Computing the log-determinant of symmetric, diagonally dominant matrices in near-linear time
WORKING DRAFT

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1. Introduction

We consider the problem of computing the determinant of symmetric, diagonally dominant (SDD) matrices, i.e. real symmetric matrices A for which:

$$A_{ii} \geq \sum_{j \neq i} |A_{ij}|$$

The set of all such matrices of size $n \times n$ is denoted SDD_n, and the set of all symmetric real matrices is called $\mathcal{S}_n$. Call m the number of non-zero entries in A. We are interested in computing the determinant of sparse matrices, i.e. matrices for which $m \ll n^2$.

The best algorithm known for computing the determinant of general matrices, the Cholesky factorization, runs in a cubic complexity $O\left(n^3\right)$. Computing the factorization can be sped up for a few specific patterns such as trees, but no algorithm has been shown to work in a generic way for SDD_n, let alone general symmetric matrices. We present an algorithm that returns an approximation of the logarithm of the determinant in time quasi-linear with the number of non-zero entries of A. More specifically, we show that our algorithm, `UltraLogDet`, computes an ϵ-approximation of the logarithm of the determinant in expected time[1]:

$$\tilde{\mathcal{O}}\left(m \left(\log n\right)^7 \epsilon^{-2} \log\left(\frac{n\kappa_A}{\epsilon}\right)\right)$$

where κ_A is the condition number of A. This algorithm builds upon the work of Spielmann and Teng on *ultra-sparsifiers* Spielman and Teng (2009), and it critically exploits the recent improvements from Koutis, Miller and Peng Koutis et al. (2010). This is to our knowledge the first algorithm that presents a nearly linear complexity which depends neither on the condition number of A (except through a log-term) nor on a specific pattern for the non-zero coefficients of A.

The high complexity of the algorithm transpires through the large exponent of $\log n$. However, our algorithm will directly benefit from any improvement on ultra-sparsifiers. Given the considerable practical importance of such preconditioners, we expect some fast improvements in this area. Also, the bulk of the work is performed in a Monte Carlo procedure that is straightforward to parallelize. Furthermore, we also present simpler, non-optimal algorithms that compute upper and lower bounds of the logarithm of the determinant, and that may be of more immediate practical interest.

Background There are two approaches in numerical linear algebra to compute approximately a determinant (or the log of the determinant): by performing a (partial) Cholesky factorization of A, or by considering the trace of some power series.

As mentioned above, the Cholesky factorization performs a decomposition of the form: $A = PLDL^TP^T$ with P a permutation matrix, L a low-triangular matrix with 1 on the diagonal and D a diagonal matrix of non-negative coefficients. Then the log-determinant of A is simply[2]:

$$\log |A| = \sum_i \log D_{ii}$$

The complexity of dense Cholesky factorization for dense matrices is $O\left(n^3\right)$. Unfortunately, Cholesky factorization usually does not gain much from the knowledge of the sparsity pattern due to the *fill-in problem* (see Meurant (1999), section 3.2). There is one case, though, for which Cholesky factorization is efficient: if the sparsity pattern of A is a tree, then performing Cholesky factorization takes $O\left(n\right)$ time, and the matrix L is a banded matrix Liu (1990). If the sparsity pattern of A is not a tree, however, this advantageous decomposition does not hold anymore.

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1. We use the notation $\tilde{O}$ to hide a factor at most $(\log \log n)^8$
2. We will use the $|\cdot|$ operator to denote the determinant, it will be clear from the context that it is different from the absolute value.

When the matrix A is close to the identity, more precisely when the spectral radius of $M = A - I$ is less than 1, one can use the remarkable Martin expansion of the log-determinant Martin (1992):

$$\log |A| = \text{Tr} \left(\log A \right) \tag{1}$$

where $\log A$ is the matrix logarithm defined by the series expansion:

$$\log A = \sum_{i=0}^{\infty} \frac{(-1)^i}{i+1} M^i \tag{2}$$

The determinant can then be computed by a sum of traces of the power of M, and the rate of convergence of this series is driven by the spectral radius M. This line of reasoning has lead to looking for decompositions of A of the form $A = U + V$ with the determinant of U being easier to compute and $U^{-1}V + I$ having a small spectral radius. Then $\log |A| = \log |U| + \log |U^{-1}V + I|$. The most common decomposition U, V is in terms of block diagonal and off-diagonal terms, which can then use Hadamard inequalities on the determinant to bound the error Ipsen and Lee (2006). Diagonal blocks also have the advantage of having determinants easy to compute. However, this approach requires some strong assumptions on the condition number of A, which may not hold in practice.

The trace approach is driven by *spectral properties* (the condition number) while the Cholesky approach is driven by *graphical* properties (the non-zero pattern). We propose to combine these two approaches by decomposing the problem with one component that is close to a tree (and is more amenable to Cholesky methods), and one component that has a bounded condition number. Our solution is to use a *spectral sparsifier* introduced by Spielman in Spielman and Teng (2008).

The problem of estimating determinants has important applications in spatial data analysis, statistical physics and statistics. In spatial statistics, it is often convenient to interpolate measurements in a 2-, 3- or 4-dimensional volume using a sparse Gaussian process, a technique known in the geospatial community as *kriging* Zhang and Wang (2010); Li and Sudjianto (2005). Computing the optimal parameters of this Gaussian process involves repeated evaluations of the partition function, which is a log-determinant. In this context, a diagonally dominant matrix for the Gram matrix of the process corresponds to weak interactions between points of measure (which is verified in some contexts Pace and Barry (1997)). Determinants also play a crucial role in quantum physics and in theoretical physics. The wave function of a system of multiple fermion particles is an antisymmetric function which can be described as a determinant (Slatter determinant, Atkins and Friedman (2011); Löwdin (1955)). In the theory of quantum chromodynamics (QCD), the interaction between fundamental particles can be discretized as a lattice, and the energy level of particles is the determinant of some functional operators over this lattice Duncan et al. (1998). It is itself a very complex problem because of the size of the matrices involved for any non-trivial problem, for which the number of variables is typically in the millions Bernardson et al. (1994). In this respect, the restriction to diagonally dominant matrices can be interpreted as an interaction between relatively massive particles de Forcrand and Gupta (1989), or as a bound on the propagation of interactions between sites in the lattice Bernardson et al. (1994).

For these reasons, computing estimates of the log-determinant has been an active problem in physics and statistics. In particular, the Martin expansion presented in Equation 1 is extensively used in quantum physics (CITE) can be combined with sampling method to estimate the trace of a matrix series (Zhang et al. (2008),McCourt (2008),Zhang and Leithead (2007)). Another different line of research has worked on bounds on the values of the determinant itself. This is deeply connected to simplifying statistical models using variational methods. Such a relaxation using a message-passing technique is presented in Wainwright and Jordan (2006). Our method is close in spirit to Reuksen's work Reusken (2002) by the use of a preconditioner. However, Reuksen considers preconditioners based on a clever approximation of the Cholesky decomposition, and its interaction with the eigenvalues of the complete matrix is not well understood. Using simpler methods based

on sampling, we are able to carefully control the spectrum of the reminder, which in turn leads to strong convergence guarantees.

A note on scaling. Unlike other characteristics of linear operators, the determinant and the log-determinant are very sensitive to dimensionality. We will follow the approach of Reuksen Reusken (2002) and consider the *regularized log-determinant* $f(A) = n^{-1}\log|A|$ instead of the log-determinant. The regularized determinant has appealing properties with respect to dimensionality. In particular, its sensitivity to perturbations does not increase with the dimensionality, but only depends on spectral properties of the operator A. For example, calling $\lambda_{\min}$ and $\lambda_{\max}$ the minimun and maximum eigenvalues of A, respectively:

$$\log\lambda_{\min} \leq f(A) \leq \log\lambda_{\max}$$

$$|f(A + \epsilon I) - f(A)| \leq \epsilon \left\|A^{-1}\right\|_2 + O\left(\epsilon^2\right)$$

The last inequality in particular shows that any perturbation to $\log|A|$ will be in the order $O(n)$, and so why all the interesting log-determinants in practice will be dominated by some $O(n)$.

The rest of the article is structured as follows. In the next section, we present some results about estimating the log-determinant from a truncated expansion. These results will justify the use of *preconditioners* to compute the determinant of a matrix. The techniques developed by Spielman et al. work on the Laplacians of weighted graphs. Section 3 introduces some new concepts to expand the notion of determinants to Laplacian matrices, and presents a few straightforward results in the relations between graph Laplacians and SDD matrices. Section 4 will use these new concepts to introduce a first family of preconditioners based on low-stretch spanning trees. Finally, Section 5 contains the proof of our main result, an algorithm to compute determinants in near-linear time.

2. Preconditioned log-determinants

We begin by considering a simple sampling algorithm to compute log-determinants, presented first in Barry and Pace (1999). We will first present some error bounds on this algorithm that expand on bounds previously presented in Bai et al. (1996) and Barry and Pace (1999).

