially): our proof must handle any sequence of random choices the generator makes, and any sequence of queries the agent may make.

Observe that the distribution of the graphs constructed by our generator is governed entirely by the samples u drawn from $F(v, a, b)$ in Algorithm 3. By our assumption, the CDF of any $F(v, a, b)$ can be efficiently computed from $\prod_{u=a}^{u'} (1 - p_{vu})$, and thus sampling with $\frac{1}{\text{poly}(n)}$ error in the L_1 -distance requires a random N -bit word and a binary-search in $\mathcal{O}(\log(b - a + 1)) = \mathcal{O}(\log n)$ iterations. Using this crucial fact, we prove our lemma that removes the perfect-precision arithmetic assumption.

► **Lemma 46.** *If Algorithm 3 (the FILL operation) is repeatedly invoked to construct a graph G by drawing the value u for at most S times in total, each of which comes from some distribution $F'(v, a, b)$ that is ϵ -close in L_1 -distance to the correct distribution $F(v, a, b)$ that perfectly generates the desired distribution G over all graphs, then the distribution G' of the generated graph G is (ϵS) -close to G in the L_1 -distance.*

Proof. For simplicity, assume that the algorithm generates the graph to completion according to a sequence of up to n^2 distinct buckets $\mathcal{B} = \langle B_{v_1}^{(u_1)}, B_{v_2}^{(u_2)}, \dots \rangle$, where each $B_{v_i}^{(u_i)}$ specifies the unfilled bucket in which any query instigates a FILL function call. Define an *internal state* of our generator as the triplet $s = (k, u, \mathbf{A})$, representing that the algorithm is currently processing the k^{th} FILL, in the iteration (the **repeat** loop of Algorithm 3) with value u , and have generated \mathbf{A} so far. Let $t_{\mathbf{A}}$ denote the *terminal state* after processing all queries and having generated the graph $G_{\mathbf{A}}$ represented by \mathbf{A} . We note that \mathbf{A} is used here in the analysis but not explicitly maintained; further, it reflects the changes in every iteration: as u is updated during each iteration of FILL, the cells $\mathbf{A}[v][u'] = \phi$ for $u' < u$ (within that bucket) that has been skipped are also updated to 0.

Let \mathcal{S} denote the set of all (internal and terminal) states. For each state s , the generator samples u from the corresponding $F'(v, a, b)$ where $\|F(v, a, b) - F'(v, a, b)\|_1 \leq \epsilon = \frac{1}{\text{poly}(n)}$, then moves to a new state according to u . In other words, there is an induced pair of collection of distributions over the states: $(\mathcal{T}, \mathcal{T}')$ where $\mathcal{T} = \{\mathbf{T}_s\}_{s \in \mathcal{S}}$, $\mathcal{T}' = \{\mathbf{T}'_s\}_{s \in \mathcal{S}}$, such that $\mathbf{T}_s(s')$ and $\mathbf{T}'_s(s')$ denote the probability that the algorithm advances from s to s' by using a sample from the correct $F(v, a, b)$ and from the approximated $F'(v, a, b)$, respectively. Consequently, $\|\mathbf{T}_s - \mathbf{T}'_s\|_1 \leq \epsilon$ for every $s \in \mathcal{S}$.

The generator begins with the initial (internal) state $s_0 = (1, 0, \mathbf{A}_\phi)$ where all cells of \mathbf{A}_ϕ are ϕ 's, goes through at most $S = O(n^3)$ other states (as there are up to n^2 values of k and $O(n)$ values of u), and reach some terminal state $t_{\mathbf{A}}$, generating the entire graph in the process. Let $\pi = \langle s_0^\pi = s_0, s_1^\pi, \dots, s_{\ell(\pi)}^\pi = t_{\mathbf{A}} \rangle$ for some \mathbf{A} denote a sequence (“path”) of up to $S + 1$ states the algorithm proceeds through, where $\ell(\pi)$ denote the number of transitions it undergoes. For simplicity, let $T_{t_{\mathbf{A}}}(t_{\mathbf{A}}) = 1$, and $T_{t_{\mathbf{A}}}(s) = 0$ for all state $s \neq t_{\mathbf{A}}$, so that the terminal state can be repeated and we may assume $\ell(\pi) = S$ for every π . Then, for the correct transition probabilities described as \mathcal{T} , each π occurs with probability $q(\pi) = \prod_{i=1}^S \mathbf{T}_{s_{i-1}}(s_i)$, and thus $G(G_{\mathbf{A}}) = \sum_{\pi: s_S^\pi = t_{\mathbf{A}}} q(\pi)$.

Let $\mathcal{T}^{\min} = \{\mathbf{T}_s^{\min}\}_{s \in \mathcal{S}}$ where $\mathbf{T}_s^{\min}(s') = \min\{\mathbf{T}_s(s'), \mathbf{T}'_s(s')\}$, and note that each \mathbf{T}_s^{\min} is not

necessarily a probability distribution. Then, $\sum_{s'} \mathsf{T}_s^{\min}(s') = 1 - \|\mathsf{T}_s - \mathsf{T}'_s\|_1 \geq 1 - \epsilon$. Define $q', q^{\min}, \mathsf{G}'(G_{\mathbf{A}}), \mathsf{G}^{\min}(G_{\mathbf{A}})$ analogously, and observe that $q^{\min}(\pi) \leq \min\{q(\pi), q'(\pi)\}$ for every π , so $\mathsf{G}^{\min}(G_{\mathbf{A}}) \leq \min\{\mathsf{G}(G_{\mathbf{A}}), \mathsf{G}'(G_{\mathbf{A}})\}$ for every $G_{\mathbf{A}}$ as well. In other words, $q^{\min}(\pi)$ lower bounds the probability that the algorithm, drawing samples from the correct distributions or the approximated distributions, proceeds through states of π ; consequently, $\mathsf{G}^{\min}(G_{\mathbf{A}})$ lower bounds the probability that the algorithm generates the graph $G_{\mathbf{A}}$.

Next, consider the probability that the algorithm proceeds through the prefix $\pi_i = \langle s_0^\pi, \dots, s_i^\pi \rangle$ of π . Observe that for $i \geq 1$,

$$\begin{aligned} \sum_{\pi} q^{\min}(\pi_i) &= \sum_{\pi} q^{\min}(\pi_{i-1}) \cdot \mathsf{T}_{s_{i-1}^\pi}^{\min}(s_i^\pi) = \sum_{s, s'} \sum_{\pi: s_{i-1}^\pi = s, s_i^\pi = s'} q^{\min}(\pi_{i-1}) \cdot \mathsf{T}_s^{\min}(s') \\ &= \sum_{s'} \mathsf{T}_s^{\min}(s') \cdot \sum_s \sum_{\pi: s_{i-1}^\pi = s} q^{\min}(\pi_{i-1}) \geq (1 - \epsilon) \sum_{\pi} q^{\min}(\pi_{i-1}). \end{aligned}$$

Roughly speaking, at least a factor of $1 - \epsilon$ of the “agreement” between the distributions over states according to \mathcal{T} and \mathcal{T}' is necessarily conserved after a single sampling process. As $\sum_{\pi} q^{\min}(\pi_0) = 1$ because the algorithm begins with $s_0 = (1, 0, \mathbf{A}_\phi)$, by an inductive argument we have $\sum_{\pi} q^{\min}(\pi) = \sum_{\pi} q^{\min}(\pi_S) \geq (1 - \epsilon)^S \geq 1 - \epsilon S$. Hence, $\sum_{G_{\mathbf{A}}} \min\{\mathsf{G}(G_{\mathbf{A}}), \mathsf{G}'(G_{\mathbf{A}})\} \geq \sum_{G_{\mathbf{A}}} \mathsf{G}^{\min}(G_{\mathbf{A}}) \geq 1 - \epsilon S$, implying that $\|\mathsf{G} - \mathsf{G}'\|_1 \leq \epsilon S$, as desired. In particular, by substituting $\epsilon = \frac{1}{\text{poly}(n)}$ and $S = O(n^3)$, we have shown that Algorithm 3 only creates a $\frac{1}{\text{poly}(n)}$ error in the L_1 -distance. \square

We remark that **RANDOM-NEIGHBOR** queries also require that the returned edge is drawn from a distribution that is close to a uniform one, but this requirement applies only *per query* rather than over the entire execution of the generator. Hence, the error due to the selection of a random neighbor may be handled separately from the error for generating the random graph; its guarantee follows straightforwardly from a similar analysis.

