

Supplementary Material: Gene Regulatory Network Inference as Relaxed Graph Matching

See next page for supplementary material in one column environment.

Proofs

The central optimization problem to solve is given as

$$\min_{W \in \mathbb{R}^{n_p \times n_p}} f(W) \text{ with } f(W) = \frac{(1-\lambda)}{4} \|WW^T - P\|^2 + \frac{\lambda}{4} \|W^T W - C\|^2 + \frac{\gamma}{2} \|W\|^2. \quad (1)$$

Solutions to the optimization problem

Theorem 1. For given $P \in \mathbb{R}^{n_p \times n_p}$ with $P = P^T$ and $C \in \mathbb{R}^{n_c \times n_c}$ with $C = C^T$, for any spectral decomposition $P = U_p D_p U_p^T$ and $C = V_c D_c V_c^T$, $\lambda \in [0, 1]$, $\Delta := D_c^{[n_p]} - D_p$,

$$\frac{1}{\lambda^2} \left(\|P\|^2 + \frac{1}{n_p} \text{tr}(P)^2 \right) + \frac{1}{n_p} (\text{tr}(\Delta))^2 > \|\Delta\|^2, \quad (2)$$

the minimization problem (1) has solutions $W^* \in \mathcal{S}$ with singular value decomposition $W^* = U_p D_w V_c^T$, where

$$d_{w,ii} = \sqrt{\max((1-\lambda)d_{p,ii} + \lambda d_{c,ii} - \gamma, 0)} \quad (3)$$

for $i \leq n_p$. For $d_{w,ii} = 0$, the corresponding columns of U_w and V_w are not restricted to eigenvectors of P and C . The eigenvalues of C are ordered so that $D_c = D_{c,\pi}$, where the permutation solves the minimization problem

$$\pi = \operatorname{argmin}_{\pi' \in \mathcal{P}} \frac{\lambda(1-\lambda)}{2} \|D_p - D_{c,\pi'}^{[n_p]}\|^2 - \frac{\lambda}{2} \|D_{c,\pi'}^{[n_p]}\|^2 + (1-\lambda)\gamma \text{tr}(D_{c,\pi'}^{[n_p]}). \quad (4)$$

Proof of Theorem 1. It is easy to verify that the gradient of the objective

$$f(W) = \frac{(1-\lambda)}{4} \|WW^T - P\|^2 + \frac{\lambda}{4} \|W^T W - C\|^2 + \frac{\gamma}{2} \|W\|^2 \quad (5)$$

is given by

$$\nabla f(W) = WW^T W - (1-\lambda) \frac{1}{2} (P + P^T) W - \frac{1}{2} \lambda W (C + C^T) + \gamma W,$$

which is zero at the extrema of the objective. Note that even for non-symmetric P and C , we could solve the problem for the symmetric $(P + P^T)/2$ and $(C + C^T)/2$. Let us rewrite the gradient with respect to a singular value decomposition of $W = U_w D_w V_w^T$

$$0 = \nabla f(W) = U_w [D_w D_w^T D_w - (1-\lambda) U_w^T P U_w D_w - \lambda D_w V_w^T C V_w + \gamma D_w] V_w^T$$

. Hence, $(1-\lambda) U_w^T (P - \gamma I) U_w D_w + \lambda D_w V_w^T (C - \gamma I) V_w = D$ needs to be a diagonal matrix so that W can be an optimum. Clearly, for $U_w = U_p$ and $V_w = V_c$, we have

$$0 = D_w D_w^T D_w - (1-\lambda) D_p D_w - \lambda D_w D_c + \gamma D_w$$

and solving for D_w leads to $d_{w,ii} = 0$ or $d_{w,ii} = \sqrt{(1-\lambda)d_{p,ii} + \lambda d_{c,ii}}$, where we follow the convention that the singular values of a matrix are positive.

The question remains whether additional zeros of the gradient exist for which $A = (1-\lambda) U_w^T (P - \gamma I) U_w$ and $B = \lambda V_w^T (C - \gamma I) V_w$ are not diagonal matrices but $AD_w + D_w B$ is. As we prove next, this is only possible if W does not have a simple spectrum so that $d_{w,ii} = d_{w,jj}$ for some $j \neq i$.

W is a local minimum iff $AD_w + D_w B = D_w D_w^T D_w$. Hence, $d_{w,ii} = 0$ or $d_{w,ii} = \sqrt{a_{ii} + b_{ii}}$ following the convention that singular values are positive. For off-diagonal elements we have

$$0 = a_{ij} d_{w,ii} + b_{ij} d_{w,jj} \quad (6)$$

Adding the elements corresponding to ij and ji and using the symmetry of A and B we receive $0 = a_{ij}(d_{w,ii} + d_{w,jj}) + b_{ij}(d_{w,ii} + d_{w,jj})$ and thus $a_{ij} = -b_{ij}$ if at least one $d_{w,ii} \neq 0$ or $d_{w,jj} \neq 0$. Plugging this relation back into Eq. (6) leads to $0 = a_{ij}(d_{w,ii} - d_{w,jj})$. For $d_{w,ii} \neq d_{w,jj}$, it follows that $a_{ij} = a_{ji} = 0$ and likewise $b_{ij} = b_{ji} = 0$. Therefore, if W has a simple spectrum with non-zero eigenvalues, $U_w^T U_p$ and $V_w^T V_c$ must be permutation matrices and W of the claimed structure.

So far we have determined the extrema of the objective but which are the global minima? To answer this question, we have to evaluate the objective function, which is $f(W) = (1-\lambda)/4 \|P - U_w D_w D_w^T U_w\|^2 + \lambda/4 \|C - V_w D_w^T D_w V_w^T\|^2 + \gamma/2 \|U_w D_w V_w^T\|^2$ for any $W = U_w D_w V_w^T$. With $\nabla f(W) = 0$ so that $d_{w,ii} = \sqrt{a_{ii} + b_{ii}}$ for $i \leq n_p$, this becomes

$$f(W) = \frac{\lambda(1-\lambda)}{4} \|\tilde{A} - \tilde{B}^{[n_p]}\|^2 + \frac{\lambda}{4} (\|C\|^2 - \|D_c^{[n_p]}\|^2) + \frac{\gamma}{2} (\lambda \text{tr}(D_p) + (1-\lambda) \text{tr}(D_c^{n_p})) - \frac{\gamma^2}{4} n_p, \quad (7)$$