Consider a real symmetric matrix $S \in \mathcal{S}_n^+$ such that its spectral radius is less than 1: $0 \preceq S \preceq (1-\delta)I$ for some $\delta \in (0,1)$. We want to compute $\log|I - S|$ up to precision ϵ and with high probability. From the Martin expansion:

$$\log|I - S| = -\text{Tr}\left(\sum_{k=1}^{\infty} \frac{1}{k} S^k\right) \tag{3}$$

This series of traces can be estimated by Monte Carlo sampling, up to precision ϵ with high probability. In order to bound the errors, we will bound the large deviation errors using Hoeffding inequality. We use a modified version of Proposition 4.2 from Bai et al. (1996):

Lemma 1 *Consider $H \in \mathcal{S}_n$ lower- and upper-bounded by λ_{min} and λ_{max}: $\lambda_{\min}I \preceq H \preceq \lambda_{\max}I$. Consider p vectors sampled from the standard Normal distribution: $\mathbf{u}_i \sim \mathcal{N}(\mathbf{0}, I_n)$ for $i = 1 \cdots p$. Then for all $\nu > 0$:*

$$\mathbb{P}\left[\left|\frac{1}{p}\sum_{i=1}^{p} \mathbf{u}_i^T H \mathbf{u}_i^T - Tr(H)\right| \geq \frac{\nu}{p}\right] \leq 2\exp\left(-\frac{2\nu^2}{p\left(\lambda_{\max} - \lambda_{\min}\right)^2}\right)$$

Proof This is a simple adaptation from Bai et al. (1996). ∎

We use the following Bernstein inequality:

4

Lemma 2 $X_1 \cdots X_U$ *are independant random variables with* $\mathbb{E}[X_u] = 0$, $|X_u| < c$. *Call* $\sigma^2 = \frac{1}{U} \sum_u Var(X_u)$, *then for all* $\epsilon > 0$:

$$\mathbb{P}\left[\frac{1}{U} \sum_u X_u \geq \epsilon\right] \leq \exp\left(-\frac{U\epsilon^2}{2\sigma^2 + 2c\epsilon/3}\right)$$

The proof of this result can be found in a lecture note from Peter Bartlett's class (stat241B/spring 2003). We can adapt some results from Barry and Pace (1999) to prove this bound on the deviation from the trace.

Lemma 3 *Consider* $H \in \mathcal{S}_n$, *and call* λ_i *the eigenvalues of* H. *Consider* p *vectors sampled from the standard Normal distribution:* $\mathbf{u}_i \sim \mathcal{N}(\mathbf{0}, I_n)$ *for* $i = 1 \cdots p$. *Then for all* $\epsilon > 0$:

$$\mathbb{P}\left[\left|\frac{1}{p} \sum_{i=1}^{p} \frac{\mathbf{u}_i^T H \mathbf{u}_i}{\mathbf{u}_i^T \mathbf{u}_i} - \frac{1}{n} Tr(H)\right| \geq \epsilon\right] \leq \exp\left(-\frac{p\epsilon^2}{2n^{-1}(\lambda_{\max} - \lambda_{\min})^2 + (\lambda_{\max} - \lambda_{\min})\epsilon}\right)$$

with $\lambda_{max} = \max \lambda_i$ *and* $\lambda_{\min} = \min \lambda_i$.

Proof The distribution of $\mathbf{u}_i$ is invariant through a rotation, so we can consider H diagonal. We assume without loss of generality that $H = \text{diag}(\lambda_1...\lambda_n)$. Again without loss of generality, we assume that $\lambda'_{\max} = \lambda_{\max} - \lambda_{\min}$ and $\lambda'_{\min} = 0$ (by considering $H' = H - \lambda_{\min}I$). Call $V_i = \frac{\mathbf{u}_i^T H \mathbf{u}_i}{\mathbf{u}_i^T \mathbf{u}_i} - n^{-1}\text{Tr}(H)$. Using results from Barry and Pace (1999), we have: $|V_i| \leq \lambda_{\max} - \lambda_{\min}$, $\mathbb{E}[V_i] = 0$ and:

$$\text{Var}(V_i) = \frac{2}{n^2} \sum_{i=1}^{n} \left(\lambda_i - n^{-1}\text{Tr}(H)\right)^2$$

Each of the variables V_i is independent, so invoking Lemma 2 gives:

$$\mathbb{P}\left[\frac{1}{p} \sum_{i=1}^{p} V_i \geq \epsilon\right] \leq \exp\left(-\frac{p\epsilon^2}{2\sigma^2 + 2(\lambda_{\max} - \lambda_{\min})\epsilon/3}\right)$$

with $\sigma^2 = \frac{2}{n^2} \sum_{i=1}^{n} \left(\lambda_i - n^{-1}\text{Tr}(H)\right)^2$ ∎

The previous lemma shows that if the eigenspectrum of a matrix is bounded, we can obtain a Hoeffding bound on the error done by sampling the trace. Furthermore, the convergence of the series 3 is also determned by the extremal eigenvalues of S. If we truncate the series (3), we can bound the truncation error using the extremal eigenvalues. We formalize this intuition in the following theorem, which is adapted from the main Theorem in Barry and Pace (1999). While that main Theorem in Barry and Pace (1999) only considered a confidence interval based on the covariance properties of Gaussian distribution, we generalize this result to more general Hoeffding bounds.

Theorem 4 *Consider* $S \in \mathcal{S}_n^+$ *with* $0 \preceq S \preceq (1-\delta)I$ *for some* $\delta \in (0,1)$. *Call* y *the quantity to estimate:*

$$y = \log|I - S|$$

and consider $\mathbf{u}_i \sim \mathcal{N}(\mathbf{0}, I_n)$ *for* $i = 1 \cdots p$. *Call* $\hat{y}_{p,l}$ *an estimator of the truncated series of* l *elements computed by sampling the trace using* p *samples:*

$$\hat{y}_{p,l} = \frac{n}{p} \sum_{j=1}^{p} \sum_{k=1}^{l} \frac{1}{k} \frac{\mathbf{u}_j^T S^k \mathbf{u}_j}{\mathbf{u}_j^T \mathbf{u}_j}$$

By choosing $p \geq 4\log(\eta^{-1})\epsilon^{-2}\left(2n^{-1}\log^2(\delta^{-1}) + \epsilon\log(\delta^{-1})\right)$ *and* $l \geq 2\delta^{-1}\log\left(\frac{n}{\delta\epsilon}\right)$, *the error probability is small:*

$$\mathbb{P}[|y - \hat{y}_{p,l}| \geq n\epsilon] \leq \eta$$

Proof The proof of this theorem follows the proof of the Main Theorem in Barry and Pace (1999) with some slight modifications. Using triangular inequality:

$$|y - \hat{y}_{p,l}| \le |\mathbb{E}\left[\hat{y}_{p,l}\right] - \hat{y}_{p,l}| + |y - \mathbb{E}\left[\hat{y}_{p,l}\right]|$$

Since S is upper-bounded, we have for all $k \in \mathbb{N}$:

$$\left|\text{Tr}\left(S^k\right)\right| \le n\left(1 - \delta\right)^k$$

Using again triangle inequality, we can bound the error with respect to the expected value:

$$
\begin{aligned}
|y - \mathbb{E}\left[\hat{y}_{p,l}\right]| &= \left|\sum_{i=l+1}^{\infty} \frac{(-1)^i}{i} \text{Tr}\left(S^k\right)\right| \\
&\le \sum_{i=l+1}^{\infty} \frac{1}{i} \left|\text{Tr}\left(S^k\right)\right| \\
&\le \frac{1}{l+1} \sum_{i=l+1}^{\infty} \left|\text{Tr}\left(S^k\right)\right| \\
&\le \frac{n}{l+1} \sum_{i=l+1}^{\infty} (1-\delta)^k \\
&\le \frac{n}{l+1} \frac{(1-\delta)^{l+1}}{\delta} \\
&\le n\frac{(1-\delta)^{l+1}}{\delta}
\end{aligned}
$$

Hence, for a choice of $l \ge \delta^{-1} \log\left(\frac{2n}{\epsilon\delta}\right)$, the latter part is less than $\epsilon/2$. We now bound the first part using Lemma 3. Call H the truncated series:

$$H = -\sum_{i=1}^{m} \frac{1}{i} S^i$$

This truncated series is upper-bounded by 0. The lowest eigenvalue of the truncated series can be lower-bounded in terms of δ:

$$H = -\sum_{i=1}^{m} \frac{1}{i} S^i \succeq -\sum_{i=1}^{m} \frac{1}{i} (1-\delta)^i I \succeq -\sum_{i=1}^{+\infty} \frac{1}{i} (1-\delta)^i I \succeq -\sum_{i=1}^{+\infty} \frac{1}{i} (1-\delta)^i I = (\log \delta) I$$

We can now invoke Lemma 3 to conclude:

$$\mathbb{P}\left[\left|\frac{1}{p}\sum_{i=1}^{p} \left(\mathbf{u}_i^T \mathbf{u}_i\right)^{-1} \mathbf{u}_i^T H \mathbf{u}_i - n^{-1}\text{Tr}\left(H\right)\right| \ge \frac{\epsilon}{2}\right] \le \exp\left(-\frac{p\epsilon^2}{8n^{-1}\left(\log\delta\right)^2 + 4\log\left(1/\delta\right)\epsilon}\right)$$

and $\exp\left(-\frac{p\epsilon^2}{8n^{-1}(\log\delta)^2 + 4\log(1/\delta)\epsilon}\right) \le \eta$. This latter inequality is verified for any

$$p \ge 4\log\left(\eta^{-1}\right)\epsilon^{-2}\left(2n^{-1}\log^2\left(\delta^{-1}\right) + \epsilon\log\left(\delta^{-1}\right)\right)$$

∎

We immediately get the following result that justifies the notion of preconditioners for determinants. The corresponding algorithm, which we call `PreconditionedLogDetMonteCarlo`, is presented in Algorithm **??**.