B Sampling from the Multivariate Hypergeometric Distribution

Consider the following random experiment. Suppose that we have an urn containing $B \leq n$ marbles (representing vertices), each occupies one of the r possible colors (representing communities) represented by an integer from $[r]$. The number of marbles of each color in the urn is known: there are C_k indistinguishable marbles of color $k \in [r]$, where $C_1 + \dots + C_r = B$. Consider the process of drawing $\ell \leq B$ marbles from this urn *without replacement*. We would like to sample how many marbles of each color we draw.

More formally, let $\mathbf{C} = \langle c_1, \dots, c_r \rangle$, then we would like to (approximately) sample a vector $\mathbf{S}_\ell^{\mathbf{C}}$ of r non-negative integers such that

$$\Pr[\mathbf{S}_\ell^{\mathbf{C}} = \langle s_1, \dots, s_r \rangle] = \frac{\binom{C_1}{s_1} \cdot \binom{C_2}{s_2} \dots \binom{C_r}{s_r}}{\binom{B}{C_1 + C_2 + \dots + C_r}}$$

where the distribution is supported by all vectors satisfying $s_k \in \{0, \dots, C_k\}$ for all $k \in [r]$ and $\sum_{k=1}^r s_k = \ell$. This distribution is referred to as the *multivariate hypergeometric distribution*.

The sample $\mathbf{S}_\ell^{\mathbf{C}}$ above may be generated easily by simulating the drawing process, but this may take $\Omega(\ell)$ iterations, which have linear dependency in n in the worst case: $\ell = \Theta(B) = \Theta(n)$. Instead, we aim to generate such a sample in $O(r \text{ poly}(\log n))$ time with high probability. We first make use of the following procedure from [GGN10].

► **Lemma 47.** *Suppose that there are T marbles of color 1 and $B - T$ marbles of color 2 in an urn, where $B \leq n$ is even. There exists an algorithm that samples $\langle s_1, s_2 \rangle$, the number of marbles of each color appearing when drawing $B/2$ marbles from the urn without replacement, in $O(\text{poly}(\log n))$ time and random words. Specifically, the probability of sampling a specific pair $\langle s_1, s_2 \rangle$ where $s_1 + s_2 = T$ is approximately $\binom{B/2}{s_1} \binom{B/2}{T-s_1} / \binom{B}{T}$ with error of at most n^{-c} for any constant $c > 0$.*

In other words, the claim here only applies to the two-color case, where we sample the number of marbles when drawing exactly half of the marbles from the entire urn ($r = 2$ and $\ell = B/2$). First we generalize this claim to handle any desired number of drawn marbles ℓ (while keeping $r = 2$).

► **Lemma 48.** *Given C_1 marbles of color 1 and $C_2 = B - C_1$ marbles of color 2, there exists an algorithm that samples $\langle s_1, s_2 \rangle$, the number of marbles of each color appearing when drawing ℓ marbles from the urn without replacement, in $O(\text{poly}(\log B))$ time and random words.*

Proof. For the base case where $B = 1$, we trivially have $\mathbf{S}_1^{\mathbf{C}} = \mathbf{C}_1$ and $\mathbf{S}_0^{\mathbf{C}} = \mathbf{C}_2$. Otherwise, for even B , we apply the following procedure.

- If $\ell \leq B/2$, generate $\mathbf{C}' = \mathbf{S}_{B/2}^{\mathbf{C}}$ using Claim 47.
 - If $\ell = B/2$ then we are done.
 - Else, for $\ell < B/2$ we recursively generate $\mathbf{S}_\ell^{\mathbf{C}'}$.
- Else, for $\ell > B/2$, we generate $\mathbf{S}_{B-\ell}^{\mathbf{C}'}$ as above, then output $\mathbf{C} - \mathbf{S}_{B-\ell}^{\mathbf{C}'}$.

On the other hand, for odd B , we simply simulate drawing a single random marble from the urn before applying the above procedure on the remaining $B - 1$ marbles in the urn. That is, this process halves the domain size B in each step, requiring $\log B$ iterations to sample $\mathbf{S}_\ell^{\mathbf{C}}$. \square

Lastly we generalize to support larger r .

► **Theorem 49.** *Given B marbles of r different colors, such that there are C_i marbles of color i , there exists an algorithm that samples $\langle s_1, s_2, \dots, s_r \rangle$, the number of marbles of each color appearing when drawing ℓ marbles from the urn without replacement, in $O(r \cdot \text{poly}(\log B))$ time and random words.*

Proof. Observe that we may reduce $r > 2$ to the two-color case by sampling the number of marbles of the first color, collapsing the rest of the colors together. Namely, define a pair $\mathbf{D} = \langle C_1, C_2 + \dots + C_r \rangle$, then generate $\mathbf{S}_\ell^{\mathbf{D}} = \langle s_1, s_2 + \dots + s_r \rangle$ via the above procedure. At this point we have obtained the first entry s_1 of the desired $\mathbf{S}_\ell^{\mathbf{C}}$. So it remains to generate the number of marbles of each color from the remaining $r - 1$ colors in $\ell - s_1$ remaining draws. In total, we may generate $\mathbf{S}_\ell^{\mathbf{C}}$ by performing r iterations of the two-colored case. The error in the L_1 -distance may be established similarly to the proof of Lemma 46. \square

► **Theorem 50.** *Given B marbles of r different colors in $[r]$, such that there are C_i marbles of color i and a parameter $k \leq r$, there exists an algorithm that samples $s_1 + s_2 + \dots + s_k$, the number of marbles among the first k colors appearing when drawing ℓ marbles from the urn without replacement, in $O(\text{poly}(\log B))$ time and random words.*

Proof. Since we don't have to find the individual counts, we can be more efficient by grouping half the colors together at each step. Formally, we define a pair $\mathbf{D} = \langle D_1, D_2 \rangle$ where $D_1 = C_1 + C_2 + \dots + C_{r/2}$ and $D_2 = C_{r/2+1} + \dots + C_{r-1} + C_r$. We then generate $\langle D'_1, D'_2 \rangle = \mathbf{S}_\ell^{\mathbf{D}}$.

- If $k < r/2$, we recursively solve the problem with the first $r/2$ colors, $B \leftarrow D'_1$, and the original value of k .
- If $k > r/2$, we recurse on the last $r/2$ colors, B set to D'_2 , and k set to $k - r/2$. In this case, we add D'_1 to the returned value.
- Otherwise, $k = r/2$ and we can return D'_1 .

The number of recursive calls is $\mathcal{O}(\log r) = \mathcal{O}(\log B)$ (since $r \leq B$). So, the overall runtime is $\mathcal{O}(\text{poly}(\log B))$. \square

B.1 Data structure

We now show that Theorem 49 may be used in order to create the following data structure. Recall that \mathbf{R} denote the given distribution over integers $[r]$ (namely, the random distribution of communities for each vertex). Our data structure generates and maintains random variables X_1, \dots, X_n , each of which is drawn independently at random from \mathbf{R} : X_i denotes the community of vertex i . Then given a pair (i, j) , it returns the vector $\mathbf{C}(i, j) = \langle c_1, \dots, c_r \rangle$ where c_k counts the number of variables X_i, \dots, X_j that takes on the value k . Note that we may also find out X_i by querying for (i, i) and take the corresponding index.