where we define $\tilde{A} = A/(1 - \lambda) = U_w^T(P - \gamma I)U_w$ and $\tilde{B} = B/\lambda = V_w^T(C - \gamma I)V_w$ and use properties of the l_2 norm and the trace, for instance, that both are invariant under multiplication with orthogonal matrices. Furthermore, we make use of the property $\|M\|^2 = \langle M, M \rangle$ with respect to the usual l_2 scalar product $\langle M, N \rangle = \sum_{i,j} i', j' m_{ij} n_{i'j'}$ for matrices M and N of the same dimensions. The next step is to simplify

$$\|\tilde{A} - \tilde{B}^{[n_p]}\|^2 = \frac{1}{\lambda^2} (\|P - \gamma I\|^2 + \|D_w D_w^T\|^2 - 2 \langle D_{\tilde{A}}, D_w D_w^T \rangle), \quad (8)$$

which is the only part of the objective that distinguishes different minima with the same ordering of C 's eigenvalues. We are particularly interested in comparing two cases: (i) W refers to a spectral decomposition of P and C so that $U_w = U_p$ and $V_w = V_c$. (ii) $d_{w,ii} = \text{tr}(A + B^{[n_p]})/n_p$ for all $i \leq n_p$, which allows for non-zero off-diagonal elements of A and minimizes $\|D_w D_w^T\|^2$. Note that the following derivations and arguments would also apply to a combination of (i) and (ii), where $A + B^{[n_p]}$ is comprised of different blocks that are of form (i) or (ii) for a subset of the eigenvalues.

In case (i), we have

$$\|\tilde{A} - \tilde{B}^{[n_p]}\|^2 = \|U_w^T U_p (D_p - \gamma I) U_p^T U_w - (V_w^T V_c (D_c - \gamma I) V_c^T V_w)^{[n_p]}\|^2 = \|D_p - D_c^{[n_p]}\|^2 = \|\Delta\|^2.$$

For case (ii), we utilize representation (8). With $\|D_w D_w^T\|^2 = n_p d_{w,11}^2 = \text{tr}(A + B^{[n_p]})^2/n_p = (\text{tr}(P)(1 - \lambda) + \lambda \text{tr}(D_c^{[n_p]}) - \gamma n_p)^2/n_p$ and $\langle D_{\tilde{A}}, D_w D_w^T \rangle = d_{w,11}^2 \langle D_{\tilde{A}}, I \rangle = d_{w,11}^2 \text{tr}(\tilde{A}) = d_{w,11}^2 (\text{tr}(P) - \gamma n_p)$, we obtain

$$\|\tilde{A} - \tilde{B}^{[n_p]}\|^2 = \frac{1}{\lambda^2} \|P\|^2 + \frac{1}{\lambda^2 n_p} \text{tr}(P) + \frac{1}{n_p} \text{tr}(\Delta)^2.$$

In consequence, a global minimum is achieved by (i) in case that $\|\Delta\|^2 < \|\tilde{A} - \tilde{B}^{[n_p]}\|^2 = \frac{1}{\lambda^2} \|P\|^2 + \frac{1}{\lambda^2 n_p} \text{tr}(P) + \frac{1}{n_p} \text{tr}(\Delta)^2$, which proves Condition (2). The optimal matching of eigenvalues of P and C is then given by minimizing $f(W)$, which is for (i):

$$\begin{aligned} \min_{\pi} f(W) &= \min_{\pi} \frac{\lambda(1 - \lambda)}{4} \|D_p - D_{c,\pi}^{[n_p]}\|^2 + \frac{\lambda}{4} (\|C\|^2 - \|D_c^{[n_p]}\|^2) + \frac{\gamma}{2} (\lambda \text{tr}(D_p) + (1 - \lambda) \text{tr}(D_c^{n_p})) - \frac{\gamma^2}{4} n_p \\ &= \min_{\pi} \frac{\lambda(1 - \lambda)}{2} \|D_p - D_{c,\pi}^{[n_p]}\|^2 - \frac{\lambda}{2} \|D_c^{[n_p]}\|^2 + (1 - \lambda) \gamma \text{tr}(D_c^{n_p}), \end{aligned}$$

where we keep only the terms that are affected by a permutation of the eigenvalues π . This derives Eq. (4) and concludes the proof. \square

Network recovery

Let Φ denote the cumulative distribution function (cdf) of a standard normal and $X \sim \text{Ber}(p)$ a Bernoulli random variable with success probability p .

Proposition 2. *Assume that we observe $P = W^{*T} W^*$, $C = W^* W^{*T}$, and $W_0 = W^* + E$ for a true underlying $W^* \in \mathbb{R}^{n_p \times n_p}$ and noise $E \in \mathbb{R}^{n_p \times n_p}$ with independent identically normally distributed components $e_{ij} \sim \mathcal{N}(0, \sigma^2)$. Further assume that P and C have a simple spectrum $\{d_1, \dots, d_{n_p}\}$. Then, for the spectral approach $\widehat{W} = \text{argmin}_{W \in \mathcal{S}} \|W - W_0\|^2$ with $\gamma = 0$, the recovery loss is distributed as $\|\widehat{W} - W^*\|^2 = 4 \sum_{i=1}^{n_p} d_i^2 R_i$, where $R_i \sim \text{Ber}(\Phi(-d_i/\sigma))$ for $d_i > 0$ and $R_i = 0$ for $d_i = 0$ are independent. For any $\epsilon > 0$, it thus holds with the usual Chernoff bound:*

$$\mathbb{P} \left(\|\widehat{W} - W^*\|^2 \leq \epsilon \right) \geq 1 - \exp \left(\epsilon - \mu - \frac{\epsilon}{4} \delta \log \left(\frac{\epsilon}{\mu} \right) \right),$$

where $\mu = \sum_i p_i$ and $\delta = \frac{1}{\max_i (d_{w,ii}^2)}$ for $\epsilon \leq \mu$ and $\delta = \frac{1}{\min_i (d_{w,ii}^2)}$ otherwise.