Corollary 5 *If A and B are positive definite matrices so that B is a $\kappa-$approximation of A:*

$$A \preceq B \preceq \kappa A \qquad\qquad (4)$$

then the algorithm `PreconditionedLogDetMonteCarlo` *computes an ϵ-approximation of $\frac{1}{n} \log \left| B^{-1} A \right|$ with high probability, by performing $O \left(\kappa \epsilon^{-2} \left(\log \kappa \right)^2 \log \left(\frac{n^2 \kappa}{\epsilon} \right) \right)$ vector inversions from B and vector multiplies from A.*

Proof *We introduce some notations that will prove useful for the rest of the article:*

$$H = I - B^{-1} A$$

$$S = I - B^{-1/2} A B^{-1/2}$$

with $B^{-1/2}$ the inverse of the square root of the positive-definite matrix B^3. The inequality 4 is equivalent to $\kappa^{-1} B \preceq A \preceq B$, or also:

$$\left(1 - \kappa^{-1} \right) I \succeq I - B^{-1/2} A B^{-1/2} \succeq 0$$

$$\left(1 - \kappa^{-1} \right) I \succeq S \succeq 0$$

∎

Proof The matrix S is a contraction, and its spectral radius is determined by κ. Furthermore, computing the determinant of $B^{-1} A$ is equivalent to computing the determinant of $I - S$:

$$
\begin{aligned}
\log |I - S| &= \log \left| B^{-1/2} A B^{-1/2} \right| \\
&= \log |A| - \log |B| \\
&= \log \left| B^{-1} A \right| \\
&= \log |I - H|
\end{aligned}
$$

and invoking Theorem 4 gives us bounds on the number of calls to matrix-vector multiplies with respect to S. It would seem at this point that computing the inverse square root of B is required, undermining our effort. However, we can reorganize the terms in the series expansion to yield only full inverses of B. Indeed, given $l \in \mathbb{N}^*$, consider the truncated series:

$$
\begin{aligned}
y_l &= -\mathrm{Tr} \left(\sum_{i=1}^{l} \frac{1}{i} S^i \right) \\
&= -\sum_{i=1}^{l} \frac{1}{i} \mathrm{Tr} \left(S^i \right) \\
&= -\sum_{i=1}^{l} \frac{1}{i} \mathrm{Tr} \left(\sum_j \binom{j}{i-j} \left(B^{-1/2} A B^{-1/2} \right)^j \right) \\
&= -\sum_{i=1}^{l} \frac{1}{i} \sum_j \binom{j}{i-j} \mathrm{Tr} \left(\left(B^{-1/2} A B^{-1/2} \right)^j \right) \\
&= -\sum_{i=1}^{l} \frac{1}{i} \sum_j \binom{j}{i-j} \mathrm{Tr} \left(\left(B^{-1} A \right)^j \right)
\end{aligned}
$$

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3. Given a real PSD matrix X, which can be diagonalized: $X = Q \Delta Q^T$ with Δ diagonal, and $\Delta_{ii} \geq 0$. Call $Y = Q \sqrt{\Delta} Q^T$ the square root of X, then $Y^2 = X$.

$$= -\sum_{i=1}^{l} \frac{1}{i} \mathrm{Tr} \left(\sum_{j} \begin{pmatrix} j \\ i-j \end{pmatrix} (B^{-1}A)^j \right)$$

$$= -\sum_{i=1}^{l} \frac{1}{i} \mathrm{Tr} \left(H^i \right)$$

Hence, the practical computation of the latter sum can be done on $A^{-1}B$. To conclude, if we compute $p = 4\epsilon^{-2} (\log \kappa)^2 \log n$ truncated chains of length $l = \kappa \left(2 \log n + \log \kappa + \log \left(\epsilon^{-1} \right) \right)$, we get our result. This requires lp multiplies by A and inversions by B. ∎

Usually, computing the exact inverse by an SDD matrix is too expensive. We can instead extend the previous result to consider a black bock that approximatively inverts compute $B^{-1}x$. If the error introduced by the approximate inversion is limited, the result from the previous corollary still holds. This is wha the following theorem establishes:

Theorem 6 *Consider $A, B \in \mathcal{S}_n^{+*}$ with B a $\kappa-$approximation of A. Furthermore, assume there exists a function C so that for all $y \in \mathbb{R}^n$, C returns an $\epsilon-$approximation of $B^{-1}y$:*

$$\|BC(y) - y\|_B \le \|B^{-1}y\|_B \epsilon$$

Given $\eta > 0$ and $\mu > 0$, if $\epsilon \le XXXX$, then the algorithm `PreconditionedLogDetMonteCarlo` returns a scalar z so that:

$$\mathbb{P} \left[n^{-1} \left| z - \log \left| B^{-1}A \right| \right| \ge \mu \right] \le \eta$$

by performing $O(YYYY)$ vector calls to the operator C and vector multiplies from A.

The proof of this result is detailed in Appendix A.

This last theorem shows that we can compute a good approximation of the log-determinant if the preconditioner B: (a) is close to A in the spectral sense, and (b) can be approximately inverted and the error introduced by the approximate inversion can be controlled. This happens to be the case for symmetric, diagonally dominant matrices.

3. Making the problem laplacian

From now on, we consider all matrices to be in SDD_n. Most techniques we will be using work on Laplacian matrices instead of SDD matrices. An SDD matrix is positive semi-definite while a Laplacian matrix is always singular, since its nullspace is spanned by $\mathbf{1}$. We generalize the definition of the determinant to handle this technicality.

Definition 7 Pseudo-log-determinant (PLD): *Let $A \in \mathcal{S}^{n+}$ be a non-null positive semi-definite matrix. The pseudo-log-determinant is defined by the sum of the logarithms of all the positive eigenvalues:*

$$ld(A) = \sum_{\lambda_i > 0} \log(\lambda_i)$$

where λ_i are the eigenvalues of A.

The interest of the PLD lies in the connection between SDD matrices and their associated Laplacian. Recall that an SDD matrix can be transformed into a Laplacian (which has all off-diagonal terms non-positive, and for which the sum of each row and each column is zero). As underlined in GREMBAN, solving an equation involving an SDD can be turned into solving an equation with an SDD in which all the off-diagonal terms are non-positive of twice the same size. This transform is also

useful for computing determinants. The following lemma shows that computing the log-determinant of an SDD with positive off-diagonal entries can be turned into computing the log-determinants of two SDD matrices with non-positive off-diagonal entries.

Lemma 8 *Consider the decomposition of a SDD matrix into a positive and a negative sum:*

$$A = P - N$$

with $P_{ij} \leq 0$ for $i \neq j$ and $N_{ij} \leq 0$ for all i, j so that $|A_{ij}| = |P_{ij}| + |N_{ij}|$. Then the matrices $\begin{pmatrix} P & N \\ N & P \end{pmatrix} \in SDD_{2n}$ and $P + N \in SDD_n$ with all the off-diagonal coefficients being negative, and we have the relation:

$$\log \left| \begin{pmatrix} P & N \\ N & P \end{pmatrix} \right| = \log |P + N| + \log |P - N|$$

Proof Call $C = \begin{pmatrix} P & N \\ N & P \end{pmatrix}$

Consider μ an eigenvalue of A, and x an associated eigenvector: $Ax = \mu x$. Then:

$$\begin{pmatrix} P & N \\ N & P \end{pmatrix} \begin{pmatrix} x \\ -x \end{pmatrix} = \begin{pmatrix} Ax \\ -Ax \end{pmatrix} = \mu \begin{pmatrix} x \\ -x \end{pmatrix}$$

which shows that the vector $\begin{pmatrix} x \\ -x \end{pmatrix}$ is an eigenvector of C with associated eigenvalue μ. Similarly, if η is an eigenvector of B with associated eigenvalue y, then η is also an eigenvector of C with associated eigenvalue $\begin{pmatrix} y \\ y \end{pmatrix}$. Since C is exactly of size $2n$, the set of eigenvalues of C is exactly the union of sets of eigenvalues of A and B. Thus $\log |C| = \sum_i \log \mu_i + \sum_i \log \eta_i = \log |A| + \log |B|$ ■

Recall that a Laplacian matrix can be constructed from any SDD with non-positive off-diagonal entries matrix by adding a "ground" node (see Gremban's thesis Gremban (1996), Chapter 4).

Definition 9 Augmented Laplacian of an SDD matrix (Definition XXX in GREMBAN): *Let $A \in SDD_n$. Let L, D be the decomposition of A into L a Laplacian matrix and D a (non-negative) diagonal matrix such that $A = L + D$. The augmented matrix of A is:*

$$L_A = \begin{pmatrix} A & -\mathbf{d} \\ -\mathbf{d}^T & h \end{pmatrix}$$

with $\mathbf{d} \in \mathbb{R}^n$: $\mathbf{d}_i = D_{ii}$ and $h = \sum_i D_{ii}$.