We maintain a complete binary tree whose leaves corresponds to indices from $[n]$. Each node represents a range and stores the vector \mathbf{C} for the corresponding range. The root represents the entire range $[n]$, which is then halved in each level. Initially the root samples $\mathbf{C}(1, n)$ from the multinomial distribution according to \mathbf{R} (see e.g., Section 3.4.1 of [Knu97]). Then, the children are generated on-the-fly using the lemma above. Thus, each query can be processed within $O(r \text{poly}(\log n))$ time, yielding Theorem 15. Then, by embedding the information stored by the data structure into the state (as in the proof of Lemma 46), we obtain the desired Corollary 16.

faster
sampling for
first k colors

C Further Analysis and Extensions of Algorithm 1

C.1 Performance Guarantee

This section is devoted to showing the following lemma that bounds the required resources per query of Algorithm 1. We note that we only require efficient computation of $\prod_{u \in [a,b]} (1 - p_{vu})$ (and not $\sum_{u \in [a,b]} p_{vu}$), and that for the $G(n, p)$ model, the resources required for such computation is asymptotically negligible.

► **Theorem 51.** *Each execution of Algorithm 1 (the NEXT-NEIGHBOR query), with high probability,*

- *terminates within $\mathcal{O}(\log n)$ iterations (of its repeat loop);*
- *computes $\mathcal{O}(\log^2 n)$ quantities of $\prod_{u \in [a,b]} (1 - p_{vu})$;*
- *aside from the above computations, uses $\mathcal{O}(\log^2 n)$ time, $\mathcal{O}(\log n)$ random N -bit words, and $\mathcal{O}(\log n)$ additional space.*

Proof. We focus on the number of iterations as the remaining results follow trivially. This proof is rather involved and thus is divided into several steps.

Specifying random choices

The performance of the algorithm depends on not only the random variables X_{vu} 's, but also the unused coins C_{vu} 's. We characterize the two collections of Bernoulli variables $\{X_{vu}\}$ and $\{Y_{vu}\}$ that cover all random choices made by Algorithm 1 as follows.

- Each X_{vu} (same as X_{uv}) represents the result for the *first* coin-toss corresponding to cells $\mathbf{A}[v][u]$ and $\mathbf{A}[u][v]$, which is the coin-toss obtained when X_{vu} becomes decided: either C_{vu} during a NEXT-NEIGHBOR(v) call when $\mathbf{A}[v][u] = \phi$, or C_{vu} during a NEXT-NEIGHBOR(u) call when $\mathbf{A}[u][v] = \phi$, whichever occurs first. This description of X_{vu} respects our invariant that, if the generation process is executed to completion, we will have $\mathbf{A}[v][u] = X_{vu}$ in all entries.
- Each Y_{vu} represents the result for the *second* coin-toss corresponding to cell $\mathbf{A}[v][u]$, which is the coin-toss C_{vu} obtained during a NEXT-NEIGHBOR(v) call when X_{vu} is already decided. In other words, $\{Y_{vu}\}$'s are the coin-tosses that should have been skipped but still performed in Algorithm 1 (if they have indeed been generated). Unlike the previous case, Y_{vu} and Y_{uv} are two independent random variables: they may be generated during a NEXT-NEIGHBOR(v) call and a NEXT-NEIGHBOR(u) call, respectively.

As mentioned earlier, we allow any sequence of probabilities p_{vu} in our proof. The success probabilities of these indicators are therefore given by $\mathbb{P}[X_{vu} = 1] = \mathbb{P}[Y_{vu} = 1] = p_{vu}$.

Characterizing iterations

Suppose that we compute NEXT-NEIGHBOR(v) and obtain an answer u . Then $X_{v, \text{last}[v]+1} = \dots = X_{v, u-1} = 0$ as none of $u' \in (\text{last}[v], u)$ is a neighbor of v . The vertices considered in the loop of Algorithm 1 that do not result in the answer u , are $u' \in (\text{last}[v], u)$ satisfying $\mathbf{A}[v][u'] = 0$ and $Y_{v, u'} = 1$; we call the iteration corresponding to such a u' a *failed iteration*. Observe that if $X_{v, u'} = 0$ but is undecided ($\mathbf{A}[v][u'] = \phi$), then the iteration is not failed, even if $Y_{v, u'} = 1$ (in which case, $X_{v, u'}$ takes the value of $C_{v, u'}$ while $Y_{v, u'}$ is never used). Thus we assume the worst-case

scenario where all $X_{v,u'}$ are revealed: $\mathbf{A}[v][u'] = X_{v,u'} = 0$ for all $u' \in (\mathbf{last}[v], u)$. The number of failed iterations in this case stochastically dominates those in all other cases.⁷

Then, the upper bound on the number of failed iterations of a call $\text{NEXT-NEIGHBOR}(v)$ is given by the maximum number of cells $Y_{v,u'} = 1$ of $u' \in (\mathbf{last}[v], u)$, over any $u \in (\mathbf{last}[v], n]$ satisfying $X_{v,\mathbf{last}[v]+1} = \dots = X_{vu} = 0$. Informally, we are asking "of all consecutive cells of 0's in a single row of $\{X_{vu}\}$ -table, what is the largest number of cells of 1's in the corresponding cells of $\{Y_{vu}\}$ -table?"

Bounding the number of iterations required for a fixed pair $(v, \mathbf{last}[v])$

We now proceed to bounding the number of iterations required over a sampled pair of $\{X_{vu}\}$ and $\{Y_{vu}\}$, from any probability distribution. For simplicity we renumber our indices and drop the index $(v, \mathbf{last}[v])$ as follows. Let $p_1, \dots, p_L \in [0, 1]$ denote the probabilities corresponding to the cells $\mathbf{A}[v][\mathbf{last}[v] + 1 \dots n]$ (where $L = n - \mathbf{last}[v]$), then let X_1, \dots, X_L and Y_1, \dots, Y_L be the random variables corresponding to the same cells on \mathbf{A} .

For $i = 1, \dots, L$, define the random variable Z_i in terms of X_i and Y_i so that

- $Z_i = 2$ if $X_i = 0$ and $Y_i = 1$, which occurs with probability $p_i(1 - p_i)$.
This represents the event where i is not a neighbor, and the iteration fails.
- $Z_i = 1$ if $X_i = Y_i = 0$, which occurs with probability $(1 - p_i)^2$.
This represents the event where i is not a neighbor, and the iteration does not fail.
- $Z_i = 0$ if $X_i = 1$, which occurs with probability p_i .
This represents the event where i is a neighbor.

For $\ell \in [L]$, define the random variable $M_\ell := \prod_{i=1}^\ell Z_i$, and $M_0 = 1$ for convenience. If $X_i = 1$ for some $i \in [1, \ell]$, then $Z_i = 0$ and $M_\ell = 0$. Otherwise, $\log M_\ell$ counts the number of indices $i \in [\ell]$ with $Y_i = 1$, the number of failed iterations. Therefore, $\log(\max_{\ell \in \{0, \dots, L\}} M_\ell)$ gives the number of failed iterations this $\text{NEXT-NEIGHBOR}(v)$ call.

To bound M_ℓ , observe that for any $\ell \in [L]$, $\mathbb{E}[Z_\ell] = 2p_\ell(1 - p_\ell) + (1 - p_\ell)^2 = 1 - p_\ell^2 \leq 1$ regardless of the probability $p_\ell \in [0, 1]$. Then, $\mathbb{E}[M_\ell] = \mathbb{E}[\prod_{i=1}^\ell Z_i] = \prod_{i=1}^\ell \mathbb{E}[Z_i] \leq 1$ because Z_i 's are all independent. By Markov's inequality, for any (integer) $r \geq 0$, $\Pr[\log M_\ell > r] = \Pr[M_\ell > 2^r] < 2^{-r}$. By the union bound, the probability that more than r failed iterations are encountered is $\Pr[\log(\max_{\ell \in \{0, \dots, L\}} M_\ell) > r] < L \cdot 2^{-r} \leq n \cdot 2^{-r}$.