Proof of Proposition 2. We assume that the root W is of the form $U D_w D_s V^T$, where we know $U = U_p$, $V = V_c$, and D_w and want to infer the signs D_s with $d_{s,ii} \in \{-1, 1\}$ for $i \leq n_p$. With the input $W_0 = W^* + E$, where the noise $E \in \mathbb{R}^{n_p \times n_p}$ has independent identically normally distributed components $e_{ij} \sim \mathcal{N}(0, \sigma^2)$, the spectral approach leads to the estimate

$$\hat{d}_{s,ii} = \text{sign} \left(\sum_{k,l} u_{ki} w_{0,kl} v_{li} \right) = \text{sign} \left(\sum_{k,l} u_{ki} (w_{*kl} + e_{kl}) v_{li} \right) = \text{sign} \left(d_{w,ii} d_{s,ii}^* + \sum_{k,l} u_{ki} e_{kl} v_{li} \right).$$

To estimate the risk of an error, we therefore need to derive the joint distribution of the random deviations $x_i = \sum_{k,l} u_{ki} e_{kl} v_{li}$. As the $e_{kl} \sim \mathcal{N}(0, \sigma^2)$ are iid, also their linear combinations x_i are jointly normally distributed with $\mathbb{E} x_i = 0$ and covariance

$$\begin{aligned} \mathbb{E}(x_i x_j) &= \mathbb{E} \left(\sum_{k,l,k',l'} u_{ki} u_{k'j} v_{li} v_{l'j} e_{kl} e_{k'l'} \right) = \sum_{k,k'} u_{ki} u_{k'j} \sum_{l,l'} v_{li} v_{l'j} \mathbb{E}(e_{kl} e_{k'l'}) \\ &= \sum_{k,k'} u_{ki} u_{k'j} \sum_{l,l'} v_{li} v_{l'j} \sigma^2 \delta_{k,k'} \delta_{l,l'} = \sigma^2 \sum_k u_{ki} u_{kj} \sum_l v_{li} v_{lj} = \sigma^2 \delta_{ij}, \end{aligned}$$

since U and V are orthogonal and thus also their columns. Thus, $X = (x_1, \dots, x_{n_p}) \sim \mathcal{N}(0, \sigma^2 I)$. This allows us to derive the distribution of the sign errors R_i , which are defined as $R_i = 1$ if $\widehat{d}_{s,ii} \neq d_{s,ii}^*$ and $R_i = 0$ otherwise. Thus, $R_i = (1 - \text{sign}(d_{w,ii} d_{s,ii}^* + x_i) d_{s,ii}^*) / 2$. It follows that these are independent Bernoulli random variables $R_i \sim \text{Ber}(p_i)$ with probability $p_i = \mathbb{P}(x_i \leq -d_{w,ii}) = \Phi(-d_{w,ii}/\sigma)$. Consequently, we have a higher error probability for small singular values $d_{w,ii}$.

It is left to show how these sign errors affect the network recovery loss

$$\|\widehat{W} - W^*\|^2 = \sum_i d_{w,ii}^2 (\widehat{d}_{s,ii} - d_{s,ii}^*)^2 = 4 \sum_i d_{w,ii}^2 R_i \leq 4d_{w,11}^2 \sum_i R_i,$$

where we assume that the singular values are ordered so that $d_{w,ii}^2 \geq d_{w,jj}^2$ for $i < j$. Hence, for all $\epsilon > 0$ we get

$$\begin{aligned} \mathbb{P}(\|\widehat{W} - W^*\|^2 \leq \epsilon) &= \mathbb{P}\left(\sum_i R_i d_{w,ii}^2 \leq \frac{\epsilon}{4}\right) \geq 1 - \min_{t>0} \exp\left(-\epsilon/4t + \mathbb{E}\left(t \sum_i R_i d_{w,ii}^2\right)\right) \\ &= 1 - \min_{t>0} \exp\left(-\frac{\epsilon}{4}t + \prod_i (1 - p_i + p_i e^{d_{w,ii}^2 t})\right) \geq 1 - \min_{t>0} \exp\left(-\frac{\epsilon}{4}t + \sum_i p_i (e^{td_{w,ii}^2} - 1)\right) \\ &\geq 1 - \exp\left(\epsilon - \mu - \frac{\epsilon}{4} \delta \log\left(\frac{\epsilon}{\mu}\right)\right) \end{aligned}$$

for $t = \delta \log(\epsilon/\mu)$, where $\mu = \sum_i p_i$ and $\delta = \frac{1}{\max_i(d_{w,ii}^2)}$ for $\epsilon \leq \mu$ and $\delta = \frac{1}{\min_i(d_{w,ii}^2)}$ otherwise. \square

Gradient dynamics

From a theoretical perspective, we can understand the gradient dynamics for specific choices W_0 as initialization. For this purpose, we take the continuous time (for infinitesimally small step size) approximation and study the corresponding gradient flow:

$$\tau \frac{dW}{dt} = -\nabla f(W) = -WW^T W + (1 - \lambda)PW + \lambda WC - \gamma W, \quad (9)$$

where we set the time unit $\tau = 1$ in the following for simplicity. If the initial W_0 has a similar singular value decomposition as a solution, the differential equation decouples and we can solve the resulting one-dimensional ordinary differential equations for the diagonal elements explicitly.

Proposition 3. For initial $W_0 = U_p D_0 V_c^T$ with $U_p D_p U_p^T$ and $V_c D_c V_c^T$, the solution of the gradient flow (9) is given by $W(t) = U_p D_t V_c^T$ with

$$d_{t,ii} = \text{sign}(d_{0,ii}) d_{w,ii} \sqrt{\frac{1}{2} h\left(d_{w,ii}^2 t + h^{-1}\left(2 \frac{d_{0,ii}^2}{d_{w,ii}^2} - 1\right)\right) + 1},$$

where $h(x) = \tanh(x)$ if $d_{0,ii}^2 < d_{w,ii}^2$ and $h(x) = \coth(x)$ otherwise.

Proof of Proposition 3. We start from the actual gradient descent, whose updates are discrete in time and given by

$$W(t+1) = W(t) - \eta \nabla f(W)$$

with $W(0) = U_p D_0 V_c^T$ and learning rate $\eta > 0$. We prove inductively that $W(t)$ has singular value decomposition $W(t) = U_p D(t) V_c^T$ (where we also allow for negative singular values). Hence, only the singular values change over time while $U_w = U_p$ and $V_w = V_c$ stay constant. Initially, the induction hypothesis is fulfilled according to our assumption, as $W(0) = U_p D_0 V_c^T$. The induction step assumes that $W(t) = U_p D(t) V_c^T$. Then, $W(t+1) = W(t) - \eta \nabla f(W) =$

$U_p D(t) V_c^T - \eta U_p [D(t) D(t)^T D(t) - (1 - \lambda) D_p D(t) - \lambda D(t) D_c + \gamma D(t)] V_c^T$. Thus, $W(t + 1) = U_p D(t + 1) V_c^T$ with diagonal $D(t + 1) = D(t) - \eta [D(t) D(t)^T D(t) - (1 - \lambda) D_p D(t) - \lambda D(t) D_c + \gamma D(t)]$.