From now on, given any $A \in SDD_n$, we will implicitly define a Laplacian L_A associated to it, using the augmented Laplacian. This process is also reversible and can be used to define a matrix $\tilde{A} \in SDD_n$ from L_A with appealing properties in a very simple way. We call this process "floating" of the Laplacian, by opposition to "grounding" the SDD matrix as a Laplacian.

Definition 10 Floating a Laplacian. *Consider L a Laplacian matrix. Call F_L the matrix formed by removing the last row and the last column from L.*

The followin lemma shows that the Laplacian matrix overdetermines a system, and that no information is lost by "floating" it.

Lemma 11 *Consider Z a (weigted) Laplacian matrix, then:*

- $L_{F_Z} = Z$

- *The eigenvalues of F_Z are the positive eigenvalues of of Z, and the corresponding eigenvectors for F_Z are the same eigenvectors, truncated by the last coefficient.*

- $ld(Z) = \log|F_Z|$

The PLD enjoys some of the usual properties of the log-determinant. The following proposition shows the interest of the PLD in the study of the Laplacian of a graph.

Proposition 12 *Let $A \in SDD_n$, and L_A its augmented Laplacian. Let $P = (I_n\ \mathbf{0})$ be a projection matrix over the first n columns of L_A. Then:*

- *If λ is an eigenvalue of A with associated eigenvector x, it is also an eigenvalue of PL_AP^T with the same eigenvector*

- $\mathrm{ld}(L_A) = \log|A|$

- *Let $A, B \in SDD_n$. $\mathrm{ld}(L_AL_B) = \mathrm{ld}(L_A) + \mathrm{ld}(L_B)$ and $\mathrm{ld}(L_B^+L_A) = \log|B^{-1}A|$ with $L_A^+$the pseudo inverse of L_A.*

Proof XXX The proofs of this proposition are technical and are contained in Appendix B. ∎

Note in particular that the PLD is well defined over connected graphs. From now on, we will consider connected graphs only. If graphs have several unconnected components, the log-determinant of the corresponding SDD is the sum of the PLDs of the Laplacians of each component.

From now on, we will focus on computing the PLD of Laplacians. Note that the kernel of all Laplacian matrices of connected graphs is precisely $\mathbb{R}\mathbf{1}_n$, so we can use the PLD with pseudo inverses as if we were using the log determinant with SDD matrices: Consider a graph $G = (V, E, w)$, identified with its Laplacian matrix L_G. Consider a weighted subgraph $H = \left(V, \tilde{E}, \tilde{w}\right)$ of G, for which it is easier to compute the determinant, and that closely approximates G in the spectral sense. From Proposition 12:

$$\log|G| = \mathrm{ld}(L_G) = \mathrm{ld}(L_H) + \mathrm{ld}\left(L_H^+L_G\right) = \log|H| + \mathrm{ld}\left(L_H^+L_G\right)$$

We will see how to adapt Spielman and Teng's remarkable work on *ultra-sparsifiers* to produce good preconditioners H for the determinant. In particular, once a good preconditioners is available for G, we present an algorithm that computes an upper bound and a lower bound of the PLD *for free*. We will improve this results to produce an algorithm that computes an ϵ-approximation with high probability.

4. A first preconditioner

While the results in this section are not the main claims of this paper, we hope they will provide some intuition.

We now present a first preconditioner that is not optimal, but that will motivate our results for stronger preconditioners: a tree that spans the graph G. Every graph has a low-stretch spanning tree, as discovered by Alon et al. Alon et al. (1995). The bound of Alon et al. was then improved by Abraham et al. Abraham et al. (2008). We restate their main result.

Lemma 13 *Consider G a weighted graph. There exists a tree T that is a subgraph of G so that:*

$$G \preceq T \preceq \kappa G$$

with $\kappa = Cm \log n \log \log n \left(\log \log \log n\right)^3$ for some constant $C > 0$.

Proof This follows directly from Abraham et al. (2008). T is a subgraph of G (with the same weights on the edges), so $T \preceq G$. Furthermore, we have $T \preceq \mathrm{st}_G(T) G$ using a result of Boman and Hendrickson Boman et al. (2004) cited by Spielman in Spielman (2010). ∎

Trees enjoy a lot of convenient properties for Gaussian elimination. The Cholesky factorization of a tree can be computed in linear time, and furthermore this factorization has a linear number of non-zero elements Spielman and Teng (2009). This factorization can be expressed as:

$$L_T = PLDL^T P^T$$

where P is a permutation matrix, L is a lower-triangular matrix with the diagonal being all ones, and D a diagonal matrix in which all the elements but the last one are positive, the last element being 0. These well-known facts about trees are presented in Spielman and Teng (2009). Once the Cholesky factorization of the tree is performed, the log-determinant of the original graph is an immediate by-product:

$$\log|T| = \sum_{i=1}^{n-1} \log D_{ii}$$

Furthermore, computing $L_T^+ x$ also takes $O(n)$ computations by forward-backward substitution. Applying Corollary 5 gives immediately:

Theorem 14 *Let G be a graph with n vertices and m edges. Its PLD can be computed up to a precision of ϵ and with high probability in time $\tilde{O}\left(mn(\log m)^3 (\log n)^2 \frac{\log \epsilon^{-1}}{\epsilon^2}\right)$.*

Proof We assume G is connected, hence $m \geq n$ and $\log \kappa = \tilde{\mathcal{O}}(\log m)$. ∎

This bound may be of independent interest since it requires relatively little machinery to compute, and it is an improvement already for graphs with small vertex degree ($m = \mathcal{O}(n^{1+o(1)})$) over the Cholesky factorization of G.

How good is the estimate provided by the tree T? Intuitively, this depends on how well the tree T approximates the graph G. This notion of quality of approximation can be formalized by the notion of *stretch*.

Definition 15 *Stretch of a graph. Consider G a weighted graph, and T a spanning tree of G. The stretch of each edge e from G is defined as $st_T(e) = \omega_e \left(\sum_{f \in P} \frac{1}{\omega_f}\right)$ where ω_e is the weight of edge e in G, and P is the unique path between the endpoints of e in the tree T. The stretch of the graph is the sum of the stretches of each edge:*

$$st_T(G) = \sum_{e \in G} st_T(e)$$

The stretch can be obtained as a by-product of the computation of low-stretch spanning trees, of which the construction can be done in $O(m \log n + n \log^2 n)$ Abraham et al. (2008). Knowing the stretch gives upper and lower bounds on the value of the log-determinant.

Proposition 16 *Stretch bounds on the tree PLD:*

$$\log|T| + (n-1)\log\left(\frac{\mathrm{st}_G(T)}{n-1}\right) \geq \log|G| \geq \log|T| + \log(\mathrm{st}_T(G) - n + 2) \tag{5}$$

Proof This is an application of Jensen's inequality on $\mathrm{ld}(T^+G)$. We have $\mathrm{ld}G = \mathrm{ld}T + \mathrm{ld}(T^+G)$ and $\mathrm{ld}(T^+G) = \mathrm{ld}\left(\sqrt{T}^+ G \sqrt{T}^+\right) = \mathrm{Tr}\left(\log^+\left(\sqrt{T}^+ G \sqrt{T}^+\right)\right)$ with $\sqrt{T}$ the matrix square root of

T. From Lemma 39, we have

$$
\begin{aligned}
\mathrm{Tr}\left(\log^+\left(\sqrt{T}^+ G\sqrt{T}^+\right)\right) &\leq (n-1)\log\left(\frac{\mathrm{Tr}\left(\sqrt{T}^+ G\sqrt{T}^+\right)}{n-1}\right) \\
&= (n-1)\log\left(\frac{\mathrm{Tr}\left(T^+ G\right)}{n-1}\right) \\
&= (n-1)\log\left(\frac{\mathrm{st}_G\left(T\right)}{n-1}\right)
\end{aligned}
$$

The lower bound is slightly more involved. Call λ_i the positive eigenvalues of $\sqrt{T^+}G\sqrt{T^+}$ and $\sigma = \mathrm{st}_T\left(G\right)$. We have $1 \leq \lambda_i \leq \sigma$ because of the inequality $T \preceq G \preceq \mathrm{st}_T\left(G\right)T$. There are precisely $n-1$ positive eigenvalues λ_i, and we have: $\mathrm{ld}\left(T^+ G\right) = \sum_i \log \lambda_i$. One can show that $\sum_i \log \lambda_i \geq \log\left(\sigma - n + 2\right)$ by considering the problem of minimizing $\sum_i \log x_i$ under the constraints $\sum_i x_i = \sigma$ and $x_i \geq 1$. This bound is tight. ∎

Intuitively since the stretch of a tree is bounded my $O\left(m\log n\right)$, it means that a low-stretch spanning tree provides an approximation of a log-determinant up to a factor of $O\left(n\log n\right)$. This could be of interest for nearly-cut graphs, with large condition numbers.

5. Incremental sparsifiers

We can do better and achieve near-linear time by using ultra-sparsifiers. The main insight of our result is that the class preconditioners presented by Spielman and Teng are based on incomplete Cholesky factorization, and hence have a determinant that is relatively easy to compute, and that furthermore they are excellent spectral preconditioners, so the procedure `PreconditionedLogDetMonteCarlo` is efficient to apply. We reintroduce some concepts presented in Koutis et al. (2010) to present a self-contained result.