Establishing the overall performance guarantee

So far we have deduced that, for each pair of a vertex v and its $\mathbf{last}[v]$, the probability that the call $\text{NEXT-NEIGHBOR}(v)$ encounters more than r failed iterations is less than $n \cdot 2^{-r}$, which is at most n^{-c-2} for any desired constant c by choosing a sufficiently large $r = \Theta(\log n)$. As Algorithm 1 may need to support up to $\Theta(n^2)$ NEXT-NEIGHBOR calls, one corresponding to each pair $(v, \mathbf{last}[v])$, the probability that it ever encounters more than $O(\log n)$ failed iterations to answer a single NEXT-NEIGHBOR query is at most n^{-c} . That is, with high probability, $O(\log n)$ iterations are required per NEXT-NEIGHBOR call, which concludes the proof of Theorem 51. \square

⁷There exists an adversary who can enforce this worst case. Namely, an adversary that first makes NEXT-NEIGHBOR queries to learn all neighbors of every vertex except for v , thereby filling out the whole \mathbf{A} in the process. The claimed worst case then occurs as this adversary now repeatedly makes NEXT-NEIGHBOR queries on v . In particular, a committee of n adversaries, each of which is tasked to perform this series of calls corresponding to each v , can always expose this worst case.

C.2 Supporting Vertex-Pair Queries

We extend our generator (Algorithm 1) to support the **VERTEX-PAIR** queries: given a pair of vertices (u, v) , decide whether there exists an edge $\{u, v\}$ in the generated graph. To answer a **VERTEX-PAIR** query, we must first check whether the value X_{uv} for $\{u, v\}$ has already been assigned, in which case we answer accordingly. Otherwise, we must make a coin-flip with the corresponding bias p_{uv} to assign X_{uv} , deciding whether $\{u, v\}$ exists in the generated graph. If we maintained the full \mathbf{A} as done in the naïve Algorithm ??, we would have been able to simply set $\mathbf{A}[u][v]$ and $\mathbf{A}[v][u]$ to this new value. However, our more efficient Algorithm 1 that represents \mathbf{A} compactly via **last** and P_v 's cannot record arbitrary modifications to \mathbf{A} .

Observe that if we were to apply the trivial implementation of **VERTEX-PAIR** in Algorithm ??, then by Lemma 4, **last** and P_v 's will only fail capture the state $\mathbf{A}[v][u] = 0$ when $u > \mathbf{last}[v]$ and $v > \mathbf{last}[u]$. Fortunately, unlike **NEXT-NEIGHBOR** queries, a **VERTEX-PAIR** query can only set one cell $\mathbf{A}[v][u]$ to 0 per query, and thus we may afford to store these changes explicitly.⁸ To this end, we define the set $Q = \{\{u, v\} : X_{uv} \text{ is assigned to } 0 \text{ during a VERTEX-PAIR query}\}$, maintained as a hash table. Updating Q during **VERTEX-PAIR** queries is trivial: we simply add $\{u, v\}$ to Q before we finish processing the query if we set $\mathbf{A}[u][v] = 0$. Conversely, we need to add u to P_v and add v to P_u if the **VERTEX-PAIR** query sets $\mathbf{A}[u][v] = 1$ as usual, yielding the following observation. It is straightforward to verify that each **VERTEX-PAIR** query requires $O(\log n)$ time, $O(1)$ random N -bit word, and $O(1)$ additional space per query.

► **Lemma 52.** *The data structures **last**, P_v 's and Q together provide a succinct representation of \mathbf{A} when **NEXT-NEIGHBOR** queries (modified Algorithm 1) and **VERTEX-PAIR** queries (modified Algorithm ??) are allowed. In particular, $\mathbf{A}[v][u] = 1$ if and only if $u \in P_v$. Otherwise, $\mathbf{A}[v][u] = 0$ if $u < \mathbf{last}[v]$, $v < \mathbf{last}[u]$, or $\{v, u\} \in Q$. In all remaining cases, $\mathbf{A}[v][u] = \phi$.*

We now explain other necessary changes to Algorithm 1. In the implementation of **NEXT-NEIGHBOR**, an iteration is not failed when the chosen X_{vu} is still undecided: $\mathbf{A}[v][u]$ must still be ϕ . Since X_{vu} may also be assigned to 0 via a **VERTEX-PAIR**(v, u) query, we must also consider an iteration where $\{v, u\} \in Q$ failed. That is, we now require one additional condition $\{v, u\} \notin Q$ for termination (which only takes $O(1)$ time to verify per iteration). As for the analysis, aside from handling the fact that X_{vu} may also become decided during a **VERTEX-PAIR** call, and allowing the states of the algorithm to support **VERTEX-PAIR** queries, all of the remaining analysis for correctness and performance guarantee still holds.

Therefore, we have established that our augmentation to Algorithm 1 still maintains all of its (asymptotic) performance guarantees for **NEXT-NEIGHBOR** queries, and supports **VERTEX-PAIR** queries with complexities as specified above, concluding the following corollary. We remark that, as we do not aim to support **RANDOM-NEIGHBOR** queries, this simple algorithm here provides significant improvement over the performance of **RANDOM-NEIGHBOR** queries (given in Corollary 11).

► **Corollary 53.** *Algorithm 1 can be modified to allow an implementation of **VERTEX-PAIR** query as explained above, such that the resource usages per query still asymptotically follow those of Theorem 51.*

⁸The disadvantage of this approach is that the generator may allocate more than $\Theta(m)$ space over the entire graph generation process, if **VERTEX-PAIR** queries generate many of these 0's.

D Alternative Generator with Deterministic Performance Guarantee

In this section, we construct data structures that allow us to sample for the next neighbor directly by considering only the cells $\mathbf{A}[v][u] = \phi$ in the Erdős-Rényi model and the Stochastic Block model. This provides $\text{poly}(\log n)$ *worst-case* performance guarantee for generators supporting only the **NEXT-NEIGHBOR** queries. We may again extend this data structure to support **VERTEX-PAIR** queries, however, at the cost of providing $\text{poly}(\log n)$ *amortized* performance guarantee instead.

In what follows, we first focus on the $G(n, p)$ model, starting with **NEXT-NEIGHBOR** queries (Section D.1) then extend to **VERTEX-PAIR** queries (Section D.2). We then explain how this result may be generalized to support the Stochastic Block model with random community assignment in Section D.3.

D.1 Data structure for next-neighbor queries in the Erdős-Rényi model

■ **Figure 10** Alternative Generator

```

procedure NEXT-NEIGHBOR( $v$ )
   $w \leftarrow \min K_v$ , or  $n + 1$  if  $K_v = \emptyset$ 
   $t \leftarrow \text{COUNT}(v)$ 
  sample  $F \sim \text{ExactF}(p, t)$ 
  if  $F \leq t$ 
     $u \leftarrow \text{PICK}(v, F)$ 
     $K_u \leftarrow K_u \cup \{v\}$ 
  else
     $u \leftarrow w$ 
    if  $u \neq n + 1$ 
       $K_v \leftarrow K_v \setminus \{u\}$ 
  UPDATE( $v, u$ )
   $\text{last}[v] \leftarrow u$ 
  return  $u$ 

```

Recall that **NEXT-NEIGHBOR**(v) is given by $\min\{u > \text{last}[v] : X_{vu} = 1\}$ (or $n + 1$ if no satisfying u exists). To aid in computing this quantity, we define:

$$\begin{aligned}
 K_v &= \{u \in (\text{last}[v], n] : \mathbf{A}[v][u] = 1\}, \\
 w_v &= \min K_v, \text{ or } n + 1 \text{ if } K_v = \emptyset, \\
 T_v &= \{u \in (\text{last}[v], w_v) : \mathbf{A}[v][u] = \phi\}.
 \end{aligned}$$

The ordered set K_v is only defined for ease of presentation within this section: it is equivalent to $(\text{last}[v], n] \cap P_v$, recording the known neighbors of v after $\text{last}[v]$ (i.e., those that have not been returned as an answer by any **NEXT-NEIGHBOR**(v) query yet). The quantity w_v remains unchanged but is simply restated in terms of K_v . T_v specifies the list of candidates u for **NEXT-NEIGHBOR**(v) with $\mathbf{A}[v][u] = \phi$; in particular, all candidates u 's, such that the

corresponding RVs $X_{vu} = 0$ are decided, are explicitly excluded from T_v .