The structure of the differential equation is preserved in the limit of infinitesimal stepsize η to obtain the gradient flow:

$$\frac{dD}{dt} = -D D^T D + (1 - \lambda) D_p D(t) + \lambda D(t) D_c - \gamma D(t)$$

so that $W(t) = U_p D(t) V_c^T$. Thus, the differential equations are decoupled and the problem is reduced to solving n_p 1-dimensional differential equations of the form $\frac{dx}{dt} = -x^3 + \mu x$, where μ depends on the respective equation as $\mu_i = (1 - \lambda) d_{p,ii} + \lambda d_{c,ii} - \gamma = d_{w,ii}^2$. We can solve this type of equation by rewriting it as

$$x \frac{dx}{dt} = \frac{1}{2} \frac{dx^2}{dt} = -x^4 + \mu x^2.$$

With a change of variable $s = x^2$, this becomes $\frac{ds}{dt} = 2s(\mu - s)$ so that we can simply integrate

$$\int_{x^2(0)}^{x^2(t)} \frac{1}{\frac{\mu^2}{4} - \left(s - \frac{\mu}{2}\right)^2} ds = 2 \int_0^t dt'.$$

This results in

$$x^2(t) = \frac{\mu}{2} \left[1 + h \left(\mu t + h^{-1} \left(2 \frac{x^2(0)}{\mu} - 1 \right) \right) \right],$$

where $h = \tanh$ if $x_0^2 < \mu$ and $h = \coth$ otherwise. In both cases, $x^2(t)$ does not pass 0 during its evolution. This is relevant, since we have an ambiguity in the sign of $x(t)$ when we know only $x^2(y)$. Passing through 0 would have been the only option for $x(t)$ to switch signs. Therefore, $x(t) = \text{sign}(x(0)) \sqrt{x^2(t)}$ inherits the sign of the initial value. Identifying $x(t)$ with $d(t)_i$ and $\mu = d_{w,ii}^2$ concludes the proof. \square

Correspondence of OTTER to PANDA

PANDA (Passing Attributes between Networks for Data Assimilation) (Glass et al. 2013) is based on the intuition that a gene regulatory matrix W should be the joint root of the gene-gene interaction matrix C and the protein-protein interaction matrix P , i.e. $W^T W \approx P$ and $W W^T \approx C$. This is realized within a message passing framework that iteratively modifies the matrices C , P , and W_0 in discrete time steps t as:

$$P(t + 1) = (1 - \alpha) P(t) + \alpha \frac{W(t) W^T(t)}{r(W(t), W^T(t))}, \quad (10)$$

$$C(t + 1) = (1 - \alpha) C(t) + \alpha \frac{W^T(t) W(t)}{r(W^T(t), W(t))}, \quad (11)$$

$$W(t + 1) = (1 - \alpha) W(t) + \alpha \frac{1}{2} \left(\frac{P(t) W(t)}{r(P(t), W(t))} + \frac{W(t) C(t)}{r(W(t), C(t))} \right), \quad (12)$$

where r denotes a centralization factor $r(M, N) := \sqrt{\|M\|^2 + \|N\|^2} - | \langle M, N \rangle |$ that prevents exploding matrix entries and $\alpha \in [0, 1]$ is a tuning parameter that is set to $\alpha = 0.05$ as a default.

In the following, we will discuss how OTTER relates to the main idea of PANDA and ignore the factor $r(\cdot, \cdot)$, as such a scaling is handled differently by the ADAM gradient descent algorithm. As a reminder, the OTTER gradient descent updates are given by

$$W(t + 1) = W(t) - \eta \gamma W(t) - \eta W(t) W^T(t) W(t) + \eta (1 - \lambda) P(t) W(t) + \eta \lambda W(t) C(t). \quad (13)$$

We claim that these are similar to the PANDA update

$$W(t + 1) = (1 - \alpha) W(t) + \alpha \frac{1}{2} (P(t) W(t) + W(t) C(t)). \quad (14)$$

At first glance, we can identify already the first two terms $W(t) - \eta \gamma W(t)$ and $(1 - \alpha) W(t)$ for $\alpha = \eta \gamma$. It would be tempting to match also the last two $P(t) W(t) + W(t) C(t)$. Yet, a noticeable difference is that PANDA updates $P(t)$ and $C(t)$ while OTTER keeps them fixed to the input. While we cannot resolve this difference completely, we can capture the dependence of $P(t)$ and $C(t)$ on $W(t)$ more adequately. From Eq. (10) we can deduce $P(t) = \frac{1}{1 - \alpha} (P(t + 1) - \alpha W(t) W^T(t))$ and $C(t) = \frac{1}{1 - \alpha} (C(t + 1) - \alpha W^T(t) W(t))$ and plug these into Eq. (14):

$$W(t + 1) = (1 - \alpha) W(t) + \alpha \frac{1}{2} \frac{1}{1 - \alpha} (P(t + 1) W(t) + W(t) C(t + 1) - 2\alpha W(t) W^T(t) W(t)),$$

which looks almost like our OTTER update (13). Only the time dependence of $P(t + 1)$ and $C(t + 1)$ cannot be resolved and remains a difference between the two approaches. Yet, considering that α is usually quite small $\alpha \approx 0.05 - 0.1$ and PANDA takes often only 40 time steps in total, the difference between both approaches is small enough that theoretical insights concerning OTTER should also reflect on PANDA.