The central idea is to sample $O\left(n\right)$ edges from the graph A, to form a subgraph B that is close to a tree (hence it is easy to compute some partial Cholesky factorization), yet it is close to the original A is the spectral sense ($A \preceq B \preceq \kappa A$), thanks to the additional edges. The partial Cholesky factorization is computed using the `GreedyElimination` algorithm presented in Koutis et al. (2010). In order for this section to be self-contained, we repeat the main results of Section 4 in Spielman and Teng (2009).

Consider a Laplacian matrix G. There exists an algorithm that computes the partial Cholesky factorization:

$$
B = PLCL^T P^T
$$

where:

- P is a permutation matrix

- L is a non-singular, low triangular matrix of the form

$$
L = \begin{pmatrix} L_{1,1} & 0 \\ L_{2,1} & I_{n_1} \end{pmatrix}
$$

  with the diagonal of $L_{1,1}$ being all ones.

- C has the form

$$
C = \begin{pmatrix} D_{n-n_1} & 0 \\ 0 & A_1 \end{pmatrix}
$$

and every row and column of A_1 has at least 3 non-zero coefficients. Furthermore, A_1 is itself Laplacian and:

$$\operatorname{ld}(B) = \sum_{1}^{n-n_1} \log D_{ii} + \operatorname{ld}(A_1)$$

The exact algorithm is detailled that achieves this factorization is presented in Koutis et al. (2010). Using this factorization, the PLD of the original Laplacian A is:

$$\begin{aligned}
\operatorname{ld}(A) &= \operatorname{ld}(B) + \operatorname{ld}(B^+ A) \\
&= \sum_{1}^{n-n_1} \log D_{ii} + \operatorname{ld}(A_1) + \operatorname{ld}(B^+ A)
\end{aligned}$$

Thus, we are left with solving a smaller problem A_1, and approximate the value of $\operatorname{ld}(B^+ A)$ using the algorithm `SampleLogDet`. ST preconditioners are appealing for this task: they guarantee that A_1 is substantially smaller than A, so the recursion completes in $O(\log \log n)$ steps. Furthermore, computing the vector product $B^+ A x$ is itself efficient (in can be done in near-linear time), so the sampling algorithm can be run is reasonable time. We formalize the notion of chain of preconditioners by reintroducing some material from Koutis et al. (2010).

Definition 17 *Definition 7.1 from Koutis et al. (2010). $\kappa(n)$-good chain. $\mathcal{C} = \{A_1 = A, B_1, A_2, \ldots A_d\}$ a chain of graphs with n_i and m_i the number of vertices and edges of A_i. $\mathcal{C}$ is $\kappa(n)$-good for A if:*

1. $A_i \preceq B_i \preceq \kappa(n_i) A_i$

2. $A_{i+1} = \operatorname{GreedyElimination}(B_i)$

3. $m_i / m_{i+1} \geq c_r \sqrt{\kappa(n_i)}$ *for some constant c_r.*

Good chains exist (Lemma 7.3 from Koutis et al. (2010)):

Lemma 18 *(Lemma 7.3 from Koutis et al. (2010)) Given a graph A, `BuildChain`(A, p) from Koutis et al. (2010) produces a $\tilde{O}(\log^4 n)$-good chain for A with probability $1 - p$. The algorithm runs in time*

$$\tilde{O}\left(\left(m \log n + n \log^2 n\right) \log(1/p)\right)$$

These chains furthermore can be used a good preconditioners for conjugate gradient and lead to near-linear algorithms for approximate inversion (Lemma 7.2 from Koutis et al. (2010))

Lemma 19 *(Lemma 7.2 from Koutis et al. (2010)) Given a $\kappa(n)$-good chain for A, a vector x such that $\left\|x - L_A^+ b\right\|_A < \epsilon \left\|L_A^+ b\right\|_A$ can be computed in $O\left(m_d^3 m_1 \sqrt{\kappa(n_1)} \log(1/\epsilon)\right)$*

It should now become clear how we can combine a $\kappa(n)$-good chain with the Algorithm `PreconditionedLogDetMonteCarlo`. We start by building a chain. The partial Cholesky factorizations provide an upper bound to $\operatorname{ld}(A)$. We then refine this upper bound by running `PreconditionedLogDetMonteCarlo` at each state of the chain to approximate $\operatorname{ld}(B_i^+ A_i)$ with high probability. The complete algorithm is presented in Algorithm **??**.

We have three sources of errors introduced in our estimate:

- The truncation of the series of $\operatorname{ld}(B^+ A)$

- The sampling error induced by having a finite number of samples when approximating the trace of $\operatorname{ld}(B^+ A)$

- The approximate inversion by B

The following lemmas show that we can reasonably control the inversion error by running the ST-solver at a higher precision $O\left(\kappa\left(n_1\right)^{-3}\kappa\left(A_1\right)^{-1}\epsilon\right)$. The ST-solvers have some convergence guarantees using the matrix norm induced by A instead of the regular Euclidian norm. The following lemmas deal with this technicality.

Lemma 20 *Consider $M \in \mathcal{S}_n^+$ with $Tr(M) = n$ for all i. Then $\log|M| \leq 0$*

Proof This is a simple consequence of the concavity of the logarithm. Call λ_i the eigenvalues of M, then $\log|M| = \sum_i \log \lambda_i$, and by concavity we have $n^{-1}\sum_i \log \lambda_i \leq \log\left(n^{-1}\sum_i \lambda_i\right) = \log\left(n^{-1}\mathrm{Tr}\left(M\right)\right) = 0$. ∎

We can use the bound on the norm of A to compute bound the error with a preconditioner:

Proposition 21 *Given a $\kappa\left(n\right)$-good chain for A, a start vector x, one can compute an $\epsilon-$estimate of the truncated series:*

$$Tr\left(\sum_{i=1}^{l}\frac{1}{i}\left(I - B_1^{-1}A\right)^i xx^T\right)$$

in time $\mathcal{O}\left(lm\sqrt{\kappa\left(n_1\right)}\left(\log \epsilon^{-1} + \log \kappa\left(n_1\right) + \log \kappa\left(B\right)\right)\right)$.

Proof Consider an $\epsilon-$approximate power sequence $\left(x^{(k)}\right)_k$ with respect to the operator $I - B^{-1}A$, and $\hat{z}$ the truncated sequence:

$$\hat{z} = \sum_{k=1}^{l}\frac{1}{k}\left(x^{(0)}\right)^T x^{(k)}$$

This sequence is an approximation of the exact sequence z:

$$z = \mathrm{Tr}\left(\sum_{i=1}^{l}\frac{1}{i}\left(I - B^{-1}A\right)^i x^{(0)}\left(x^{(0)}\right)^T\right)$$

We now bound the error between the two sequences:

$$|\hat{z} - z| \leq \sum_{k=1}^{l}\frac{1}{i}\left|x_0^T\left(R^k x_0 - x_k\right)\right| \leq \sum_{k=1}^{l}\left|x_0^T\left(R^k x_0 - x_k\right)\right| \leq \sum_{k=1}^{l}\left|\left(B^{-1}x_0\right)^T B\left(R^k x_0 - x_k\right)\right|$$

Using the Cauchy-Schwartz inequality, we obtain:

$$\left|\left(B^{-1}x_0\right)^T B\left(R^k x_0 - x_k\right)\right| = \left|\left\langle B^{-1}x_0, R^k x_0 - x_k\right\rangle_B\right| \leq \left\|B^{-1}x_0\right\|_B\left\|R^k x_0 - x_k\right\|_B$$

so that we can bound the deviation:

$$|\hat{z} - z| \leq \left\|B^{-1}x_0\right\|_B\sum_{k=1}^{l}\left\|R^k x_0 - x_k\right\|_B \leq 4\epsilon\kappa^3\left\|B^{-1}x_0\right\|_B\left\|x_0\right\|_B \leq 4\epsilon\kappa^3\kappa\left(B\right)\left\|x_0\right\|^2$$

where $\kappa\left(B\right)$ is the condition number of B. Now, we can call the ST-solver routine with $\tilde{\epsilon} = \kappa^{-3}\kappa\left(B\right)^{-1}\epsilon$, the cost of each call to the operator R being then $\mathcal{O}\left(m\sqrt{\kappa}\left(\log \epsilon^{-1} + \log \kappa + \log \kappa\left(B\right)\right)\right)$. ∎

We now have all the elements required to prove our main theorem. Now we can use the previous proposition to bound the error done during the estimation part. We have already found some bounds for the estimates of the log-determinant of the preconditioners, and some probability estimates for the error bounds on the trace series.