Unlike the approach of Algorithm 1 that simulates coin-flips even for decided X_{vu} 's, here we only flip undecided coins for the indices in T_v : we have $|T_v|$ Bernoulli trials to simulate. Let F be the random variable denoting the first index of a successful trial out of $|T_v|$ coin-flips, or $|T_v| + 1$ if all fail; denote the distribution of F by $\text{ExactF}(p, |T_v|)$. The CDF of F is given by $\mathbb{P}[F = f] = 1 - (1 - p)^f$ for $f \leq |T_v|$ (i.e., there is some success trial in the first f trials), and $\mathbb{P}[F = |T_v| + 1] = 1$. Thus, we must design a data structure that can compute w_v , compute $|T_v|$, find the F^{th} minimum value in T_v , and update $\mathbf{A}[v][u]$ for the F lowest values $u \in T_v$ accordingly.

Let $k = \lceil \log n \rceil$. We create a range tree, where each node itself contains a balanced binary search tree (BBST), storing **last** values of its corresponding range. Formally, for $i \in [0, n/2^j]$ and $j \in [0, k]$, the i^{th} node of the j^{th} level of the range tree, stores **last**[v] for every $v \in (i \cdot 2^{k-j}, (i + 1) \cdot 2^{k-j}]$. Denote the range tree by \mathbf{R} , and each BBST corresponding to the range $[a, b]$ by $\mathbf{B}_{[a,b]}$. We say that the range $[a, b]$ is *canonical* if it corresponds to a range of some $\mathbf{B}_{[a,b]}$ in \mathbf{R} .

Again, to allow fast initialization, we make the following adjustments from the given formalization above: (1) values **last**[v] = 0 are never stored in any $\mathbf{B}_{[a,b]}$, and (2) each $\mathbf{B}_{[a,b]}$ is created on-the-fly

during the first occasion it becomes non-empty. Further, we augment each $\mathbf{B}_{[a,b]}$ so that each of its node maintains the size of the subtree rooted at that node: this allows us to count, in $O(\log n)$ time, the number of entries in $\mathbf{B}_{[a,b]}$ that is no smaller than a given threshold.

Observe that each v is included in exactly one $\mathbf{B}_{[a,b]}$ per level in \mathbf{R} , so $k + 1 = O(\log n)$ copies of $\mathbf{last}[v]$ are stored throughout \mathbf{R} . Moreover, by the property of range trees, any interval can be decomposed into a disjoint union of $O(\log n)$ canonical ranges. From these properties we implement the data structure \mathbf{R} to support the following operations. (Note that \mathbf{R} is initially an empty tree, so initialization is trivial.)

- **COUNT**(v): compute $|T_v|$.
We break $(\mathbf{last}[v], w_v)$ into $O(\log n)$ disjoint canonical ranges $[a_i, b_i]$'s each corresponding to some $\mathbf{B}_{[a_i, b_i]}$, then compute $t_{[a_i, b_i]} = |\{u \in [a_i, b_i] : \mathbf{last}[u] < v\}|$, and return $\sum_i t_{[a_i, b_i]}$. The value $t_{[a_i, b_i]}$ is obtained by counting the entries of $\mathbf{B}_{[a_i, b_i]}$ that is at least v , then subtract it from $b_i - a_i + 1$; we cannot count entries less than v because $\mathbf{last}[u] = 0$ are not stored.
- **PICK**(v, F): find the F^{th} minimum value in T_v (assuming $F \leq |T_v|$).
We again break $(\mathbf{last}[v], w_v)$ into $O(\log n)$ canonical ranges $[a_i, b_i]$'s, compute $t_{[a_i, b_i]}$'s, and identify the canonical range $[a^*, b^*]$ containing the i^{th} smallest element (i.e., $[a_i, b_i]$ with the smallest b satisfying $\sum_{j \leq i} t_{[a_j, b_j]} \geq F$ assuming ranges are sorted). Binary-search in $[a^*, b^*]$ to find exactly the i^{th} smallest element of T . This is accomplished by traversing \mathbf{R} starting from the range $[a^*, b^*]$ down to a leaf, at each step computing the children's $T_{[a,b]}$'s and deciding which child's range contains the desired element.
- **UPDATE**(v, u): simulate coin-flips, assigning $X_{vu} \leftarrow 1$, and $X_{v,u'} \leftarrow 0$ for $u' \in (\mathbf{last}[v], u) \cap T_v$. This is done implicitly by handling the change $\mathbf{last}[v] \leftarrow u$: for each BBST $\mathbf{B}_{[a,b]}$ where $v \in [a, b]$, remove the old value of $\mathbf{last}[v]$ and insert u instead.

It is straightforward to verify that all operations require at most $O(\log^2 n)$ time and $O(\log n)$ additional space per call. The overall implementation is given in Algorithm 10, using the same asymptotic time and additional space. Recall also that sampling $F \sim \text{ExactF}(p, t)$ requires $O(\log n)$ time and one N -bit random word for the $G(n, p)$ model.

D.2 Data structure for Vertex-Pair queries in the Erdős-Rényi model

Recall that we define Q in Algorithm 1 as the set of pairs (u, v) where X_{uv} is assigned to 0 during a VERTEX-PAIR query, allowing us to check for modifications of \mathbf{A} not captured by $\mathbf{last}[v]$ and K_v . Here in Algorithm 10, rather than checking, we need to be able to count such entries. Thus, we instead create a BBST Q'_v for each v defined as:

$$Q'_v = \{u : u > \mathbf{last}[v], v > \mathbf{last}[u], \text{ and } X_{uv} \text{ is assigned to 0 during a VERTEX-PAIR query}\}.$$

This definition differs from that of Q in Section C.2 in two aspects. First, we ensure that each $\mathbf{A}[v][u] = 0$ is recorded by either \mathbf{last} (via Lemma 4) or Q'_v (explicitly), but *not both*. In particular, if u were to stay in Q'_v when $\mathbf{last}[v]$ increases beyond u , we would have double-counted these entries 0 not only recorded by Q'_v but also implied by $\mathbf{last}[v]$ and K_v . By having a BBST for each Q'_v , we can compute the number of 0's that must be excluded from T_v , which cannot be determined via $\mathbf{last}[v]$ and K_v alone: we subtract these from any counting process done in the data structure \mathbf{R} .

Second, we maintain Q'_v separately for each v as an ordered set, so that we may identify non-neighbors of v within a specific range – this allows us to remove non-neighbors in specific range,

ensuring that the first aspect holds. More specifically, when we increase $\mathbf{last}[v]$, we must go through the data structure Q'_v and remove all $u < \mathbf{last}[v]$, and for each such u , also remove v from Q'_u . There can be as many as linear number of such u , but the number of removals is trivially bounded by the number of insertions, yielding an amortized time performance guarantee in the following theorem. Aside from the deterministic guarantee, unsurprisingly, the required amount of random words for this algorithm is lower than that of the algorithm from Section C (given in Theorem 51 and Corollary 53).

► **Theorem 54.** *Consider the Erdős-Rényi $G(n, p)$ model. For NEXT-NEIGHBOR queries only, Algorithm 10 is a generator that answers each query using $O(\log^2 n)$ time, $O(\log n)$ additional space, and one N -bit random word. For NEXT-NEIGHBOR and VERTEX PAIR queries, an extension of Algorithm 10 answers each query using $O(\log^2 n)$ amortized time, $O(\log n)$ additional space, and one N -bit random word.*

D.3 Data structure for the Stochastic Block model

We employ the data structure for generating and counting the number of vertices of each community in a specified range from Section 4.2. We create r different copies of the data structure \mathbf{R} and Q'_v , one for each community, so that we may implement the required operations separately for each color, including using the COUNT subroutine to sample $F \sim \text{ExactF}$ via the corresponding CDF, and picking the next neighbor according to F . Recall that since we do not store $\mathbf{last}[v] = 0$ in \mathbf{R} , and we only add an entry to K_v , P_v or Q'_v after drawing the corresponding X_{uv} , the communities of the endpoints, which cover all elements stored in these data structures, must have already been determined. Thus, we obtain the following corollary for the Stochastic Block model.