Gene regulation

The central dogma of molecular biology describes the flow of information in a cell from DNA to RNA and finally to proteins. DNA is the blueprint of the functional capacity of a cell, and has certain regions - genes - that can be considered functional units. Each gene codes for a specific protein, which, when produced, performs a specific function in the cell. Gene regions in double-stranded DNA are *transcribed* to a single-stranded mRNA transcript molecule that serves as a template for the protein construction. The mRNA transcript is then *translated* into the corresponding protein. The extent to which a protein is expressed, as measured by protein abundance, thus depends (in part) on the extent to which the gene is expressed (transcribed) and the abundance of the corresponding mRNA. The regulation of genes, including under which conditions and to what degree they are expressed, defines a cell's to respond to environmental stimulus, helps define and distinguish individual tissues, allows for developmental processes to occur, and mediates the development and progression of diseases, including their response to therapies. Transcription factors are proteins within the cell that bind to the DNA in "promoter regions" of individual genes and regulate the expression of that gene by recruiting the "transcriptional machinery" to allow mRNA to be synthesized (for a useful review on gene regulation, see (Todeschini, Georges, and Veitia 2014)). Different transcription factors (TFs) regulate different genes in a many-to-many relationship, and sometimes require co-operativity with each other TFs (Figure S1 A). We can represent the regulatory relationships between TFs and genes as a bipartite network (Figure S1 B). Because the TFs are themselves encoded by genes in the genome, the entire regulatory network represents a complex, adaptive system. Differences between biological states, such as between health and disease, are determined by activation or repression of individual regulatory edges between TFs and genes. Because every cell must carry out some basic functions, including respiration and metabolic processes, much of the network active in any two cells will be identical. It is often the small differences in GRN structure between states that define those states.

Datasets for gene regulatory network inference

We demonstrate the functionality of OTTER on three cancer datasets from The Cancer Genome Atlas (<https://www.cancer.gov/about-nci/organization/ccg/research/structural-genomics/tcga>) representing tumors of the liver, cervix, and breast.

Cancer gene expression data

Gene expression data in The Cancer Genome Atlas (TCGA) (Tomczak, Czerwińska, and Wiznerowicz 2015) was downloaded from recount2 (Collado-Torres et al. 2017) at <https://jhubiostatistics.shinyapps.io/recount/> on 01/10/2020.

Defining the dimensions of C and P

For each tissue, we need to define the dimensions of C and P , namely the set of TFs $[n_p] = \{1, \dots, n_p\}$ and the set of genes $[n_c] = \{1, \dots, n_c\}$, respectively. A list of all known TF gene names and ENSEMBL ids was downloaded from http://humantfs.ccb.utoronto.ca/download/v_1.01/TFs_Ensembl_v_1.01.txt and http://humantfs.ccb.utoronto.ca/download/v_1.01/TF_names_v_1.01.txt on 03/09/2020. The reshape R package (Collado-Torres et al. 2017) was used to normalize gene expression measurements as Transcripts Per Million (TPM), which accounts for biases introduced by sample read depth and gene length. For each tissue, we removed genes with consistently low expression, having a TPM ≤ 0.25 across at least 80% of the samples. This resulted in gene sets of size $n_c = 31,247$ for breast tissue, $n_c = 30,181$ for cervix tissue and 27,081 for liver tissue.

Transcription factors were found to have, on average, lower expression than other genes (Figures S1-S3), thus, to include a transcription factor in our analysis, we only required that the transcription factor was expressed with a standard deviation > 0 . All 1,637 were expressed in all tissues, making $n_p = 1,637$ for breast, cervix and liver tissues.

We made the gene expression data after processing available for download at https://netzoo.s3.us-east-2.amazonaws.com/supData/otter/DataS1_Breast/tcga_breast_TPM_otter.txt, https://netzoo.s3.us-east-2.amazonaws.com/supData/otter/DataS1_Breast/tcga_cervix_TPM_otter.txt, and https://netzoo.s3.us-east-2.amazonaws.com/supData/otter/DataS1_Breast/tcga_liver_TPM_otter.txt. Row and column names of the matrix are available on the same homepage at <https://netzoo.github.io/zooanimals/otter/>.

Constructing C , P and W_0

Gene co-expression matrix, C For each tissue, the gene co-expression matrix, representing genes likely co-regulated, was constructed by calculating the Pearson correlation coefficient between all pairs of genes. This resulted in the square matrix C , with dimension $n_c = 31,247$ for breast tissue, $n_c = 30,181$ for cervix tissue and 27,081 for liver tissue. For each tissue, we made it available for download at <https://netzoo.s3.us-east-2.amazonaws.com/supData/otter/corBreast.csv>, <https://netzoo.s3.us-east-2.amazonaws.com/supData/otter/corCervix.csv>, and <https://netzoo.s3.us-east-2.amazonaws.com/supData/otter/corLiver.csv>.

Protein-protein interaction matrix, P A list of protein-protein interactions used in (Sonawane et al. 2017) was downloaded from <https://sites.google.com/a/channing.harvard.edu/kimberlyglass/tools/gtex-networks> on 09/09/2019. These protein-protein interactions were filtered to those involving transcription factors, and used to populate the $n_p \times n_p$ PPI matrices P . Pairs of TFs for which no interaction data was available were set to 0. P is identical for all tissues and available for download at https://netzoo.s3.us-east-2.amazonaws.com/supData/otter/PPI_matrix_breast.txt.

Motif-based GRN prior, W_0 The initial estimate W_0 of the gene regulatory network is constructed based on TF motif information. The FIMO software (Grant, Bailey, and Noble 2011) from MEME suite (Bailey et al. 2009) was used to scan the hg38 human genome assembly for known TF motifs - sequences which are predicted to be bound by specific TFs. Motif matches with a p-value $\leq 10^{-4}$ were considered significant. The positions and IDs of Ensembl genes in the hg38 genome assembly were downloaded from the UCSC Table browser <https://genome.ucsc.edu/cgi-bin/hgTables> on 11/13/2019, and from <https://www.genecodegenes.org/human/> on 03/09/2020. Gene promoter regions were defined as the 1000bp (base pair) region [-750bp, +250bp] around the gene's annotated transcriptional start site, taking into account the strand on which the gene resides. The GenomicRanges R package (Lawrence et al. 2013) was used to overlap motif hits with gene promoters, resulting in a set of TF-gene associations, indicating that a motif of a TF was found overlapping with the promoter region of a gene. These associations were then used to populate the $n_p \times n_c$ matrix W_0 with $W_0[ij] = 1$ if the motif of TF i was found in the promoter of gene j and $W_0[ij] = 0$ otherwise.

They are available for download at https://netzoo.s3.us-east-2.amazonaws.com/supData/otter/DataS1_Breast/motif_prior_matrix_breast.txt, https://netzoo.s3.us-east-2.amazonaws.com/supData/otter/DataS1_Breast/motif_prior_matrix_cervix.txt, and https://netzoo.s3.us-east-2.amazonaws.com/supData/otter/DataS1_Breast/motif_prior_matrix_liver.txt.