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Theorem 22 *Consider A a symmetric, diagonally dominant matrix of size $n \times n$ with m non-zero entries, and $0 < \epsilon < \log^{-5} n$. One can compute $y \in \mathbb{R}$ so that $\mathbb{P}\left(|y - \log|A|| > \epsilon\right) \leq \frac{1}{n}$ in expected time $\tilde{O}\left(m\epsilon^{-2} \log^7 n \left(\log\left(\frac{n\kappa(A)}{\epsilon}\right)\right)\right)$.*

Proof Consider a $\tilde{O}\left(\log^4 n\right)$-chain 18 for the Laplacian of A. The cost of constructing such a chain is negligible against the sampling step. From Corollary 5, for each level of the chain, we compute $p = \tilde{O}\left(\epsilon^{-2} \log n\right)$ approximate truncated chains of length $l = \tilde{O}\left(\log^4 n \left(\log n + \log\left(\epsilon^{-1}\right)\right)\right)$. From Proposition 33, the cost of running each chain is $\tilde{O}\left(lm \log^2 n \left(\log \epsilon^{-1} + \log n + \log \kappa(A)\right)\right)$. Thus the time to approximate the residue PLD at level i is bounded by $\tilde{O}\left(m\epsilon^{-2} \log^7 n \left(\log \epsilon^{-1} + \log n + \log \kappa(A)\right)\right)$. Finally, since m_i decreases faster than geometrically, the number d of steps in the chain is $\tilde{O}(1)$. ∎

6. Structural bounds on the log-determinant

How good is the estimate provided by the tree T? Intuitively, this depends on how well the tree T approximates the graph G. This notion of quality of approximation can be formalized by the notion of *stretch*.

Definition 23 *Stretch of a graph. Consider G a weighted graph, and T a spanning tree of G. The stretch of each edge e from G is defined as $st_T(e) = \omega_e \left(\sum_{f \in P} \frac{1}{\omega_f}\right)$ where ω_e is the weight of edge e in G, and P is the unique path between the endpoints of e in the tree T. The stretch of the graph is the sum of the stretches of each edge:*

$$st_T(G) = \sum_{e \in G} st_T(e)$$

The stretch can be obtained as a by-product of the computation of low-stretch spanning trees, of which the construction can be done in $O\left(m \log n + n \log^2 n\right)$ Abraham et al. (2008). Knowing the stretch gives upper and lower bounds on the value of the log-determinant.

Proposition 24 *Stretch bounds on the tree PLD:*

$$\log|T| + (n-1)\log\left(\frac{st_G(T)}{n-1}\right) \geq \log|G| \geq \log|T| + \log\left(st_T(G) - n + 2\right) \tag{6}$$

Proof This is an application of Jensen's inequality on $\mathrm{ld}\left(T^+ G\right)$. We have $\mathrm{ld}G = \mathrm{ld}T + \mathrm{ld}\left(T^+ G\right)$ and $\mathrm{ld}\left(T^+ G\right) = \mathrm{ld}\left(\sqrt{T}^+ G \sqrt{T}^+\right) = \mathrm{Tr}\left(\log^+\left(\sqrt{T}^+ G \sqrt{T}^+\right)\right)$ with $\sqrt{T}$ the matrix square root of T. From Lemma 39, we have

$$\mathrm{Tr}\left(\log^+\left(\sqrt{T}^+ G \sqrt{T}^+\right)\right) \leq (n-1)\log\left(\frac{\mathrm{Tr}\left(\sqrt{T}^+ G \sqrt{T}^+\right)}{n-1}\right)$$

$$= (n-1)\log\left(\frac{\mathrm{Tr}\left(T^+ G\right)}{n-1}\right)$$

$$= (n-1)\log\left(\frac{st_G(T)}{n-1}\right)$$

The lower bound is slightly more involved. Call λ_i the positive eigenvalues of $\sqrt{T^+} G \sqrt{T^+}$ and $\sigma = st_T(G)$. We have $1 \leq \lambda_i \leq \sigma$ because of the inequality $T \preceq G \preceq st_T(G) T$. There are precisely $n-1$ positive eigenvalues λ_i, and we have: $\mathrm{ld}\left(T^+ G\right) = \sum_i \log \lambda_i$. One can show that

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$\sum_i \log \lambda_i \geq \log (\sigma - n + 2)$ by considering the problem of minimizing $\sum_i \log x_i$ under the constraints $\sum_i x_i = \sigma$ and $x_i \geq 1$. This bound is tight. ∎

Intuitively since the stretch of a tree is bounded my $O(m \log n)$, it means that a low-stretch spanning tree provides an approximation of a log-determinant up to a factor of $O(n \log n)$. This could be of interest for nearly-cut graphs, with large condition numbers.

Lemma 25 *Jensen inequality for the matrix logarithm. Given $A \in \mathcal{S}_n^+$, $0 \prec A \prec 2$, the following inequalities hold:*

$$\log\left(\frac{Tr(A)}{n}\right) \geq \frac{1}{n} Tr(\log A)$$

$$ld\left(\frac{Tr(A)}{n-1}\right) \geq \frac{1}{n-1} Tr(\log A)$$

with $\log A = \sum_{k \geq 1} \frac{1}{k}(I - A)^k$

Proof Consider the diagonalization of A: $A = P\Delta P^T$ with Δ a diagonal (positive) matrix, and P an orthogonal matrix. Then

$$\log A = \sum_{k \geq 1} \frac{1}{k}\left(PP^T - P\Delta P^T\right)^k = \sum_{k \geq 1} \frac{1}{k}\left[P(I - \Delta)P^T\right]^k = P\left[\sum_{k \geq 1} \frac{1}{k}(I - \Delta)^k\right]P^T = P\Gamma P^T$$

with Γ a diagonal matrix that verifies $\Gamma_{ii} = \log \Delta_{ii}$. We can then conclude using the concavity of the logarithm over the reals:

$$\log\left(\frac{\text{Tr}(A)}{n}\right) = \log\left(\frac{\sum_i \Delta_{ii}}{n}\right) \geq \frac{1}{n}\sum_i \log \Delta_{ii} = \frac{1}{n}\text{Tr}(\Gamma) = \frac{1}{n}\text{Tr}(\log A)$$

The same reasoning holds for the pseudo-log-determinant while considering all but one eigenvalue ∎

Lemma 26 *Power relation for the matrix log: Given $A \in \mathcal{S}_n^+$, $0 \prec A \prec 2$, and $k \in \mathbb{N}$, then $\log\left(A^k\right) = k \log A$*

6.1 Stretch of a graph

We introduce here a refinement on an upper bound that is a byproduct of using the algorithm XXX.

Definition 27 *We define the **stretch of a graph** $G = (V, E, \omega)$ with respect to a subgraph $H = \left(V, \tilde{E}, \tilde{\omega}\right) \subset G$ by the weighted sum of effective resistances of edges $e \in E$ with respect to the graph H:*

$$st_H(G) = \sum_{e \in E} \omega_e \, eff_H(e)$$

This is a generalization of the notion of stretch defined by Alon, Karp, Peleg and West in .... We can use this definition to generalize theorem 2.1 in Spielman and Woo (2009)

Theorem 28 *Let $G = (V, E, \omega)$ be a connected graph and let $H = \left(V, \tilde{E}, \tilde{\omega}\right)$ be a connected subgraph of G. Let L_G and L_H be the Laplacian matrices of G and H respectively. Then:*

$$Tr\left(L_H^+ L_G\right) = st_H(G)$$

where L_H^+ is the pseudo inverse of L_H.

Proof The proof is nearly identical to that of Spielman and Woo (2009), except for the last line:

$$
\begin{aligned}
\mathrm{Tr}\left(L_H^+ L_G\right) &= \sum_{(u,v)\in E} \omega\left(u,v\right)\mathrm{Tr}\left(L_{(u,v)}L_H^+\right) \\
&= \sum_{(u,v)\in E} \omega\left(u,v\right)\mathrm{Tr}\left((\psi_u - \psi_v)(\psi_u - \psi_v)^T L_H^+\right) \\
&= \sum_{(u,v)\in E} \omega\left(u,v\right)(\psi_u - \psi_v)^T L_H^+ (\psi_u - \psi_v)
\end{aligned}
$$

and the latter term is the effective resistance between u and v in the graph H:

$$
\begin{aligned}
&= \sum_{(u,v)\in E} \omega\left(u,v\right)\mathrm{eff}_H\left(u,v\right) \\
&= \mathrm{st}_H\left(G\right)
\end{aligned}
$$

∎

From a practical perspective, the graph stretch can be computed in $\tilde{O}\left(m\log n/\epsilon^2\right)$

Proposition 29 *There exists an algorithm that computes an ϵ-approximation of $st_H\left(G\right)$ in $\tilde{O}\left(m\log n/\epsilon^2\right)$*

Proof This is the second main result from Spielman and Srivastana (XXX cite). ∎

Comments

A first approximation upper-bound of the log-determinant follows immediately from the computation of the $\kappa-$good chain. We presented in Section 4 a first analysis to bound the value of the residue PLD. This analysis was done using trees as preconditioners, it can be carried on on more general preconditioners by introducing a generalization of the stretch over a subgraph (see the Appendix, section 6.4). Since the bulk of the computations are performed in estimating the residue PLD, it would be interesting to see if this could be bypassed using better bounds based on the stretch.

When looking at each step of the analysis, one can see that the ϵ^{-2} factor comes from the approximation of the trace of a matrix by sampling. This seems to be a fundamental limitation of this method and it is shared with other algorithms that rely on random projections. This result is absolute. It would be interesting to see if the analysis could be tightened to present a relative bound that does not depend on the condition number of A. Also, even if this algorithm presents a linear bound, it requires a fairly advanced machinery (ST solvers) that may limit its practicality. Some heuristic implementation, for example based on algebraic multi-grid methods, could be a first step in this direction.

The authors are much indebted to Satish Rao and Jim Demmel for suggesting the original idea and their helpful comments on the draft of this article.