► **Corollary 55.** *Consider the Stochastic Block model with randomly-assigned communities. For NEXT-NEIGHBOR queries only, Algorithm 10 is a generator that answers each query using $O(r \text{ poly}(\log n))$ time, random words, and additional space per query. For NEXT-NEIGHBOR and VERTEX-PAIR queries, Algorithm 10 answers each query using $O(r \text{ poly}(\log n))$ amortized time, $O(r \text{ poly}(\log n))$ random words, and $O(r \text{ poly}(\log n))$ additional space per query additional space, and one N -bit random word.*

E Additional related work

Random graph models

The Erdős-Rényi model, given in [ER60], is one of the most simple theoretical random graph model, yet more specialized models are required to capture properties of real-world data. The Stochastic Block model (or the planted partition model) was proposed in [HLL83] originally for modeling social networks; nonetheless, it has proven to be an useful general statistical model in numerous fields, including recommender systems [LSY03, SC11], medicine [SPT⁺01], social networks [For10, NWS02], molecular biology [CY06, MPN⁺99], genetics [CAT16, JTZ04, CSC⁺07], and image segmentation [SM00]. Canonical problems for this model are the community detection and community recovery problems: some recent works include [CRV15, MNS15, AS15, ABH16]; see e.g., [Abb16] for survey of recent results. The study of Small-World networks is originated in [WS98] has frequently been observed, and proven to be important for the modeling of many real world graphs such as social networks [DMW03, TM67], brain neurons [BB06], among many others. Kleinberg’s model on the simple lattice topology (as considered in this paper) imposes a geographical that allows navigations, yielding important results such as routing algorithms (decentralized search) [Kle00, MN04]. See also e.g., [New00] and Chapter 20 of [EK10].

Generation of random graphs

The problem of local-access implementation of random graphs has been considered in the aforementioned work [GGN03, NN07, ELMR17], as well as in [MRVX12] that locally generates out-going edges on bipartite graphs while minimizing the maximum in-degree. The problem of generating full graph instances for random graph models have been frequently considered in many models of computations, such as sequential algorithms [MKI⁺03, BB05, NLKB11, MH11], and the parallel computation model [AK17].

Query models

In the study of sub-linear time graph algorithms where reading the entire input is infeasible, it is necessary to specify how the algorithm may access the input graph, normally by defining the type of queries that the algorithm may ask about the input graph; the allowed types of queries can greatly affect the performance of the algorithms. While **NEXT-NEIGHBOR** query is only recently considered in [ELMR17], there are other query models providing a neighbor of a vertex, such as asking for an entry in the adjacency-list representation [GR97], or traversing to a random neighbor [BK10]. On the other hand, the **VERTEX-PAIR** query is common in the study of dense graphs as accessing the adjacency matrix representation [GGR98]. The **ALL-NEIGHBORS** query has recently been explicitly considered in local algorithms [FPSV17].

F Dyck Path Generator

► **Theorem 56.** *There are $\frac{1}{n+1} \binom{2n}{n}$ Dyck paths for length $2n$ (construction from [Sta15]).*

Proof. Consider all possible sequences containing $n + 1$ up-steps and n down-steps with the restriction that the first step is an up-step. We say that two sequences belong to the same *class* if they are cyclic shifts of each other. Because of the restriction, the total number of sequences is $\binom{2n}{n}$ and each class is of size $n + 1$. Now, within each class, exactly one of the sequences is such that the prefix sums are *strictly greater* than zero. From such a sequence, we can obtain a Dyck sequence by deleting the first up-step. Similarly, we can start with a Dyck sequence, add an initial up-step and consider all $n + 1$ cyclic shifts to obtain a *class*. This bijection shows that the number of Dyck paths is $\frac{1}{n+1} \binom{2n}{n}$. \square

F.1 Approximating Close-to-Central Binomial Coefficients

We start with Stirling's approximation which states that

$$m! = \sqrt{2\pi m} \left(\frac{m}{e}\right)^m \left(1 + \mathcal{O}\left(\frac{1}{m}\right)\right)$$

We will also use the logarithm approximation when a better approximation is required:

$$\log(m!) = m \log m - m + \frac{1}{2} \log(2\pi m) + \frac{1}{12m} - \frac{1}{360m^3} + \frac{1}{1260m^5} - \dots \quad (10)$$

This immediately gives us an asymptotic formula for the central binomial coefficient as:

► **Lemma 57.** *The central binomial coefficient can be approximated as:*

$$\binom{n}{n/2} = \sqrt{\frac{2}{\pi n}} 2^n \left(1 + \mathcal{O}\left(\frac{1}{n}\right)\right)$$

Now, we consider a “off-center” Binomial coefficient $\binom{n}{k}$ where $k = \frac{n+c\sqrt{n}}{2}$.

► **Lemma 58.** *Proof from [Spe14]*

$$\binom{n}{k} = \binom{n}{n/2} e^{-c^2/2} \exp(\mathcal{O}(c^3/\sqrt{n}))$$

Proof. We consider the ratio: $R = \binom{n}{k} / \binom{n}{n/2}$:

$$R = \frac{\binom{n}{k}}{\binom{n}{n/2}} = \frac{(n/2)!(n/2)!}{k!(n-k)!} = \prod_{i=1}^{c\sqrt{n}/2} \frac{n/2 - i + 1}{n/2 + i} \quad (11)$$

$$\Rightarrow \log R = \sum_{i=1}^{c\sqrt{n}/2} \log\left(\frac{n/2 - i + 1}{n/2 + i}\right) \quad (12)$$

$$= \sum_{i=1}^{c\sqrt{n}/2} -\frac{4i}{n} + \mathcal{O}\left(\frac{i^2}{n^2}\right) = -\frac{c^2 n}{2} + \mathcal{O}\left(\frac{(c\sqrt{n})^3}{n^2}\right) = -\frac{c^2}{2} + \mathcal{O}\left(\frac{c^3}{\sqrt{n}}\right) \quad (13)$$

$$\Rightarrow \binom{n}{k} = \binom{n}{n/2} e^{-c^2/2} \exp(\mathcal{O}(c^3/\sqrt{n})) \quad (14)$$

\square

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F.2 Dyck Path Boundaries and Deviations

► **Lemma 59.** *Given a random walk of length $2n$ with exactly n up and down steps, consider a contiguous sub-path of length $2B$ that comprises of U up-steps and D down-steps i.e. $U + D = 2B$. Both $|B - U|$ and $|B - D|$ are $\mathcal{O}(\sqrt{B \log n})$ with probability at least $1 - 1/n^4$.*

Proof. We consider the random walk as a sequence of unbiased random variables $\{X_i\}_{i=1}^{2n} \in \{0, 1\}^{2n}$ with the constraint $\sum_{i=1}^{2n} X_i = n$. Here, 1 corresponds to an up-step and 0 corresponds to a down step. Because of the constraint, X_i, X_j are negatively correlated for $i \neq j$ which allows us to apply Chernoff bounds. Now we consider a sub-path of length $2B$ and let U denote the sum of the X_i s associated with this subpath. Using Chernoff bound with $\mathbb{E}[X] = B$, we get:

$$\mathbb{P}\left[|U - B| < 3\sqrt{B \log n}\right] = \mathbb{P}\left[|U - B| < 3\frac{\sqrt{\log n}}{\sqrt{B}}B\right] < e^{\frac{9 \log n}{3}} \approx \frac{1}{n^3}$$

Since U and D are symmetric, the same argument applies. \square

► **Corollary 60.** *With high probability, every contiguous sub-path in the random walk (with U up and D down steps) satisfies the property with high probability. Specifically, if $U + D = 2B$, then $|B - U|$ and $|B - D|$ are upper bounded by $c\sqrt{B \log n}$ w.h.p. $1 - 1/n^2$ for all contiguous sub-paths (for some constant c).*

Proof. We can simply apply Lemma 59 and union bound over all n^2 possible contiguous sub-paths. \square