ChIP-seq experimental data for validation

Chromatin immunoprecipitation (ChIP)-seq is a technique that allows for the experimental identification of protein-DNA interactions, and can thus provide a validation data set for TF binding of gene promoters. ChIP-seq experiments are performed individually per TF, and thus, one can only obtain binding site information for TFs that have specifically been studied before with this technique. ChIP-seq data consisting of the genome-wide binding regions of select TFs for the HeLa cervical cancer cell line (48 TFs), HepG2 liver cancer cell line (77 TFs) and MCF7 breast cancer cell line (62 TFs) were downloaded from the ReMap2018 database <http://pedagogix-tagc.univ-mrs.fr/remap/> on 01/15/2020. These cell lines represent the closest tissues to those of the expression data for which ChIP-seq data was available. We recognize that many cancers have distinct subtypes that often differ substantially from one-another; we ignore those subtypes given the limitations of the available data and recognizing that subtype differences will be smaller than differences between cervix, liver, and breast tumors ChIP-seq-determined binding regions for each TF in each cell line were mapped to the promoter regions of genes in the same manner as described for motif regions. This allowed us to construct a validation regulatory subnetwork, allowing us to validate the our predicted regulatory relationships from OTTER (and other GRN estimation methods) for the portion of TFs for which ChIP-seq data was available. Precision-recall and ROC curves were calculated using the precec R package (Saito and Rehmsmeier 2017).

The data is available for download at https://netzoo.s3.us-east-2.amazonaws.com/supData/otter/DataS1_Breast/chipseq_postive_edges_breast.txt, https://netzoo.s3.us-east-2.amazonaws.com/supData/otter/DataS1_Breast/chipseq_postive_edges_cervix.txt, and https://netzoo.s3.us-east-2.amazonaws.com/supData/otter/DataS1_Breast/chipseq_postive_edges_liver.txt.

Algorithms and model parameters

The best performing method is based on ADAM gradient descent (Kingma and Ba 2014) as stated below.

Algorithm 1: ADAM gradient descent.

Inputs: $W, P, C, \nabla f(\cdot)$

Parameters: η (learning rate), I (number of iterations)

$\beta_1 = 0.9; \beta_2 = 0.999; \epsilon = 0.00000001;$

$\beta_{1,t} = \beta_1; \beta_{2,t} = \beta_2;$

$m = 0; v = 0;$

for $i = 1, \dots, I$ **do**

$m = \beta_1 m + (1 - \beta_1) \nabla f(W, P, C);$

$v = \beta_2 v + (1 - \beta_2) (\nabla f(W, P, C))^2;$

$\beta_{1,t} = \beta_{1,t} \beta_1; \beta_{2,t} = \beta_{2,t} \beta_1;$

$\alpha = \eta \frac{\sqrt{1 - \beta_{2,t}}}{1 - \beta_{1,t}};$

$\epsilon_t = \epsilon \sqrt{1 - \beta_{2,t}};$

$W = W - \alpha \frac{m}{\epsilon_t + \sqrt{v}};$

end for

We adapt the learning rate η , exponent b , the number of iterations I and the parameters of the gradient for each method that can also take different transformations of the original matrices P_0, C_0, W_0 into account. Our specific choices are listed in Table S1. The respective gradients are defined as $\nabla f = 4WW^TW - 4(1 - \lambda)PW - 4\lambda WC + 2\gamma W$ for OTTER, $\nabla f = P^2W + WC^2 - 2PWC + \gamma W$ for QAP, and $\nabla f = P^2W + WC^2 - 2PWC + \gamma W - \delta J$ for GRAMPA. The remaining methods are parameterized as follows. OTTER (spectral) uses the parameters $\mu = 0.0043208$ and $\lambda = 0.99498$, while the one based on transformed inputs uses $\mu = 0.335$ and $\lambda = 0.0035$. GENIE3 and TIGRESS have been computed only with respect to transcription factors that meet the gene expression filter criterion. Accordingly, we have also restricted the validation to those transcription factors. This was meant to make the task easier but the algorithms still showed inferior performance with respect to binding prediction. We used the default parameters, i.e. random forests consisting of 1000 trees and $K = \sqrt{p}$ for GENIE3 and $nstepsLARS = 5, \alpha = 0.2$, and $nsplit = 100$ for TIGRESS. Furthermore, we had to restrict TIGRESS and PAR COR to the much smaller number of transcription factors in our validation set to reduce the computational load.

Computational complexity

OTTER GRAD computes T gradient steps (with $T = 60$). Each step costs $O(n_p n_c^2)$ computations. (Most expensive is the multiplication WC). In total, we have a complexity of $O(T n_p n_c^2)$. Yet, the matrix multiplications and additions can be efficiently parallelized depending on the number of available cores. The inference of a GRN in Matlab takes 20 – 30 minutes on a MacBook Pro with 2.9 GHz Intel Core i9 processor and 32 GB 2400 MHz DDR4 memory. This represents a reasonable time in comparison with other methods.

Biological validation

In order to determine whether OTTER networks capture expected biological functional information, we constructed an OTTER network representing healthy liver and cancerous liver, and investigated the biological functions enriched in areas of the networks which differ between cancer vs. healthy expression data.

A similar process as described above was used to construct process gene expression data and construct OTTER networks. The healthy OTTER network was constructed making use of liver gene expression data from The Genotype Tissue Expression Project (GTEx) (Lonsdale et al. 2013), whereas the cancer network was constructed using expression data from TCGA (Tomczak, Czerwińska, and Wiznerowicz 2015). Both gene expression datasets were downloaded from recount2 (Tomczak, Czerwińska, and Wiznerowicz 2015).

From the resulting OTTER networks, a difference network was constructed by taking the absolute value of the difference between corresponding edge weights of the two networks. Lastly, we calculated TF degrees and gene degrees in the resulting difference network, allowing genes and TFs to be ranked by these degrees. Genes/TFs with high “difference degree” are thus those whose neighboring edges have large differences between healthy and cancer networks.