Appendix A: Proof of Theorem 6

We prove here the main result of Section 2. In the following, A and B are positive-definite matrices in $\mathcal{S}_n$, and B is a $\kappa-$approximation of A ($A \preceq B \preceq \kappa A$). The following notations will prove useful:

$$
S = I - B^{-1/2}AB^{-1/2} \tag{7}
$$

$$R = I - B^{-1}A \tag{8}$$

$$\tilde{R}(x) = x - C(Ax)$$

$$\varphi = \kappa^{-1}$$

Lemma 30 *S and R are contractions for the Euclidian and B−norms:*

$$\begin{aligned} \|S\| &\leq 1 - \varphi \\ \|R\| &\leq 1 - \varphi \\ \|R\|_B &\leq (1-\varphi)^2 \end{aligned}$$

Proof Recall the definition of the matrix norm:$\|S\| = \max_{x^T x \leq 1} \sqrt{x^T S x}$. Since we know that $S \preceq (1-\varphi) I$, we get the first inequality.

The second inequality is a consequence of Proposition 3.3 from Spielman and Teng (2009): A and B have the same nullspace and we have the linear matrix inequality $A \preceq B \preceq \kappa A$, which implies that the eigenvalues of $B^{-1}A$ lie between $\kappa^{-1} = \varphi$ and 1. This implies that the eigenvalues of $I - B^{-1}A$ are between $1 - \varphi$ and 0.

Recall the definition of the matrix norm induced by the B-norm over $\mathbb{R}^n$:

$$\begin{aligned} \|R\|_B &= \max_{x \neq 0} \frac{\|Rx\|_B}{\|x\|_B} \\ &= \max_{\|x\|_B^2 \leq 1} \sqrt{x^T R^T B R x} \\ &= \max_{x^T B x \leq 1} \sqrt{x^T R^T B R x} \\ &= \max_{y^T y \leq 1} \sqrt{y^T B^{-1/2} R^T B R B^{-1/2} y} \end{aligned}$$

and the latter expression simplifies:

$$\begin{aligned} B^{-1/2} R^T B R B^{-1/2} &= B^{-1/2} \left(I - AB^{-1}\right) B \left(I - B^{-1}A\right) B^{-1/2} \\ &= \left(I - B^{-1/2} A B^{-1/2}\right) \left(I - B^{-1/2} A B^{-1/2}\right) \\ &= S^2 \end{aligned}$$

so we get:

$$\|R\|_B = \left\|S^2\right\| \leq \|S\|^2 \leq (1-\varphi)^2$$

∎

The approximation of the log-determinant is performed by computing sequences of power series $\left(R^k x\right)_k$. These chains are computed approximately by repeated applications of the R operator on the previous element of the chain, starting from a Gaussian white noise element $x_0 \sim \mathcal{N}(0, \mathbf{I})$. We formalize the notion of an approximate chain.

Definition 31 Approximate power sequence. *Given a linear operator R, a start point $x^{(0)} \in \mathbb{R}^n$, and a positive-definite matrix B, we define an $\epsilon−$approximate power sequence as a sequence that does not deviate too much from the power sequence:*

$$\left\|x^{(k+1)} - R x^{(k)}\right\|_B \leq \epsilon \left\|R x^{(k)}\right\|_B$$

We now prove the following result that is quite intuitive: if the operator R is a contraction and if the relative error ϵ is not too great, the sum of all the errors on the chain is bounded.

Lemma 32 *Given the previous hypothesis, and assuming furthermore that $\|R\|_B \leq 1 - \eta$ and that $2\epsilon \leq \eta \leq 1/2$, the total error is bounded by $\mathcal{O}\left(\eta^{-3}\epsilon\right)$:*

$$\sum_{k=0}^{\infty} \left\|x^{(k)} - R^k x^{(0)}\right\|_B \leq 4\epsilon\eta^{-3} \left\|x^{(0)}\right\|_B$$

Proof   Call $\omega_k = \left\|x^{(k)} - R^k x^{(0)}\right\|_B$ and $\theta_k = \left\|Rx^{(k)}\right\|_B$. We are going to bound the rate of convergence of these two series. We have first using triangular inequality on the B norm and then the definition of the induced matrix norm.

$$\begin{aligned}
\theta_k &\leq& \left\|Rx^{(k)} - R^k x^{(0)}\right\|_B + \left\|R^k x^{(0)}\right\|_B \\
&=& \omega_k + \left\|R^k x^{(0)}\right\|_B \\
&\leq& \omega_k + \|R\|_B^k \left\|x^{(0)}\right\|_B
\end{aligned}$$

We now bound the error on the ω_k sequence:

$$\begin{aligned}
\omega_{k+1} &=& \left\|x^{(k+1)} - Rx^{(k)} + Rx^{(k)} - R^{k+1}x^{(0)}\right\|_B \\
&\leq& \left\|Rx^{(k)} - R^{k+1}x^{(0)}\right\|_B + \left\|x^{(k+1)} - Rx^{(k)}\right\|_B \\
&\leq& \|R\|_B \left\|x^{(k)} - R^k x^{(0)}\right\|_B + \epsilon \left\|Rx^{(k)}\right\|_B \\
&=& \|R\|_B \,\omega_k + \epsilon\theta_k \\
&\leq& \|R\|_B \,\omega_k + \epsilon\left(\omega_k + \|R\|_B^k \left\|x^{(0)}\right\|_B\right) \\
&\leq& \left[(1-\eta)^2 + \epsilon\right]\omega_k + \epsilon\,(1-\eta)^{2k} \left\|x^{(0)}\right\|_B
\end{aligned}$$

Note that the condition $(1-\eta)^2 + \epsilon \leq 1 - \eta$ is equivalent to $\epsilon \leq \eta - \eta^2$. We can assume without loss of generality that $0 \leq \eta \leq 1/2$. Under this condition, $\eta/2 \leq \eta - \eta^2$. So the condition $2\epsilon \leq \eta$ implies $(1-\eta)^2 + \epsilon \leq 1 - \eta$ which leads to:

$$\omega_{k+1} \leq (1-\eta)\,\omega_k + \epsilon\,(1-\eta)^{2k} \left\|x^{(0)}\right\|_B$$

By induction, one obtains:

$$\omega_k \leq \omega_1\,(1-\eta)^k + \frac{\epsilon\left\|x^{(0)}\right\|_B}{\eta}\,(1-\eta)^{2k-1}$$

and since $\omega_1 = \left\|x^{(1)} - Rx^{(0)}\right\|_B \leq \epsilon\left\|Rx^{(0)}\right\|_B \leq \epsilon\|R\|_B\left\|x^{(0)}\right\|_B \leq \epsilon\,(1-\eta)^2\left\|x^{(0)}\right\|_B$, we have a final bound that depends on ϵ:

$$\omega_k \leq \epsilon\,(1-\eta)^2\left\|x^{(0)}\right\|_B\,(1-\eta)^k + \frac{\epsilon\left\|x^{(0)}\right\|_B}{\eta}\,(1-\eta)^{2k-1}$$

This is the sum of two geometric series, which give the bound:

$$\sum_k \omega_k \leq \epsilon\eta^{-1}\left[1 + \frac{1}{\eta^2\,(1-\eta)^2}\right]\left\|x^{(0)}\right\|_B$$

Since $\eta \leq 1/2$, it implies $(1 - \eta)^{-2} \leq 4$ and $1 \leq \eta^{-2}$, so we can further simplify:

$$\sum_k \omega_k \leq 4\epsilon\eta^{-3} \left\| x^{(0)} \right\|_B$$

■

We can use the bound on the norm of A to compute bound the error with a preconditioner:

Proposition 33 *Given a $\kappa(n)$-good chain for A, a start vector x, one can compute an $\epsilon-$estimate of the truncated series:*

$$Tr\left(\sum_{i=1}^{l} \frac{1}{i} \left(I - B_1^{-1}A \right)^i xx^T \right)$$

in time $\mathcal{O}\left(lm\sqrt{\kappa(n_1)} \left(\log \epsilon^{-1} + \log \kappa(n_1) + \log \kappa(B) \right) \right)$.