► **Lemma 22.** *Consider a contiguous sub-path of a simple Dyck path of length $2n$ where the sub-path is of length $2B$ comprising of U up-steps and D down-steps (with $U + D = 2B$). Then there exists a constant c such that the quantities $|B - U|$, $|B - D|$, and $|U - D|$ are all $< c\sqrt{B \log n}$ with probability at least $1 - 1/n^2$ for every possible sub-path.*

Proof. As a consequence of Theorem 56, we can sample a Dyck path by first sampling a *balanced* random walk with n up steps and n down steps and adding an initial up step. We can then find the corresponding Dyck path by taking the unique cyclic shift that satisfies the Dyck constraint (after removing the initial up-step). Any interval in a cyclic shift is the union of at most two intervals in the original sequence. This affects the bound only by a constant factor. So, we can simply use Corollary 60 to finish the proof. Notice that since $|U - D| \leq |B - U| + |B - D|$, $|U - D| = \mathcal{O}(\sqrt{B \log n})$ comes for free. \square

► **Lemma 23.** *Given a Dyck path sampling problem of length B with U up and D down steps with a boundary at k , there exists a constant c such that if $k > c\sqrt{B \log n}$, then the distribution of paths sampled without a boundary $C_\infty(U, D)$ (hypergeometric sampling) is statistically $\mathcal{O}(1/n^2)$ -close in L_1 distance to the distribution of Dyck paths $C_k(U + D)$.*

Proof. We use \mathcal{D} and \mathcal{R} to denote the set of all valid Dyck paths and all random sequences respectively. Clearly, $\mathcal{D} \subseteq \mathcal{R}$. Let c be a constant satisfying Corollary 60. Since the random walk/sequence distribution is uniform on \mathcal{R} , and by Corollary 60 we see that at least $1 - 1/n^2$ fraction of the elements of \mathcal{R} do not violate the boundary constraint. Therefore, $|\mathcal{D}| \geq (1 - 1/n^2)|\mathcal{R}|$ and so the L_1 distance between $\mathcal{U}_{\mathcal{D}}$ and $\mathcal{U}_{\mathcal{R}}$ is $\mathcal{O}(1/n^2)$. \square

F.3 Computing Probabilities

Oracle for estimating probabilities:

► **Lemma 61.** *Given a Dyck sub-path problem within a global Dyck path of size $2n$ and a probability expression of the form $p_d = \frac{S_{left} \cdot S_{right}}{S_{total}}$, there exists a $\text{poly}(\log n)$ time oracle that returns a $(1 \pm 1/n^2)$ multiplicative approximation to p_d if $p_d = \Omega(1/n^2)$ and returns 0 otherwise.*

Proof. We first compute a $1 + 1/n^3$ multiplicative approximation to $\ln p_d$. Using $\mathcal{O}(\log n)$ terms of the series in Equation 10, it is possible to estimate the logarithm of a factorial up to $1/n^c$ additive error. So, we can use the series expansion from Equation 10 up to $\mathcal{O}(\log n)$ terms. The additive error can also be cast as multiplicative since factorials are large positive integers.

The probability p_d can be written as an arithmetic expression involving sums and products of a constant number of factorial terms. Given a $1 \pm 1/n^c$ multiplicative approximation to $l_a = \ln a$ and $l_b = \ln b$, we wish to approximate $\ln(ab)$ and $\ln(a+b)$. The former is trivial since $\ln(ab) = \ln a + \ln b$. For the latter, we assume $a > b$ and use the identity $\ln(a+b) = \ln a + \ln(1+b/a)$ to note that it suffices to approximate $\ln(1+b/a)$. We define $\hat{l}_a = l_a \cdot (1 \pm \mathcal{O}(1/n^c))$ and $\hat{l}_b = l_b \cdot (1 \pm \mathcal{O}(1/n^c))$. In case $\hat{l}_b - \hat{l}_a < c \ln n \implies b/a < 1/n^c$, we approximate $\ln(a+b)$ by $\ln a$ since $\ln(1+b/a) = \mathcal{O}(1/n^c)$ in this case. Otherwise, using the fact that $l_a - l_b = o(n^2)$, we compute:

$$1 + e^{\hat{l}_b - \hat{l}_a} = 1 + \frac{b}{a} \cdot e^{\mathcal{O}(\frac{l_b - l_a}{n^c})} = 1 + \frac{b}{a} \cdot \left(1 \pm \mathcal{O}\left(\frac{1}{n^{c-2}}\right)\right) = \left(1 + \frac{b}{a}\right) \cdot \left(1 \pm \mathcal{O}\left(\frac{1}{n^{c-2}}\right)\right)$$

In other words, the value of c decreases every time we have a sum operation. Since there are only a constant number of such arithmetic operations in the expression for p_d , we can set c to be a high enough constant (when approximating the factorials) and obtain the desired $1 \pm 1/n^3$ approximation to $\ln p_d$. If $\ln p_d < -3 \ln n$, we approximate $p_d = 0$. Otherwise, we can exponentiate the approximation to obtain $p_d \cdot e^{-\mathcal{O}(\ln n/n^3)} = p_d (1 \pm \mathcal{O}(1/n^2))$. \square

F.4 Sampling the Height

- $d < c \cdot \sqrt{B} \log n$
- $k < c \cdot \sqrt{B} \log n \implies U - D < c \cdot \sqrt{B} \log n$
- $k' < c \cdot \sqrt{B} \log n$
- $B > \log^2 n \implies \sqrt{B} \log n < B$

► **Lemma 62.** *For $x < 1$ and $k \geq 1$,*

$$1 - kx < (1 - x)^k < 1 - kx + \frac{k(k-1)}{2} x^2.$$

► **Lemma 25.** $S_{left} \leq c_1 \frac{k \cdot \sqrt{\log n}}{\sqrt{B}} \cdot \binom{B}{D-d}$ for some constant c_1 .

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fix

Proof. This involves some simple manipulations.

$$S_{left} = \binom{B}{D-d} - \binom{B}{D-d-k} \quad (15)$$

$$= \binom{B}{D-d} \cdot \left[1 - \frac{(D-d)(D-d-1) \cdots (D-d-k+1)}{(B-D-d+k)(B-D-d+k-1) \cdots (B-D-d+1)} \right] \quad (16)$$

$$\leq \binom{B}{D-d} \cdot \left[1 - \left(\frac{D-d-k+1}{B-D-d+k} \right)^k \right] \quad (17)$$

$$\leq \binom{B}{D-d} \cdot \left[1 - \left(\frac{U+d+k-(U-D+d+k-1)}{U+d+k} \right)^k \right] \quad (18)$$

$$\leq \binom{B}{D-d} \cdot \left[1 - \left(\frac{U+d+k-\mathcal{O}(\sqrt{B \log n})}{U+d+k} \right)^k \right] \quad (19)$$

$$\leq \Theta \left(\frac{k\sqrt{\log n}}{\sqrt{B}} \right) \cdot \binom{B}{D-d} \quad (20)$$

□

► **Lemma 26.** $S_{right} < c_2 \frac{k' \cdot \sqrt{\log n}}{\sqrt{B}} \cdot \binom{B}{U-d}$ for some constant c_2 .

Proof.

$$S_{right} = \binom{B}{U-d} - \binom{B}{U-d-k'} \quad (21)$$

$$= \binom{B}{U-d} \cdot \left[1 - \frac{(U-d)(U-d-1) \cdots (U-d-k'+1)}{(B-U-d+k')(B-U-d+k'-1) \cdots (B-U-d+1)} \right] \quad (22)$$

$$\leq \binom{B}{U-d} \cdot \left[1 - \left(\frac{U-d-k'+1}{B-U-d+k'} \right)^{k'} \right] \quad (23)$$

$$\leq \binom{B}{U-d} \cdot \left[1 - \left(\frac{2D-U-d-k'+1}{2U-D+k+d} \right)^{k'} \right] \quad (24)$$

$$\leq \binom{B}{U-d} \cdot \left[1 - \left(\frac{U+k+d-(2U-2D+2d+2k-1)}{U+k+d} \right)^{k'} \right] \quad (25)$$

$$\leq \binom{B}{U-d} \cdot \left[1 - \left(\frac{U+k+d-\mathcal{O}(\sqrt{B \log n})}{U+k+d} \right)^{k'} \right] \quad (26)$$

$$\leq \Theta \left(\frac{k' \sqrt{\log n}}{\sqrt{B}} \right) \cdot \binom{B}{U-d} \quad (27)$$

□

► **Lemma 63.** $S_{tot} \geq \binom{2B}{2D} \cdot \left[1 - \left(1 - \frac{k'}{2U+1} \right)^k \right]$.