GOrilla (Eden et al. 2009) was then used to determine which Gene Ontology (GO) biological process terms were enriched in the top of the ranked lists vs the bottom, thus determining which biological functions are enriched in those genes/TFs. Enrichment results (Figures S8 and S9, Tables S2, S3) highlighted several expected cancer-related functions and pathways, including cell differentiation, cell-cell adhesion, generation of precursor metabolites and energy, regulation of cell development, cell migration and cell motility. OTTER networks thus capture expected biological signal related to the context of the gene expression data. Note that some of the related tables and figures are not included in this pdf because they are too large to attach them to this file directly but can be found with the provided links.

Supplementary Figures and Tables

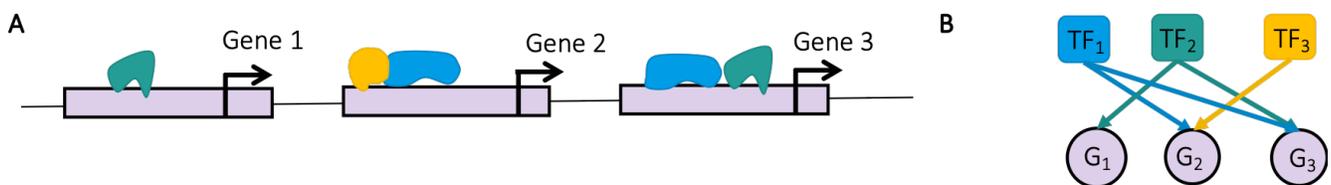


Figure S1: Gene regulation. A. Transcription factors (TFs) are represented by green, blue, and yellow objects that bind to the genome (gray band) in vicinity of the start site of a gene (black arrow) to regulate its expression. B. Representation of A as bipartite gene regulatory network.

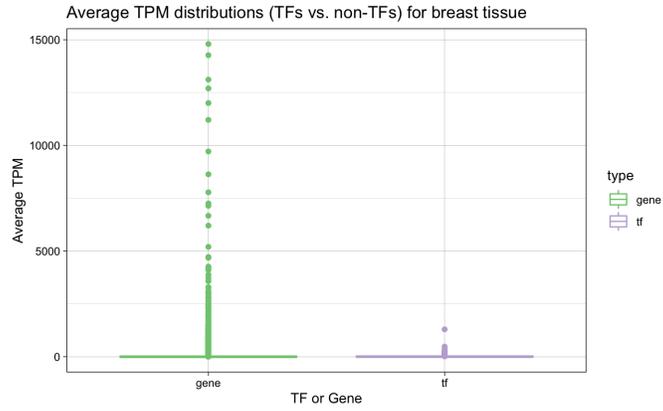


Figure S2: TPM distributions for breast tissue.

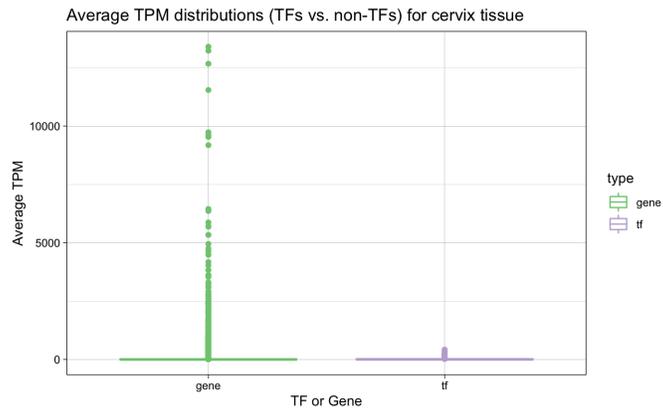


Figure S3: TPM distributions for cervix tissue.

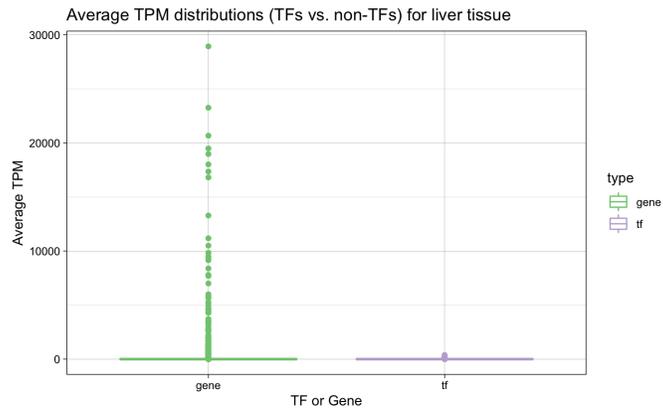


Figure S4: TPM distributions for liver tissue.

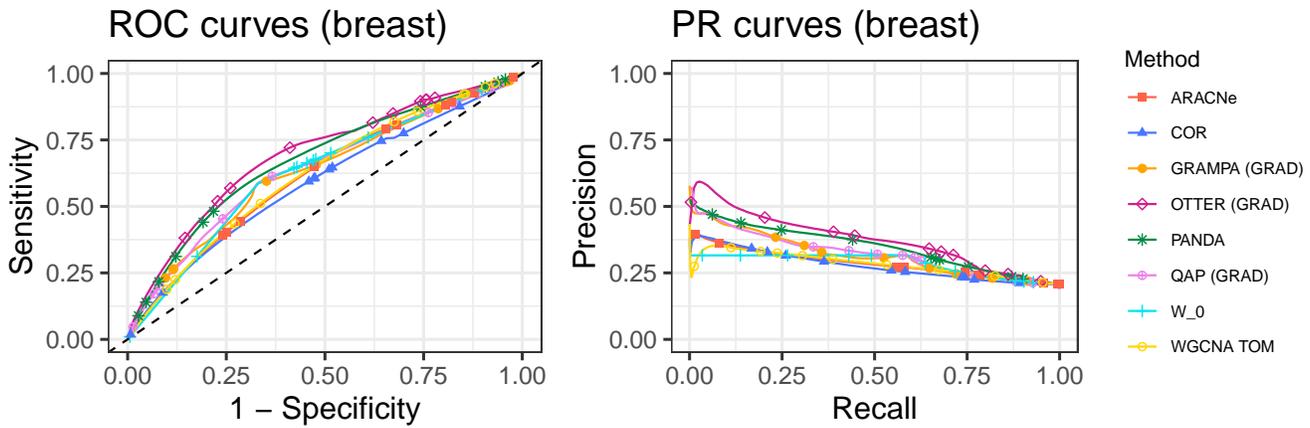


Figure S5: Performance curves for breast.