Proof Consider an $\epsilon-$approximate power sequence $\left(x^{(k)} \right)_k$ with respect to the operator $I - B^{-1}A$, and $\hat{z}$ the truncated sequence:

$$\hat{z} = \sum_{k=1}^{l} \frac{1}{k} \left(x^{(0)} \right)^T x^{(k)}$$

This sequence is an approximation of the exact sequence z:

$$z = Tr\left(\sum_{i=1}^{l} \frac{1}{i} \left(I - B^{-1}A \right)^i x^{(0)} \left(x^{(0)} \right)^T \right)$$

We now bound the error between the two sequences:

$$|\hat{z} - z| \leq \sum_{k=1}^{l} \frac{1}{i} \left| x_0^T \left(R^k x_0 - x_k \right) \right| \leq \sum_{k=1}^{l} \left| x_0^T \left(R^k x_0 - x_k \right) \right| \leq \sum_{k=1}^{l} \left| \left(B^{-1}x_0 \right)^T B \left(R^k x_0 - x_k \right) \right|$$

Using the Cauchy-Schwartz inequality, we obtain:

$$\left| \left(B^{-1}x_0 \right)^T B \left(R^k x_0 - x_k \right) \right| = \left| \left\langle B^{-1}x_0, R^k x_0 - x_k \right\rangle_B \right| \leq \left\| B^{-1}x_0 \right\|_B \left\| R^k x_0 - x_k \right\|_B$$

so that we can bound the deviation:

$$|\hat{z} - z| \leq \left\| B^{-1}x_0 \right\|_B \sum_{k=1}^{l} \left\| R^k x_0 - x_k \right\|_B \leq 4\epsilon\kappa^3 \left\| B^{-1}x_0 \right\|_B \left\| x_0 \right\|_B \leq 4\epsilon\kappa^3 \kappa(B) \left\| x_0 \right\|^2$$

where $\kappa(B)$ is the condition number of B. Now, we can call the ST-solver routine with $\tilde{\epsilon} = \kappa^{-3}\kappa(B)^{-1}\epsilon$, the cost of each call to the operator R being then $\mathcal{O}\left(m\sqrt{\kappa} \left(\log \epsilon^{-1} + \log \kappa + \log \kappa(B) \right) \right)$.
■

6.2 Pseudo-log-determinant and pseudo-matrix-logarithm

This section provides the proofs related to the PLD. These proofs are elementary and do not provide much insight. In this section, we call $\mathcal{D}_n^+$ the set of all non-zero diagonalizable matrices in $\mathbb{R}^{n \times n}$ with non-negative eigenvalues.

Lemma 34 *Given two non-empty orthornormal families P and Q that span the same space, $P^T Q$ is invertible and we have:*

$$\left(P^T Q \right)^{-1} = Q^T P$$

Proof Move the proof here. ■

Lemma 35 *Given $A \in \mathcal{D}_n^+$ and P an orthonormal basis for $span\,(A)$, we have the relation:*

$$ld(A) = \log \left| P^T A P \right|$$

Proof Since A is diagonalizable, consider its decomposition $A = Q \Delta Q^T$ with Δ a diagonal matrix with positive entries on the diagonal. Note that Δ exists since $A \neq 0$. By definition of the PLD, $\mathrm{ld}\,(A) = \sum_i \log \Delta_i$. Since $\mathbb{R}^n = \mathrm{span}\,(Q) \oplus \mathrm{Ker}\,(A) = \mathrm{span}\,(P) \oplus \mathrm{Ker}\,(A)$, there exists an invertible matrix B such that $Q = PB$. Using the fact that P is an orthonormal family, we get

$$P^T Q = P^T P B = B$$

Furthermore, B is invertible, so $Q B^{-1} = P$. Using the fact that the eigenvalues make an orthonormal family, we get: $B^{-1} = Q^T P$, hence:

$$\left(P^T Q \right)^{-1} = Q^T P$$

Now we wan conclude:

$$\left| P^T A P \right| = \left| P^T Q \Delta Q^T P \right| = \left| P^T Q \right| \left| \Delta \right| \left| Q^T P \right| = \left| \Delta \right|$$

Hence $\log \left| P^T A P \right| = \sum_i \log \Delta_i = \mathrm{ld}\,(A)$. ■

Lemma 36 *Given $A \succ 0$, $B \succ 0$, then AB is diagonalizable and $AB \succ 0$. Same thing for $A \succeq 0$ and $B \succeq 0$.*

Proof The proof of this lemma is in [cite Spielman]. ■

Lemma 37 *Given $A, B \in \mathcal{D}_n^+$ so that $Ker(A) = Ker(B)$, then $C = AB \in \mathcal{D}_n^+$ and $Ker(C) = Ker(A)$.*

Proof Consider the diagonalization of A and B: $A = Q_A \Delta_A Q_A^T$ and $B = Q_B \Delta_B Q_B^T$, and call $D = Q_A^T Q_B$. Since $\Delta_A D \Delta_B$ is invertible, $\mathrm{Ker}\,(C) = \mathrm{Ker}\,(A)$. Furthermore, consider a non-null eigenvalue $u = Q_A s$. Then s verifies the equation:

$$\Delta_A D \Delta_B D^{-1} s = \lambda s$$

So all the eigenvalues of AB are that of $\Delta_A D \Delta_B D^{-1}$, and they are positive from the lemma above. ■

Lemma 38 *Consider $A, B \in \mathcal{D}_n^+$ with $Ker(A) = Ker(B)$, then:*

$$ld(AB) = ld(A) + ld(B)$$

Proof From the lemma above, the product AB is in $\mathcal{D}_n^+$ and the term $\mathrm{ld}\,(AB)$ is well defined. Consider the diagonalization of A and B: $A = Q_A \Delta_A Q_A^T$ and $B = Q_B \Delta_B Q_B^T$. Then

$$
\begin{aligned}
\mathrm{ld}\,(AB) &= \log \left| Q_A^T A B Q_A \right| \\
&= \log \left| \Delta_A Q_A^T Q_B \Delta_B \left(Q_A^T Q_B \right)^{-1} \right| \\
&= \log |\Delta_A| + \log |\Delta_B| \\
&= \mathrm{ld}\,(A) + \mathrm{ld}\,(B)
\end{aligned}
$$

∎

6.3 Other inequalities

Lemma 39 *Jensen inequality for the matrix logarithm. Given $A \in \mathcal{S}_n^+$, $0 \prec A \prec 2$, the following inequalities hold:*

$$
\log \left(\frac{Tr(A)}{n} \right) \geq \frac{1}{n} Tr(\log A)
$$

$$
ld \left(\frac{Tr(A)}{n-1} \right) \geq \frac{1}{n-1} Tr(\log A)
$$

with $\log A = \sum_{k \geq 1} \frac{1}{k} (I - A)^k$

Proof Consider the diagonalization of A: $A = P \Delta P^T$ with Δ a diagonal (positive) matrix, and P an orthogonal matrix. Then

$$
\log A = \sum_{k \geq 1} \frac{1}{k} \left(P P^T - P \Delta P^T \right)^k = \sum_{k \geq 1} \frac{1}{k} \left[P (I - \Delta) P^T \right]^k = P \left[\sum_{k \geq 1} \frac{1}{k} (I - \Delta)^k \right] P^T = P \Gamma P^T
$$

with Γ a diagonal matrix that verifies $\Gamma_{ii} = \log \Delta_{ii}$. We can then conclude using the concavity of the logarithm over the reals:

$$
\log \left(\frac{Tr(A)}{n} \right) = \log \left(\frac{\sum_i \Delta_{ii}}{n} \right) \geq \frac{1}{n} \sum_i \log \Delta_{ii} = \frac{1}{n} Tr(\Gamma) = \frac{1}{n} Tr(\log A)
$$

The same reasoning holds for the pseudo-log-determinant while considering all but one eigenvalue ∎

Lemma 40 *Power relation for the matrix log: Given $A \in \mathcal{S}_n^+$, $0 \prec A \prec 2$, and $k \in \mathbb{N}$, then $\log \left(A^k \right) = k \log A$*

6.4 Stretch of a graph

We introduce here a refinement on an upper bound that is a byproduct of using the algorithm XXX.

Definition 41 *We define the **stretch of a graph** $G = (V, E, \omega)$ with respect to a subgraph $H = \left(V, \tilde{E}, \tilde{\omega} \right) \subset G$ by the weighted sum of effective resistances of edges $e \in E$ with respect to the graph H:*

$$
st_H(G) = \sum_{e \in E} \omega_e \, \mathit{eff}_H(e)
$$

This is a generalization of the notion of stretch defined by Alon, Karp, Peleg and West in .... We can use this definition to generalize theorem 2.1 in Spielman and Woo (2009)

Theorem 42 *Let $G = (V, E, \omega)$ be a connected graph and let $H = \left(V, \tilde{E}, \tilde{\omega}\right)$ be a connected subgraph of G. Let L_G and L_H be the Laplacian matrices of G and H respectively. Then:*

$$Tr\left(L_H^+ L_G\right) = st_H\left(G\right)$$

where L_H^+ is the pseudo inverse of L_H.

Proof The proof is nearly identical to that of Spielman and Woo (2009), except for the last line:

$$
\begin{aligned}
\mathrm{Tr}\left(L_H^+ L_G\right) &= \sum_{(u,v)\in E} \omega\left(u,v\right) \mathrm{Tr}\left(L_{(u,v)} L_H^+\right) \\
&= \sum_{(u,v)\in E} \omega\left(u,v\right) \mathrm{Tr}\left(\left(\psi_u - \psi_v\right)\left(\psi_u - \psi_v\right)^T L_H^+\right) \\
&= \sum_{(u,v)\in E} \omega\left(u,v\right) \left(\psi_u - \psi_v\right)^T L_H^+ \left(\psi_u - \psi_v\right)
\end{aligned}
$$

and the latter term is the effective resistance between u and v in the graph H:

$$
\begin{aligned}
&= \sum_{(u,v)\in E} \omega\left(u,v\right) \mathrm{eff}_H\left(u,v\right) \\
&= \mathrm{st}_H\left(G\right)
\end{aligned}
$$

∎

From a practical perspective, the graph stretch can be computed in $\tilde{O}\left(m\log n/\epsilon^2\right)$

Proposition 43 *There exists an algorithm that computes* an ϵ-approximation of $\mathrm{st}_H\left(G\right)$ in $\tilde{O}\left(m\log n/\epsilon^2\right)$

Proof This is the second main result from Spielman and Srivastana (XXX cite). ∎

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