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Proof.

$$S_{tot} = \binom{2B}{2D} - \binom{2B}{2D-k} \quad (28)$$

$$= \binom{2B}{2D} \cdot \left[1 - \frac{(2D)(2D-1) \cdots (2D-k+1)}{(2B-2D+k)(2B-2D+k-1) \cdots (2B-2D+1)} \right] \quad (29)$$

$$\geq \binom{2B}{2D} \cdot \left[1 - \left(\frac{2D-k+1}{2B-2D+1} \right)^k \right] \quad (30)$$

$$\geq \binom{2B}{2D} \cdot \left[1 - \left(\frac{2U - (2U - 2D + k - 1)}{2U + 1} \right)^k \right] \quad (31)$$

$$\geq \binom{2B}{2D} \cdot \left[1 - \left(\frac{(2U + 1) - k'}{2U + 1} \right)^k \right] \quad (32)$$

$$\geq \binom{2B}{2D} \cdot \left[1 - \left(1 - \frac{k'}{2U + 1} \right)^k \right] \quad (33)$$

$$(34)$$

□

Reference previous lemma

► **Lemma 24.** When $kk' > 2U + 1$, $S_{total} > \frac{1}{2} \cdot \binom{2B}{2D}$.

Proof. When $kk' > 2U + 1 \implies k > \frac{2U+1}{k'}$, we will show that the above expression is greater than $\frac{1}{2} \binom{2B}{2D}$. Defining $\nu = \frac{2U+1}{k'} > 1$, we see that $(1 - \frac{1}{\nu})^k \leq (1 - \frac{1}{\nu})^\nu$. Since this is an increasing function of ν and since the limit of this function is $\frac{1}{e}$, we conclude that

$$1 - \left(1 - \frac{k'}{2U + 1} \right)^k > \frac{1}{2}$$

□

► **Lemma 27.** When $kk' \leq 2U + 1$, $S_{total} < c_3 \frac{k \cdot k'}{B} \cdot \binom{2B}{2D}$ for some constant c_3 .

Proof. Now we bound the term $1 - \left(1 - \frac{k'}{2U+1} \right)^k$, given that $kk' \leq 2U + 1 \implies \frac{kk'}{2U+1} \leq 1$. Using Taylor expansion, we see that

$$1 - \left(1 - \frac{k'}{2U + 1} \right)^k \quad (35)$$

$$\leq \frac{kk'}{2U + 1} - \frac{k(k-1)}{2} \cdot \frac{k'^2}{(2U + 1)^2} \quad (36)$$

$$\leq \frac{kk'}{2U + 1} - \frac{k^2 k'^2}{2(2U + 1)^2} \quad (37)$$

$$\leq \frac{kk'}{2U + 1} \left(1 - \frac{kk'}{2(2U + 1)} \right) \quad (38)$$

$$\leq \frac{kk'}{2(2U + 1)} \leq \frac{kk'}{\Theta(B)} \quad (39)$$

$$(40)$$

□

F.5 First Return Sampling

► **Corollary 33.** When $d \notin \mathcal{R}$, $S_{left}(d) \cdot S_{right}(d) = \Theta \left(\frac{2^{U+D}}{\sqrt{d(U+D-2d-k)}} \cdot e^{-r(d)} \cdot \frac{k-1}{d+k-1} \cdot \frac{U-D+k}{U-d+1} \right)$ where $r(d) = \mathcal{O}(\log^2 n)$.

Proof. This follows from the fact that both $r_{left}(d)$ and $r_{right}(d)$ are $\mathcal{O}(\log^2 n)$. □

► **Lemma 31.** If $d > \log^4 n$, then $S_{left}(d) = \Theta \left(\frac{2^{2d+k}}{\sqrt{d}} e^{-r_{left}(d)} \cdot \frac{k-1}{d+k-1} \right)$ where $r_{left}(d) = \frac{(k-2)^2}{2(2d+k-2)}$. Furthermore, $r_{left}(d) = \mathcal{O}(\log^2 n)$.

Proof. In what follows, we will drop constant factors: Refer to Figure 8 for the setup. The left section of the path reaches one unit above the boundary (the next step would make it touch the boundary). The number of up-steps on the left side is d and therefore the number of down steps must be $d+k-2$. This includes d down steps to cancel out the upwards movement, and $k-2$ more to get to one unit above the boundary. The boundary for this section is $k' = k-1$. This gives us:

$$S_{left}(d) = \binom{2d+k-2}{d} - \binom{2d+k-2}{d-1} \quad (41)$$

$$= \binom{2d+k-2}{d} \left[1 - \frac{d}{d+k-1} \right] = \binom{2d+k-2}{d} \frac{k-1}{d+k-1} \quad (42)$$

Now, letting $z = 2d+k-2$, we can write $d = \frac{z-(k-2)}{2} = \frac{z-\frac{k-2}{\sqrt{z}}\sqrt{z}}{2}$. Using Lemma 22, we see that $\frac{k-2}{\sqrt{z}}$ should be $\mathcal{O}(\sqrt{\log n})$. If this is not the case, we can simply return 0 because the probability associated with this value of d is negligible. Since $z > \log^4 n$, we can apply Lemma 58 to get:

$$S_{left}(d) = \Theta \left(\binom{z}{z/2} e^{\frac{(k-2)^2}{2z}} \frac{k-1}{d+k-1} \right) = \Theta \left(\frac{2^{2d+k}}{\sqrt{d}} e^{\frac{(k-2)^2}{2(2d+k-2)}} \frac{k-1}{d+k-1} \right)$$

□

► **Lemma 32.** If $U+D-2d-k > \log^4 n$, then $S_{right}(d) = \Theta \left(\frac{2^{U+D-2d-k}}{\sqrt{U+d-2d-k}} e^{-r_{right}(d)} \cdot \frac{U-D+k}{U-d+1} \right)$ where $r_{right}(d) = \frac{(U-D-k+1)^2}{4(U+D-2d-k+1)}$. Furthermore, $r_{right}(d) = \mathcal{O}(\log^2 n)$.

Proof. The right section of the path starts from the original boundary. Consequently, the boundary for this section is at $k' = 1$. The number of up-steps on the right side is $U-d$ and the number of down steps is $D-d-k+1$. This gives us:

$$S_{right}(d) = \binom{U+D-2d-k+1}{U-d} - \binom{U+D-2d-k+1}{U-d+1} \quad (43)$$

$$= \binom{U+D-2d-k+1}{U-d} \left[1 - \frac{D-d-k+1}{U-d+1} \right] \quad (44)$$

$$= \binom{U+D-2d-k+1}{U-d} \frac{U-D+k}{U-d+1} \quad (45)$$

Now, letting $z = U+D-2d-k+1$, we can write $U-d = \frac{z+(U-D+k-1)}{2} = \frac{z+\frac{U-D+k-1}{\sqrt{z}}\sqrt{z}}{2}$. Using Lemma 22, we see that $\frac{k-2}{\sqrt{z}}$ should be $\mathcal{O}(\sqrt{\log n})$. If this is not the case, we can simply return 0

because the probability associated with this value of d is negligible. Since $z > \log^4 n$, we can apply Lemma 58 to get:

$$S_{right}(d) = \Theta \left(\binom{z}{z/2} e^{\frac{(U-D+k-1)^2}{2z}} \frac{U-D+k}{U-d+1} \right) \quad (46)$$

$$= \Theta \left(\frac{2^{U+D-2d-k}}{\sqrt{U+D-2d-k}} e^{\frac{(U-D+k-1)^2}{2(U+D-2d-k+1)}} \frac{U-D+k}{U-d+1} \right) \quad (47)$$

□