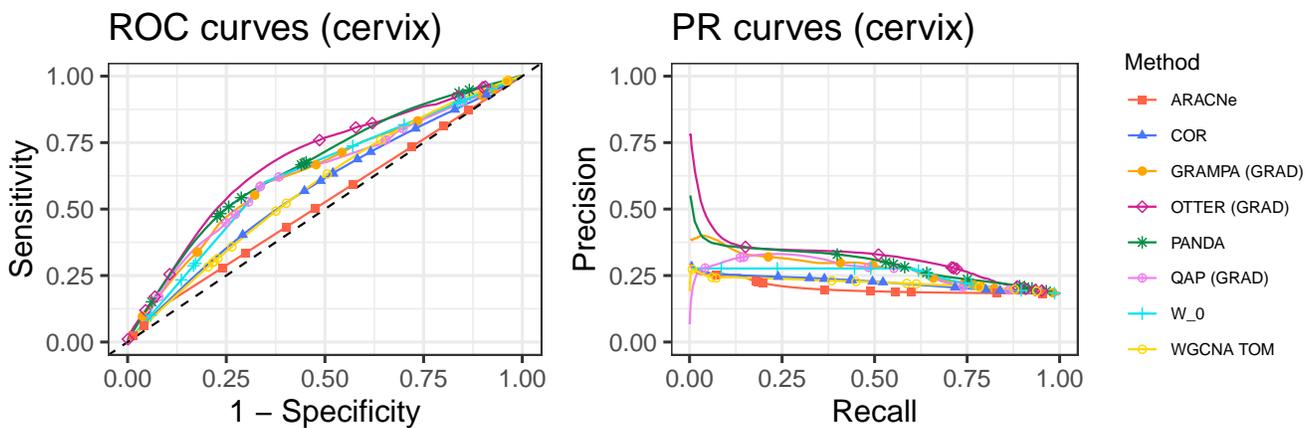


Figure S6: Performance curves for cervix.

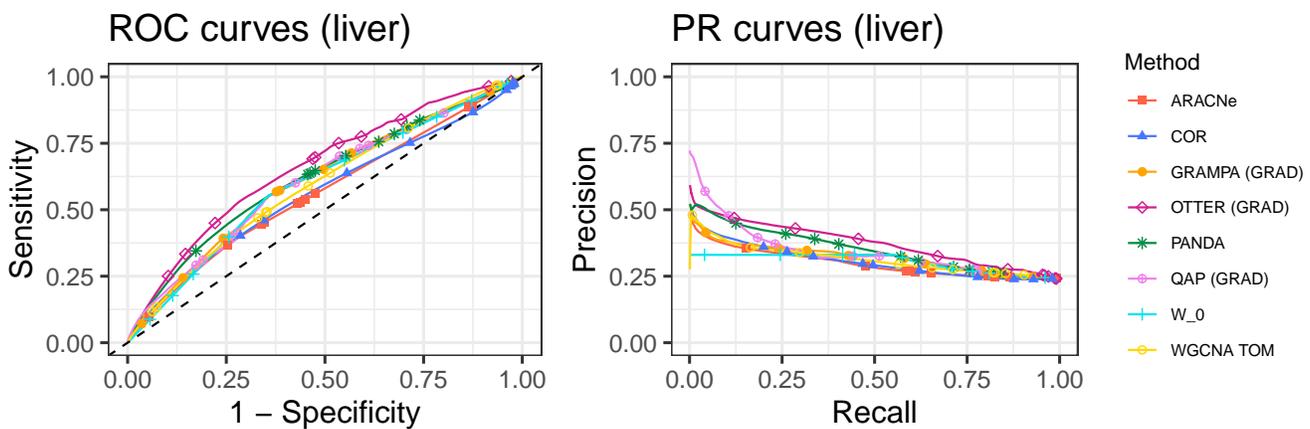


Figure S7: Performance curves for liver.

Figure S8: Gene Ontology (GO) term enrichment visualization for healthy (GTEx) vs cancerous (TCGA) liver tissue gene differential degree. Enrichment performed and visualized using GOrilla (Eden et al. 2009). See file *FigureS7.png*:https://netzoo.s3.us-east-2.amazonaws.com/supData/otter/Supplementary_Figures.zip

Figure S9: Gene Ontology (GO) term enrichment results for healthy (GTEx) vs cancerous (TCGA) liver tissue TF differential degree. Enrichment performed using GOrilla (Eden et al. 2009). See file *FigureS7.png*: https://netzoo.s3.us-east-2.amazonaws.com/supData/otter/Supplementary_Figures.zip

Table S1: Parameters for models taking P and W_0 into account.

	INPUTS			η	PARAMETERS		
	W	P	C		I	γ	MISC.
GRAMPA GRAD	$W_0/\sqrt{\text{tr}(W_0W_0^T)}$	$P_0/\text{tr}(P_0)$	$C_0/\text{tr}(C_0)$	0.00001	4	0.35	$\delta = 0.00001$
QAP GRAD	$W_0/\sqrt{\text{tr}(W_0W_0^T)}$	$P_0/\text{tr}(P_0)$	$C_0/\text{tr}(C_0)$	0.00001	17	0.35	-
OTTER GRAD	$W_0/\sqrt{\text{tr}(W_0W_0^T)}$	$P_0/\text{tr}(P_0)$	$C_0/\text{tr}(C_0)$	0.00001	60	0.335	$\lambda = 0.035$
PANDA	W_0	P_0	C_0	-	40	-	$\alpha = 0.1$

Table S2: Gene Ontology (GO) term enrichment results for healthy (GTEx) vs cancerous (TCGA) liver tissue gene differential degree. Enrichment performed using GOrilla (Eden et al. 2009). See *TableS2.xlsx*: https://netzoo.s3.us-east-2.amazonaws.com/supData/otter/Supplementary_Tables.zipTable S3: Gene Ontology (GO) term enrichment results for healthy (GTEx) vs cancerous (TCGA) liver tissue TF differential degree. Enrichment performed using GOrilla (Eden et al. 2009). See *TableS3.xlsx*: https://netzoo.s3.us-east-2.amazonaws.com/supData/otter/Supplementary_Tables.zip

Supplementary Data

The supplementary data can be found at <https://netzoo.github.io/zooanimals/otter/>. The inferred networks are available for download at <https://grand.networkmedicine.org/cancers/>.

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